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Faculty of Natural Sciences and Engineering | Department of Textiles, Graphic Arts and Design

CROSSING BOUNDARIES

50th International Symposium on Novelties in Textiles

10th Conference on Information and Graphic Arts Technology

PROCEEDINGS

29–30 May 2025,
Ljubljana, Slovenia

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KEYNOTE LECTURES

ORAL PRESENTATION

CLOSING THE LOOP: APPLICATION OF TRANSFORMATIVE SUSTAINABILITY PEDAGOGY AND ACTION RESEARCH TO IMPLEMENT SCALABLE ZERO TEXTILE WASTE MODEL AT A UNIVERSITY CAMPUS

Iva Jestraijević[1]

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To address the textile industry's waste issues, textile waste (TW) prevention programs are crucial. The Transformative Sustainability Pedagogy (TSP) approach has been praised for using educational interventions to create transformational sustainability learning in higher education settings. From the TSP perspective, university campuses, as living labs, represent perfect conditions for conducting action research providing students opportunities to "get their hands dirty" while trying to find solutions for existing problems that go far beyond the classroom. This study contributes to the scholarship on sustainability education in the postsecondary textile and apparel field by providing practical guidance on embedding TSP and action research into the purposeful creation of a campus wide TW prevention project. In March 2024, action research was undertaken by a faculty member at a large Southwestern university to support transformative learning about TW prevention through a yearlong campus project geared towards the collection and redirection of TW from local communities and landfills through creative reuse, recycling, donation, and swap events. This project had four main objectives: 1.) to use campus as a living laboratory for testing and implementing solutions for circular, closed-loop TW systems; 2.) to engage students in action research in which students were taught how to collect, sort, manage, and divert TW during one school year; 3.) to collect data on TW diversion rates iteratively assessing social and environmental benefits of the project; 4.) to propose tested, scalable and replicable solutions to tackle TW on a university campus. The results demonstrated the high effectiveness of the zero TW project and TSP. Within a year, the achieved environmental impact included over 8,280 collected items which resulted in the diversion of 2.2 tons (4840 pounds) of textiles from local landfills. Social impact accounted for 67% of collected items that were given back to those in need. In financial terms, this would be equivalent to $13,558.21 of monetary savings that would be otherwise spent if all recipients of free garments purchased them in a thrift store. The project engaged 200 student volunteers, while close to 600 students attended thrifting and sorting events. Researchers collected 224 written reflections where students unanimously commented on how participation in this project transformed their awareness of TW issues, their attitudes, and behaviors. Students echoed numerous benefits that this project created. Specifically, 45% of comments praised the environmental impact of the project, 25% praised the accessibility to clothing the initiative offered, 57% valued the community-building, and 15% made note of financial relief. The identified advantages of living lab and TSP are many. First, this project offers practical and tangible benefits as items recovered are reused and they are prevented from entering a landfill. Second, project offers replicable models for other educational institutions. Third, TSP, in the context of live labs, presents a powerful tool that can transform a campus from a passive to an active environment for teaching and learning. Lastly, this project opened a door for community building, fostering a sense of belonging and shared purpose among individuals that otherwise would not be connected.

Keywords: *zero textile waste, Transformative Sustainability Pedagogy, university campus, textile waste sorting, community building*

ORAL PRESENTATION

LIVING IN A CONTAINER

Dan Podjed[1]

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Abstract: *This article examines the container as a metaphor for globalization, standardization and isolation in a time of unprecedented technological development. Through an ethnographic case study of the earthquake in Petrinja, Croatia, it shows how containers have become a central element in the organization of human life in times of crisis and beyond. Using examples ranging from post-earthquake settlements to shopping malls and stadiums, the article argues that containers symbolize a broader societal trend towards modular, interchangeable and increasingly alienated lives within predefined boundaries – both in physical and digital reality. The discussion establishes a link between this „container life“ and broader processes of globalization, late capitalism and digital isolation, suggesting that our existence is becoming increasingly compartmentalized – physically, digitally, socially, ideologically and spiritually.*

Keywords: *container; globalization; standardization; isolation; post-disaster recovery*

1. INTRODUCTION

In an era defined by the movement of goods, ideas, and people, the container has become one of the central symbols of globalization. Emerging from the post-WWII drive for efficiency and compatibility, it embodies the pursuit of standardization and homogenization that characterizes global interconnectedness. However, the container is not just a technical and industrial innovation; instead, it can be understood as a “homogenizing machine,” shaping economies, societies, cities, settlements, and even individual ways of living. From the standardized ports of international trade to the *ad hoc* container settlements, the container has infiltrated daily existence far beyond its original logistical function.

This paper, based on ethnographic field research, carried out in 2023, explores the metaphorical meaning of containers, drawing connections between their use in post-disaster locations and their broader significance in a world increasingly organized into modular, isolated, and interchangeable units. In doing so, it asks whether “containerization” reflects deeper social transformations toward alienation, standardization, and life within ever more rigid boundaries and confined structures.

2. THEORETICAL BACKGROUND

The image of universality, standardization, and homogenization, represented by a container, is important for understanding the phenomenon associated with globalization. Creating comparability is a central feature of globalization, explains Thomas Hylland Eriksen (2014) and points to shipping containers as a prerequisite for modern globalization that is just as important as the launch of the first communications satellites.

Why did the container change the world so much? Before standardized containers were introduced in shipping, goods were loaded directly from trucks or trains onto ships. In the mid-1950s, Malcolm McLean, a truck driver, came up with an innovation: he designed a standard-sized container to make it easier to load and transport goods, thereby contributing to the standardization of transport. He succeeded, and today containers are a key element of global trade. The vast majority of goods transported abroad are shipped in containers that are loaded and unloaded at specialised ports and terminals around the world. Standardisation also includes the introduction of automated container handling systems, which further increase efficiency and reduce costs (Levinson 2006). The logistics of producing, moving and selling the contents of containers is comparable all over the world. The con-

tainer is therefore effectively a “homogenizing machine” (Eriksen 2014: 70) that is transforming the world, perhaps even more than many other high-tech devices.

3. CONTAINER LIFE IN PETRINJA, CROATIA

The study presented in this paper is based on ethnographic research conducted after the 2020 earthquake in Petrinja, Croatia. The main part of the field research was conducted in March 2023, when the author of this paper contacted residents of container settlements and individual container houses through interviews and participant observation. The location was selected for the research as part of a wider study of isolated people and communities in Slovenia and Croatia.

The location became particularly important for the research as a part of Croatia was hit by a natural disaster in 2020. On 29 December that year, the region, which was already struggling, was hit by a devastating earthquake measuring 6.2 on the Richter scale. The epicenter was about three kilometers from Petrinja, Croatia, a small town with a population of around 15,000. The consequences of the earthquake were devastating, with more than 40,000 houses and infrastructure facilities in the broader region of Banija damaged or destroyed, and the total financial damage estimated at €5.5 billion (Kersten-Pejanić 2022: 103). The earthquake, which destroyed towns, villages, and hamlets in Banija, forced many locals to seek shelter in temporary dwellings – either in containers placed in front of their homes or in container settlements built in Petrinja, Glina, and Sisak. At the beginning of 2021, three large settlements resembling refugee camps and similar structures erected in crisis areas around the world sprang up on the outskirts of Petrinja. The settlements were built on vacant lots, many of which have connectivity and accessibility issues, mainly due to dilapidated roads. The next problem for the residents of the settlements was overcrowding, as individuals often had to share their place with other people.



Figure 1: Consequences of the earthquake in Petrinja (photo credit: Dan Podjed, March 2023)

Containers have – as presented more in-depth in other publications (see, e.g., Peternel & Podjed 2024) – left their mark on the image of Petrinja, and the “outsiders” are greeted by a huge “homogenizing machine” when they arrive in the town and park next to a huge temporary building that had been erected a few months after the earthquake to provide essential infrastructure for the residents of the container settlement: shops, restaurants, cafés... The scene is even more surprising because of the design of the complex, which could have been found anywhere, as it resembles similar “non-places” (Augé 1992) elsewhere in the world. The complex, somewhat paradoxically and ironically named the Center of New Life (Croatian: *Centar novog* života), was built in September 2021, nine months after the earthquake. It consists of 168 shipping containers and houses 50 companies, which employed

163 people at the time of the study. The building, painted in a striking red, black, and white pattern, was soon unofficially named by locals Šarengrad, meaning "Colorful City." Some found the structure interesting and attractive when it was first erected, while others insisted that they would never set foot in such a grotesque building, as it did not fit into their home environment.



Figure 2: Center of New Life, constructed of 168 shipping containers, in Petrinja, Croatia (photo credit: Dan Podjed, March 2023)

4. OTHER EXAMPLES OF CONTAINERIZATION

What if our lives have become "container lives" – even beyond the post-earthquake sites and the physical reality? Perhaps the online social media have made people isolated in different digital "containers," which Eli Pariser (2012) calls "filter bubbles." In them, people mainly see themselves and their own problems, forgetting about the world beyond the mental barrier designed to "filter" information. When we start perceiving the world from such a perspective, the container is in fact turned in the central metaphor of the present world. Things we use and eat come to us in containers. We throw things away when they have served their purpose, and food leftovers that we do not eat also end up in containers. People who find themselves in distress and have no roof over their heads after an earthquake or other natural disaster are put in containers. Even the construction workers who come from abroad to help rebuild infrastructure after a disaster find shelter in them.

However, containers are not just grim dwellings where people find shelter in times of crisis. They are also objects of desire, especially when they are converted into "mobile homes" where families can enjoy their holidays by the sea. In Qatar, shipping containers were even used to build a magnificent football stadium, which hosted the 2022 World Cup. The central idea behind the construction of this facility, called Stadium 974, was that it would be dismantled after the event and the containers used for other temporary structures and buildings. (The number 974 in the name of this huge structure was not chosen at random, as it represents the number of shipping containers used to build it, and is also Qatar's international dialing code.) The shipping container was therefore a central, but perhaps overlooked, metaphor for an event watched by a billion and a half people around the world.



Figure 3: Stadium 974 during the 2022 FIFA World Cup, Doha, Qatar (photo credit: Wikipedia, CC BY-SA 4.0)

5. CONCLUSION

After all, containers are also a kind of everyday dwelling, i.e., apartments and houses that are becoming increasingly standardized and uniform, where people are often confined and isolated, even though they are actually next to each other. In apartments in reinforced concrete blocks and high-rises, they can hear their neighbors, and the whole building echoes when someone is renovating their apartment and drilling into the walls with a power tool.

The constitutive idea behind them is that people can be physically close to each other, but remain isolated and anonymous, or – as Karl Marx argued – alienated from the community and work, which divides the individual himself and transforms him into an automatic mechanism for performing a partial task (Marx 1961: 410). Such individualisation leads not only to the automatization of work, but also to general alienation – as if we were all locked in boxes, making even those who are physically close to us seem like strangers (cf. Krašovec 2021 with a similar discussion of alienation from work and existence, as well as the “alienization of capital” in the age of new technological solutions).

From this perspective, containers could also predict the future. Perhaps in the era of late capitalism, which is turning into “technofeudalism” (Varoufakis 2023), such dwellings represent ideal units for living and working, which can take place entirely within a container. As mentioned, containers bring people things and food, and then they throw their trash into containers, and in a container called a coffin, they leave this world. This is another reason why life is becoming increasingly containerized – and consequently isolated within the pre-defined boundaries.

6. ACKNOWLEDGEMENTS:

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7. REFERENCES:

Augé, M. 1992. *Non-places: Introduction to an Anthropology of Supermodernity.* Le Seuil: Verso.
Eriksen, T. H. 2014. *Globalization: The Key Concepts* (2nd edition). London & New York: Bloomsbury.
Kersten-Pejanić, R. 2022. "The Good, the Bad, and the Needy: Discourses of Helpfulness after the 2020 Earthquakes in Croatia." *Comparative Southeast European Studies* 70 (1): 103–124.
Krašovec, P. 2021. *Tujost kapitala [Alien Capital].* Ljubljana: Sophia.
Levinson, M. 2006. *The Box: How the Shipping Container Made the World Smaller and the World Economy Bigger.* Princeton (NJ): Princeton University Press.
Marx, K. 1961 (1867). *Kapital – Kritika politične ekonomije: Proces produkcije kapitala* (volume 1, book 1). Ljubljana: Cankarjeva založba.
Pariser, E. 2012. *The Filter Bubble: How the New Personalized Web Is Changing What We Read and How We Think.* New York: Penguin Books.
Peternel, L. & Podjed, D. 2025. "Container Life in Post-earthquake Croatia." Focaal (online first): 1–14. Available at: https://doi.org/10.3167/fcl.2024.100702
Podjed, D. 2024. *Krizolacija: Znanstveno branje o izoliranih ljudeh [Crisolation: Scientific Reading about Isolated People].* Ljubljana: Založba ZRC.
Varoufakis, Yanis. 2023. *Technofeudalism: What Killed Capitalism.* London: The Bodley Head.

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ORAL PRESENTATION

INNOVATING THE SKIES: PIPISTREL'S COMPOSITE REVOLUTION WITH TEXTILES, ADVANCED MATERIALS AND 3D TECHNIQUES IN AVIATION

Ingrid Heuffel Berginc

Pipistrel, d.o.o., Slovenia

The revolution of new technologies and development is reflected in Pipistrel's efforts to push boundaries. One of the company's greatest achievements is the Velis Electro, the world's first certified electric aircraft. Since 2022, Pipistrel has been part of Textron Inc., enabling further advancements in cutting-edge technologies, high-quality systems, and sustainable aviation solutions.

A key milestone in 2025 marks progress in the development of advanced, sustainable, and multifunctional unmanned aerial systems with the Nuuva V300 (eVTOL UAV)—a revolutionary autonomous electric vertical takeoff and landing (eVTOL) aircraft. Designed for cargo logistics and delivery, it offers 10 times greater efficiency than today's helicopters, requires no runways, and enhances safety and reliability through Pipistrel's certified electric motors.

Humanity has always faced risks, and unidentified, overlooked, or poorly managed risks often lead to errors. In aviation, where technological processes are highly complex and follow precisely defined timeframes, even the smallest mistake can have serious consequences. At Pipistrel, we are acutely aware of this, which is why we strive for the highest safety standards, continuous technological improvements, and meticulously controlled procedures. Our goal is to ensure that innovations in sustainable aviation not only drive progress but also guarantee the highest possible level of safety for everyone involved in air traffic.

An essential tool for enhancing safety culture and quality at Pipistrel is our Safety Management System (SMS), which enables early risk detection and error management. Additionally, our Quality Assurance System, aligned with EASA aviation regulations, ensures compliance with industry standards.

To achieve the required quality standards in aircraft component manufacturing (fuselage, wings, etc.), Pipistrel uses various advanced materials. Understanding material structure and properties and conducting quality tests are critical.

The materials used in Pipistrel aircraft are modern composite materials—consisting of two or more different materials at a macroscopic level. These materials offer low weight, high strength, dimensional stability under extreme conditions, and corrosion resistance. The two main production technologies used are: wet lamination and prepreg technology.

Prepreg (pre-impregnated fibers) are composite materials where fibers are already impregnated with resin in a controlled environment. This process ensures higher repeatability, improved mechanical performance, and reduced risk of errors as the materials cure under high temperature and pressure in an autoclave. Prepreg is commonly used in high-performance aircraft and complex structures.

To ensure quality control, both destructive and non-destructive testing methods are employed during the composite part manufacturing process. A crucial quality characteristic is the adhesion between the matrix and the reinforcement element, which ensures the final strength of the composite product.

In addition to composite parts, 3D printing technology is also used in Pipistrel aircraft components. HP's Multi Jet Fusion (MJF) technology has revolutionized design and production processes, enabling the manufacture of complex components that would be impossible to create using traditional methods.

3D-printed parts are mechanically equivalent to injection-molded plastic, isotropic, waterproof, and airtight, without requiring additional tooling—a 3D model is sufficient.

The key advantage of 3D printing is the ability to produce complex parts in a single piece, simplifying manufacturing and reducing aircraft production time. Other benefits include weight savings, increased precision, improved aesthetics, and the elimination of additional subassembly steps.

Overall, 3D printing enhances the quality, durability, and adaptability of aircraft components, representing a significant step forward in modernizing aviation manufacturing.

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CROSSING BOUNDARIES

50th International Symposium on Novelties in Textiles





INVITED LECTURES

SESSION-INVITED LECTURE

ORAL PRESENTATION

BETI'S TRANSFORMATION FROM A LABOUR–INTENSIVE TO A DEVELOPMENT–AND INNOVATION–ORIENTED COMPANY

Petra Kovačič[1]

[1]BETI textile industry d.o.o., Slovenia

Abstract: *Beti is a leading European manufacturer of sustainable and functional dyed yarn. The beginnings of the company Beti date back to the year 1959. Over the years, Beti has specialized in the production of polyamide and polyester yarn. Beti yarn is exported all over the world from Europe, North America, North Africa, Middle East and even to Asia. Besides the traditional markets of Italy, France and United States, we have strengthened our presence in Central and Northern Europe in the last years. The main users of Beti's yarn are manufacturers in the sportswear, fashion, technical and medical textile industries who are committed to achieving sustainability goals. Leading sports and fashion brands are setting ambitious sustainability targets, such as reaching 50% sustainable product lines by the end of 2025. Beti's development activities are strategically aligned with these development objectives, in order to support clients' sustainability efforts while enhancing competitive market position. The most recent research projects are focused on development of: i) yarn with a low carbon footprint to reduce water, energy, dyestuff and chemical consumption, ii) advanced functional yarn for smart textiles, iii) yarns for thermo-regulation, iv) a distinctive collection of Slovenian sustainable underwear considering circular design principles. In Beti we are aware that every small innovation in processes, products and technologies contributes to more efficient, sustainable, and value-driven future. With everyday research activities Beti is thus transitioning from a labor-intensive to a development- and innovation oriented company.*

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SESSION-INVITED LECTURES

ORAL PRESENTATION

INNOVATIVE MATERIAL AND ETHICS EXPLORATION IN FASHION: THE WORK OF TINA GORJANC

Tina Gorjanc Safhalter[1]

[1]Freelance designer, Slovenia

Abstract: *Wearable design is evolving alongside other design disciplines by increasingly integrating scientific methods to tackle urgent ethical and sustainability challenges. Tina Gorjanc's work exemplifies this transformative shift, blending biotechnology and scientific data analysis with experimental material innovation to challenge conventional materials and spark critical discussions on design-related ethics. Through her projects, Gorjanc questions traditional perceptions of sustainability and ethical design, pushing the boundaries of what is possible, implementable or acceptable. This presentation seeks to illuminate her work's methodology and design thinking, showcasing how design within planetary boundaries can redefine creativity, responsibility, and innovation in the modern design landscape.*

Keywords: *Holistic Design, Material Innovation, Critical Fashion*

1. INTRODUCTION

Tina Gorjanc critiques the idea of "silver bullet" solutions in sustainable fashion and advocates for ethically sourced and environmentally appropriate materials tailored to specific contexts. Her designs challenge industry norms, promoting higher ethical standards and holistic sustainability without greenwashing, which is becoming increasingly particularly important in an industry often criticized for its dependence on unsustainable resources, exploitative labour, and profit-driven practices.

2. COLLABORATION BETWEEN SCIENCE AND DESIGN

A cornerstone of Gorjanc's work is her ability to bridge the creative and scientific domains through effective collaboration with scientists. Her partnerships with material scientists and researchers have allowed her to explore experimental technologies that might otherwise remain confined to laboratories. By adopting this interdisciplinary approach, she advances material innovation and underscores the role of design as a tool for science communication. Gorjanc demonstrates how designers can act as mediators, translating complex scientific concepts into tangible artefacts that engage the public and provoke critical debate.

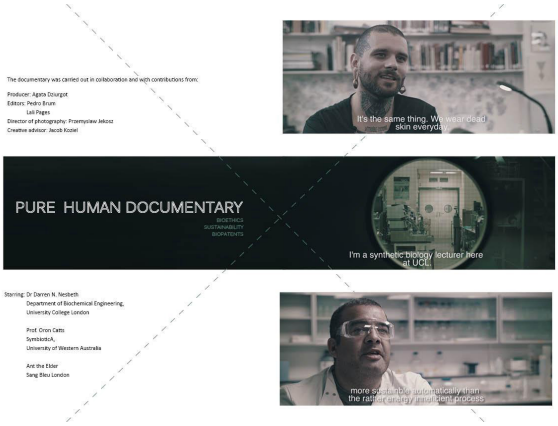


Figure 1: Pure Human Documentary poster

2.1 Pure Human

The Pure Human project exemplifies Gorjanc's commitment to ethical and innovative material design. By creating speculative artefacts—such as leather bags and jackets derived from human genetic material—she explores how biotechnology can produce bespoke materials while addressing provocative ethical and legal questions around ownership and the commodification of human biology.



Figure 2: Tattooed leather jackets mimic inked skin alteration techniques



Figure 3: The pigmented product exploits the ability of the TYR gene to promote the production of the pigment melanin. The stimulation of the gene's performance is achieved with biological agents. Depending on the amount of the applied agent, the accumulated melanin can appear on a more minor (freckles) or larger (moles) scale.

While controversial, Pure Human has drawn critical attention to how biotechnology could transform material production, particularly in industries like fashion, which heavily rely on animal-based resources. The project redefines traditional notions of materiality, encouraging designers and consumers to reconsider the origins and ethical implications of the materials they use and wear.



Figure 4: Pure Human material-making process

The project operates outside traditional commercial frameworks and relies on speculative design principles. This approach assesses how effectively Pure Human navigates the space between current realities and potential future scenarios. In doing so, Gorjanc challenges entrenched assumptions about material use and product roles in everyday life, fostering a reimagining of materials in a more ethically conscious future.

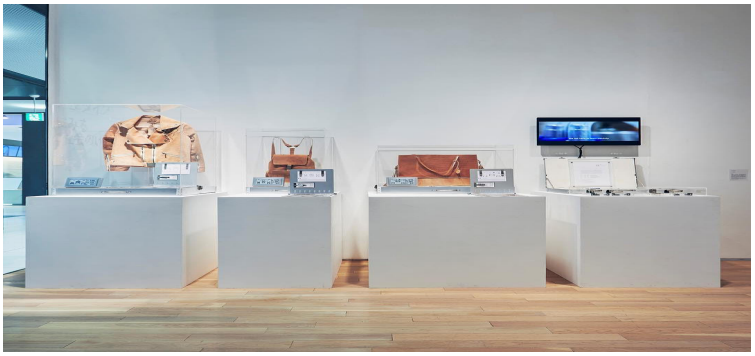


Figure 6: Pure Human whole project display

2.2 Phylogenetic Atelier

With Phylogenetic Atelier, Gorjanc redefines the future of bio-based design. Her participation in renowned events such as Science Gallery Dublin, Artez 2018, and the London Design Festival highlights her commitment to bridging biotechnology and mainstream conversations. These projects push the boundaries of innovation by challenging conventional material lifecycles tied to specific timelines. Using cutting-edge scientific techniques akin to those in science fiction, Phylogenetic Atelier showcases bio-fabricated materials as transformative solutions to critical issues like resource scarcity.



Figure 7: Phylogenetic Atelier whole project display

In collaboration with Revive & Restore, a California-based research lab focused on reviving extinct species, Gorjanc explores sustainable approaches to lab-grown leather. One notable initiative involves recreating „de-extinct“ passenger pigeon leather—achieved without rebounding the extinct bird for over 100 years.

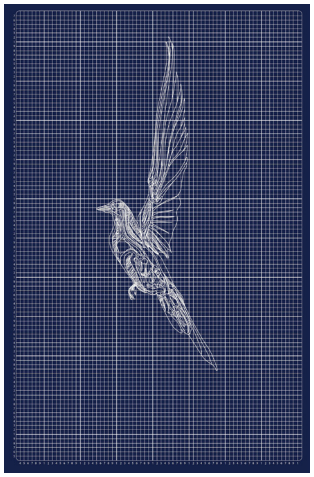


Figure 8: Passenger pigeon blueprint

This project allows audiences to critically examine the potential impacts of such designs before their commercial introduction, guiding development and aligning with sustainable and ethical objectives.



Figure 9: Glove from pigeon leather, which replicates the de-extinct pigeon skin

2.3 Ceros

Beyond speculative design, Gorjanc is committed to raising public awareness about artificially inflated material values and their broader implications. Featured in publications like Dezeen, The Guardian (Jones,2016) and Vice Media (Cole, 2017), she addresses misconceptions about biotechnological processes, tackling fears of „playing God“ and the ethical challenges of genetic modification and artificial material creation.

Ceros represents a transition from speculation to tangible innovation, demonstrating how dark design can foster positive creativity by addressing enduring challenges. During the COVID-19 pandemic, Gorjanc developed a biologically identical alternative to rhino horn in her makeshift home studio, using readily available chemicals. This project critiques the luxury market’s obsession with rhino horn while exposing the ethical issues surrounding wildlife trafficking.



Figure 10: Ceros material sample

By sparking thoughtful discourse, Ceros invites viewers to reflect critically on these controversies, fostering curiosity about laws, political systems, ethics, values, and the broader implications of material culture. It demonstrates how design can be critical for envisioning a more ethical and socially conscious future.



Figure 11: Beaded bracelet from Ceros material



Figure 12: Grinding down bracelet beads for consumption, believed to cure disease in Chinese medicine

3. VISION FOR THE FUTURE OF DESIGN

Gorjanc envisions a future where materials are sustainably sourced and designed to integrate seamlessly into both natural ecosystems and commercial systems. To achieve this, she adopts a multilayered approach. Alongside her provocative conceptual projects, she has launched a creative studio and consultancies that offer more practical, tangible solutions for immediate implementation.

3.1 Material Libraries And Resources For Other Designers

As a permanent Learning Department associate at ITS Arcademy—the Museum of Art in Fashion in Trieste—and through collaborations, including mentoring students from London's fashion universities, Gorjanc actively shares her expertise in innovative material design. She focuses on advancing material fabrication methods that reduce reliance on nonrenewable resources while delivering high-performance alternatives.

By considering the entire lifecycle of materials—from creation to disposal—Gorjanc curates bespoke material libraries for institutions and individuals. This process includes defining sustainable terminology, categorizing areas of interest, and vetting material suppliers. Her work challenges designers to adopt a holistic, systems-thinking approach to material innovation.

Gorjanc's vision aligns with regenerative design principles, where materials are viewed not merely as products but as interconnected components of broader ecological systems. Her efforts encourage designers to embrace sustainability and creativity in tandem.

3.2 Critical Animal

The creative studio operates on the foundation of the consumer vs. citizen paradox, which highlights the disconnect between discussing societal issues as responsible citizens and acting as consumers who shape reality through their purchasing habits. The studio bridges expert knowledge with the public's struggle to navigate information overload, fostering dialogue and critical engagement around ethical and sustainable uses of animal-based materials.

Gorjanc's studio adopts a multifaceted approach to design. It collaborates with one of the world's largest leather trade shows to repurpose deadstock, spearheads recycling initiatives, and creates designs that connect materials to their origins through texture and shape. Additionally, the studio focuses on designing customizable, interchangeable objects, encouraging consumers to adapt or modify items instead of discarding them for new ones. This approach reduces waste and challenges traditional consumption patterns, promoting a more sustainable, mindful relationship with materials.

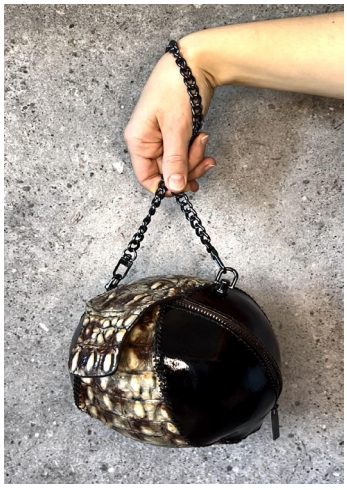


Figure 13: Crock bag

4. CONCLUSION

Tina Gorjanc's work showcases the transformative power of design when guided by ethics, innovation, and a sense of responsibility. She challenges students and emerging designers to push beyond traditional boundaries and explore the vast potential of materials, demonstrating that design is not only about creating aesthetically pleasing products but also about addressing real-world challenges like resource scarcity and ethical dilemmas.

Through projects like Pure Human, Phylogenetic Atelier, and Ceros, Gorjanc encourages rethinking the relationship between design, science, and society. Her work provokes ideas and invites the public to explore speculative concepts that can drive meaningful change. She emphasizes that a designer's role is to challenge conventions, question assumptions, and lead discussions on issues that shape the future.

By embracing interdisciplinary thinking and a holistic approach, designers can redefine materiality, create sustainable solutions, and contribute to an ecosystem where products are not merely objects but integral parts of a more ethical and sustainable world. Gorjanc's vision calls us to think critically, use design as a tool for positive change, and take responsibility for creating with purpose.

5. REFERENCES

Mitrović, I., Auger, J., Hanna, J., Helgason, I. (2019) 'Speculations: Beyond Human-Centered Design', in *Beyond Speculative Design: Past – Present – Future*, pp. 207-210. Split: SpeculativeEdu; Arts Academy, University of Split.
Beaussart , M. (2019) 'The self-donor workshop' in *HIGGS*, Issue 3. London: Higgs
Beaussart , M. (2019) 'Phylogenetic Atelier', in *HIGGS*, Issue 2. London: Higgs
Beaussart , M. (2019) 'Pure Human 0.01', *HIGGS*, Issue 1. London: Higgs
Dustman, E. A. (2017) 'Art + Science | Culture', *E-Squared Magazine*, Issue 3. SSN 2474-3984.
Guttridge-Hewitt M. (2017) 'Future Forecast', in *Design Exchange Magazine*, Issue 14.
Lončar, T. (2024) 'In Search of a Better Future: Designer Profile', *Vogue Adria*, March issue.
Studio FranklinTill (2018) *Viewpoint #41 - The Tactility Issue*, pp.39
Gorjanc, T., Nicolaides, N. (2019) 'Harvest', MLitt Curatorial Practice, Glasgow School of Art.
Gorjanc, T. (2019) 'Searching For The New Luxury', Artez Journal: Fashion Colloquium, Artez University Arnhem.
Berden, B. (2016) 'Pure Human: Leather Alternatives Inspired by Biological Systems', Trend Tablet. Available at: https://www.trendtablet.com/48147-pure-human-by-tina-gorjanc/ (Accessed: 04 November 2024).
Cole, S. (2017) 'The Future of Textiles: Biofabrication and Innovation', Vice Media. Available at: https://www.vice.com/en/article/mbz54v/the-future-of-textiles-tina-gorjanc (Accessed: 04 November 2024).
Delmage, L. (2019) 'Are We Playing God Too Much?', Metal Magazine. Available at: https://metalmagazine.eu/post/tina-gorjanc-are-we-playing-god-too-much (Accessed: 04 November 2024).
Jones, J. (2016) 'Reimagining Materials: The Work of Tina Gorjanc', The Guardian. Available at: https://www.theguardian.com/artanddesign/tina-gorjanc-bio-design (Accessed: 04 November 2024).
Mitrović, M. (2021) 'Interview with Tina Gorjanc: Exploring the Intersection of Fashion and Biotechnology'. Available at: https://speculativeedu.eu/interview-tina-gorjanc/ (Accessed: 04 November 2024).
Paton, E. (2016) 'Emerging Biodesign Trends', New York Times. Available at: https://www.nytimes.com/tina-gorjanc-bio-design (Accessed: 04 November 2024).
Rodríguez Fernández, C. (2019) 'Self-Donor Workshop: Creating Biodesign Solutions', Metal Magazine. Available at: https://metalmagazine.eu/en/post/interview/tina-gorjanc (Accessed: 04 November 2024).
Tucker, E. (2016) 'The Rise of Biodesign', Dezeen. Available at: https://www.dezeen.com/tina-gorjanc-biodesign (Accessed: 04 November 2024).
Wharry, J. (2019) 'Tina Gorjanc Interview: Are We Pushing the Boundaries of Design?' Available at: https://www.geraldinewharry.com/getinspired/tina-gorjanc-interview-xt4kt (Accessed: 04 November 2024).
Gorjanc, T. (2016) Exploring the Intersection of Design and Biotechnology: New Materials for Sustainable Fashion. PhD thesis, Central Saint Martins, University of the Arts London.
Pfeiffer, K. (2024) Redeeming Making? Biodesign and the Hope for Better Production. PhD Thesis, University College London. Submitted for Doctor of Philosophy 13 November 2023, Corrected 4 March 2024.

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TEXTILE FIBERS

POSTER PRESENTATION

ANALYSIS OF SILKWORM *BOMBYX MORI* L. COCOONS MADE AFTER FLAT SPINNING

Tatjana Rijavec[1], Alenka Šalej Lah[1] and Rebeka Lucijana Berčič[2]

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Abstract: *The silkworm Bombyx mori L. normally produces a three-dimensional cocoon to protect itself during the metamorphosis to pupa and moth. Such normal cocoons (NC) differ from cocoons made by caterpillars after they are included in flat spinning where they extrude major part of liquid silk. In this preliminary study of silkworm flat-spinning process the silkworm larvae were enabled to naturally complete their life cycle after flat spinning. More than 60% of the live larvae completed their life cycle with the formation of cocoons after three days of flat spinning. The analysis of these cocoons (AFSCs) shows that silkworms extruded (produced) about 0.35 g silk/larvae after flat spinning and about 0.24 g/insect when they firmed cocoons.*

Keywords: *cocoon shape, effective rate of rearing, silk shell, silk floss.*

1. INTRODUCTION

The silkworm Bombyx mori L. normally produces a three-dimensional cocoon to protect itself during transformation to pupa and moth. Such cocoons are usually referred to as normal cocoons (NC). When the is placed on a flat surface, it deposits the liquid silk jet on it, forming a two-dimensional structure named as a flat cocoon (FC). The possibility of the formation of FC by the Bombyx mori L. has attracted the interest of textile designers (Essig, 2025). FC is a kind of "laid scrim", in which the straightened threads are laid one on top of the other in a specific pattern and glued together, rather than intertwined as in weaving or knitting. Due to the biocompatibility of fibroin and sericin, FCs are also interesting for technical applications, especially in the medical field (Wu et al., 2022, Wang et al., 2024).

This is a preliminary study on optimizing the silkworm flat-spinning process, with the goal of enabling the natural completion of the silkworm life cycle after flat spinning. Therefore, we let the moth in a cocoon to secrete a liquid to partly dissolve the cocoon and exit from it. The studied cocoons were made after flat spinning – we called them after-flat-spinning cocoons, AFSCs. On the Figure 1 moth that has left the AFSC through the opening (brown area) (a), a cocoon with silk floss (b), a cleaned cocoon (c) and an exuvia of levitation of pupae (left) and caterpillar (middle) extracted from the cut cocoon and silk shell (right) (d) are shown.



a) b) c) (d)

Figure 1: Moth (a), after-flat-spinning cocoon (AFSC) (b), and its parts (c, d).

2. EXPERIMENTAL

2.1 Materials

The genetic material (eggs of an European silkworm hybrid) was provided by the Institute of Sericulture, CREA, Padova, Italy. Silkworm eggs were hatched and larvae reared until the end of 5th instar by Rebeka Lucijana Berčič, who transported them to NTF UL just before the start of pupation. In October 2024, Prof. Marija Jenko created two artistic sculptures with silkworm Bombyx mori L. (Jenko, 2025). After three days, she and Mojca Košir stopped the larvae from spinning and transferred them into four cardboard boxes with mulberry leaves and twigs (Box 1–Box 4 in Figure 2); we also received a certain number (70) of larvae and placed them in individual cardboard and plastic compartments (Box 5 in Figure 2) so that they would pupate and transform into butterflies, thus completing their natural life cycle (Figure 3).



AFSC - Box 1 AFSC - Box 2 AFSC - Box 3 AFSC - Box 4 AFSC - Box 5

Figure 2: After-flat-spinning of silkworms *Bombyx mori* L. in boxes.

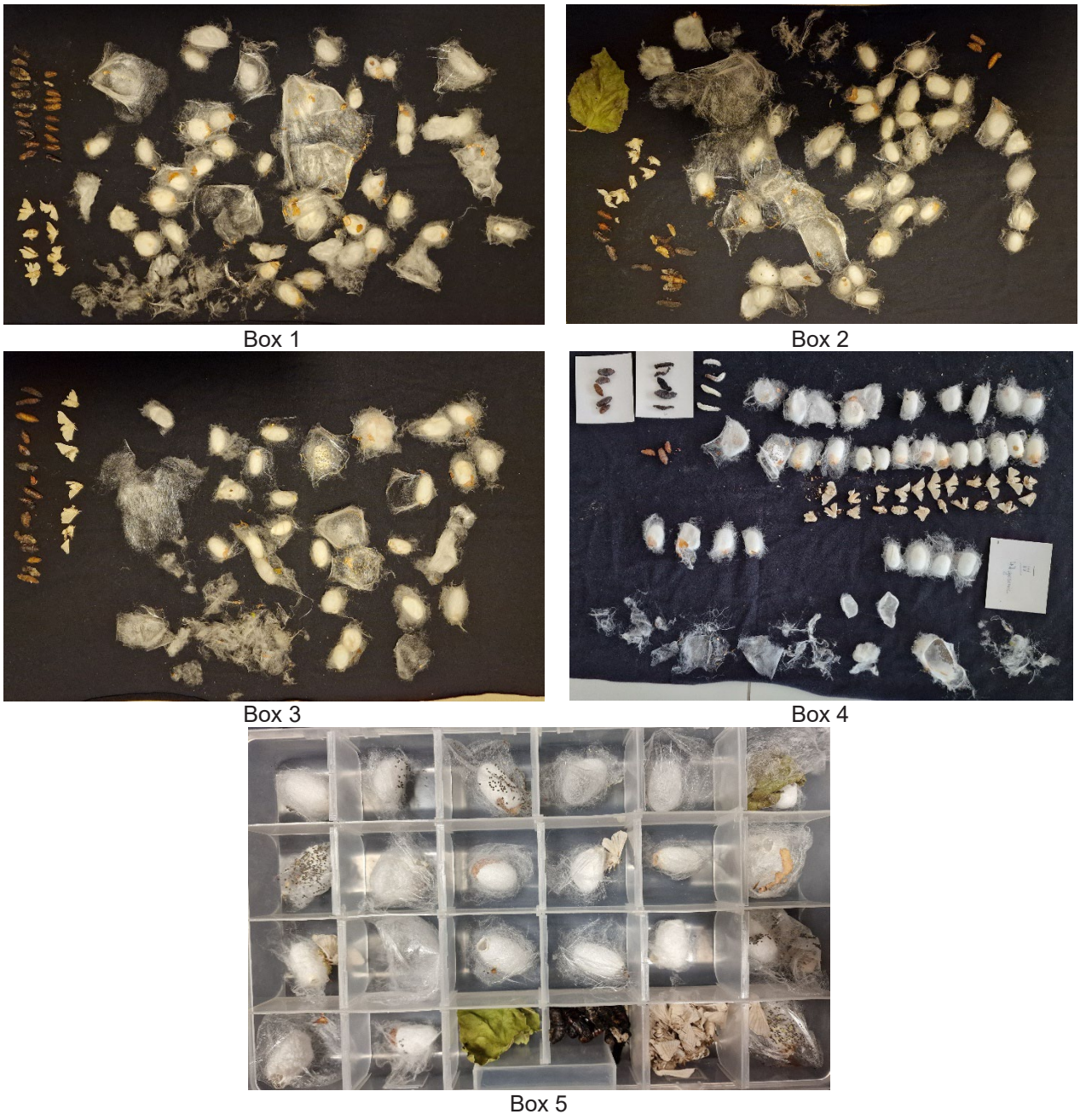


Figure 3: After-flat-spinning cocoons (AFSC), moths, pupas, dead larvae, and exuviahs in boxes.

2.2 Methods

After about four weeks, the boxes were opened and analysed their contents: butterflies, larvae, cocoons (AFSC) and incomplete cocoons were sorted and photographed (Figure 3). The outer floss layer was removed from each AFSC, and then the dimensions of the clean AFSCs were measured at the thickest and thinnest points with a caliper, each clean AFSC was weighed on an analytical balance, the AFSC was opened by using surgical scissors, and the silk shell separated from the remains of the insect. The silk shells were also weighted and assessed the shapes of the AFSCs.

Calculation of an effective rate of rearing AFSCs by number:

$$ERRn = \frac{Number\ of\ AFSCs}{Number\ of\ alive\ caterpillars\ moved\ into\ boxes} \times 100\ (\%) \qquad (1)$$

For statistical analysis, one-way ANOVA was used (Statgraphics Centurion XV, Version 15.1.02).

3. RESULTS AND DISCUSSION

From 300 larvae 293 were involved in the flat-spinning process for the creation of artistic sculptures, of which 11 died during flat-spinning (3.75%), and 282 survived and were included in after-flat-spinning cocooning in five boxes (Figure 2). Seven (7) from 300 larvae were not included in the flat-spinning but were let to make normal cocoons (NC), four of them were measured (data presented as NC).

From survived 282 larvae transferred after flat-spinning into boxes (Figure 1) 177 larvae made cocoons (AFSCs). These data were used for calculation an effective rate of rearing of AFSCs by number (ERRn) (Figure 4a): the established average ERRn was 62.8%: min. 60% for Boxes 1 and 4 and max. 67% for Box 5. Shifa (Shifa, 2015) states the lowest ERRn of 54.17% for Korea-3 and the highest ERRn 92.0% for Mult-yel and Mult-wh races of silkworm *Bombyx mori* L in normal cocoon spinning process.

Under favourable conditions, a moth emerges from the cocoon and in a cocoon, shell remains only an exuvia. Analysed remains of the insects in AFSCs from the Boxes 1, 2, 4 and 5 (Figure 4b) show that 73.3% moths left the AFSCs: from 66.7% (Box 1) to 87.5% (Box 4) where FSCs contained only exuviae. Data on insect remains in normal cocoons (NC) are not available, as NC are collected and dried for the pupae suffocated, to stop the silkworm's life cycle. Our research offers a more humane approach to this insect, as it enables to preserve the silkworm's life cycle. Spinning in boxes with mulberry twigs and leaves proved to be beneficial for the caterpillars but there were more opportunities for the emergence of double AFSCs (made by two caterpillars) (Figure 5) with a higher mass of AFSCs and silk shells.

101 larvae (35.82%) of 282 all larvae included in flat spinning did not make AFSCs; they made only silk floss, they died or transformed into pupa without making AFSCs and later to moth in the boxes.

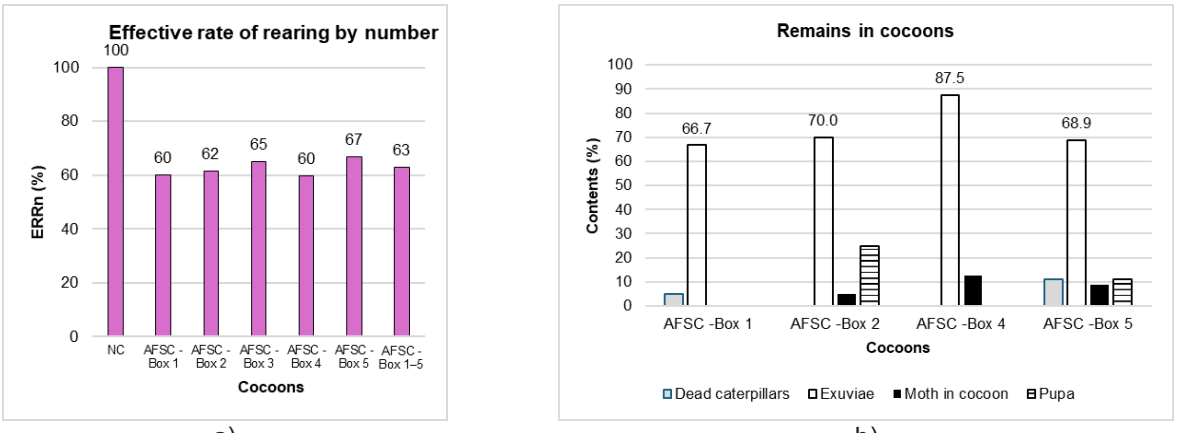


Figure 4: Effective rate of rearing AFSCs by number (ERRn) (a), and remains in AFSCs (b)

NC and AFSCs naturally dried at room temperature were analysed. The mass of NC with a dead larvae was 0.4735 g, its shell 0.2132 g (45.03% of NC mass); the average mass of NCs with exuviae was 0.3128 g, of shell 0.2823 g (Figure 5). A lower casing weight may be the result of the larvae dying before the completion of the burrowing process.

Large differences in mass were found between the AFSCs (Figure 5): the mass of the AFSCs was between 0.054 g and 1.464 g (average 0.315 g), mass of silk shell was between 0.064 g and 0.884 g (average 0.207 g). The extremely high masses are due to the double cocoons. The lowest masses were recorded in cocoons left by moths. The average mass of the exuviae (of pupa and larvae) were only 0.02 g. These cocoons were extremely thin and light with silk shell of only 0.0717 g or thick and heavy with shell mass of 0.3151 g. Silk shell presented on average 91.9% of these cocoons mass. This means that not only the amount of liquid silk in the glands is important for cocoon formation and the successful completion of the silkworm's life cycle, but that there are also other environmental factors that stimulate or inhibit the silkworm's activity.

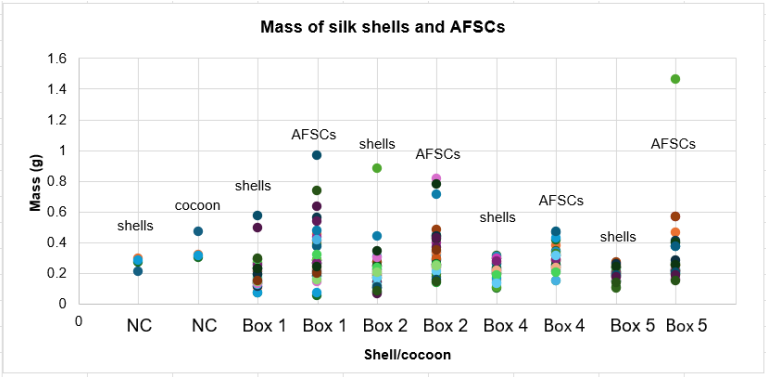
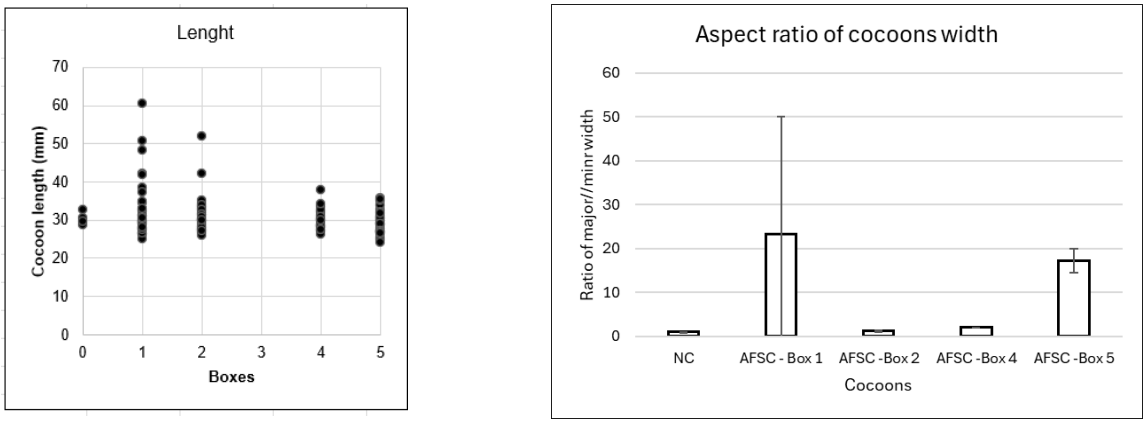


Figure 5: Distribution of silk shells and after flat spinning cocons (AFSCs) mass

The average length of cocoons was 30.7 mm, the minimum length was 24.99 mm, and the maximum length was 60.36 mm (Figure 6a).

A distinctive characteristic of the cocoon shape was its flatness, which was defined by the aspect ratio of the cocoon width (the quotient between the major and minor width of a cocoon). The closer the aspect ratio is to 1, the more evenly thick the cocoon is, and higher values mean greater flattening of the cocoon. The best-formed cocoons were in Boxes 2 and 4, while the worst were in Box 1. The reasons for this could not be determined as we did not analyze the size of the boxes or the amount of leaves and twigs in them.



a) b)

Figure 6: Dimensions of NC and AFSCs

From the ANOVA statistical test (Table 1), it was confirmed that the place of post-flat cocoon formation has no significant influence in terms of the number of cocoons, but it has influence on cocoon mass. Since the P-value of the F-test is less than 0.05, it is statistically significant that minor is associated with lower cocoon shell mass.

Table 1: ANOVA

Dependent variable	Factor	F-ratio	p-value
Boxes	Length of cocoons	1.11	0.4486
Boxes	Major width	1.32	0.3046
Boxes	Minor width	1.23	0.3818
Boxes	**Cocoon mass**	**16.97**	**0.0188**
Boxes	Shell mass	0.78	0.7153
Shell mass	Length	1.65	0.1540
Shell mass	Cocoon mass	7.40	0.0611
Shell mass	Major width	1.96	0.0944
Shell mass	**Minor width**	**6.66**	**0.0012**

4. CONCLUSION

The main findings of the experiment are listed in the Table 2. Tin order to plan a successful flat spinning process, an analysis of the larvae before and after flat spinning should be included. At the end, it is also necessary to determine the quality and usability of the whole silk after the silkworm's life cycle is complete.

Table 2: Summary of cocoon analysis made by post-flat cocoon formation

Properties	Values
Number of alive larvae included in flat spinning	278
Number of after flat spinning cocoons (AFSCs)	181
Effective rate of rearing by number	63.67%
Silk floss (all floss/floss per cocoon)	19.94 g/0.07 g
Shells (all shells/shell per cocoon)	42.69 g/0.24 g
Raw silk (all floss and shells/floss and shell per cocoon)	62.63 g/0.35 g

5. REFERENCES

Jenko, M. 2025. “Sviloprejke, živa materija v umetniških procesih.” Tekstilec 68(SI2): 114−115.

Shifa, K., Tilahun, A., Terefe, M., Ibrahim, A., Birtu, K., Menbere, S. 2015. “Evaluation of different strains of mulberry silkworms /Bombyx mori L. / for their adaptability and silk yield in Ethiopia”. Eth. J. Anim. Prod., 15(1)-2015:187-200.

Wang, S., Wang, Y., Wang, Y., Liu, J., Liu, F., Dai, F., Li, J., and Li, Z. “Pollen-Modified Flat Silk Cocoon Pressure Sensors for Wearable Applications.” Sensors 24, no. 14 (July 19, 2024): 4698. https://doi.org/10.3390/s24144698.

Wu, B., Tong, X., Cheng, L., Jiang, S., Li, Z., Li, Z., Song, J., and Dai, F. “Hybrid Membrane of Flat Silk Cocoon and Carboxymethyl Chitosan Formed through Hot Pressing Promotes Wound Healing and Repair in a Rat Model.” Frontiers in Bioengineering and Biotechnology, 10 (November 1, 2022). https://doi.org/10.3389/fbioe.2022.1026876.

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POSTER PRESENTATION

DEGUMMING OF SILK PRODUCED IN SLOVENIA

Petra Forte Tavčer[1], Maša Šturm[1] and Tatjana Rijavec[1]

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Abstract: *Silk degumming is the process of removing sericin, a gummy protein, from silk fibres. This is typically achieved through hydrolytic or enzymatic methods, breaking down sericin's peptide bonds. The goal is to produce silk that is softer, shinier, and more lustrous.*

Raw silk, obtained from various Slovenian silk growers, was treated in aqueous solutions with the addition of various chemicals, soap, sodium carbonate, citric acid, and urea under different conditions. Both fibres unwound from cocoons and whole cocoons were treated. Experiments were also conducted on lower quality, damaged, or incompletely developed cocoons. The rate of the degumming was assessed by weighing the fibres before and after treatment and observing them under an electron microscope.

Keywords: *silk, yarn, cocoon, degumming*

1. INTRODUCTION

Silk, a natural biopolymer synthesised primarily by silkworms and certain other species, has excellent mechanical strength, aesthetic properties and biocompatibility (Altman, 2003). These properties make it very versatile and enable applications in the textile industry and biomedicine (Aramwit, 2010).

Silk fibres produced by the silkworm Bombyx mori L. consist mainly of two proteins, fibroin and sericin. Fibroin is the structural protein that forms the core of silk fibres. Fibroin consists of repeating amino acid sequences, mainly glycine (45%), alanine (30%) and serine (12%), which allow tight packing into β-sheet structures that provide strength and elasticity (Altman et al., 2003). Sericin is a water-soluble protein that coats the fibroin core and acts as a natural adhesive. It is rich in amino acids such as serine, aspartic acid and threonine, which give it hygroscopic and protective properties (Aramwit, 2010). In recent years, silk fibroin has attracted much attention in various fields such as biomedicine, tissue engineering, food processing, photochemistry and biosensing due to its remarkable biocompatibility, machinability and chemical modifiability (Huang, 2023). Sericin has also become a research focus among new natural biomedical materials due to its good moisture absorption, membrane-forming property, antioxidant capacity, antibacterial capacity, tyrosinase inhibition, cell adhesion and proliferation activity, low immunogenicity, hypoglycemic effect and other properties. (Zhi-Lin Zhao, 2020)

The removal of sericin from the surface of silk fibres is called degumming. This can be achieved by physical, chemical or enzymatic methods. Alkaline solutions (e.g. sodium carbonate) or soaps are commonly used to dissolve sericin. Although effective, excessive concentrations of chemicals can damage fibroin (Kweon, 2001). Specific enzymes such as proteases selectively degrade the sericin without damaging the fibroin. This method is more environmentally friendly and preserves the mechanical properties of the silk (Aramwit, 2010). Techniques such as ultrasound, microwave-assisted steam degumming (Pan et al., 2024) or high-pressure processes remove the sericin mechanically (Altman, 2003).

Degumming considerably improves the texture, lustre and quality of the silk. Degummed silk is used extensively for luxury textiles and medical applications, including sutures, scaffolds and drug delivery systems. The efficiency of degumming has a direct impact on the biocompatibility and functionality of silk, especially in biomedical applications (Aramwit, 2010). The choice of degumming method can have a significant impact on the molecular weight, structure, morphology and properties of silk fibroin and is therefore crucial for both textile and non-textile

applications (Vyas, 2015, Zhu, 2022). As part of a bilateral project (Berčič, 2021), several farmers from Slovenia started rearing silkworms and harvesting silk cocoons in 2015–2021. They produced a considerable amount of high-quality silk cocoons, but some imperfect, damaged cocoons also occurred. The aim of our work was to investigate how to extract fibroin from these imperfect cocoons. Various chemicals were used for degumming: soap, sodium carbonate, citric acid and urea under different working conditions.

2. METHODS

2.1 Materials and methods

The silk cocoons were produced in Slovenia in 2024, selected, dried for 24 hours at 60 °C and reeled up. The remains after reeling the cocoons were used for analysis.

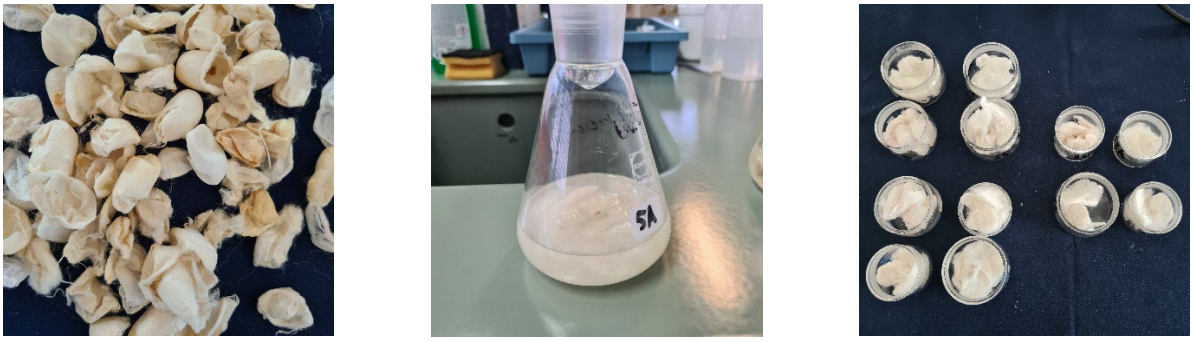
The cocoons were opened manually with scissors and the pupa was removed. Before degumming, the cocoons were yellowish in colour. Four to five cocoons with a total mass of about 1 g were processed together in the same degumming bath. Figure 1 shows the silk covers of the cocoons after removal of the pupae.

Four different degumming baths were prepared. The recipes are listed in Table 1. Sodium carbonate, urea and acetic acid were purchased from Sigma Aldrich.

Table 1: Recipes of the degumming baths

No.	Additive	Concentration
1.	demineralized water	100%
2.	sodium carbonate	3 g/l
3.	citric acid	1,5%
4.	urea	60 g/l

The treatment was carried out in the Starlet-2 dyeing apparatus (DaeLim, Korea) at 98 °C and a liquor/fibre ratio of 1:100 for 30, 60 and 90 minutes. After treatment, the silk fibres were removed from the degumming baths and rinsed thoroughly with tap water. The fibres were then dried in the air.



a) b) c)

Figure 1: Silk shells before (a), during (b) and after (c) treatment

2.2 Analyses

The amount of sericin removed was determined by weighing the silk shells before and after treatment and calculating the remaining ratio of fibres to removed material as a percentage. Photomicrographs of untreated and all treated samples were taken using a scanning electron microscope (Jeol 5610, Japan).

3. RESULTS AND DISCUSSION

Figure 2 shows the proportion of sericin removed from the silk cocoons. It can be seen that the proportion of sericin removed is high in all treatments, ranging from 15 % to 23 %. The highest removal occurred in the treatment with sodium carbonate and citric acid, while less sericin was removed in the treatment with water and urea. No clear time dependence was observed, suggesting that a shorter treatment duration of 30 to 60 minutes was sufficient to remove most of the sericin.

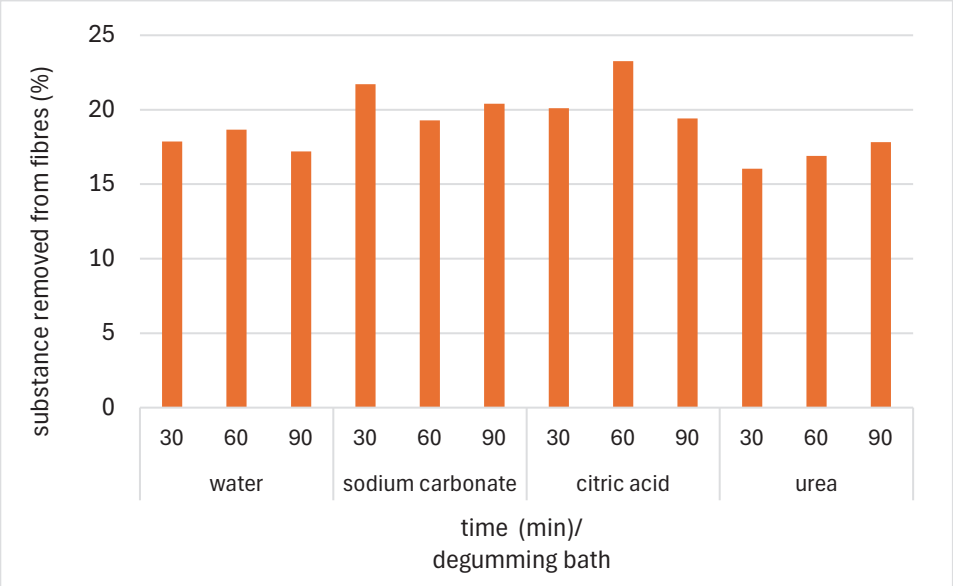


Figure 2: The proportion of removed substance (sericin) from silk fibres during degumming.

Figure 3 shows silk fibres before and after 90 minutes of degumming with different solutions. Two images are shown for each sample: one at lower magnification (230x) and another at higher magnification (1600x). At lower magnification, degummed silk fibres and fine fibrils can be seen in all treated samples, although the fibrils are more pronounced in the acetic acid treated samples. At higher magnification, some longitudinal damage to the fibres is also visible, indicating that all treatments have caused some fibre damage. This damage may be due to the high temperatures, long processing times and intense agitation during treatment. In order to obtain high-quality silk threads, the degumming process must be optimised.

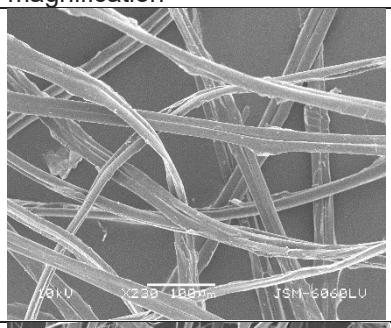
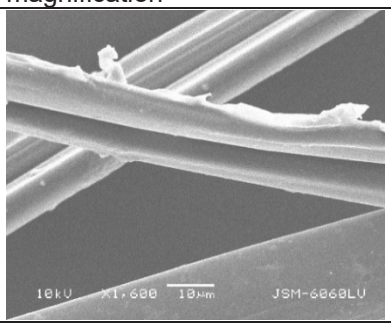
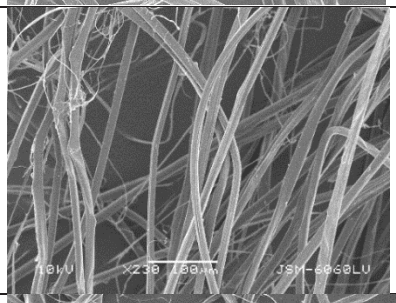
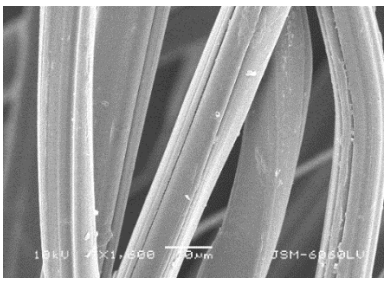
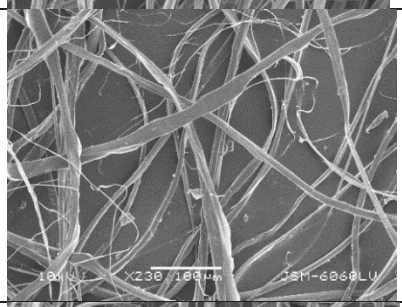
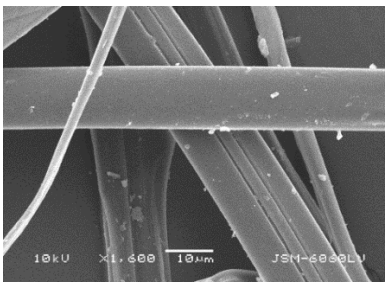
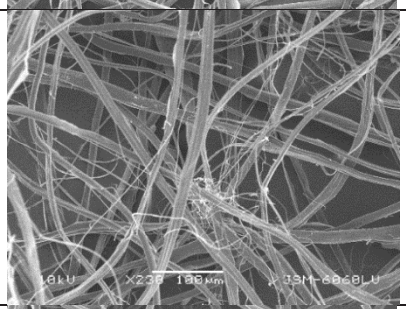
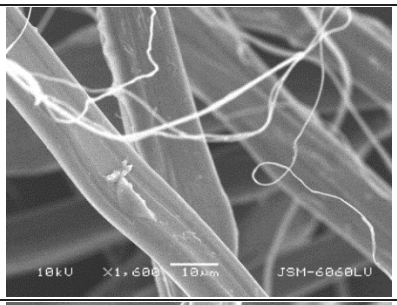
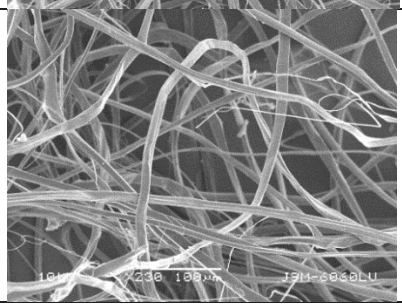
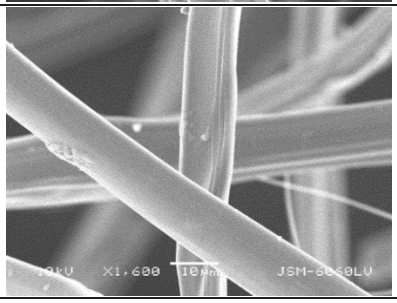
	SEM photo of silk fibres at 230x magnification	SEM photo of silk fibres at 1600x magnification
untreated		
water		
soda		
citric acid		
urea		

Figure 3: Microphotographs of silk fibres before and after 90 minutes of degumming with different solutions at 230x and 1600x magnification.

4. CONCLUSION

We can conclude that damaged cocoons can be degummed using the same methods as raw silk threads. The sericin is effectively removed, resulting in fibres that can be spun into pure silk threads or used in blends with other textile fibres. The sericin removed from the fibres, which remains in the degumming bath, could also be recycled. During processing, the fibres are damaged, so the processes need to be adapted accordingly. Further research will determine the properties of the cleaned fibres and their potential applications.

5. ACKNOWLEDGEMENT

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6. REFERENCES

Altman, G. H., Diaz, F., Jakuba, C., et al. 2003. "Silk-based biomaterials." *Biomaterials 24*(3): 401-416.
Aramwit, P., Kanokpanont, S., Nakpheng, T., et al. 2010. "The effect of sericin removal on the properties of regenerated silk fibroin films." *International Journal of Molecular Sciences 11*(12)**:** 4650-4661.
Berčič, R. L. **2021.** »Influence of feeding silkmoth (Bombyx mori L.) hybrid larvae with leaves of old local Hungarian and Slovenian mulberry (Morus alba L.) genotypes on the development and health status of larvae«: project code : OTKA SNN 116993 : report. Budapest: University of Veterinary Medicine Budapest.
Kweon, H. Y., Ha, H. C., Um, I. C., et al. 2001. "Physical properties of silk fibroin/chitosan blend films." *Journal of Applied Polymer Science 80*(7): 928-934.
Pan, M., Jin, Y., Ye, Y., Jiang, W., Zhu, L., & Lu, W. 2024. »An efficient and eco-friendly method for removing sericin using microwave-assisted steam degumming.« *Environmental Technology & Innovation* 35: 103674.
Vyas, S., Shukla, S. R. 2015. "Comparative study of degumming of silk varieties by different techniques." *The Journal of The Textile Institute* 107: 191 - 199.
Zhu, L., Lin, J., Pei, L. et all. 2015 "Recent Advances in Environmentally Friendly and Green Degumming Processes of Silk for Textile and Non-Textile Applications." *Polymers* 14(4): 659.
Rastogi, S., Kandasubramanian, B. 2020. "Processing trends of silk fibres: Silk degumming, regeneration and physical functionalization." *The Journal of The Textile Institute* 111(12): 1794-1810.
Zhao, Z.L., Zhang, Y.Q. 2020. "Greener degumming production of layered sericin peptides from a silkworm cocoon and their physicochemical characteristics and bioactivities in vitro." *Journal of Cleaner Production* 261: 121080
Huang, L.L., Shi, J.F., Zhou, W., Zhang Q. 2023. "Advances in Preparation and Properties of Regenerated Silk Fibroin." *International Journal of Molecular Sciences* 24(17): 13153.
Allardyce, B. J. et all., 2015. "The impact of degumming conditions on the properties of silk films for biomedical applications." *Textile Research Journal* 86(3): 275-287.

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POSTER PRESENTATION

DIMENSIONAL STABILITY OF SILK BLEND KNITTED FABRICS

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Abstract: *During knitting, the threads are under tension, which deforms the fabric. As soon as the fabric is removed from the machine, it relaxes and its dimensions change. The aim of the research is to investigate the dimensional stability of knitted fabrics made from tussah silk blends, which can be used in various applications such as clothing, sportswear and more. Tussah silk is the most important wild silk used commercially. 16 different knitted fabrics were designed and produced from yarns consisting of four different silk blends with wool, cotton, lyocell and acrylic fibres and four different single jersey knit structures. The highest change in dimensional stability was achieved with knitted fabrics made from silk-wool blended yarn, the lowest with knitted fabrics made from a blend of cotton, acrylic and silk. The knitting structures have a small influence on the dimensional stability and other measured properties, but there is also a big difference between the dimensional stability of plain jersey and other structures with tuck stitches, which tend to be looser structures.*

Keywords: *knitted fabrics, silk blends, structures of knitted fabrics, dimensional stability, thickness.*

1. INTRODUCTION

Tussah silk is the most important wild silk. Tussah silk is obtained from several species of silkworms of the genus Antheraea. These worms feed almost exclusively on the oak Quercus serrata. Despite the different species of worms that produce tussah silk, the cocoons are sufficiently uniform and produce a homogeneous material. The properties of the silk are more influenced by the climatic conditions. Tussah silk differs considerably in appearance from Bombyx mori silk. The cocoons of tussah silk have a greener colour and are covered with tufts of red hair, which is why bleaching and chemical treatment is often necessary. Wild silk is also irregular in width and is characterised by longitudinal stripes and flattened areas with horizontal stripes. Wild silk is less durable but is valued for its strength and resilience (Cook, 1993). Tussah silk not only has a luxurious and elegant appearance, but also has physical properties such as high strength and good stretchability (Wang, 2023).

The dimensional stability of knitted fabrics is an important factor in the knitting industry. There are several factors that affect the dimensional stability as well as the shrinkage and spirality of knitted fabrics. Although factors such as fibre properties, stitch length, machine gauge, yarn twist and knitting tension causes dimensional variations, the most important factor that causes the spirality of a single jersey fabric is the relaxation of torsional stresses in the yarn (Hossain, 2012)

During the knitting process, the yarns forming the fabric are constantly under stress. As a result, the fabric is more deformed on the machine than in its natural, relaxed state. When the fabric is removed from the machine, it has time to relax and overcome this tension. This form of relaxation can be easily recognised by the changed dimensions. For the same fabric structure, different yarn types have different effects on relaxation and physical properties (Quaynor, 2000). Dimensional changes occur either as shrinkage or expansion, but the predominant source of dimensional change in knitted fabrics is yarn relaxation. Due to the extensible nature of knitted fabrics, the limits of dimensional change in knitted fabrics are not considered as critical as in woven fabrics. Most dimensional changes due to relaxation shrinkage occur during the first wash cycle, with fabrics changing progressively with each subsequent wash cycle until stability is achieved (Van Amber, 2010).

Different fibre blends also have different effects on the change in dimensional stability and other properties of knitted fabrics. Blending natural fibres with man-made fibres can offer the advantage of combining the good prop-

erties of both fibre components, such as comfort, softness, strength, etc. The blend highlights the good properties of the fibres and minimises the bad ones (Pooja, 2021).
The aim of the study is to compare the dimensional stability and the change in horizontal and vertical density of knitted fabrics, the change in thickness of different silk blend knitted fabrics and different structures after washing.

2. EXPERIMENTAL

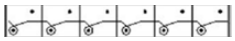
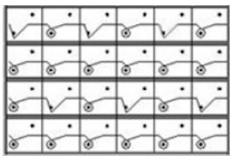
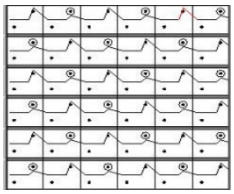
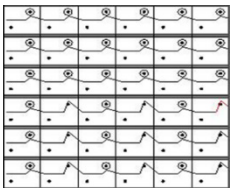
In our reserch, the dimensional stability of knitted fabrics made from silk blends was investigated. For this purpose, sixteen knitted fabrics were designed and produced on the Shima Sheiki SES 122 RT knitting machine with a gauge 12 E, using the same settings for all knitted fabrics. Four different silk blend yarns and four different single jersey structures were used. As the linear density of the yarns of the different materials was not the same for all yarns, two, three or four threads were used for one yarn to produce knitted fabrics. The materials used for the research are presented in Table 1 and the structures of the knitted fabrics are presented in Table 2. The knitted fabrics were washed five times under the same conditions. The washing was carried out in a Gorenje Wavw active washing machine, in the sports programme at 30°C and 800 revolutions. 18 ml of a commercially available detergent was used for each wash cycle. The washing time was 39 minutes. After each wash cycle, the samples were dried horizontally.
For the purpose of the study horizontal and vertical density was measured on the raw samples, after the first wash and after the five washes. The horizontal and vertical densities (Dh and Dv) were determined by counting the loops over a length of 20 mm.

Table 1: Presentation of the materials used in the research.

Sample	Material code	Material	Tt* yarn (tex)	No. of threads in knitted fabric	Total Tt* (tex)
1	SE/WO	70 % tussah silk, 30 % wool	58.8	1	58.8
2					
3					
4					
5	CLY/SE	70 % lyocell 30 % tussah silk	40	2	80
6					
7					
8					
9	CO/PAN/SE	35 % cotton, 35 % acrylic, 30 % tussah silk	29.4	3	88.2
10					
11					
12					
13	CO/SE	70 % cotton, 30 % tussah silk	20	4	80
14					
15					
16					

*TT – LINEAR DENSITY OF YARNS

Table 2: Presentation of the knitted structures used in the research.

Name of structure	Single jersey (SJ)	Single piqué (SP)	Single fang (SF)	honeycomb (H)
Structure				
No. of sample	1, 5, 9, 13	2, 6, 10, 14	3, 7, 11, 15	4, 8, 12, 16

The change in dimensional stability was measured in accordance with the standard EN ISO 5077:2008 (Textiles - Determination of dimensional change in washing and drying). Dimensional stability was measured after each wash. Longitudinal and vertical markings were applied to the samples. The length in the longitudinal direction was 50 cm and in the vertical direction 35 cm, as the samples were very wide. Three measurements were carried out for each sample. The dimensional stability was calculated according to equation 1, where l_{washed} is the length measured after washing and drying and $l_{original}$ is the length measured before washing:

$$\text{dimensional change } (\%) = \frac{l_{original} - l_{washed}}{l_{original}} \cdot 100 \qquad (1)$$

The area dimensional stability was also calculated using equation 2:

$$\text{area dimensional change } (\%) = \frac{(l_{Horiginal} \cdot l_{Voriginal}) - l_{Hwashed} \cdot l_{Vwashed})}{l_{Horiginal} \cdot l_{Voriginal}} \cdot 100 \qquad 2$$

The thickness of the knitted fabric was measured on the raw samples, after the first and after five washes with a pressure of 20 cN/cm^2. The thickness of the knitted fabric was measured according to the standard SIST EN ISO 5084:1999 (Textiles - Determination of thickness of textiles and textile products).

After five washes, the mass per unit area of the knitted fabric was measured in accordance with the standard SIST EN 12127: 1999 (Textiles - Fabrics - Determination of mass per unit area using small samples).

3. RESULTS WITH DISCUSSION

All knitted fabrics were produced with the same set density (yarn feed tension, cam setting and take-down tension), but have different degrees of relaxation after knitting due to differences in the knitted structure and the material used. This influences the different horizontal (Dh) and vertical density (Dv) of the knitted samples. As can be seen in Table 3, the highest horizontal density was found in plain single jersey structures (SJ), while the lowest was achieved with single fang (SF) and honeycomb structures (H). While in vertical density shows the opposite, the highest density is achieved with honeycomb structures and the lowest with plain simple single jersey structures. These results show that the structure has a major influence on the horizontal and vertical density of knitted fabrics, much more than the material used. Single jersey (SJ) is the simplest knitted structure where all stitches are the same, while the structures with more tuck stitches are more stretchy in width and more compressed vertically.

Our research has shown that dimensional stability varies greatly depending on the structure and material used. All knitted fabric samples produced shrank after washing. As expected, the greatest change in dimensional stability, both horizontally and vertically, was observed after the first washing and drying of the fabrics. The samples shrank

by 8 to 20 % in the horizontal direction and by 4 to 16 % in the vertical direction. After further washes, the shrinkage is not as high but depends on the type of structure and the material used, as can be seen in Figures 1 and 2.

The shrinkage is generally highest in the horizontal direction. This can also be confirmed from the literature (Quaynor, 1999), which states that silk fabrics actually tend to stretch in the lengthwise direction (negative shrinkage). Figure 3, which shows the area dimensional stability confirms that the highest shrinkage in both directions is observed in knitted fabrics made of silk-wool blends, followed by knitted fabrics made of cotton-silk blends, while knitted fabrics made of lyocell and silk blends as well as cotton, acrylic and silk blends show the least change in dimensional stability. One of the reasons for the highest shrinkage of silk and wool blends is the dimensional instability of the wool. The flake structure of the wool led to a slight flattening of the knitted fabric after the four and five washes, which resulted in even greater shrinkage. The structure and properties of the wool have a major influence on the properties of the knitted fabric in the silk/wool blend, even though the proportion of wool in the blend is only 30%. Due to the high proportion of silk, a greater number of washes may also be required to achieve a fully relaxed state (Van Amber, 2010). One of the reasons why shrinkage is highest in silk-wool blends is also the linear density of the yarn. The linear density is the lowest and allows for more shrinkage because the structure is more porous and provides more room for shrinkage.

Table 3: Horizontal and vertical density of knitted fabrics before washing and mass per unit area after five washes.

	Before washing					
Sample	**Dh (wales/2cm)**	**C V (%)**	**Dv (courses/2cm)**	**CV (%)**	**Mass after 5 washes (g/m²)**	**CV (%)**
1	**12.85**	5.20	**16.45**	2.66	**247.47**	0.18
2	**11.2**	2.31	**19.5**	2.09	**290.88**	0.29
3	**9.15**	2.64	**22.7**	2.79	**302.09**	0.20
4	**8.9**	2.37	**25.35**	5.20	**318.33**	0.13
5	**12.85**	1.88	**15.8**	2.67	**299.3**	2.35
6	**11**	4.29	**19.45**	2.25	**334.06**	0.95
7	**9.2**	2.81	**22.1**	1.43	**322.96**	0.47
8	**9.2**	2.81	**21.05**	1.75	**314.44**	1.86
9	**12.45**	2.96	**16.55**	2.65	**343.67**	0.13
10	**11.75**	6.10	**20.1**	3.48	**387.02**	0.29
11	**9.35**	3.61	**18.8**	3.12	**394.89**	0.39
12	**9.15**	2.64	**22.95**	2.40	**351.75**	0.37
13	**12.65**	3.25	**16.35**	2.52	**341.43**	0.20
14	**11.6**	3.40	**20.45**	2.43	**351.99**	1.74
15	**9,75**	3,63	**18,15**	2,61	**355,68**	1,49
16	**9,45**	3,00	**22,05**	1,29	**340,77**	0,63

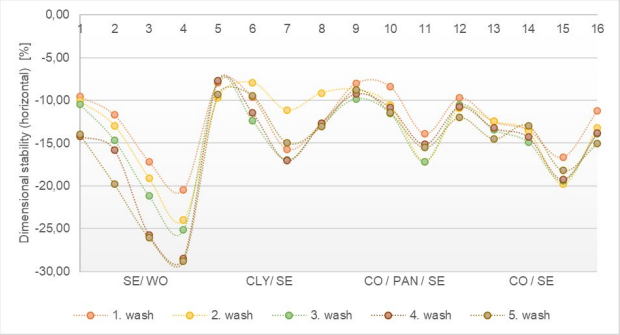


Figure 1: Change in dimensional stability of knitted fabrics - horizontal before washing and after the 1st and 5 washes

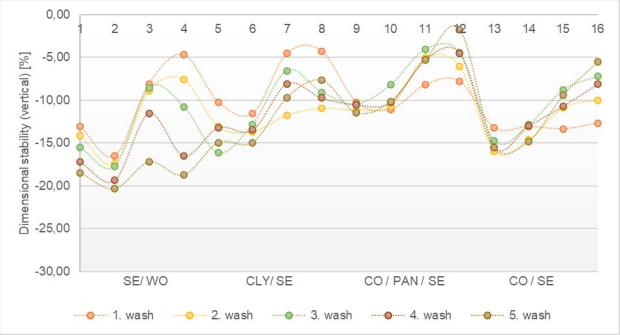


Figure 2: Change in dimensional stability of knitted fabrics - vertical before washing and after the 1st and 5 washes

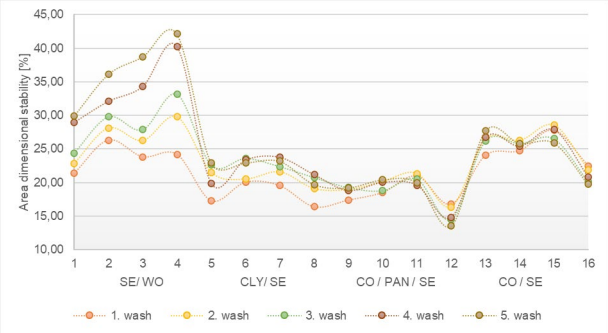


Figure 3: Ara dimensional stability change of knitted fabrics after all five washes.

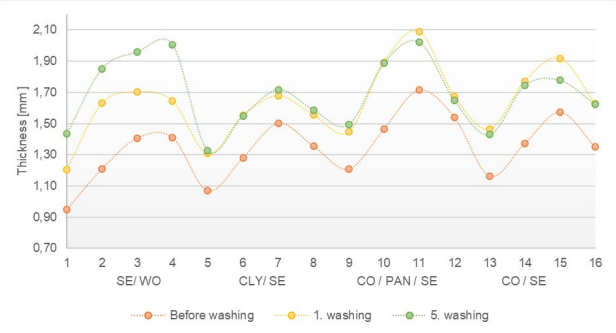


Figure 3: Change in the thickness of knitted fabrics before washing and after the 1st and 5 washes.

High shrinkage is also achieved with knitted fabrics made from cotton-silk blends. The blend consists of 30% silk and 70% cotton, which can shrink during washing. Figures 1, 2 and 3 show that the knitted fabrics made from a cotton-silk blend shrinks the most in the horizontal and vertical directions after the first wash. After two, three and four washes there is only a slight change in dimensional stability, after five washes an expansion of the knitted fabrics is even observed in knitted structures with touch stiches.

The least change in dimensional stability is observed in knitted fabrics made from acrylic and silk blends. One of the reasons for this is the proportion of 30% acrylic fibres, which are non-absorbent and do not tend to shrink after washing. This blend also has the highest linear density of the yarn and thus the most compact structure and therefore the least shrinkage.

The knitted structure also has an influence on the dimensional stability of knitted fabrics. In the horizontal direction, the greatest change in dimensional stability was observed in knitted fabrics with more tuck stitches, such as single fang (SF) and honeycomb (H) structures, while single jersey (SJ) fabrics showed the least shrinkage. The reason for this is the tuck stitches in the structure. In the horizontal direction, the tuck stitches shrink the structure of the knitted fabric and thus also influence the dimensional stability after washing.

In the vertical direction, shrinkage after washing is highest in single jersey (SJ), while shrinkage is lower in tuck knitted structures. The more tuck stitches, the wider the fabrics; the lowest shrinkage is observed with single fang (SF) and honeycomb (H). Structures with tuck stitches are more stretchable in width, as tuck stitches are looser.

The change in the thickness of the knitted fabric was also analysed after the first and after the five washes. The results showed that the thickness increased on average by slightly more than 20% after the first wash, depending on the structure and material of the knitted fabric, while the change in thickness after the five washes was only about 4% more than after the first wash. After the first wash, the thickness of the knitted fabric increased the most in wool-silk blends and cotton-silk blends, which also show the highest shrinkage. After the fifth wash, the

thickness of wool and silk blends knitted fabrics increased significantly, while the increase in the other materials was minimal. The structure of the knitted fabric also has a major influence on the change in thickness. In general, knitted structures with tuck stitches have a higher increase in the thickness of the knitted fabrics, as structures with tuck stitches also have a higher shrinkage. In general, structures with tuck stitches are thicker than single jersey structures.

The change in dimensional stability also has an effect on the mass per unit area, as can be seen in Table 3. Fabrics with higher shrinkage also have a higher mass per unit area after five washes.

4. CONCLUSIONS

The results of the study show how the different silk blend yarns used for the knitted fabrics and their structure influence the physical properties, such as horizontal and vertical density, dimensional stability and thickness. It also shows how the different silk blends differ from each other and how the dimensional stability changes after each of the five washes. From the results, it can be concluded that the highest change in dimensional stability of the tested knitted fabrics is observed in knitted fabrics made from a blend of silk and wool, followed by knitted fabrics made from cotton and silk, while the lowest change in dimensional stability is observed in knitted fabrics made from cotton, acrylic and a silk blend.

The knitted structure also has a major influence on physical properties such as horizontal and vertical density, mass per unit area and dimensional stability. As expected, the knitted fabrics with more tuck stitches shrink more than plain single jersey structures. The more tuck stitches, the looser the structure and the higher the shrinkage. The greatest change in dimensional stability was observed in the honeycomb structure and the single fang structure.

5. REFERENCES

Cook, G. 1993. *Handbook of Textile Fibres*. Shildon : Merrow.

Hossain M., et al. 2012. “Impact of Various Yarn of Different Fiber Composition on the Dimensional Properties of Different Structure of Weft Knitted Fabrics.” *International Journal of Textile and Fashion Technology (IJTFT)* 2(1): 34–44.

Jingyu Wang, Xinxi Liu. 2023. “Research on the Characteristics and Development of Liaoning Tussah Silk.” *Frontiers in Art Research* 5(6): 53–57.

Pooja, Bains, S., Singh, P. 2021. “Evaluation of mechanical properties of oak tasar silk waste/viscose blended knitted fabrics.” *The Pharma Innovation Journal* 10(1): 735–738.

Quaynor, L., Takahashi, M., Nakajima, M. 2000. “Effects of Laundering on the Surface Properties and Dimensional Stability of Plain Knitted Fabrics” *Textile Research Journal* 70(1): 28–35.

Quaynor, L., Nakajima, M., Takahashi, M. 1999. “Properties of Silk and Silk-blend Knitted Fabrics”. *Textile Research Journal* 80(15): 1557–1568.

Van Amber, R.R, Niven, B.E., Wilson, C. A. 2010. “Effects of Laundering and Water Temperature on the Properties of Silk and Silk-blend Knitted Fabrics”. *Textile Research Journal* 80(15): 1557–1568.

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SUSTAINABLE AND ECO-FRIENDLY TEXTILE MATERIALS

ORAL PRESENTATION

NATURAL PROTECTION OF BACTERIAL CELLULOSE DURING INCUBATION

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Abstract: *Bacterial cellulose (BC) is a natural polymer with potential textile applications, but its industrial production faces challenges due to the fungal contamination during incubation. This study investigates natural bioactive compounds from avocado seeds and white grape bagasse (WGB) as sustainable BC culture media additives. BC was cultivated in three media: Hestrin-Schramm (HS), HS with ground avocado seeds (HS+AS), and WGB medium. WGB medium yielded the highest BC production (2.38 ± 0.12 g/L), significantly outperforming HS medium, while HS+AS inhibited BC production (0.20 ± 0.03 g/L). WGB medium exhibited high polyphenol content (476.8 ± 2.5 mg/L) and antioxidant activity (88.4 ± 0.2%), attributed to compounds like catechin and quercetin-3-glucoside, which effectively inhibited fungal contamination. Morphological analysis showed compact fibrillar structures with fewer pores in WGB-produced BC. These findings highlight WGB's polyphenol-rich profile as a sustainable solution for fungal contamination and enhanced BC production, offering a promising approach for eco-friendly industrial applications.*

Keywords: *bacterial cellulose, natural protection, polyphenols, antioxidant activity.*

1. INTRODUCTION

Cellulose is the most widespread, renewable and commonly used natural polymer, mainly derived from plants, but can also be synthesized by bacteria, which represent an increasingly important sustainable source of cellulose (Seddiqi 2021). Bacterial cellulose (BC) has been investigated as an alternative material in several areas, including the textile industry (Ogrizek 2021; Ogrizek 2024). The potential use of BC in future textile applications ranges from simple clothing and accessories to wearable electronics (Nayak 2024). During the cultivation (incubation) of bacterial cellulose, especially when culturing under non-sterile conditions, e.g. in industry, fungal contamination can sometimes be detected, which is an undesirable infection and can significantly affect the quality of BC. As an option to limit contamination, the addition of sodium benzoate and potassium sorbate or lowering the acidity of the medium below pH 4 by adding citric acid and disodium hydrogen phosphate is recommended (Laavanya 2021; Quijano 2017; Revin 2018). However, plant extracts are widely recognized for their bioactive compounds, particularly phenolic groups, which exhibit antimicrobial properties against food pathogens and spoilage microorganisms (Gonelimali 2018; Kaur 2021). Key antifungal constituents include phenolic compounds like gallic acid, flavonoids (e.g., catechin), and tannins, which disrupt microbial membranes and enzymatic pathways (Hsu 2021; Efenberger-Szmechtyk 2021). Natural antimicrobial agents can be derived from cultivated plants, such as thyme and rosemary, or from by-products like avocado seeds (Rojas-García 2022). Avocado seeds, a significant by-product of the avocado processing industry, account for approximately 16–20% of the fruit's mass and are rich in carbohydrates, polyphenols (e.g., catechins, flavonoids), and tannins, which exhibit strong antimicrobial and antioxidant properties (Pedreschi 2019; Zaki 2020). Their bioactivity varies with extraction methods, with water-based extractions demonstrating high antioxidant and antimicrobial efficacy (Nwaoguikpe 2011; Ong 2022).

Grape bagasse, a by-product of winemaking, is a rich source of polyphenols, including phenolic acids (gallic and ellagic), flavonoids (catechin and epicatechin), proanthocyanidins, and stilbenes (Jug 2016; Troilo 2021). Polyphenols in grape bagasse play a crucial role in protecting plants against pathogens, making them promising candidates for antifungal and antibacterial applications. Approximately 60–70% of total polyphenols are concentrated in the seeds, which are particularly rich in antioxidant compounds such as vitamin E, flavonoids, and stilbenes.

The skin and pulp also contribute significant amounts of polyphenols, including flavonols (quercetin, kaempferol) and fibres (Jug 2016; Troilo 2021).

2. EXPERIMENTAL

2.1 BC PRODUCTION AND HARVEST

Bacterial cellulose was grown in different culture media as described in Table 1 below in Hestrin-Schramm (HS) medium, a modified HS medium with added ground avocado seed (HS+A) and white grape bagasse medium (WGB) using the procedure as described here (Ogrizek 2021).

Table 1: Procedures for BC preparation and labelling of samples were carried out according to the established protocol.

Medium	Composition of medium	Sample label
Hestrin-Schramm	20 g/L glucose 5 g/L yeast extract 5 g/L peptone 4.5 g/L Na_2HPO_4 distilled water to 1 L	HS
Modified HS medium with added ground avocado seed	20 g/L glucose 5 g/L yeast extract 5 g/L peptone 4.5 g/L Na_2HPO_4 10 g/L ground avocado seed	HS+AS
White grape bagasse	white grape bagasse extract only	WGB

3. ANALYSIS

BC production was recorded as the dry weight of BC within the volume of medium, according to Equation (1) (Vazquez 2013):

$$BC\ production = \frac{m}{V} \quad (1)$$

where *m* is the dry weight of BC (g), and *V* is the volume (L) of the medium for BC production.

The morphological characteristics of BC were examined using a scanning electron microscope (SEM) (JSM-6060LV, JEOL, Japan). Total polyphenols in the WGB medium were analysed according to procedure described in Di Stefano and Guidoni (1989) and Rigo et al. (2000). The antioxidant activity (AA) in HS and WGB media was analysed according to procedure described in Šmid et al. 2023.

4. RESULTS WITH DISCUSSION

We hypothesized that natural antimicrobial compounds from plant food waste could prevent mould contamination without inhibiting *K. xylinus* growth. Based on its selective activity, avocado seed powder was identified as a candidate. Previous observations suggested that white grape bagasse (WGB) medium prevents contamination. To confirm these findings, BC production was monitored in HS, WGB, and HS supplemented with 10 g/L avocado seed powder (HS+AS) over three weeks (Figure 1).

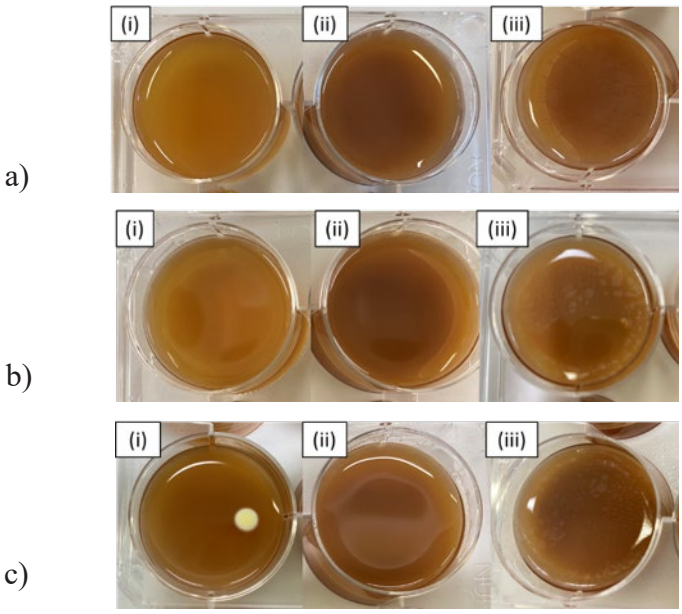


Figure 1: Media (i) HS, (ii) WGB, and (iii) HS+AS for BC production: a) after one week, b) after two weeks, c) after three weeks of incubation.

After one and two weeks of incubation, no visible changes were observed in the culture media. However, turbidity was noticed in the medium containing the avocado seed (Figure 1a (iii) and 1b (iii)). This turbidity may be attributed to the starch content of the avocado seed (Tesfaye 2018, Esquivel-Fajardo 2022, Lubis 2018). When starch granules dissolve or become suspended in water, they can alter the optical properties of the solution, including increased turbidity (Tesfaye 2018, Humaj 2023). After a three-week incubation period, fungal contamination was detected only in the HS medium (Figure 1c (i)).

The influence of the avocado seed on the morphology of BC membranes (Figure 2) and BC production (Figure 3) was also investigated. Regardless of the medium used for BC production, all BC membranes formed a 3D structure with interwoven cellulose fibrils (Figure 2). BC membranes cultivated in WGB and HS+AS media exhibited a more compact structure, characterized by densely arranged and interwoven fibrils. Consequently, their surfaces displayed fewer visible pores, or none, compared to the BC membrane produced in the HS medium (Figure 2a).

In the WGB sample (Figure 2b), the presence of *K. xylinus* bacteria on the surface was observed, likely due to the intentional termination of the BC cultivation process, as all membranes were prepared simultaneously. *K. xylinus* bacteria remain active (and viable) as long as a sufficient nutrient supply is available. The WGB medium still contained adequate nutrients when the cultivation process was halted, and the subsequent NaOH post-treatment did not fully remove the bacteria.

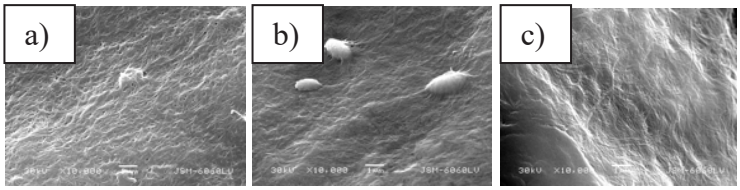


Figure 2: SEM images of BC membranes produced in a) HS, b) WGB in c) HS+AS media.

The results of BC membrane production are presented in Figure 3. After three weeks of cultivation, the BC yield was highest in the WGB medium, reaching 2.38 ± 0.12 g/L, 3.5 times greater than the BC production obtained from the conventional HS medium (0.67 ± 0.13 g/L). In the HS+AS medium, a significant reduction in BC production was observed, with a production of only 0.20 ± 0.03 g/L (Figure 3). This indicates that the avocado seed exerts an inhibitory effect not only on fungal growth but also on BC production. From this perspective, using avocado seed for BC production is not advisable.

Subsequently, the total polyphenol content (TPC) and antioxidant activity of the WGB medium were determined, along with the comparison of these parameters in HS and WGB media (Table 2).

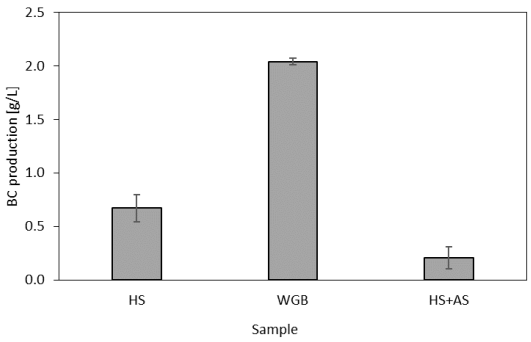


Figure 3: Production (g/L) of BC in HS, WGB and HS+AS media.

Table 2 shows that the WGB culture medium has a high antioxidant activity, while the HS medium does not. The high antioxidant activity of the WGB medium is related to a high content of polyphenols (476.8 ± 2.5 mg/l), which act as natural antimicrobial agent and inhibit the growth and development of pathogenic microorganisms, including moulds.

Table 2: Total polyphenols (TPC) in WGB medium and antioxidant activity (AA) in HS and WGB media.

Medium	TPC (mg/l)	AA (%)
HS	–*	22.5 ± 0.3
WGB	476.8 ± 2.5	88.4 ± 0.2

* The value was not determined.

Polyphenols act as natural antimicrobial agents, inhibiting the growth and development of pathogenic microorganisms, including moulds (Jug 2016, Humaj 2023, Czaplicka 2022). Humaj et al. (Humaj 2023) analyzed polyphenols in the leaves, stems, skins, and seeds of the grapevine cultivar Souvignier gris (the same variety used in our study) and identified a total of 33 polyphenols. The dominant compound varied for each plant part. The primary polyphenols in the skin were quercetin-3-glucoside, caftaric acid, and coutaric acid; in the seeds, catechin, epicatechin, procyanidin B2, C, and B1, and gallic acid predominated; and in the stems, catechin, procyanidin B1, caftaric acid, coutaric acid, trans-resveratrol, and quercetin-3-glucoside were most prevalent. Czaplicka et al. (Czaplicka 2022) also demonstrated that the Souvignier gris variety exhibits significant antioxidant properties due to its high polyphenol content.

5. CONCLUSIONS

WGB contains various polyphenols, such as quercetin-3-glucoside, catechin, and epicatechin, which exhibit antimicrobial properties by inhibiting the growth of microorganisms, including moulds. The presence of these natural compounds not only offers a promising approach to reducing microbial contamination but also aligns with the principles of sustainable and eco-friendly production practices. Utilizing such bioactive compounds in industrial BC production can provide a dual benefit: minimizing the need for synthetic preservatives or strict sterile condi-

tions, while simultaneously enhancing the overall yield and quality of BC. These findings highlight the potential of integrating natural, polyphenol-rich resources into biotechnological processes, paving the way for cost-effective and environmentally responsible production strategies.

6. REFERENCES

Caponio, G.R., Noviello, M., Calabrese, F.M., Gambacorta, G., Giannelli, G. and De Angelis, M. 2022. "Effects of grape pomace polyphenols and in vitro gastrointestinal digestion on antimicrobial activity: Recovery of bioactive compounds." Antioxidants, 11: 1–14.
Corrales, M., Fernandez, A., Pinto, M.G., Butz, P., Franz, C.M., Schuele, E. and Tauscher, B. 2010. "Characterization of phenolic content, in vitro biological activity, and pesticide loads of extracts from white grape skins from organic and conventional cultivars." Food and Chemical Toxicology, 48: 3471–3476.
Czaplicka, M., Parypa, K., Szewczuk, A., Gudarowska, E., Rowińska, M., Zubaidi, M.A. and Nawirska-Olszańska, A. 2022. "Assessment of selected parameters for determining the internal quality of white grape cultivars grown in cold climates." Applied Sciences, 12: 1–7.
Efenberger-Szmechtyk, M., Nowak, A. and Czyzowska, A. 2021. "Plant extracts rich in polyphenols: Antibacterial agents and natural preservatives for meat and meat products." Critical Reviews in Food Science and Nutrition, 61: 149–178.
Esquivel-Fajardo, E.A., Martinez-Ascencio, E.U., Oseguera-Toledo, M.E., Londoño-Restrepo, S.M. and Rodriguez-García, M.E. 2022. "Influence of physicochemical changes of the avocado starch throughout its pasting profile: Combined extraction." Carbohydrate Polymers, 281:1–9.
Gonelimali, F.D., Lin, J., Miao, W., Xuan, J., Charles, F., Chen, M. and Hatab, S.R. 2018. "Antimicrobial properties and mechanism of action of some plant extracts against food pathogens and spoilage microorganisms." Frontiers in Microbiology, 9: 1–9.
Hsu, H., Sheth, C.C. and Veses, V. 2021. "Herbal extracts with antifungal activity against Candida albicans: A systematic review." Mini Reviews in Medicinal Chemistry, 21: 90–117.
Humaj, J., Kostelnikova, K., Sochor, J., Kumsta, M. and Baron, M. 2023 "Study of polyphenolic compounds in wines and different parts of the grapevine." Folia Horticulturae, 35: 297–306.
Ivanova, V., Stefova, M., Vojnoski, B., Dörnyei, Á., Márk, L., Dimovska, V., Stafilov, T. and Kilár, F. 2011. "Identification of polyphenolic compounds in red and white grape varieties grown in R. Macedonia and changes of their content during ripening." Food Research International, 44: 2851–2860.
Jug Novšak, K. 2016 "Protimikrobna učinkovitost izvlečkov fenolnih spojin iz grozdnih tropin" Master thesis, Ljubljana, 75 pp.
Kaur, N., Bains, A., Kaushik, R., Dhull, S.B., Melinda, F. and Chawla, P. 2021. "A review on antifungal efficiency of plant extracts entrenched polysaccharide-based nanohydrogels." Nutrients, 13: 1–26.
Laavanya, D., Shirkole, S. and Balasubramanian, P. 2021. "Current challenges, applications and future perspectives of SCOBY cellulose of Kombucha fermentation." Journal of Cleaner Production, 295: 126454.
Lubis, M., Harahap, M.B., Ginting, M.H., Sartika, M. In Azmi, H. 2018. "Production of bioplastic from avocado seed starch reinforced with microcrystalline cellulose from sugar palm fibers." Journal of engineering science and technology, 13: 381–393.
Mihelčič, A., Vanzo, A., Sivilotti, P., Vrščaj, B. In Lisjak, K. 2023. "An investigation of vine water status as a major factor in the quality of Merlot wine produced in terraced and non-terraced vineyards in the Vipava Valley, Slovenia." OENO One, 57: 231–246.
Nayak, R., Cleveland, D., Tran, G. and Joseph, F. 2024. "Potential of bacterial cellulose for sustainable fashion and textile applications: A review." Journal of Materials Science, 1–26.
Nwaoguikpe, R.N., Braide, W., Ujowundu, C.O. 2011. "Biochemical composition and antimicrobial activities of seed extracts of avocado (Persea americana)." Journal of Microbiology and Antimicrobials, 3: 184–190.
Ogrizek, L., Lamovšek, J., Čuš, F., Leskovšek, M. and Gorjanc, M. 2021. "Properties of bacterial cellulose produced using white and red grape bagasse as a nutrient source." Processes, 9(7): 1–15.
Ogrizek, L., Lamovšek, J., Primc, G., Leskovšek, M., Vesel, A., Mozetič, M., Gorjanc, M. 2024. "Improved adhesion of bacterial cellulose on plasma-treated cotton fabric for development of all-cellulose biocomposites." Molecules, 29(21): 1–15.
Olejar, K.J., Ricci, A., Swift, S., Zujovic, Z., Gordon, K.C., Fedrizzi, B., Versari, A. In Kilmartin, P.A. 2019. "Characterization of an antioxidant and antimicrobial extract from cool climate, white grape marc." Antioxidants, 8: 1–13.
Ong, E.S., Low, J., Tan, J.C., Foo, S.Y. In Leo, C.H. 2022." Valorization of avocado seeds with antioxidant capacity using pressurized hot water extraction." Scientific Reports, 12: 1–11.
Pedreschi, R., Uarrota, V., Fuentealba, C., Alvaro, J.E., Olmedo, P., Defilippi, B.G., Meneses, C. In Campos-Vargas, R. 2019. "Primary metabolism in avocado fruit." Frontiers in Plant Science, 10: 1–16.
Quijano, L. 2017 Embracing bacterial cellulose as a catalyst for sustainable fashion: thesis. Lynchburg: Liberty University, 40 pp.
Revin, V., Liyaskina, E., Nazarkina, M., Bogatyreva, A. and Shchankin, M. 2018. "Cost-effective production of bacterial cellulose using acidic food industry by-products." Brazilian Journal of Microbiology, 49: 151–159.
Rigo, A., Vianello, F., Clementi, G., Rossetto, M., Scarpa, M., Vrhovšek, U. In Mattivi, F. 2000. "Contribution of proanthocyanidins to the peroxy radical scavenging capacity of some Italian red wines." Journal of agricultural and food chemistry, 48: 1996–2002.

Rojas-García, A., Fuentes, E., Cádiz-Gurrea, M.D., Rodriguez, L., Villegas-Aguilar, M.D., Palomo, I., Arráez-Román, D. In Segura-Carretero, A. 2022. ”Biological evaluation of avocado residues as a potential source of bioactive compounds.” Antioxidants, 11: 1–23.
Sánchez, M., FRANCO, D., SINEIRO, J., Magariños, B. In Núñez, M.J. 2009. ”Antioxidant power, bacteriostatic activity, and characterization of white grape pomace extracts by HPLC–ESI–MS.” European Food Research and Technology, 230: 291–301.
Seddiqi, H., Oliaei, E., Honarkar, H., Jin, J., Geonzon, L.C., Bacabac, R.G. and Klein-Nulend, J. 2021. ”Cellulose and its derivatives: Towards biomedical applications.” Cellulose, 28: 1893–1931.
Šmid, S., Verbič, A., Zemljič, L.F. In Gorjanc, M. 2023. ”Eco-Finishing of Cotton with Chitosan and Giant Goldenrod (Solidago gigantea Aiton) Aqueous Extract for Development of Antioxidant and UV Protective Textiles.” Journal of Natural Fibers, 20: 1–13.
Tesfaye, T., Gibril, M., Sithole, B., Ramjugernath, D., Chavan, R., Chunilall, V. In Gounden, N. 2018. ”Valorisation of avocado seeds: extraction and characterisation of starch for textile applications.” Clean Technologies and Environmental Policy, 20: 2135–2154.
Troilo, M., Difonzo, G., Paradiso, V.M., Summo, C. In Caponio, F. 2021. ”Bioactive compounds from vine shoots, grape stalks, and wine lees: Their potential use in agro-food chains.” Foods, 10: 1–16.
Vazquez, A., Foresti, M.L., Cerrutti, P. In Galvagno, M. 2013. ”Bacterial cellulose from simple and low cost production media by Gluconacetobacter xylinus.” Journal of Polymers and the Environment, 21: 545–554.
Zahan, K.A., Pa'e, N. In Muhamad, I.I. 2015. ”Monitoring the effect of pH on bacterial cellulose production and Acetobacter xylinum 0416 growth in a rotary discs reactor.” Arabian Journal for Science and Engineering, 40: 1881–1885.
Zaki, S.A., Ismail, F.A.-A., Abdelatif, S.H., El-Mohsen, N.R. In Helmy, S.A. 2020. ”Research article bioactive compounds and antioxidant activities of avocado peels and seeds.” Pakistan Journal of Biological Sciences, 2020, 23: 345–350.

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ORAL PRESENTATION

VEGAN LEATHER WALLET MADE WITH APPLE WASTE

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Abstract: *Vegan leather wallets represent an innovative and ethical alternative to traditional leather goods, aligning with the growing demand for sustainable and cruelty-free products. This abstract explores the composition, benefits, and market impact of vegan leather wallets. Made from various plant-based or synthetic materials, such as cork, pineapple leaves, and recycled plastics, vegan leather offers comparable durability and aesthetic appeal to animal leather without the associated environmental and ethical concerns. The adoption of vegan leather in the fashion industry reflects a significant shift towards eco-conscious consumerism, driven by awareness of animal rights and environmental sustainability. This trend is supported by advancements in material technology, enabling the production of high-quality, versatile vegan leather products. Vegan leather wallets exemplify this shift, offering consumers stylish, functional, and ethical options that contribute to a more sustainable future. In this novel study we have produced a synthetic vegan leather with apple waste. We have tested the wallet for crocking and abrasion resistance on denim pants. Results showed that in the crouching fastness it is in the accepted area but it can be improved abrasion resistance showed that there was no change in color in the wallet or in the denim. Also there were no damages in both.*

Key words: *Synthetic Leather, Vegan, Sustainability, Accessory*

1. INTRODUCTION

Scientific researchers and the footwear business have been following the slow but steady progress toward developing leather substitutes over the past few decades, which has resulted in the creation of a variety of synthetic and natural materials. The fashion industry, with its constantly shifting trends and fashions, does its best to draw in customers by providing reasonably priced goods, but most consumers are unaware that this business is a major contributor to global pollution due to its vast waste output. Furthermore, the growing production of leather fashion items from natural resources like animal pelts is progressively turning into a serious problem for sustainability for both present and future generations. As a result, creating eco-friendly products and developing other sources are crucial (Saha,2020).

Luxury brands who want to integrate sustainability into their business practices; these brands target millennial consumers who are concerned about the environment (Rolling, 2020). As a result, many fashion brands concentrate on developing substitutes for animal goods. This kind of activity will undoubtedly boost sales and upset the current social order. The desire to improve animal rights and welfare is what drives the creation of alternative materials, which is a sustainable indicator for businesses looking to expand while simultaneously taking care of the environment (Choi, 2021). With these concerns we have studied ways to both have the sustainable and cruel-free approach and to have a good garment quality as normal leather products. We have used polyester as base fabric and used polyurethane-waste from apple processing for the outer of the wallet.

For several reasons, urethane adhesives offer better adhesion (Eling, 2004). They may successfully saturate nearly any substrate's surface. Because of hydrogen bonding, they engage in polar interactions with the surface. They can penetrate the majority of porous substrates due to their small molecular size or low molecular weight. They also create covalent connections with substrates that contain hydrogen atoms in an active state. Adhesive

stiffness, adhesive strength, elasticity, and cross-linking can therefore be adjusted to meet certain demands and specifications by adjusting the molecular makeup and type of polyurethane glue used (Fitzgerald, 2013).

2. DESIGN AND EXPERIMENTAL

The vegan leather wallet emphasizes sustainability, durability, and security, appealing to environmentally aware consumers who prioritize aesthetics and utility. Apple leather, the principal material, is sourced from waste generated by the apple industry, thereby diminishing environmental impact while providing a soft, high-quality texture akin to conventional leather. A layer of PU (polyurethane) coating is applied to augment durability and ensure endurance, offering resistance to wear, dampness, and daily use while preserving a lightweight structure. The design adopts a minimalist and ergonomic approach, incorporating many card slots for convenient access and organization while maintaining a slim profile.

For the future we are planning to put an RFID-blocking layer, composed of a thin but efficient conductive fabric or aluminum shielding, is seamlessly incorporated between the material layers to thwart unlawful scanning and data theft. This functionality is especially advantageous for consumers possessing contactless payment cards or digital access keys. The manufacturing process emphasizes low-impact dyes, non-toxic adhesives, and energy-efficient production techniques, thereby guaranteeing an ethical and sustainable supply chain. The cardholder features meticulous stitching and edge-sealing methods to improve its durability while preserving a sophisticated, contemporary appearance. The product, encased in recyclable or biodegradable materials, corresponds with a sustainable lifestyle, rendering it an optimal selection for anyone desiring a fashionable, environmentally conscious, and reliable daily accessory.

We have our material from VAKKO company. The material are 18% PL, 43% PU(polyurethane) and 39% WAP(waste of apples)

2.1 Methods

Coagulation

The support is first impregnated with a mixture of PU and Apple waste. The coagulation process starts after when the impregnated fabric goes in the water with DMF solvent. After the material is coagulated it is washed to be cleaned from all the solvent residuals. Then is finally dried in the ovens. The coagulation process allows the production of synthetic leather with breathable and aesthetic effects that make it very similar to authentic leather.

Coating

This process can be separated in 3 layers:

- first Pu or PU/APPLE layer (preskin) coated directly onto the release paper; this will be the visible one that must have the highest resistance to scratching, flexion, wear and tear

-a second and a third PU layer (skin or body), coated directly onto the previous layers

-a final glue layer to stick the textile support or coagulated material whose function is to act as reinforcement.

Embossing

The texture of the material given by the cylinder in the embossing machine.

2.2 Testing

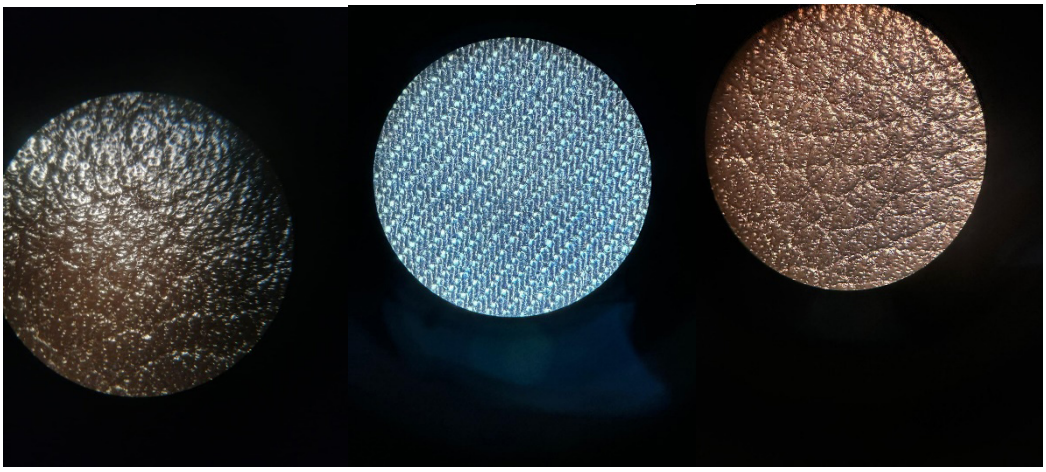
Testing of the material has been done with their standarts as crocking fastness ISO 105-X12 with SDL Atlas M238AA and abrasion resistance ISO 12947 modified with Nu-Martindale abrasion and pilling tester. The modification is changing the abrasion cloth with denim to see the effect of the wallet to the fabric.

3. RESULTS AND DISCUSSION

Crocking fastness results for Melavir sample Dry 3-4 and for wet 3.

The results are in the acceptable region but improvements can be made.

Abrasion resistance results are shown below on Figure 1.



A) B) C)

Figure 1: Abrasion resistance of the studied samples: A) Before test, B) Denim Fabric after test, C) Leather after test

After 20.000 revolutions there were no breakage on the wallet and there were no damage or color changes on the denim fabric.

4. CONCLUSIONS

In conclusion, the journey towards developing sustainable and cruelty-free leather alternatives has made significant strides, driven by the fashion industry's need to address its environmental impact. The use of innovative materials such as polyester base fabric combined with polyurethane waste from apple processing exemplifies the creative approaches being taken to produce high-quality synthetic leather. This process, involving multiple layers and advanced techniques like coagulation, yields a material that closely resembles genuine leather in both aesthetics and functionality.

Our testing results, including crocking fastness and abrasion resistance, indicate that the synthetic leather created through this method meets industry standards. However, there is always room for improvement, and continuous refinement of these materials will ensure even better performance and greater acceptance in the market.

Ultimately, the development of eco-friendly leather alternatives is a vital step towards a more sustainable fashion industry. By reducing reliance on animal products and minimizing environmental impact, we can pave the way for a future where fashion and sustainability coexist harmoniously.

For future of this study we are going to try different approaches to waste and try to incorparete functionality as anti-theft to contactless payments

5. REFERENCES:

Choi, Y. H. and Lee, K. H. 2021. “Ethical Consumers’ Awareness of Vegan Materials: Focused on Fake Fur and Fake Leather.” *Sustainability* 13 (1): 436.

Eling, B. and Phanopolous, C. 2004. *Polyurethane Adhesives and Binders*. Greenwood Village, CO: Poisindex, Micromedex.

Fitzgerald, K. T. and Bronstein, A. C. 2013. “Polyurethane Adhesive Ingestion.” *Topics in Companion Animal Medicine* 28 (1): 28–31.

Rolling, V., Seifert, C., Chattaraman, V. and Sadachar, A. 2020. “Pro-Environmental Millennial Consumers’ Responses to the Fur Conundrum of Luxury Brands.” *International Journal of Consumer Studies* 44 (6): 1–14.

Saha, N., Ngwabebhoh, F. A., Nguyen, H. T. and Saha, P. 2020. “Environmentally Friendly and Animal Free Leather: Fabrication and Characterization.” In *AIP Conference Proceedings*, Vol. 2289, No. 1. Melville, NY: AIP Publishing.

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POSTER PRESENTATION

CHARACTERIZATION OF MELT-EXTRUDED PA 6 FILAMENTS MODIFIED WITH ZnO NANOPARTICLES

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Abstract: *This study investigates the potential of ZnO-modified polyamide 6 (PA 6) fibres produced by melt spinning to support sustainable textile production. Melt spinning, a chemical spinning technique, is an efficient and cost-effective method to incorporate active nanoparticles into polymer fibres. Recycled PA 6 fibres were modified with ZnO nanoparticles (ZnO NPs) in concentrations of 0.1 to 2.0 wt % of the polymer. Morphological analysis by SEM showed the successful incorporation of the ZnO NPs, which appear as white, irregular structures on the filament surfaces, with the surface roughness increasing at higher concentrations. Elemental analysis by ICP-MS confirmed that the concentrations and sizes of the ZnO NPs were within the expected range. This approach is in line with environmental goals as it combines recycled materials with functional improvements for high performance applications.*

Keywords: *melt spinning, recycled PA 6, ZnO NPs, SEM microscopy, ICP-MS spectroscopy*

1. INTRODUCTION

In recent years, the textile industry has increasingly focused on sustainable production methods due to technological advances, growing environmental concerns and stricter legal requirements. Global challenges such as climate change and the depletion of natural resources have led the industry to adopt the principles of the circular economy, which focus on reducing waste, recycling materials and maximising the use of resources (Chen et al., 2021). As one of the biggest polluters, the textile industry faces particular challenges. It needs to reduce its carbon footprint, manage textile waste and develop materials that meet both performance and sustainability standards (Vollmer et al., 2020).

As part of this effort, melt spinning has emerged as one of the most promising techniques to promote sustainable textile production. This cost-effective and versatile chemical spinning process facilitates the integration of active particles directly into polymer fibres, enabling the production of functionalized textiles in a streamlined and efficient manner (Hufenus et al., 2020). Melt spinning not only supports the incorporation of additives, but also enables the use of recycled raw materials, making it an ideal technology for addressing environmental concerns (Kim et al., 2024). By simplifying the production process and reducing energy consumption, this method meets modern sustainability goals while delivering high-performance textile products (Zhang et al., 2023).

Polyamide 6 (PA 6), a thermoplastic polymer widely used in the textile industry, plays a central role in this transformation. PA 6 is known for its exceptional mechanical properties, including durability, wear resistance and chemical stability, and is particularly well suited to recycling processes (Zhang et al., 2014). The possibility of reusing PA 6 waste into high-quality fibres underlines its importance in the development of sustainable textile solutions (Kim et al., 2024). However, as consumer demand shifts towards multifunctional materials that offer additional properties beyond durability, there is an increasing need to improve the inherent properties of PA 6 (Zhang et al., 2022).

Nanotechnology offers innovative solutions to improve polymer functionality, with zinc oxide nanoparticles (ZnO NPs) emerging as an important additive for textile applications. ZnO NPs offer a range of beneficial properties, in-

cluding antibacterial activity, odour absorption and UV protection, which are highly desirable for hygiene-sensitive applications such as sportswear, outdoor protective clothing and medical textiles (Verbič et al., 2019). In addition, ZnO NPs contribute to the development of textiles that are both high-performance and environmentally friendly, as they enable the production of functional fibres with minimal ecological impact (Ludaš Dujmić et al., 2024).

The integration of ZnO NPs into recycled PA 6 fibres through melt spinning represents a significant advance in the field of sustainable textiles. This approach not only extends the life cycle of polymer materials, but also increases their value by providing additional functionalities (Bashal et al., 2022). By meeting the dual goals of performance and sustainability, ZnO-modified PA 6 fibres have the potential to transform the textile industry and adapt it to the growing demand for environmentally friendly and multifunctional products (Vitchuli et al., 2011).

2. EXPERIMENTAL

To investigate the potential of ZnO NPs to improve the properties of recycled polyamide 6 polymer filaments, a series of experiments were conducted using the melt spinning technique and different concentrations of ZnO NPs.

2.1 Materials and methods

Recycled polyamide polymer granulate (PA 6) obtained by recycling fishing net waste and purchased from the company AquafilSLO, Ljubljana (Slovenia), was used for the study. Prior to extrusion, 600 g of PA 6 polymer was dried at a temperature of 80 °C for 24 hours. ZnO nanoparticles (Alfa Aesar GmbH&Co), size 40 - 100 nm, melting point 1975 °C, were added in 5 different ratios (0.1 %, 0.5 %, 1 %, 1.5 %, 2 %) to the weight of the PA 6 polymer.

The extrusion process was carried out using a Rondol Bench Top 21 mm twin-screw extruder (Rondol Technology Ltd., Staffordshire, UK). Before adding PA 6 polymer and ZnO nanoparticles to the extruder charge, the parameters of the twin-screw extruder were optimized for the chemical melt spinning process (Table 1).

Table 1: Optimization of a twin-screw extruder for chemical melt spinning

Pressure	**Torque**	**Screw Diameter**	**Six Heating Zones**	**Cooling medium**
0.7–2.0 bar	50–80 rpm	21 mm	1st zone: 220 °C, 2nd to 5th zones: 230 °C 6th zones: 233 °C	Water

After the extrusion process, the samples were analyzed with a scanning electron microscopy (SEM) using the Prisma E microscope (Thermo Fisher Scientific Inc., Waltham, MA, USA) to gain insight into the morphological properties of the samples. For the analysis of the samples with the scanning electron microscope, gold was vapor-deposited in order to obtain an electrically conductive sample on which the rays could be reflected. The morphological view of the samples was created at a magnification of 1600x and 8100x.

Polymer granules treated with ZnO NPs and untreated polymer granules were brought into contact with the simulant ultrapure water at a mass-to-volume ratio of 5 g = 0.1 l at 40 °C for 10 days. After the migration test, the samples were homogenized for 30 minutes at room temperature in an ultrasonic bath with ZnO NPs and characterized using the Agilent 7900 single quadrupole mass spectrometer (ICP-MS) (Santa Clara, USA), instrument operational parameters are shown in Table 2.

For the measurement of total Zn, the samples were subjected to microwave digestion. The samples were digested by microwave digestion in the Multiwave PRO sample digestion and extraction system (Anton Paar, Austria). The digestion amount for polymer granulate samples was 0.2 g. The reagent used was a mixture of 5.0 ml ultrapure water, 2.0 ml nitric acid (ultra trace 69%, Scharlau) and 1.0 ml hydrogen peroxide (suprapur 30%, Merck). After digestion, the samples were filtered with filter paper (blue tape) and diluted to 25 ml in volumetric flasks and analyzed in the Agilent 7900 ICP-MS. Two silver dispersions with different lot numbers (MKCH0301 and MKCK6165) of standard reference materials were used to characterize the ZnO particles to confirm the accuracy of the method.

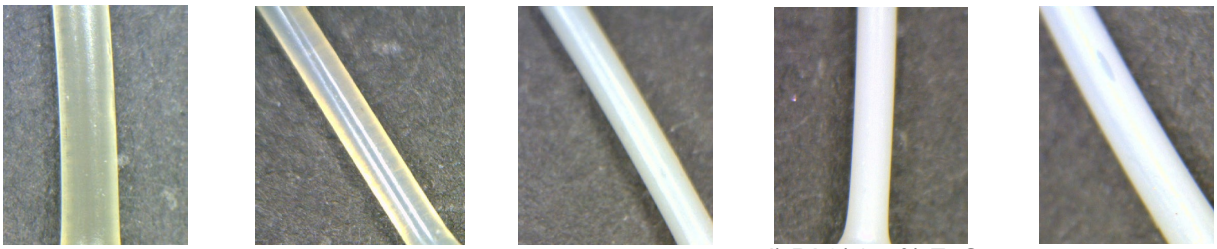
Single particle ICP-MS (spICP-MS) was used to characterize the ZnO NPs dispersed or suspended in ultrapure water. Elemental signals of individual ZnO particles were detected using the spICP-MS instrument, which allows the simultaneous determination of particle number and size distribution as well as concentrations of particles and dissolved elements.

Table 2: Instrument operational parameters of the Agilent 7900 ICP-MS

RF power (W)	Sampling depth (mm)	Carrier gas (L/min)	Sample uptake rate (mL/min)	Spray chamber temp. (°C)	Dwell time (µs)	Masses monitored	Data acquisition time (s/element)
1550	8	1.05	0.31	2	100	66 Zn	60

3. RESULTS AND DISCUSSION

Five different filaments were produced by extruding recycled polyamide polymer granules (PA 6), incorporating ZnO nanoparticles in defined weight fractions (t.2.1). The process demonstrates the effective combination of optimized extrusion parameters and precise integration of nanoparticles to achieve tailored material properties. Figure 1 shows the resulting filaments, which were photographed with a Dino-Lite digital microscope at 60x magnification.

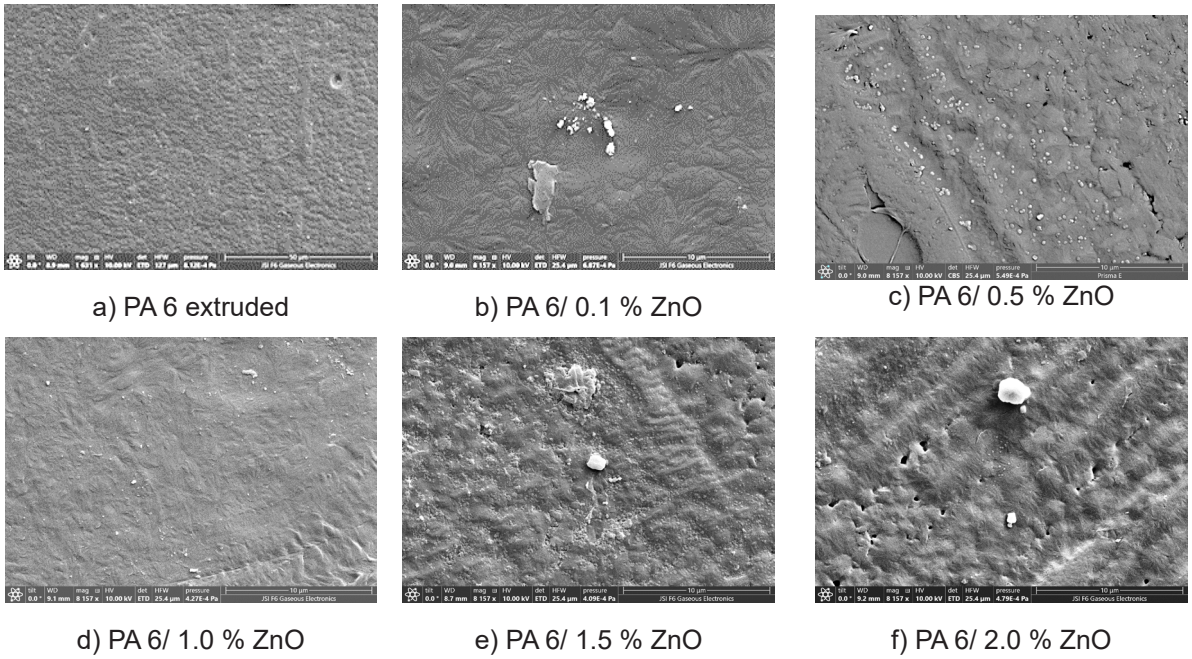


a) PA6/ 0.1 % ZnO b) PA6/ 0.5 % ZnO c) PA6/ 1 % ZnO d) PA6/ 1.5 % ZnO e) PA6/ 2 % ZnO

Figure 1. Produced filaments photographed with a Dino-Lite digital microscope at 60x magnification

The morphological examination of the samples was carried out at magnifications of 1600x and 8100x in order to obtain detailed insights into the surface properties of the material. In contrast to the raw PA 6 polymer sample, which has a relatively smooth and uniform surface, the morphological SEM analysis shows distinct features related to the incorporation of ZnO NPs. These nanoparticles appear as white, irregularly shaped structures distributed over the filament surfaces. With increasing ZnO concentration, remarkable changes in surface morphology can be observed. The filament surfaces show an increased relief and a significant increase in surface roughness, indicating the interaction between the polymer matrix and the nanoparticles (Figure 2). At higher concentrations of nanoparticles, the formation of agglomerates characterized by clusters of ZnO particles randomly dispersed over the polymer surface becomes evident. This random dispersion contributes to the heterogeneity of the surface texture and emphasizes the challenge of achieving a uniform distribution of nanoparticles at high concentrations.

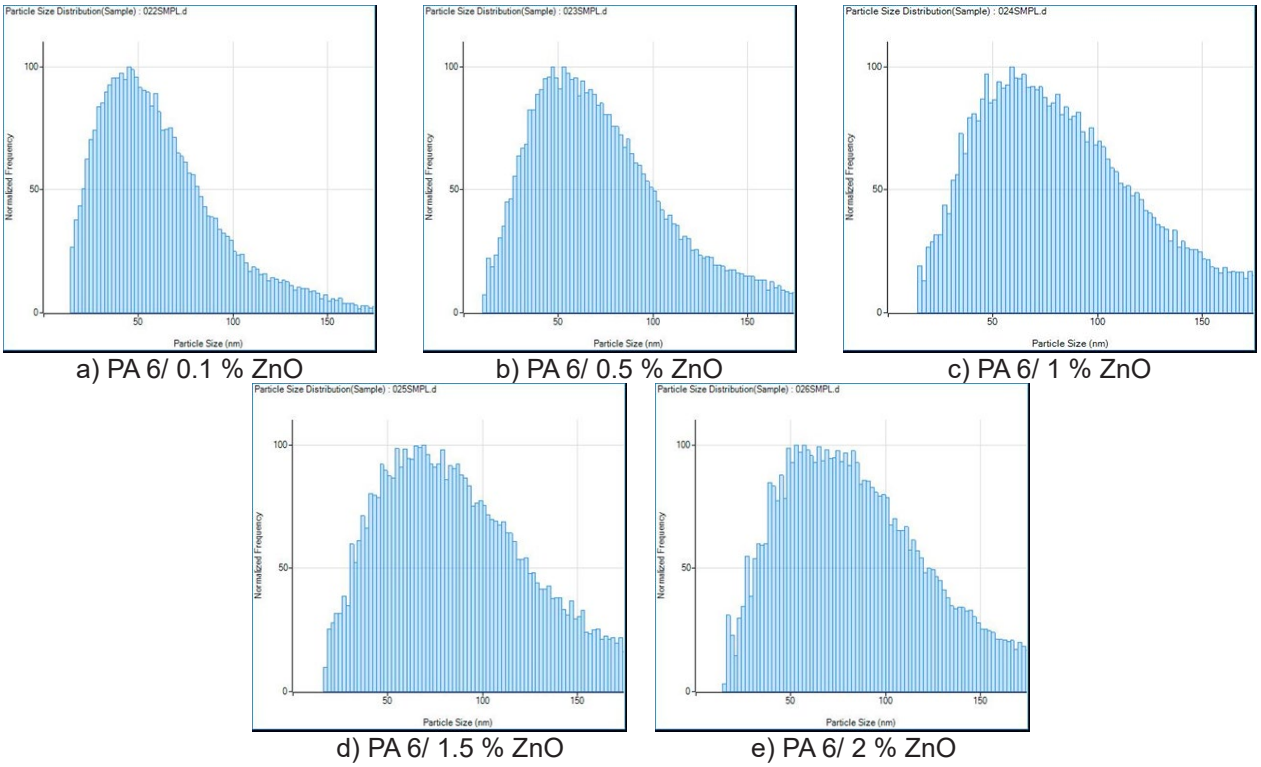
The elemental analysis after the migration test at 40 °C for 10 days, the results (Figure 3) showed good agreement with the ZnO NPs embedded in the polymer. The measured concentration of ZnO NPs in the sample with 0.1% ZnO was 56 000 ng/L, 0.5% ZnO was 83 000 ng/L, 1% ZnO was 105 000 ng/L, 1.5% ZnO was 155 000 ng/L and increased to a concentration value of 192 000 ng/L in the sample with 2.0% ZnO. Furthermore, the mean size of the ZnO NPs was 63.5 – 95 nm, depending on the embedded concentration in the polymer material. The obtained results showed a good correlation with the reported size range of the ZnO NPs (40 - 100 nm). Based on the results obtained, it can be assumed that the migration conditions at 40 °C for 10 days are more suitable for the migration of nanoparticles from this type of polymer.



a) PA 6 extruded b) PA 6/ 0.1 % ZnO c) PA 6/ 0.5 % ZnO

d) PA 6/ 1.0 % ZnO e) PA 6/ 1.5 % ZnO f) PA 6/ 2.0 % ZnO

Figure 2. Morphological SEM analysis of PA 6 polymer, extruded with different concentrations of ZnO nanoparticles; a) magnification of 1600x, b-f) 8100x



a) PA 6/ 0.1 % ZnO b) PA 6/ 0.5 % ZnO c) PA 6/ 1 % ZnO

d) PA 6/ 1.5 % ZnO e) PA 6/ 2 % ZnO

Figure 3. Particle size distribution of ZnO nanoparticles in ultrapure water extract: a) - e); 0.1 % - 2 % ZnO after migation during 10 days at 40 °C

4. CONCLUSION

The study successfully demonstrated the production of filaments from recycled polyamide (PA 6) with different concentrations of ZnO NPs using optimized extrusion parameters. Morphological SEM analyzes confirmed that the incorporation of ZnO nanoparticles significantly altered the surface properties of the filaments, with increased surface relief and roughness observed with increasing nanoparticle concentration. At higher concentrations, the formation of agglomerates made it clear how difficult it is to achieve a uniform distribution of the ZnO NPs.

The migration tests showed a direct correlation between the concentration of ZnO NPs embedded in the polymer and their release under controlled conditions. The measured concentrations of ZnO NPs in the migration medium ranged from 56,000 ng/L for the sample with 0.1 % ZnO to 192,000 ng/L for the sample with 2.0 % ZnO. The mean size of the ZnO NPs (63.5 – 95 nm) matched well with the expected range, indicating a consistent particle size distribution.

These results suggest that migration conditions of 40 °C for 10 days are particularly effective for evaluating the release of nanoparticles from PA 6-based polymers. The results provide valuable insights into the potential for tailoring the material properties, release behaviour of nanoparticles in recycled polymers, and support their application in the development of advanced materials.

5. REFERENCES

Bashal, A.H. et al. 2022. “Bio-Based (Chitosan-ZnO) Nanocomposite: Synthesis, Characterization, and Its Use as Recyclable, Ecofriendly Biocatalyst for Synthesis of Thiazoles Tethered Azo Groups.” *Polymers*, 14(386): 1–10.

Chen, X. et al. 2021. “Circular Economy and Sustainability of the Clothing and Textile Industry.” *Mater Circ Econ* **3(12**): 1–9.

Hufenus, R., Yan, Y., Dauner, M., Kikutani, T. 2020. “Melt-Spun Fibers for Textile Applications.” *Materials* 13(19): 1–32.

Kim, K. et al. 2024. “Melt Spinnability Comparison of Mechanically and Chemically Recycled Polyamide 6 for Plastic Waste Reuse.” *Polymers* 16(3152): 1–14.

Ludaš Dujmić, A. et al. 2024. “Characterization of Melt-Spun Recycled PA 6 Polymer by Adding ZnO Nanoparticles during the Extrusion Process.” *Polymers* 16(1883): 1–13.

Verbič, A., Gorjanc, M., Simončič, B. 2019. “Zinc Oxide for Functional Textile Coatings: Recent Advances”. *Coatings* 9(9): 1–26.

Vitchuli, N., et al. 2011. “Multifunctional ZnO/Nylon 6 nanofiber mats by an electrospinning–electrospraying hybrid process for use in protective applications.” *Science and Technology of Advanced Materials* 12(5): 1–7.

Vollmer, I. et al. 2020. “Beyond Mechanical Recycling: Giving New Life to Plastic Waste.” *Angew. Chem. Int. Ed.* 59(15402): 1-22.

Zhang, D. 2014. *Advances in Filament Yarn Spinning of Textiles and Polymers*, Cambridge, UK: Woodhead Publishing.

Zhang, S. et al. 2022. “Preparing cationic dyeable polyamide 6 filaments by combining the masterbatch technique with melt copolymerization. ” *Textile Research Journal* 92(3-4): 511–524.

Zhang, S., Wu, Y., Ji, P., Ran, Q., Wang, H., Chen, B. and Wang, C. 2023. “Sustainable Production of Polyamide 6 Fibers: Direct Melt Spinning and Efficient Reuse of Residual Oligomers during Polymerization.” *ACS Sustainable Chemistry & Engineering* 11(9): 3789–3800

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POSTER PRESENTATION

UV RADIATION PROTECTION OF COTTON AND WOOL FUNCTIONALISED WITH HOP LEAVES

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Abstract: *In this research, wool and cotton fabrics were bio-mordanted with pomegranate peel extract and subsequently dyed with hop leaf extracts. The extracts were prepared using either crushed or ground leaves in tap or distilled water. Dyeing was performed after the bio-mordanting process. The textile samples were analysed for their colour using a reflectance spectrophotometer and their transmittance in the ultraviolet (UV) range using a UV/Vis spectrophotometer. The results revealed that bio-mordanting enhanced the colour yield of the dyed fabrics, leading to a higher ultraviolet protection factor (UPF) and classification in the excellent protection category. Additionally, the preparation method of the extract proved to be crucial, as crushed hop leaves extracted in tap water yielded the best dyeability and functional properties of the fabrics.*

Keywords: *cotton, wool, bio-mordanting, eco-finishing, food waste, pomegranate peels, hop leaves, UV protection.*

1. INTRODUCTION

Increasingly strict environmental regulations and legislations in the field of environmental protection are boosting the use of natural ingredients. People have become more environmentally and health conscious and many are looking for products that help protect the environment, reduce the global problem of pollution, and use products in their lives that are sustainable and toxin-free. It is crucial to focus on environmentally friendly processes that are in line with EU priorities with Zero pollution action plan and the Chemicals strategy for sustainability. Pomegranate peel extract can serve as both a dyeing agent and a bio-mordant (Bouaziz, 2021; Hosseinnezhad, 2022; Mansour, 2022; Shahid, 2019). The peel is a rich source of tannins, punicalins, punicalagins, gallic acid, and ellagic acid (Shahid, 2019). When used as a bio-mordant, it can induce colour changes in wool dyed with weld, particularly at higher concentrations (Hosseinnezhad, 2022). However, in the case of dyeing wool with madder, it does not affect the coloration (Hosseinnezhad, 2022). Batool et al. (Batool, 2023) compared the use of mineral mordants and bio-mordants for cotton fabric and found that pomegranate peel extract yielded the best results when dyeing with eggplant waste. To date, no published research has explored dyeing or finishing textiles with hop leaves, despite findings on the polyphenol compounds present in hop leaves extracts prepared with ethanol, methanol, and ethanol-water mixtures (80:20) (Abram, 2015; Chiancone, 2023; Čeh, 2007; Muzykiewicz, 2019). The major phenolics in hop leaves include flavanol glycosides with quercetin, kaempferol glycosides, and chlorogenic acid (Chiancone, 2023). These compounds contribute to the antioxidant and antibacterial properties of hop leaf extracts. The aim of our research was to develop sustainable bio-based textiles with UV-protective properties using extracts derived from food waste products, specifically pomegranate peel as a bio-mordant and hop leaves extract as a dyebath.

2. EXPERIMENTAL

2.1 Material

For the research raw wool (171.6 g/m^2; 32 warp/cm, 24 weft/cm; WO) and raw, scoured cotton (128 g/m^2; 55 warp/cm, 37 weft/cm; CO) fabrics were used. Hop leaves were collected at The Slovenian institute of hop research and brewing, Žalec, Slovenia.

2.2 Bio-mordant preparation and fabric functionalisation

Bio-mordanting was performed by using pomegranate peels (cleaned, dried and grinded). Hot distilled water was poured over 2 g/l of pomegranate peels, extracting at boiling for 5 minutes, left to cool and macerate for 24 hours at room temperature. After the mixture was filtered, the resulting extract was used for bio-mordanting of WO and CO in GyroWash 815 (James Heal, UK), with the liquor to goods ratio (L:G) equal to 40:1, at 60 °C, for 30 min. The samples were wrung and left to air dry.

2.3 Hop leaves extract preparation and fabric dyeing

Hop leaves extract was prepared by pouring hot distilled or hard water over 40 g/L dried and grinded or crushed leaves. This was followed by extracting at boiling temperatures for 5 min and left to cool for 30 min. After filtration the extracts were used for dyeing unmordanted and bio-mordanted WO and CO samples in Gyrowash, at L:G = 40:1, temperature 60 °C, for 60 min. The samples were rinsed with hard or distilled water, wrung and left to air dry. The marking of samples is presented in Table 1.

Table 1: Marking of WO and CO samples according to the treatment

Wool marking	Cotton marking	Bio-mordanting	Extraction water for hop leaves	Hop leaves preparation
WO_raw	CO_raw	N/A	N/A	N/A
WO_bio	CO_bio	Yes	N/A	N/A
WO_T_G	CO_T_G	No	Tap	Grinded
WO_B_T_G	CO_B_T_G	Yes		
WO_T_C	CO_T_C	No		Crushed
WO_B_T_C	CO_B_T_C	Yes		
WO_D_G	CO_D_G	No	Distilled	Grinded
WO_B_D_G	CO_B_D_G	Yes		
WO_D_C	CO_D_C	No		Crushed
WO_B_D_C	CO_B_D_C	Yes		

N/A stands for not applicable

2.4 Analysis

All textile samples were analysed for their colour and colour yield using reflectance spectrometer Spectro 1050, with 9 mm aperture. Five measurements were taken for each fabric sample. The colour yield (ΔK/S) was calculated from reflectance measurements (R) of untreated and treated CO or WO sample, using equation 1:

$$\Delta\frac{K}{S} = \left[\frac{(1-R_{UN})^2}{2R_{UN}}\right] - \left[\frac{(1-R_T)^2}{2R_T}\right] \qquad (1)$$

where R_{UN} is reflectance of untreated sample and R_T is the reflectance of treated sample.

The protection against UV radiation was determined using Lambda 850+ UV/Vis spectrometer (Perkin Elmer). The transmittance of UV radiation measurements and UV protection factor (UPF) calculations were performed according to the AATCC 183 test method (AATCC 2020). We performed six measurements (at 0°, 45°, and 90°) per sample. The UV protection factor (UPF) was calculated according to the equation 2:

$$UPF = \frac{\sum_{290}^{400} E(\lambda) \cdot S(\lambda)}{\sum_{290}^{400} E(\lambda) \cdot S(\lambda) \cdot T(\lambda)} \qquad (2)$$

The UPF values were determined based on the AS/NZ 4399:2017 standard, which determines the effectiveness of textile protection against UV rays. Protection is classified into three categories – minimal, good and excellent. Values below 15 mean insufficient UV protection, values between 15 and 30 minimal UV protection, between 30 and 50 good UV protection, and above 50 excellent UV protection.

3. RESULTS WITH DISCUSSION

The CIELAB colour coordinates of textile samples are presented in Table 2. The results show that bio-mordanting with pomegranate peel extract decreases the CIE L* values of the samples, meaning they become darker. Bio-mordanting also affects the CIE a* and b* values: WO becomes redder and yellower (both values increase), while CO becomes yellower (only the CIE b* value changes). This trend continues after dyeing, as bio-mordanted dyed samples are darker, redder, and yellower compared to unmordanted dyed samples. The type of water used (distilled or tap) for preparing hop leaves extracts significantly influences the colour of dyed CO and WO, with the effect being more pronounced for CO. The CO dyed with hop leaves extract prepared using tap water appears much darker, slightly redder, and slightly yellower compared to CO dyed with hop leaves extracts prepared using distilled water. For WO, dyeing with extracts prepared with tap water slightly darkens the samples, causes a minor shift towards the red axis, and significantly increases yellowing. The method of preparing the hop leaves (using crushed or ground leaves) for extraction also affects the colour of the dyed samples. Using ground hop leaves results in slightly lighter and yellower coloration of CO, while WO samples exhibit darker coloration regardless of the type of water used for extract preparation.

Table 2: CIELAB colour coordinates of WO and CO samples

Sample	CIE L*	CIE a*	CIE b*
CO_raw	87.80	1.24	10.06
CO_bio	84.06	1.00	15.69
CO_T_G	75.62	5.42	16.12
CO_B_T_G	69.53	6.45	22.12
CO_T_C	75.01	5.06	18.64
CO_B_T_C	69.17	5.83	22.92
CO_D_G	77.03	4.76	17.85
CO_B_D_G	71.13	5.88	22.74
CO_D_C	76.32	4.54	17.28
CO_B_D_C	69.79	5.84	22.69
WO_raw	87.20	-0.40	13.51
WO_bio	79.39	2.16	16.74
WO_T_G	75.32	3.82	20.07
WO_B_T_G	69.88	4.81	23.77
WO_T_C	72.37	4.96	21.40
WO_B_T_C	68.31	4.85	24.37
WO_D_G	75.88	3.23	21.70
WO_B_D_G	70.89	4.17	23.52
WO_D_C	74.84	2.97	20.88
WO_B_D_C	69.12	4.25	23.72

The ΔK/S value of dyed CO and WO samples was calculated by comparing untreated and treated samples (i.e., raw/mordanted and dyed/undyed), and the results are presented in Figure 1. The ΔK/S values align with the CIELAB coordinates shown in Table 2. Bio-mordanting enhances the colour yield, with a more pronounced effect observed in samples dyed with hop leaves extract prepared using tap water compared to distilled water. Figure 1 also reveals that hop leaves extracts exhibit a better affinity towards WO fabrics than towards CO fabrics. Additionally, using crushed rather than ground leaves for extract preparation results in a higher colour yield, regardless of the substrate or the type of water used for extract preparation.

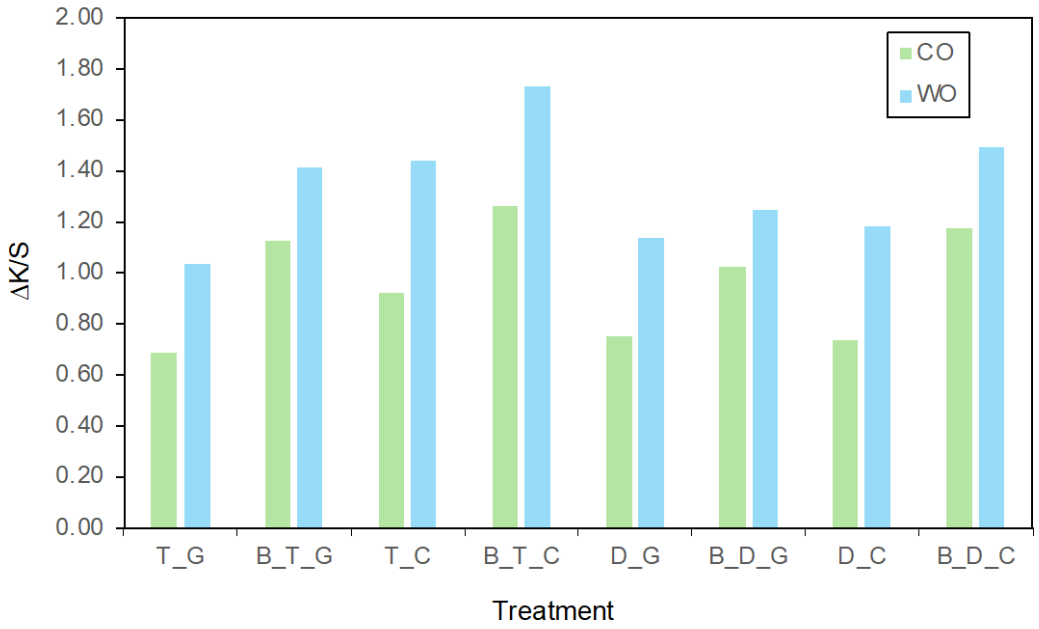


Figure 1: ΔK/S of CO and WO dyed with hop leaves extract

The influence of using either crushed or ground hop leaves for dyeing is more evident in the functional properties of textiles. Table 3 presents the UV protection factor (UPF) and protection category of the textile samples. The lowest UPF value, 11.40, was observed for raw CO, which provides insufficient protection against UV radiation. All other samples demonstrated either good or excellent UV protection. Bio-mordanting and dyeing significantly enhanced UV protection, with the most pronounced increases in UPF values found in samples dyed with extracts prepared from crushed hop leaves, regardless of the type of water used for extraction.

Table 3: UV protection factor (UPF), transmittance in UVA and UVB (%), UVA and UVB blocking (%) and protection category of CO and WO samples.

Sample	UPF	UVA transmittance (%)	UVB transmittance (%)	UVA blocking (%)	UVB blocking (%)	Protection category
CO_raw	11.40	14.71	7.34	85.29	92.66	Insufficient
CO_bio	52.22	3.29	1.42	96.71	98.58	Excellent
CO_T_G	39.46	4.44	2.11	95.56	97.89	Good
CO_B_T_G	118.00	1.62	0.70	98.38	99.30	Excellent
CO_T_C	54.80	3.23	1.53	96.77	98.47	Excellent
CO_B_T_C	131.72	1.41	0.63	98.59	99.37	Excellent
CO_D_G	40.11	4.43	2.08	95.57	97.92	Good
CO_B_D_G	105.02	1.76	0.79	98.24	99.21	Excellent
CO_D_C	48.23	3.86	1.73	96.14	98.27	Good
CO_B_D_C	115.86	1.64	0.72	98,36	99.28	Excellent
WO_raw	59.10	9.70	0.56	90.30	99.44	Excellent
WO_bio	119.15	3.12	0.43	96.88	99.57	Excellent
WO_T_G	121.93	3.47	0.37	96.53	99.63	Excellent
WO_B_T_G	201.35	1.71	0.27	98.29	99.73	Excellent
WO_T_C	181.36	2.23	0.26	97.77	99.74	Excellent
WO_B_T_C	255.79	1.31	0.22	98.69	99.78	Excellent
WO_D_G	120.77	3.42	0.39	96.58	99.61	Excellent
WO_B_D_G	226.26	1.48	0.25	98.52	99.75	Excellent
WO_D_C	138.56	2.88	0.35	97.12	99.65	Excellent
WO_B_D_C	270.92	1.31	0.20	98.69	99.80	Excellent

4. CONCLUSIONS

Using crushed hop leaves for extract preparation results in higher colour yield and improved UV protection for both CO and WO compared to ground leaves, particularly when the extract is prepared with tap water instead of distilled water. These effects are further enhanced when functionalisation is performed on bio-mordanted samples.

5. ACKNOWLEDGEMENT

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6. REFERENCES

Abram, V., Čeh, B., Vidmar, M., Hercezi, M., Lazić, N., Bucik, V., Smole Možina, S., J. Košir, I., Kač, M., Demšar, L., Poklar Ulrih, N. 2015. "A comparison of antioxidant and antimicrobial activity between hop leaves and hop cones." *Industrial Crops and Products* 64: 124-134.

Batool, F., Iqbal, N., Adeel, S., Azeem, M., Mumtaz, S. and Hussaan, M. 2023. "Exploration of natural colourant of (Solanum melongena L.) brinjal plant residues for fabric dyeing: a novel approach towards textile processing." *Natural Poroduct Research:* 1-7.

Bouaziz, A., Dridi, D., Gargoubi, S., Chelbi, S., Boudokhane, C., Kenani, A. and Aroui, S. 2021. "Analysis of the Coloring and Antibacterial Effects of Natural Dye: Pomegranate Peel." *Coatings* 11 (1277): 1−9.

Chiancone, B., Guarrasi, V., Leto, L., Del Vecchio, L., Calani, L., Ganino, T., Galaverni, M. and Cirlini, M. 2023. "Vitro-derived hop (Humulus lupulus L.) leaves and roots as source of bioactive compounds: antioxidant activity and polyphenolic profile." *Plant Cell, Tissue and Organ Culture 153*: 295-306.

Čeh, B., Kač, M., J. Košir, I., Abram, V. 2007. “Relationships between Xanthohumol and Polyphenol Content in Hop Leaves and Hop Cones with Regard to Water Supply and Cultivar.” *International Journal of Molecular Sciences* 8: 989-1000.
Hosseinnezhad, M., Gharanjig, K., Rouhani, S., Razani, N. and Imani, H. 2022. “Environmentally friendly dyeing of wool yarns using of combination of bio-mordants and natural dyes.” *Environmental Progress & Sustainable Energy 41* (5): 1-9.
Shahid, M., Islam, S., Rather, L, J., Manzoor, N. and Mohammad, F. 2019. “Simultaneous shade development, antibacterial, and antifungal functionalization of wool using Punica granatum L. Peel extract as a source of textile dye.” *Journal of Natural Fibers* 16 (4): 555−556.
Mansour, R., Dhouib, S. and Sakli, F. 2022. “UV Protection and Dyeing Properties of Wool Fabrics Dyed with Aqueous Extracts of Madder Roots, Chamomiles, Pomegranate Peels, and Apple Tree Branches Bark.” *Journal of Natural Fibers* 19 (2): 610−620.
Muzykiewicz, A., Nowak, A., Zielonka-Brzezicka, J., Florkowska, K., Duchnik, W., Klimowicz, A. 2019. “Comparison of antioxidant activity of extracts of hop leaves harvested in different years.” *Herba Polonica* 65 (3): 1-9.

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POSTER PRESENTATION

PIGMENT PRINTING WITH DYE EXTRACTS FROM INVASIVE ALIEN PLANTS

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Abstract: *The use of natural dyes in the dyeing and printing of textiles is becoming increasingly important, especially when invasive alien plants that overgrow the land are used for their production. In our study, the dye extracts from the petals of the goldenrod, the leaves of the Japanese knotweed and the petals of the Himalayan balsam were used to produce screen printing inks. For comparison, the pigment printing paste with a pH value of 7.4, which was produced by mixing the individual ingredients, and the pigment printing paste with a pH value of 8.1, which is already commercially available, were used. The inks made from three dye extracts, which were produced with two different printing pastes, were printed on cotton and polyester fabrics using the flat screen printing process. The colour of the prints was evaluated spectrophotometrically and the resistance of the prints to rubbing, wet hot pressing, washing and light was tested. The research results confirmed that the inks produced with the two pigment printing pastes made from natural dyes can be successfully used for screen printing on fabrics. The prints produced with the yellow dye extract from goldenrod flowers showed the best fastness properties with even excellent light fastness.*

Keywords: *natural dye, invasive alien plant, printing, cotton, polyester.*

1. INTRODUCTION

Interest in the use of natural dyes is increasing nowadays, as natural dyes derived from plants are non-toxic, sustainable and biodegradable and have many positive effects on human health (Rungruangkitkrai, 2012). Invasive alien plants pose an ecological problem as they quickly overgrow and displace native plants in a harmful way, which is why the possibility of using them as a source of natural dyes for dyeing and printing textiles has already been investigated (Gorjanc, 2016; Gorjanc, 2019; Klančnik, 2021; Klančnik, 2021; Klančnik, 2024; Topič, 2017).

Our research tested the applicability of natural dyes extracted from three different invasive alien plants, namely the yellow petals of goldenrod, the green leaves of Japanese knotweed and the pink petals of Himalayan balsam, for screen printing on cotton and polyester fabrics as well as the influence of two printing pastes with slightly different pH values in the formulation of screen printing inks on the final colour of the prints and the fastness properties to rubbing, wet hot pressing, washing and light. The printing paste with a pH value of 7.4 was produced by mixing an acrylic thickener and an acrylic binder in distilled water, while the printing paste with a pH value of 8.1 was already commercially available. Printing with dyes from Himalayan balsam (Klančnik, 2021) and Japanese knotweed leaves (Klančnik, 2024) has already been researched, but not printing with dyes from goldenrod and the use of printing pastes with different pH values in comparison.

2. EXPERIMENTAL

2.1 Dye extracts

The dye extracts from the leaves of Japanese knotweed, form the petals of goldenrod and Himalayan Balsam were obtained from National Institute of Chemistry (Ljubljana, Slovenia).

2.2 Printing Ink Preparation

For the screen printing inks, the already commercially prepared pigment printing paste Transparent Elastil FGI (AchitexMinerva Ltd., Vaiano Cremasco, Italy) with a pH value of 8.1 was used and the printing paste, which we prepared by mixing the individual ingredients according to the following recipe: 150 g Binder SE conc. (Achitex-Minerva Ltd., Vaiano Cremasco, Italy), 18 g thickener Clear MCS (AchitexMinerva Ltd., Vaiano Cremasco, Italy) and up to 1000 g demineralized water to form a homogeneous paste with a pH value of 7.4.
The dye extract from goldenrod petals was added in the following concentrations: 1 and 3 g per 100 g of the printing paste we produced with a pH value of 7.4 and per 100 g of the commercially available Transparent Elastil printing paste with a pH value of 8.1. The dye extracts from the Japanese knotweed leaves and Himalayan balsam petals were added in concentrations of 1 and 3 g per 100 g of Transparent Elastil printing paste with a pH value of 8.1 and in a concentration of 3 g per 100 g of the printing paste with a pH value of 7.4. The formulated inks are shown in Figure 1.

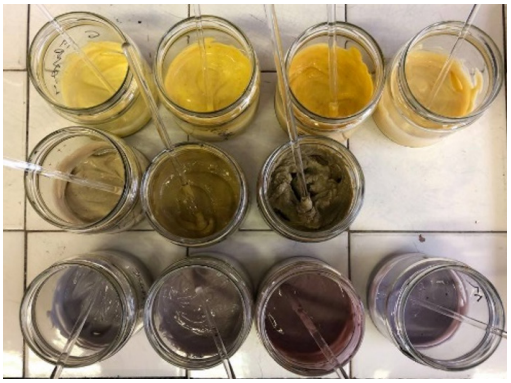


Figure 1: The printing inks produced with dye extracts from goldenrod (in the first row), with dye extracts from Japanese knotweed leaves (in the second row) and with dye extracts from Himalayan balsam (in the third row).

2.3 Printing Materials

Cotton fabric (manufacturer Tekstina Ltd., Ajdovščina, Slovenia) in plain weave with a surface mass of 122.73 g/m², hereinafter referred to as CO, and polyester fabric (supplier Luna Ltd., Ljubljana, Slovenia) in plain weave with a surface mass of 175.99 g/m², hereinafter referred to as PES, were used for printing.

2.4 Printing

The printing inks were applied to fabrics using the semi-automatic screen-printing machine SD 05 (RokuPrint Ltd., Darmstadt, Germany) with the flat printing screen made of polyester fabric with 77 threads/cm and a thread diameter of 55 µm with three strokes of squeegee. The prints were dried at room temperature overnight and then cured at 150 °C for 5 minutes.

2.5 Spectrophotometric Measurements

Colour measurements of the prints were made using the Eye-One i1 Pro spectrophotometer (X-Rite, Grand Rapids, MI, USA) with 45/0 plane geometry, illuminant D65, 10° standard observer and a 4.5 mm diameter aperture. The CIELAB colour coordinates: L* (lightness), a* (red-green value), b* (yellow-blue value) in the range of 380 to 730 nm were measured, the average of three measurements for each print was taken, and h_{ab} (hue) and C^*_{ab} (chroma) were calculated.

2.6 Colour Fastness Tests

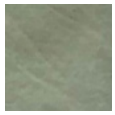
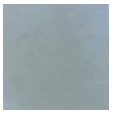
The fastness of prints on fabrics to dry and wet rubbing was tested with the electronic Crocmeter M2388 rub tester (SDL Atlas, Rock Hill, SC, USA) according to ISO 105-X12: 2016. The resistance of printed ink on fabrics to wet hot pressing was tested according to ISO 105-X11: 1996. The fastness of the prints on fabrics to domestic

and commercial laundering was tested according to ISO 105-C06: 2010 - test A1S at 40 °C for 30 minutes in the standard washing machine Launder-O-meter (Atlas, Rock Hill, SC, USA). The colour loss of the prints and the staining on the white adjacent fabrics after the tests were visually evaluated using the grey scales according to ISO 105-A02: 1993 and ISO 105-A03: 2019, respectively with ratings from 1 to 5, with 5 being the best value. The colour fastness of the prints to artificial light (xenon arc fading lamp) was tested according to ISO 105-B02: 2014 using the Xenotest Alpha tester (Atlas, Rancho Cucamonga, CA, ZDA) under the following conditions: 35 °C, 35% relative humidity and 72 h, together with the standard blue reference scale. The colour change of the exposed prints was visually assessed using the blue wool references with ratings from 1 to 8, with 8 being the best value.

3. RESULTS WITH DISCUSSION

The prints produced with inks made from the yellow dye extract from goldenrod petals were light yellow. The inks had a pleasant floral scent. More yellow and more intense prints were obtained with the ink made with the printing paste with a pH value of 8.1 than with the printing paste with a pH value of 7.4. The prints on cotton fabric were also more intense and more yellow than the prints on polyester fabric, as shown in Table 1.

Table 1: Colour values of prints produced with goldenrod dye extract

Colour values	1 g/100 g paste of pH 7.4	3 g/100 g paste of pH 7.4	1 g/100 g paste of pH 8.1	3 g/100 g paste of pH 8.1
On cotton fabric				
				
L*	92.26	91.63	91.73	91.01
a*	-1.81	-2.76	-2.76	-4.77
b*	6.92	10.51	10.50	21.56
C^*_{ab}	7.15	10.87	10.86	22.08
h_{ab} (°)	104.66	104.71	104.73	102.48
On polyester fabric				
				
L*	89.69	90.22	88.53	91.22
a*	-0.93	-1.34	-3.55	-3.86
b*	-0.21	2.07	10.41	16.01
C^*_{ab}	0.95	2.47	11.00	16.47
h_{ab} (°)	192.72	122.92	108.83	103.56

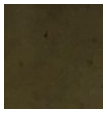
The prints produced with both printing pastes on both fabrics showed excellent dry and wet rub fastness as well as excellent wet iron fastness (grade 5), as shown in Table 2. The wash fastness of the prints at 40 °C was very good on cotton fabric with both pastes (grade 4-5), also on polyester fabric with the printing paste of pH 8.1, but only moderate (grade 3-4) with the printing paste of pH 7.4. The light fastness of the prints on cotton fabric was excellent (grade 8), but the light fastness on polyester fabric was only excellent when using the printing paste with pH 7.4, with the printing paste of pH 8.1 the prints faded strongly (grade 4).

Table 2: Fastness properties of prints made with goldenrod dye extract

Fastness	1 g/100 g paste of pH 7.4	3 g/100 g paste of pH 7.4	1 g/100 g paste of pH 8.1	3 g/100 g paste of pH 8.1
On cotton fabric				
Dry rubbing	5	5	5	5
Wet rubbing	5	5	5	5
Wet ironing (staining wet fabric)	5	5	5	5
Wet ironing (staining dry fabric)	5	5	5	5
Wet ironing (colour change)	5	5	5	5
Washing (staining of fabric)	4	4	4-5	4-5
Washing (colour change)	4-5	5	4-5	5
Light fastness	8	8	7	8
On polyester fabric				
Dry rubbing	5	5	5	5
Wet rubbing	5	5	5	5
Wet ironing (staining wet fabric)	5	5	5	5
Wet ironing (staining dry fabric)	5	5	5	5
Wet ironing (colour change)	5	5	5	5
Washing (staining of fabric)	5	5	5	5
Washing (colour change)	4	3-4	4	4-5
Light fastness	8	8	5	4

The prints made with inks from the dye extract of Japanese knotweed leaves were yellowish-green. The prints made with the printing paste with a pH value of 8.1 on cotton fabric were more yellow and intense than prints made with the printing paste with a pH value of 7.4, which were greener (Table 3). The prints on cotton fabric were also more intense and more yellow than the prints on polyester fabric.

Table 3: Colour values of prints produced with Japanese knotweed dye extract

Colour values	1 g/100 g paste of pH 7.4	3 g/100 g paste of pH 7.4	1 g/100 g paste of pH 8.1	3 g/100 g paste of pH 8.1
On cotton fabric				
				
L*	/	79.09	85.53	73.18
a*	/	-1.28	-2.28	0.58
b*	/	33.80	22.41	37.18
C^*_{ab}	/	33.82	22.52	37.18
h_{ab} (°)	/	92.17	95.81	89.11
On polyester fabric				
				
L*	/	75.48	83.21	61.77
a*	/	-0.12	-0.43	3.25
b*	/	29.64	10.71	30.41
C^*_{ab}	/	29.64	10.72	30.58
h_{ab} (°)	/	90.24	92.30	83.90

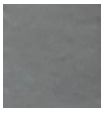
The prints produced with both printing pastes on both fabrics showed excellent dry rub fastness (grade 5), very good wet rub fastness (grade 4-5) and also wet iron fastness (grade 4-5), as shown in Table 4. The printing paste with a pH value of 8.1 showed half a level better wet rub fastness and iron fastness on cotton (grade 5). The wash fastness of the prints with the pH 8.1 printing paste was very good on both fabrics (grade 4-5), and grade 3-4 when the pH 7.4 printing paste was used. The prints with both printing pastes were very sensitive to light, the colour changed from yellowish-green to yellow on cotton fabric and to orange on polyester fabric (light fastness grade 2).

Table 4: Fastness properties of prints made with Japanese knotweed dye extract

Fastness	1 g/100 g paste of pH 7.4	3 g/100 g paste of pH 7.4	1 g/100 g paste of pH 8.1	3 g/100 g paste of pH 8.1
On cotton fabric				
Dry rubbing	/	5	5	5
Wet rubbing	/	4-5	5	5
Wet ironing (staining wet fabric)	/	4-5	5	5
Wet ironing (staining dry fabric)	/	5	5	5
Wet ironing (colour change)	/	5	5	5
Washing (staining of fabric)	/	4-5	4-5	4-5
Washing (colour change)	/	3-4	4	5
Light fastness	/	3	1	2
On polyester fabric				
Dry rubbing	/	5	5	5
Wet rubbing	/	4	5	5
Wet ironing (staining wet fabric)	/	4-5	5	4-5
Wet ironing (staining dry fabric)	/	4-5	5	5
Wet ironing (colour change)	/	5	5	5
Washing (staining of fabric)	/	5	5	5
Washing (colour change)	/	4	3-4	4-5
Light fastness	/	2	1	2

The prints obtained with inks made from the dye extract of Himalayan balsam petals with the printing paste of pH 7.4 were violet-brown and somewhat more intense than prints with the printing paste of pH 8.1, which were browner. The prints on cotton were slightly less intense at the higher dye concentration than on polyester (Table 5).

Table 5: Colour values of prints produced with Himalayan balsam dye extract

Colour values	1 g/100 g paste of pH 7.4	3 g/100 g paste of pH 7.4	1 g/100 g paste of pH 8.1	3 g/100 g paste of pH 8.1
On cotton fabric				
				
L*	/	77.12	86.75	78.96
a*	/	5.42	0.30	2.55
b*	/	12.43	8.35	11.46
C^*_{ab}	/	13.56	8.36	11.74
h_{ab} (°)	/	66.44	87.94	77.45
On polyester fabric				
	/			
L*	/	67.19	83.97	75.75
a*	/	8.29	0.93	3.02
b*	/	12.23	3.44	12.60
C^*_{ab}	/	14.78	3.56	12.96
h_{ab} (°)	/	55.87	74.87	76.52

The prints made with both printing pastes on both fabrics showed excellent fastness to dry rubbing and wet ironing (grade 5), still excellent wet rub fastness on cotton fabric and very good wet rub fastness on polyester fabric (grade 4-5), as shown in Table 6. The wash fastness of the prints on cotton with both printing pastes was moderate (grade 3), on polyester with the printing paste of pH 7.4 grade 2-3 and with the printing paste of pH 8.1 grade 1-2. The prints made with both pastes were also very sensitive to light and faded considerably at the higher dye concentration (light fastness grade 2-3).

Table 6: Fastness properties of prints made with Himalayan balsam dye extract

Fastness	1 g/100 g paste of pH 7.4	3 g/100 g paste of pH 7.4	1 g/100 g paste of pH 8.1	3 g/100 g paste of pH 8.1
On cotton fabric				
Dry rubbing	/	5	5	5
Wet rubbing	/	5	5	5
Wet ironing (staining wet fabric)	/	4-5	5	5
Wet ironing (staining dry fabric)	/	5	5	5
Wet ironing (colour change)	/	5	5	5
Washing (staining of fabric)	/	4-5	4-5	4-5
Washing (colour change)	/	3	3-4	3
Light fastness	/	3	6	3
On polyester fabric				
Dry rubbing	/	5	5	5
Wet rubbing	/	4-5	5	4-5
Wet ironing (staining wet fabric)	/	4-5	5	5
Wet ironing (staining dry fabric)	/	4-5	5	5
Wet ironing (colour change)	/	5	5	5
Washing (staining of fabric)	/	5	5	5
Washing (colour change)	/	2-3	2	1-2
Light fastness	/	2-3	5	2

4. CONCLUSION

The research results confirmed that the printing inks produced with both pigment printing pastes made from natural dyes can be successfully used for screen printing on fabrics. The different pH value of the printing paste also had a major influence on the colour hue and colour intensity of the prints as well as on the fastness properties, as the dye extracts contain many flavonoids whose structure depends on the pH value. The correct choice of printing paste must be made before printing according to the particular dye extract in order to achieve the best print quality. The prints made with the yellow dye extract from goldenrod flowers showed the best fastness properties with even excellent light fastness on cotton fabric with the both printing pastes and on polyester fabric when the printing paste with a pH value of 7.4 was used.

5. REFERENCES

Gorjanc, M., Savić, A., Topalić-Trivunović, L., Mozetič, M.; Zaplotnik, R., Vesel, A., Grujić, D. (2016) 'Dyeing of plasma treated cotton and bamboo rayon with Fallopia Japonica extract.' *Cellulose*, 23, pp. 2221–2228.

Gorjanc, M., Kert, M., Mujadžić, A., Simončič, B., Forte-Tavčer, P., Tomšič, B., Kostanjšek, K. (2019) 'Cationic pretreatment of cotton and dyeing with Fallopia Japonica leaves.' *Tekstilec*, 62, pp.181–186.

Klančnik, M. (2021) 'Screen Printing with Natural Dye Extract from Japanese Knotweed Rhizome.' *Fiber Polym.*, 22, pp. 2498–2506.

Klančnik, M. (2021) 'Printing with Natural Dye Extracted from Impatiens glandulifera Royle.' *Coatings*, 11, pp. 445–457.

Klančnik, M. (2024) 'Printing with Natural Dye Extract from Japanese Knotweed Leaves.' *Fibers Polym.*, 25, pp. 4771–4785.

Rungruangkitkrai, N, Mongkholrattanasit, R. (2012) In *Proceedings of the International Conference: Textiles & Fashion.* Bangkok, Thailand.

Topič, T., Gorjanc, M., Kert, M. (2018) 'The influence of the treatment process on the dyeability of cotton fabric using goldenrod dye.' *Tekstilec*, 61, pp. 192–200.

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SMART AND FUNCTIONAL TEXTILES

ORAL PRESENTATION

POLYPROPYLENE NONWOVEN MATERIAL MODIFIED WITH (3-AMINOPROPYL) TRIALKOXYSYLOXANE AND Ag-BASED NANOPARTICLES

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Abstract: *Pandemic COVID19 revealed the importance of face masks for the protection of medical staff and patients as well as the need for face masks with antimicrobial properties. To address this issue, nonwoven polypropylene materials were impregnated with Ag-based nanoparticles after activation with corona discharge at atmospheric pressure and modification with (3-aminopropyl) triethoxysilane (APTES). Ag-based nanoparticles were synthesized in situ on polypropylene nonwoven material using Cannabis sativa L., Cannabaceae (CS), and Paliurus spina-christi Mill., Rhamnaceae (PSC) extracts. The amounts of synthesized Ag-based nanoparticles were sufficient to impart a strong antibacterial activity against Gram-negative bacteria Escherichia coli and Gram-positive bacteria Staphylococcus aureus, and fungistatic properties against yeast Candida albicans. In addition, they were non-cytotoxic to HaCaT and MRC5 cells.*

Keywords: *polypropylene, APTES, Ag nanoparticles, plant extract, antimicrobial activity.*

1. INTRODUCTION

The awareness of face masks importance significantly increased during the COVID-19 pandemic. They prevent the spreading of viral infections, the transfer of droplets, splashes, and sprays in healthcare settings, and they reduce exposure to airborne particulate matter. Face masks are usually made of nonwoven polypropylene (PP) materials. Taking into account a need for antimicrobial masks and the fact that PP fibers are chemically inert, the main goal of this study was to fabricate antimicrobial PP nonwoven material by in situ synthesis of Ag-based nanoparticles (NPs). This is very difficult due to chemical inertness and high hydrophobicity of PP fibers. To enable the binding of Ag^+-ions from $AgNO_3$ solution, PP nonwoven fabric was activated with corona discharge at atmospheric pressure and subsequently modified with (3-aminopropyl) triethoxysilane (APTES). Recently, the extracts of various plants (fruits, vegetables, and herbs) have become attractive for the metal NPs synthesis. The extracts of different parts of plants (root, leaves, flowers, fruits, barks, peels, shells, stems) contain flavonoids, terpenoids, alkaloids, and polyphenols recognized as efficient reducing, capping and stabilizing agents (Akintelu et al. 2020; Mali et al. 2020). However, there are only few studies reporting in situ biosynthesis of Ag-based NPs on textile fibers (Štular et al. 2021; Čuk et al. 2021). Thus, an effort has been made in this study to synthesize Ag-based NPs on PP nonwoven material using *Cannabis sativa* L., Cannabaceae (CS) and *Paliurus spina-christi* Mill., Rhamnaceae (PSC) extracts.

2. EXPERIMENTAL

PP nonwoven material (40 g/m^2) was treated with corona discharge at atmospheric pressure using a Vetaphone, Corona-Plus, type TF-415 device. The power was set to 700 W. The distance between the electrode and the fabric was adjusted to 2.2 mm. Both sides of the material passed through corona discharge 15 times. The coating procedure with APETES is described in literature (Marković et al. 2020). Briefly, a 4% (w/w) solution of hydrolyzed APTES precursor was prepared in ethanol and applied to corona-treated PP nonwoven fabric using the pad-dry-cure method, resulting in an add-on of 3.981.81%. These samples are labeled as CPP-APTES.

The plant *C. sativa* and *P. spina-christi* extracts were prepared by adding 6.00 g of milled leaves in 100 mL of distilled water, and stirring at 80°C for 2 h. Prepared extracts were filtered and immediately used for the synthesis of Ag-based NPs. 0.25 g of CPP-APTES sample was immersed in 25 mL of 20 mM solution of $AgNO_3$ for 2 h. Afterwards, the sample was rinsed with deionized water and put in the plant extract. The synthesis was carried out at 60 °C for 1 h. After rinsing with distilled water, the samples were left to dry. The samples decorated with Ag-based NPs synthesized in the presence of *C. sativa* and *P. spina-christi* denoted CPP-APTES-Ag-CS and CPP-APTES-Ag-PSC, respectively.

Chemical changes induced by corona treatment and modification with APTES were assessed by Fourier transform infrared spectroscopy (FTIR) in ATR mode using a Nicolet iS5 FTIR Spectrometer (Thermo Scientific) at 4 cm^{-1} resolution, in the wavenumber range 500–4000 cm^{-1}. The morphology of fibers NPs was evaluated by field emission scanning electron microscopy (FE-SEM, Tescan Mira3 FEG). The size of NPs was determined by analyzing the acquired FESEM images with the open-access imaging software, ImageJ.The total amount of Ag in all samples was measured by atomic adsorption spectroscopy (AAS, Spectra AA 55B, Varian).

Antimicrobial activity of the samples with Ag-based NPs was tested against Gram-negative bacteria *E. coli* (ATCC 25922), Gram-positive bacteria *S. aureus* (ATCC 25923) and yeast *C. albicans* using a standard test method for determination of the antimicrobial activity of immobilized antimicrobial agents under dynamic contact conditions ASTM E 2149-01 (2001). Cytotoxicity of the samples with synthesized Ag-based NPs was evaluated on human keratinocyte cells (HaCaT cell line obtained from ATCC) and fibroblast cells (MRC5 cell line obtained from ATCC) using a MTT test.

3. RESULTS AND DISCUSSION

The evaluation of chemical modifications resulting from corona and APTES treatments was conducted through FTIR spectroscopy (illustrated in Figure 1). The FTIR spectrum of PP sample displays bands that are characteristic of PP, including the CH_3 and CH_2 asymmetric and symmetric stretching vibrations (2950–2830 cm^{-1}), the CH_3 asymmetric deformation vibrations or the CH_2 scissor vibrations and the CH_3 symmetric deformation vibrations (1457–1356 cm^{-1}), and the vibrations associated with C–C bonding (1200–800 cm^{-1}) (Kostov et al. 2013). The corona treatment of PP samples led to the formation of two new bands at 1728 and 1642 cm^{-1}, which are attributed to carbonyl groups in aldehydes and ketones, as well as COO^- asymmetric stretching vibrations, respectively (Kostov et al. 2013; Moldovan et al. 2016). The subsequent coating with APTES resulted in a diminished intensity of these bands (1728 cm^{-1} and 1642 cm^{-1}).

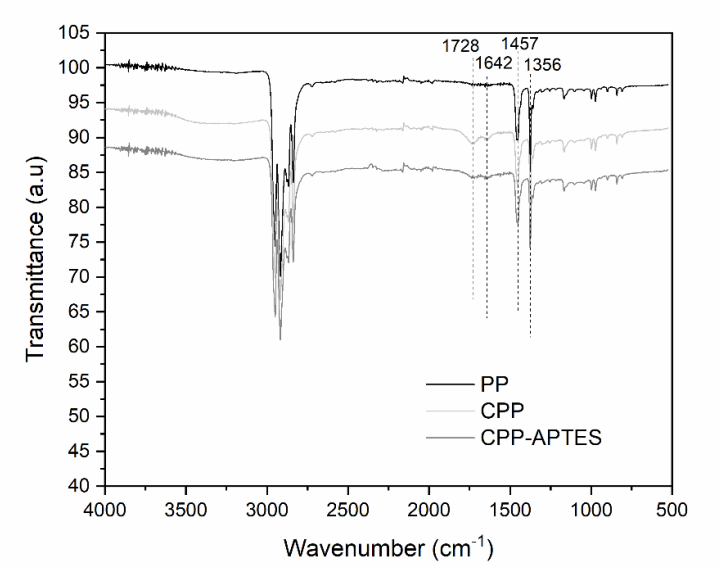


Figure 1: FTIR spectra of PP, CPP and CPP-APTES

FESEM images shown in Figures 2 and 3 reveal that spherical, mostly single Ag-based NPs evenly covered the surface of both CPP-APTES-Ag-CS and CPP-APTES-Ag-PSC fibers. The average size of single NPs was 48±13 nm and 31±11 nm on CPP-APTES-Ag-CS and CPP-APTES-Ag-PSC fibers, respectively. However, evidence of agglomeration was apparent on the CPP-APTES-Ag-CS sample. The total content of silver on CPP-APTES-Ag-CS and CPP-APTES-Ag-PSC samples were 1.52±0.35 mg/g and 1.08±0.27 mg/g, respectively. A higher content of Ag on CPP-APTES-Ag-CS sample is attributed to larger NPs.

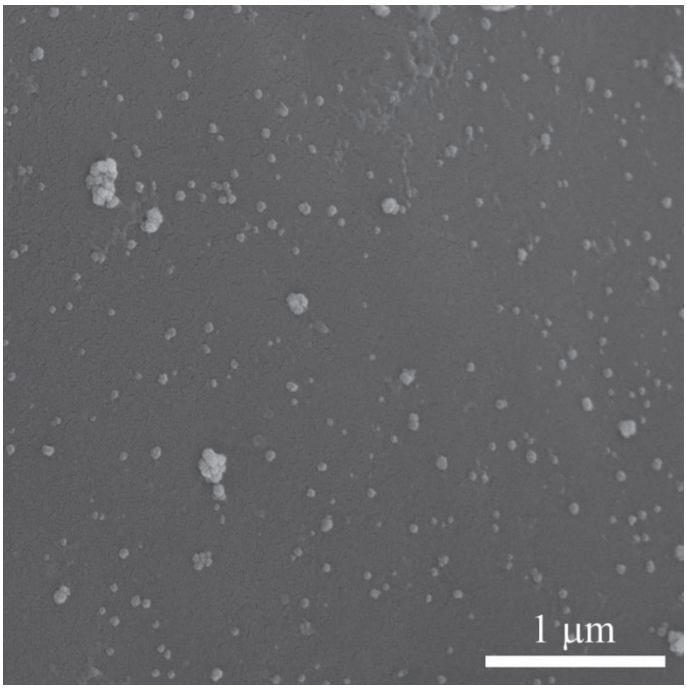


Figure 2: FESEM image of CPP-APTES-Ag-CS fiber

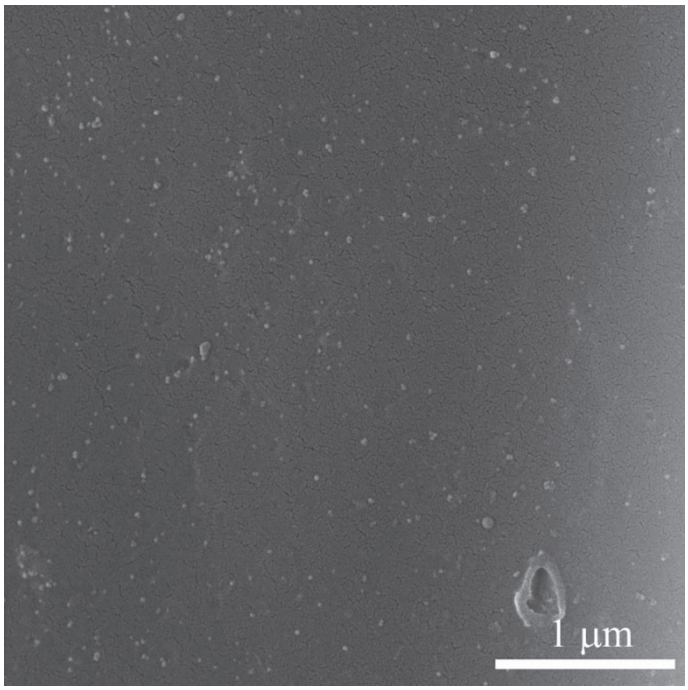


Figure 3: FESEM image of CPP-APTES-Ag-PSC fiber

Antimicrobial activity of the control and modified samples is shown in Figure 4. The application of corona treatment, both independently and in combination with APTES modification, resulted in a moderate decrease in *E. coli* bacterial colonies, achieving reductions of 82.5% and 88.9%, respectively. In contrast, the reduction of *S. aureus* was minimal, with values of 21.2% and 43.7%, respectively. Furthermore, samples treated with corona alone exhibited no antifungal properties, while the APTES modification yielded only a 7.67% reduction in the yeast *C. albicans*.The impregnation with Ag-based NPs imparted strong antibacterial activity to CPP-APTES fibers, independently of the plant extract (bacteria reduction of 99.9%). In contrast to superior antibacterial activity against *E coli* and *S. aureus*, only fungistatic activity towards *C. albicans* was obtained. The percentage of HaCaT and MRC5 cells survival after 24 h long contact with sample extracts in comparison with native cells (control) was over 80%, implying that fabricated samples could be considered non-cytotoxic to these cells.

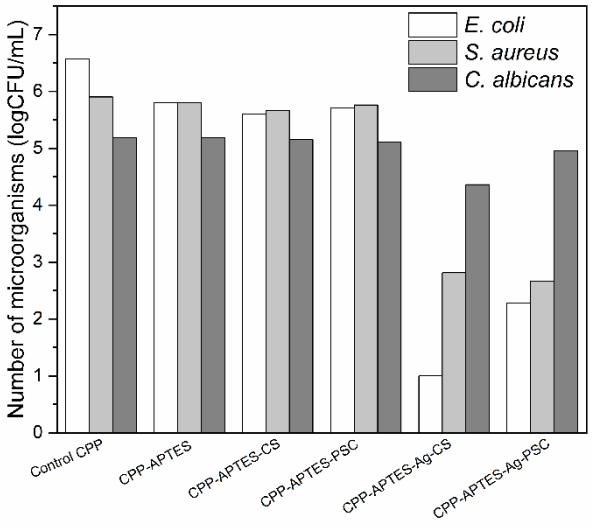


Figure 4: Antimicrobial activity of the control and modified PP samples

4. CONCLUSIONS

This study showed that corona discharge at atmospheric pressure successfully activated PP fibers surface prior to modification with APTES, which provided functional groups for improved uptake of Ag^+-ions. Spherical Ag-based NPs evenly distributed over the fiber surface were synthesized in the presence of *C. sativa* and *P. spina-christi* extracts. Fabricated nonwoven materials exhibited maximum antibacterial activity (99.9%) against *E. coli* and *S. aureus*, and fungistatic activity against yeast *C. albicans*. At the same time, they were non-cytotoxic towards HaCaT and MRC5 cells. Good antibacterial activity and non-cytotoxicity make developed materials an attractive candidate for the face masks production.

5. ACKNOWLEDGEMENT

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6. REFERENCES

Akintelu, S.A., Folorunso, A.S., Folorunso, F.A., Oyebamiji, A.K. 2020. „Green synthesis of copper oxide nanoparticles for biomedical application and environmental remediation.“, *Helyion* 6: e04508.

Čuk, N., Šala, M., Gorjanc, M. 2021. „Development of antibacterial and UV protective cotton fabrics using plant food waste and alien invasive plant extracts as reducing agents for the in-situ synthesis of silver nanoparticles.“ *Cellulose* 28: 3215-3233.

Kostov, k.G., Nishime, T.M.C., Hein, L.R.O., Toth, A. 2013. „Study of polypropylene surface modification by air dielectric barrier discharge operated at two different frequencies.“ *Surface and Coatings Technology* 234: 60-66.

Mali, S.C., Dhaka, A., Githala, C.K., Trivedi R. 2020. „Green synthesis of copper nanoparticles using *Celastrus paniculatus* Willd leaf extract and their photocatalytic and antifungal properties.“ *Biotechnology Reports* 27: e00518.

Marković, D., Vasiljević, J., Ašanin, J., Ilić-Tomić, T., Jokić, B., Simončič, B., Mitrić, M., Mišić, D., Radetić, M. 2020. „The influence of coating with aminopropyl triethoxysilane and CuO/Cu_2O nanoparticles on antimicrobial activity of cotton fabrics under dark conditions.“ *Journal of Applied Polymer Science* 137: e49194.

Moldovan, B., David, L., Achim, M., Clichici, S., Filip, G. A. 2016. „A green approach to phytomediated synthesis of silver nanoparticles using *Sambucus nigra* L. fruits extract and their antioxidant activity.“ *Journal of Molecular Liquids* 221: 271–278.

Štular, D., Savio, E., Simončič, B., Šobak, M., Jerman, I., Poljanšek, I., Ferri, A., Tomšič, B. 2021. „Multifunctional antibacterial and ultraviolet protective cotton cellulose developed by in situ biosynthesis of silver nanoparticles into a polysiloxane matrix mediated by sumac leaf extract.“ *Applied Surface Science* 563: 150361.

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ORAL PRESENTATION

MULTIFUNCTIONAL TiO_2 BASED COATINGS FOR ADVANCED TEXTILE APPLICATIONS

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Abstract: *This study presents a sustainable approach to the development of multifunctional nanocomposite coatings for textiles by combining TiO_2 with various organofunctional trialkoxysilane precursors. An optimised 4% titanium isopropoxide (TTIP) served as the TiO_2 source. Using in-situ low-temperature sol-gel and sol-gel/hydrothermal methods, TiO_2 was doped with Ag (Ag-TiO_2) or coupled with reduced graphene oxide (rGO/ TiO_2) and further modified with (3-(trimethoxysilyl)propyl)ammonium chloride (SiQAC), aminopropyltriethoxysilane (APTES) and the phosphorus-based flame retardant TPMP. Ag-TiO_2 enabled self-sterilisation, UV protection and photocatalytic self-cleaning through the controlled release of Ag/Ag_2O. Functionalisation with TPMP/SiQAC or TPMP/APTES influenced the formation of Ag species and multifunctionality via TiO_2/Ag/AgCl or TiO_2/Ag heterocomposites. The introduction of rGO into the TPMP/APTES-modified TiO_2 matrix provided a more environmentally friendly alternative and delivered excellent multifunctional performance. These novel nanocomposite coatings offer promising routes for the sustainable advancement of technical textiles with customised functionalities for specific applications.*

Keywords: *cotton, titanium dioxide (TiO_2), Ag loading, reduced graphene oxide (rGO), surface functionalization, organofunctional trialkoxysilanes*

1. INTRODUCTION

The concepts of green and sustainable chemistry in the textile industry focus on the development and production of nanostructured multifunctional textiles using safe and environmentally friendly chemicals, processes and technological approaches. The sol-gel technique is recognised as an environmentally friendly nanotechnology method for the synthesis of nanomaterials with different morphologies and plays a key role in the production of metal and metal oxide nanoparticles (NPs). These NPs or nanofilms contribute to the functionalisation of textiles by imparting unique protective properties while maintaining low processing costs and a controlled morphology.

TiO_2 is a well-established photocatalyst characterised by high chemical stability, non-toxicity and affordability (Linsebigler et al., 1995). To improve its functional properties, surface modifications have been explored, with sol-gel precursors — especially organofunctional trialkoxysilanes — proving to be very effective. These hybrid compounds contain an organic functional group covalently bonded to a reactive trialkoxysilane unit and enable the functionalisation of the fibre surface by thin film deposition. Research shows that TiO_2 NPs in combination with organofunctional trialkoxysilanes can provide photocatalytic, water and oil repellent properties as well as antimicrobial activity (Shaheen et al., 2019; Riaz et al., 2019).

However, there are still some challenges in the development of functional coatings with organofunctional trialkoxysilanes. Previous studies have focussed on TiO_2 coatings with a single silane precursor, which limits multifunctionality. In addition, TiO_2 nanoparticles are often physically bound to polysiloxane hybrid films, which raises concerns about the durability of such nanocomposite coatings due to a gradual release of the nanoparticles.

The main objective of this research is to develop an innovative and sustainable approach to produce multifunctional nanocomposite textile finishes. This is achieved by modifying TiO_2 surfaces by doping and coating with silver (Ag), coupling with reduced graphene oxide (rGO) and incorporating selected organofunctional trialkoxysilane

precursors. The aim is to increase the photocatalytic activity of TiO_2 while ensuring chemical bonding between modified TiO_2 and the functional groups of the fibres to improve the durability of the nanocomposite coating. The study focuses on cellulosic fibres, which are widely used in technical, medical, protective, sports and leisure textiles. In order to achieve the main objective, the study was divided into the following sections: (i) Optimisation of the in situ synthesis method of TiO_2 at different TTIP concentrations; (ii) surface modification of Ag-doped TiO_2 using a binary mixture of sol-gel precursors — either (3-(trimethoxysilyl)propyl)ammonium chloride (SiQAC) and phosphorus-based flame retardant TPMP or aminopropyltriethoxysilane (APTES) and TPMP; (iii) coupling of TiO_2 with rGO/GO followed by nanocomposite modification with a binary mixture of sol-gel precursors TPMP and APTES.

2. EXPERIMENTAL

2.1 Materials

The alkaline-scoured, bleached and mercerized 100% cotton plain weave fabric with a weight of 120 g/m2 and a density of 50 and 30 threads/cm in warp and weft directions, respectively, was used. Trought experiment four sol–gel precursors were used: titanium isopropoxide (TTIP) (≥ 97.0 wt. %; Sigma Aldrich) as the TiO_2 precursor; silver nitrate ($AgNO_3$; Sigma Aldrich) as the Ag precursor; 3-(trihydroxysilyl)propyl methylphosphonate, monosodium salt solution (TPMP, 50 wt. % in H_2O; Sigma Aldrich) as the flame retardant agent; dimethyloctadecyl (3-(trimethoxysilyl) propyl)ammonium chloride (SiQAC, 40 wt. % in methanol; Sigma Aldrich) and (3-aminopropyl) triethoxysilane (APTES, 99 wt. %; Sigma Aldrich) as the antimicrobial biobarrier agents. The ethanol (concentration ≥99.8%), the organic dye methylene blue (MB), Rhodamine Blue (RhB) and the acetic acid were supplied by Honeywell Research Chemicals (Seetze, Germany) and CARLO ERBA Reagents S.A.S (Barcelona, Spain), respectively. All reagents are of analytical grade and were used without further purification.

2.2 Preparation of TTIP sol and application procedure

TiO_2 nanosols were prepared by mixing TTIP in ethanol to obtain concentrations of 2, 4, and 6%. Into the TiO_2 nanosols glacial acetic acid was added dropwise under constant stirring, where the mass ratio between TTIP and glacial acid was set at 7:1. Detailed application process is explained in (Rashid et al., 2022a). Briefly, TiO_2 nanosols were applied to cotton fabric using sol-gel pad-dry-cure, pad-hydrothermal, and exhaustion-hydrothermal methods. In the pad-based methods, cotton samples were impregnated with TiO_2 nanosols, padded to achieve 80±2% wet pick-up, and either dried and cured (pad-dry-cure; samples labelled 2S, 4S and 6S) or dried and hydrothermally treated (pad-hydrothermal, samples labelled 2H, 4H, 6H). In the exhaustion-hydrothermal method, samples were immersed in TiO_2 nanosols under constant stirring for 1 hour, padded, and hydrothermally treated (samples labeled 2E, 4E, 6E). For the purpose of comparison, commercial TiO_2 was also applied to the cotton fabric using the pad-dry-cure method.

For the Ag-dopped TiO_2 detailed application procedure is described in (Rashid et al., 2022b). Briefly, the cotton samples were firstly modified to a 4% TiO_2 nanosol following pad-dry- hydrothermal treatment, whereas $AgNO_3$ water solutions of different concentrations, i.e., 0.5, 1.0 and 2.0 mM was utilised during hydrothermal treatment. At the end, the samples were dried at 100 °C.

For the modification of the Ag-loaded TiO_2 sol mixtures of TTIP+TPMP+SiQAC and TTIP+TPMP+APTES were prepared using an equimolar ratio (1:1:1) (Rashid et al., 2024a). TTIP (4%) was dissolved in ethanol, followed by TPMP, SiQAC or APTES, and a small amount of 0.1 M HCl, with stirring for two hours to complete hydrolysis. Cotton samples were immersed in the sol mixtures, padded (0.8 bar, 80±5% wet pick-up), air-dried, and hydrothermally treated in a Starlet-2 DL 600 Plus (Komachine, Korea) at 120°C for 60 min, either in water or a 2 mM $AgNO_3$ bath (1:50 ratio), then rinsed and dried. The samples hydrothermally treated in water are labeled as TiO_2/TPMP/SiQAC and TiO_2/TPMP/APTES, samples hydrothermally treated in a 2 mM $AgNO_3$ bath are labeled as Ag/TiO_2/TPMP/SiQAC or Ag/TiO_2/TPMP/APTES.

For the *in situ* synthesis of rGO/TiO_2 nanocomposites modified with a combination of TPMP and APTES on sol-gel method was used (Rashid, 2024b). The sol-gel precursor mixture was prepared in a molar ratio of TTIP:TPMP:APTES = 1:1:2. Ascorbic acid was used as the reducing agent for GO, which was used in two concentrations, 0.75 and 1.50 mg/ml. The treated samples were labelled as S-(TiO_2+APTES+TPMP/rGO-x), where x denotes the concentration of GO used.

2.3 Characterization

Chemical and morphological changes in cotton fibres were analyzed using scanning electron microscopy (SEM; JSM-6060 LV, Jeol, Japan) and energy-dispersive X-ray spectroscopy (EDS; Thermo Fisher Scientific Quattro S, USA). Additionally, X-ray diffraction (XRD) analysis was performed using a PANalytical X'Pert PRO diffractometer ($CuK\alpha_1$ = 1.5406 Å) equipped with a fully open X'Celerator detector (2.122° 2θ).

The functional properties of the coated fabric were evaluated through UV transmittance measurements using a Lambda 800+ UV/Vis spectrophotometer (Perkin Elmer, UK) and calculation of the UV protection factor (UPF) according to EN 13758-1:2001.

Photocatalytic self-cleaning activity was assessed by monitoring the discoloration of a 0.2 mM RhB dye solution or fading of an MB dye stain on cotton samples via spectrophotometric analysis. For RhB dye degradation, functionalized cotton samples were immersed in 4 mL of RhB solution and irradiated with daylight in a Q-SUN Xe-3-HSE chamber (Q-Lab, UK) for up to 4 hours at 1-hour intervals. The absorbance at λmax = 552.93 nm was recorded, and the remaining RhB concentration was determined using a pre-established calibration curve. Dye discoloration was expressed as the Ct/C0 ratio, where Ct and C0 represent the RhB concentrations after time "t" and at the initial time (t = 0), respectively.

For MB dye stain degradation, TiO_2-treated cotton samples were stained with 0.05% methylene blue (MB) solution and exposed to a Xenotest Alpha instrument (Atlas, USA) equipped with a xenon arc lamp (300–400 nm, 0.8–2.5 kVA) for up to 180 minutes. Dye degradation was assessed based on the reflectance (R) of the samples, measured using a Datacolor Spectraflash SF 600 spectrophotometer under D 65/10 illumination.

Antibacterial performance was tested against *Staphylococcus aureus* (Gram-positive) and *Escherichia coli* (Gram-negative) in accordance with the ASTM E 2149-01.

Flame retardancy and thermal stability were evaluated via simultaneous thermal analysis in air using the simultaneous TGA/DSC1 analyser (Mettler Toledo, Schwerzenbach, Switzerland). In addition, vertical flame test was performed following DIN 53906 standard method.

3. RESULTS WITH DISCUSSION

The concentration of TTIP and the deposition method significantly influence the absorption and distribution of TiO_2 on cotton fibres (Figure 1a). The sol-gel method resulted in a TiO_2 film on the fibre surface at all three TTIP concentrations, while the sol-gel/hydrothermal method resulted in a combination of TiO_2 particles and a continuous film. Namely, SEM images of samples modified by the exhaustion/hydrothermal method showed no TiO_2 particles or film on the fibre surface, indicating penetration of TiO_2 into the fibre interior. Regardless of the deposition method, amorphous TiO_2 was formed (Figure 1b). However, the application method influenced the optical properties of amorphous TiO_2 which were determined using Tauc plots and band gap energy (Eg) calculations (Figure 1c). In this case a comparable TiO_2 structure for the sol-gel/hydrothermal and exhaustion/hydrothermal methods to the commercial TiO_2 was observed, as these samples demonstrated similar Eg values.

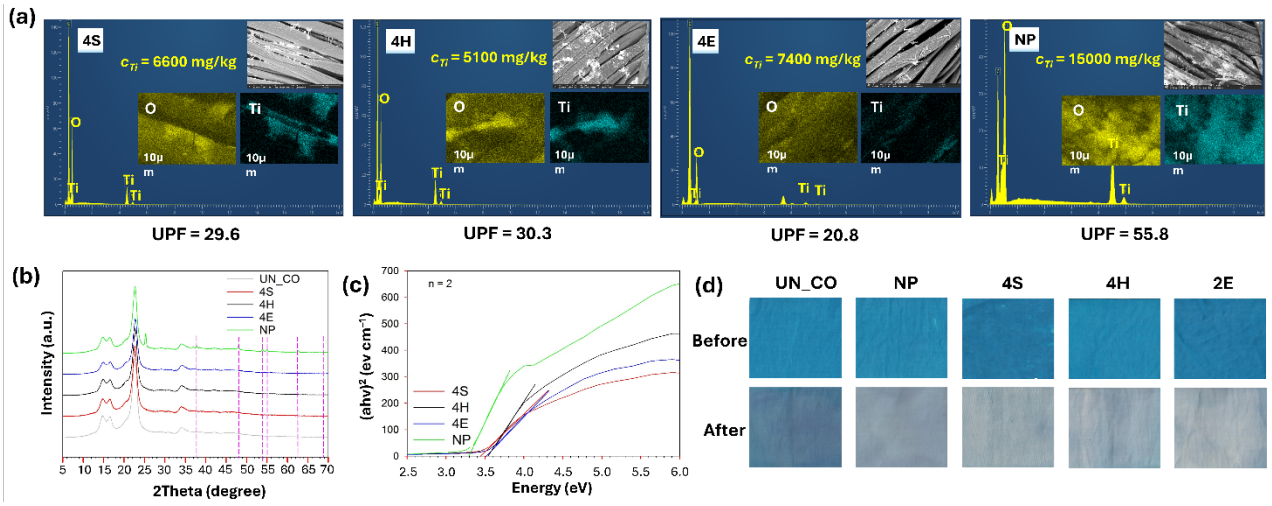


Figure 1: (a) EDS spectra and elemental mapping of TiO_2-treated cotton samples with corresponding UPF values, (b) XRD spectra, (c) Tauc plots of $(\alpha h\nu)^n$ versus photon energy for n = 2, and (d) images of MB-stained samples before and after 90 minutes of illumination under a visible xenon arc lamp (1.67 W/cm²).

The samples modified with synthesised TiO_2 showed effective UV protection, with samples 2E and 4S exhibiting the highest self-cleaning activity (Figure 1d). They achieved 80.0% and 79.9% methylene blue (MB) degradation, outperforming commercial TiO_2. These low-temperature in situ TiO_2 synthesis methods have great practical potential due to the lower energy and chemical requirements. For further studies on TiO_2 doping to enhance photocatalytic activity, the sol-gel/hydrothermal method with 4% TTIP sol was selected as it offers high UV protection and high self-cleaning efficiency.

Doping TiO_2 with small amounts of biocidal Ag has shown promise, as optimal Ag concentrations improve the adhesion and distribution of TiO_2 particles on textile fibres while limiting the release of Ag ions from the Ag/TiO_2 complex. Results of previous research (Rashid et al., 2022b) has shown that the combination of TiO_2 photocatalytic activity and controlled release of the biocidal Ag/Ag_2O complex enabled highly effective self-sterilisation of the modified cotton surface by inhibiting the growth of *E. coli* and *S. aureus*. Ag doping not only improved the antimicrobial properties, but also the UV protection and photocatalytic self-cleaning efficiency of TiO_2, resulting in a 69% degradation of the model dye. Based on these results, the optimal $AgNO_3$ concentration for TiO_2 doping was set at 2.0 mM, which ensures a synergistic effect between Ag and TiO_2.

In continuation of the research surface modification of Ag-doped TiO_2 was performed using a bicomponent mixture of organofunctional alkyltrialkoxysilanes: SiQAC and TPMP or APTES and TPMP in order to assess the influence of the bio-barrier's chemical structure (SiQAC or APTES) on the functional properties of the modified samples as well as to confer improved thermo-oxidative stability of the modified cotton. The results are presented in Figure 2.

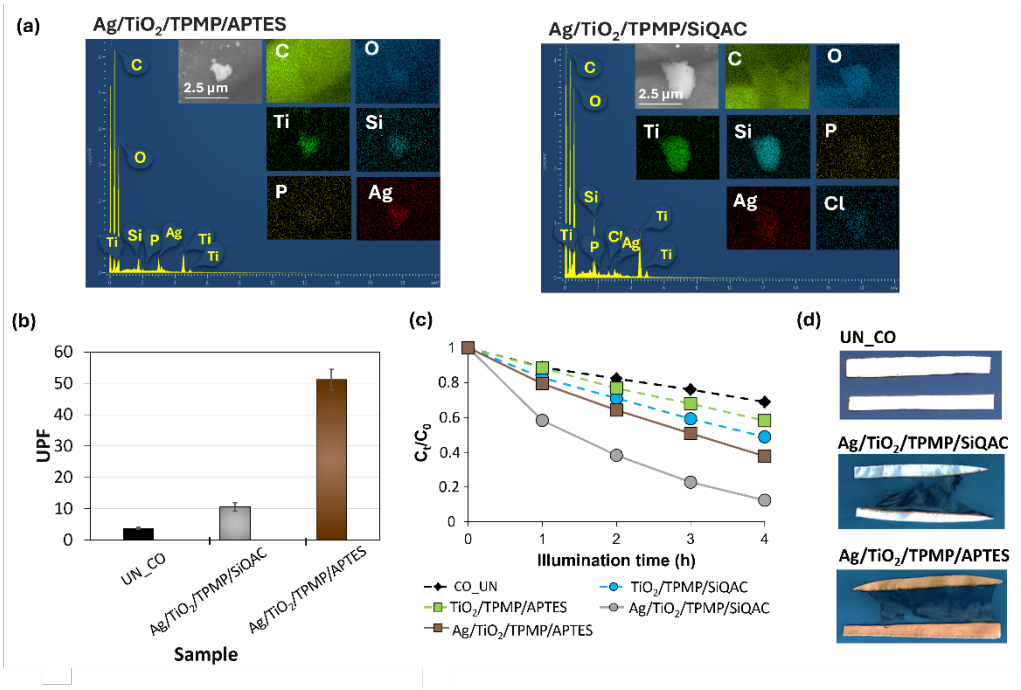


Figure 2: (a) EDS spectra and elemental mapping of Ag-doped TiO_2-modified cotton samples, (b) UPF values of modified TiO_2- and Ag-doped TiO_2-treated cotton samples, (c) discoloration activity of RhB after 4 hours of solar illumination and (d) with corresponding char residue images.

The TPMP/SiQAC sol led to the formation of a TiO_2/Ag/AgCl nanocomposite that exhibited exceptional photocatalytic self-cleaning activity but did not provide sufficient UV protection (Figures 2a and 2b). In contrast, TPMP/APTES led to the formation of a TiO_2/Ag nanocomposite (Rashid et al., 2023), ensuring excellent UV protection due to the complementary activity of TiO_2 and Ag nanoparticles, but exhibited lower photocatalytic self-cleaning efficiency (Figure 2c). Namely in the TiO_2/Ag/AgCl composite, which forms a semiconductor-metal-semiconductor heterojunction on the Ag/ TiO_2/TPMP/SiQAC sample, facilitates the transfer of photogenerated holes from Ag to the valence band (VB) of AgCl, leading to the formation of highly reactive •OH species via photooxidation and the oxidation of Cl^- to reactive Cl* (Rashid et al., 2022b). However, the generation of holes on Ag can be hindered by its electron cloud, limiting hole transfer to AgCl. In contrast, the TiO_2/Ag nanocomposite in Ag/TiO_2TPMP/APTES forms a semiconductor-metal interface that generates •OH species only in the VB of TiO_2 (Rashid et al., 2023), resulting in a lower RhB photodegradation rate compared to TiO_2/Ag/AgCl.

The deposition of Ag on TiO_2 enabled complete self-sterilisation of the cotton surface (data not shown), regardless of the type of bio-barrier in the mixture. However, in combination with APTES, the Ag nanoparticles formed hindered the successful formation of a TPMP-derived char layer, which was not the case with the TPMP/SiQAC mixture. In this case, TPMP effectively triggered the dehydration of the cellulose during thermal degradation and stabilised the char layer at higher temperatures (Rasid et al., 2024a).

In line with the principles of sustainability, TPMP/APTES-functionalised TiO_2 was combined with rGO/GO to replace Ag in the TiO_2-based nanocomposite. The results showed that rGO/GO significantly improved the multifunctional protective properties of the nanocomposite film (Figure 3). The modified cotton samples provided excellent UV protection by improving UVA and UVB blocking capabilities while providing good photocatalytic self-cleaning properties due to the synergistic effect between rGO/GO and TiO_2. In addition, TiO_2 coupled with rGO/GO while ensured effective surface sterilisation and demonstrated improved thermo-oxidative stability compared to untreated cotton, which was achieved by the successful formation of a TPMP-derived protective char layer (Rashid et al., 2024b).

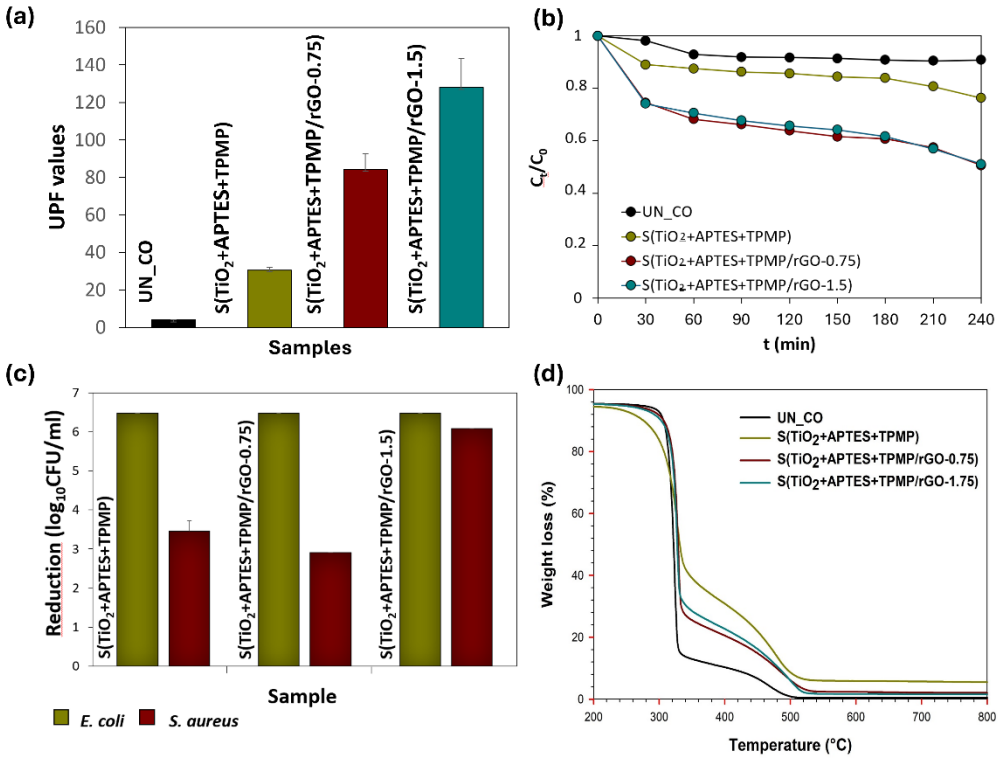


Figure 3: Functional UV-protective (a), self-cleaning (b) and antibacterial (c) properties of the cotton samples functionalised with modified rGO-coupled TiO_2 and their corresponding TGA curves (d).

4. CONCLUSIONS

A low-temperature in-situ sol-gel method using 4% TTIP enabled the formation of Ag-TiO_2 film on fibre surfaces, while the sol-gel/hydrothermal approach yielded both Ag-TiO_2 particles and a continuous film. Although both methods showed practical potential, the sol-gel/hydrothermal method was favoured due to its superior UV protection and photocatalytic performance. Silver-loaded Ag-TiO_2 was modified for the first time *in situ* with TPMP and two bio-barrier forming trialkoxysilanes, SiQAC and APTES. These modifications influenced the formation of Ag species and thus modulated the overall multifunctional performance by developing TiO_2/Ag/AgCl or TiO_2/Ag heterocomposites. The introduction of rGO into the TPMP/APTES-modified Ag-TiO_2 system provided a more sustainable alternative to Ag–TiO_2 delivering excellent multifunctional properties. The resulting nanocomposite coatings are promising for the sustainable development of technical textiles offering distinct advantages tailored to specific applications.

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5. REFERENCES

Linsebigler, A. L., Lu, G., & Yates, J. T. 1995. “Photocatalysis on TiO_2 surfaces: principles, mechanisms, and selected results.” *Chemical Reviews* 95: 735–758.

Rashid, M. M., Zorc, M., Simončič, B., Jerman, I. and Tomšič, B. 2022a. “In-situ functionalization of cotton fabric by TiO_2: the influence of application routes.” *Catalysts* 12 (11): 1–17.

Rashid, M. M., Tomšič, B., Simončič, B., Jerman, I., Štular, D. and Zorc, M. 2022b. “Sustainable and cost-effective functionalization of textile surfaces with Ag-doped TiO_2/polysiloxane hybrid nanocomposite for UV protection, antibacterial and self-cleaning properties.” *Applied Surface Science* 595: 1–15.

Rashid, M. M., Tomšič, B., Simončič, B., Jerman, I., Štular, D., Zorc, M. and Čelan Korošin, N. 2023. “In situ tailoring of Ag-doped TiO_2/

TPMP/cotton nanocomposite with UV-protective, self-sterilizing and flame-retardant performance for advanced technical textiles." *Polymer Degradation and Stability* 216: 1–11.
Rashid, M. M., Simončič, B., Zorc, M., Čelan Korošin, N., Jerman, I. and Tomšič, B. 2024a. "Sustainable in situ synthesis of silver/titanium dioxide/organofunctional trialkoxysilane nanocomposite coatings on cotton fabric to tailor superior multifunctional protective properties." *Surfaces and Interfaces* 49: 1–16.
Rashid, M. M., Zorc, M., Simončič, B., Jerman, I., & Tomšič, B. 2024b. "Ag doping and rGO coupling of TiO_2 within polysiloxane matrix for the ecofriendly development of high-performance cotton fabric." *Materials Science Forum* 1117: 9-15.
Riaz, S., Ashraf, M., Hussain, T., Hussain, M. T. and Younus, A. 2019. "Fabrication of Robust Multifaceted Textiles by Application of Functionalized TiO_2 Nanoparticles." *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 581: *123799.*
Shaheen, T. I., Salem, S. S. and Zaghloul, S. 2019. "A new facile strategy for multifunctional textiles development through *in situ* deposition of SiO_2/TiO_2 nanosols hybrid." *Industrial and Engineering Chemistry Research* 58 (44): 20203–20212

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ORAL PRESENTATION

THE RESEARCH JOURNEY: INVESTIGATING THE ROLE OF TEXTILE PROPERTIES IN BACTERIAL ADHESION

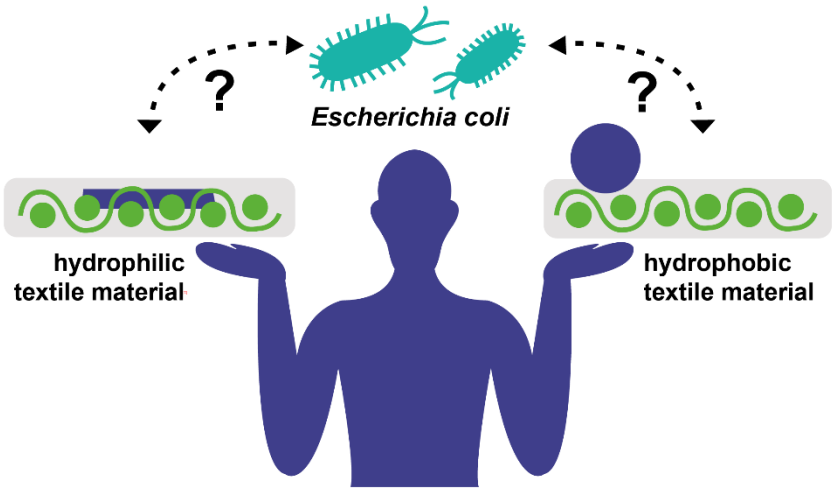
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Abstract: *An interdisciplinary team from the University of Ljubljana, Slovenia, recently investigated the topic of bacterial adhesion to textiles. When reviewing the literature, the contradictory conclusions of the various articles became clear. For this purpose, the bacterial strain Escherichia coli, which is part of the normal human microbiota, was included as a test organism in this study. Different textile raw materials, namely cotton and polyester, were used as substrates. The chemical parameters of woven fabrics were analysed using Fourier Transform Infrared Spectroscopy. Additionally, some of the physical properties including thickness and mass per unit area were measured. Finally, bacterial adhesion was determined, and it was found that the material properties have a direct influence on bacterial adhesion, as the bacterial strain E. coli adheres more strongly to hydrophobic polyester than to hydrophilic cotton. In addition to the results for researchers, professors and other interested parties, this article also describes the research process as a practical example for young students.*

Keywords: *young researcher's perspective, interdisciplinary research journey, woven fabric, bacterial adhesion.*

Graphic abstract:



1. INTRODUCTION

Bacterial adhesion to various materials is a complex and multifaced process that is not yet fully understood. When observing bacterial adhesion to different textile materials, this complexity is compounded by the interplay of two important and unpredictable factors. Firstly, as living microorganisms, bacteria exhibit different adhesion mechanisms that are influenced by their physiological state and environmental conditions. Secondly, textiles are characterised by unique physicochemical and structural properties that respond differently to environmental stimuli.

These two factors can be analysed both individually and in relation to each other. In addition, a third critical component — the external environment — must also be considered, as it significantly influences bacterial adhesion through variables such as humidity, temperature and the possible presence of bioactive compounds.
Given these complex relationships, it is not surprising that the results of the various studies are often contradictory, as we pointed out in our earlier literature review (Čuk, 2024). From the perspective of a young researcher, this can be particularly challenging, as enthusiasm for new findings is interrupted by a sudden shift in understanding when one encounters new literature. This requires an adaptive approach, similar to the behaviour of bacteria themselves: constantly adapting to new information and external influences. Interest in bacterial adhesion to textiles has increased 45-fold over the last two decades, judging by the number of published studies on this topic (Web of Science search on 22 January 2025 using the keywords »bacterial adhesion or bacterial adherence« and »textile or fabric« for the years 2003–2023). This result illustrates both the complexity and the potential of the topic. The challenges are great, but they also offer opportunities for innovative, interdisciplinary and holistic research.

After identifying a relevant research gap, the individual properties of the selected textiles were analysed, followed by an investigation of bacterial adhesion to their surfaces. Among the textile factors, the chemical composition plays a key role in determining the properties of the textile material and consequently the extent of bacterial adhesion. In particular, the chemical structure or the presence or absence of certain functional groups in the chemical formula of the fibre-forming polymers determine the hydrophilicity or hydrophobicity of the textiles themselves. However, a review of existing studies shows contradictory conclusions as to whether hydrophilic or hydrophobic textile fibres are more susceptible to bacterial adhesion (Čuk, 2024).

The aim of this study is therefore to contribute to solving the above dilemma (i). In addition to providing valuable insights for researchers and other stakeholders, a secondary objective was to illustrate the theoretical research process for students using a real-life example (ii). However, it should be emphasised that this study is only one part of a larger research framework aimed at gaining a comprehensive and interdisciplinary understanding of bacterial adhesion to textiles. The full scope of our team's interdisciplinary research approach is illustrated in Figure 1.

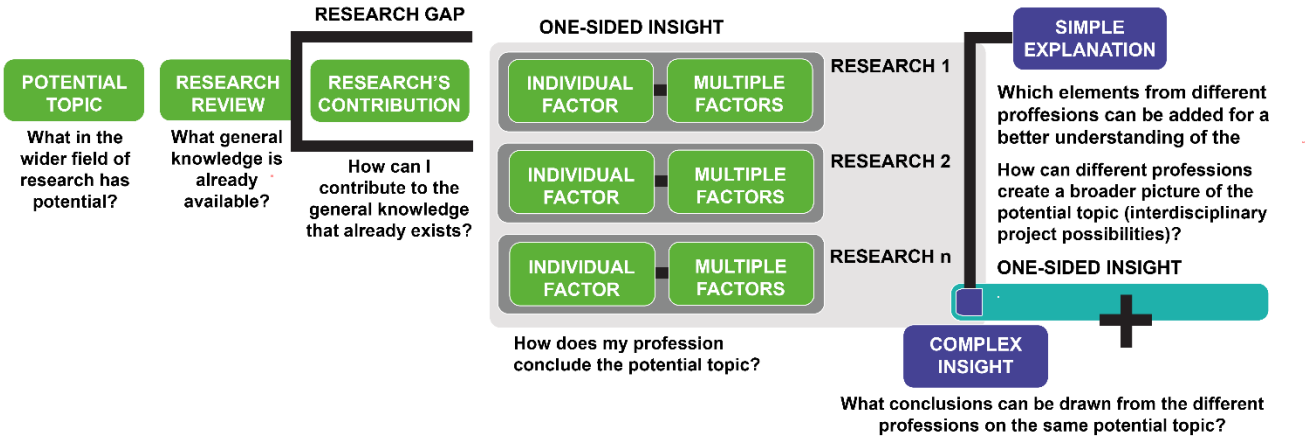


Figure 1: Our interdisciplinary research journey of a potential topic

2. EXPERIMENTAL WORK

2.1 Tested materials and included test organisms

Two different woven fabrics in satin weave were produced on the Minifaber weaving machine with electronic jacquard T.I.S. (Minifaber Spa, Italy) at the Faculty of Natural Sciences and Engineering of the University of Ljubljana (Ljubljana, Slovenia). Warp cotton with the sequence (1 black: 1 white), fineness 2 x 8 tex and with 100% optically bleached white warp threads was used. Cotton (60 tex) and polyester (25 tex) were used as weft threads. The warp density for both samples was 40 threads/cm, the weft density 18 threads/cm.

The test organism *Escherichia coli* ATCC 35 218 (*E. coli*) was obtained from the collection of the Faculty of Health Sciences of the University of Ljubljana. The cryopreserved bacterial strain was inoculated on Tryptic Soy Agar and incubated at 37 °C for 24 hours to obtain initial cells. The woven fabric samples, medium and solution were autoclaved before the experiment.

2.2 Methods used

Fourier Transform Infrared Spectroscopy (FTIR) was performed to confirm the hydrophilicity or hydrophobicity of cotton and polyester woven fabrics. The thickness of fabrics was measured according to the SIST EN ISO 5084 standard, while the mass per unit area was measured according to SIST EN 12127 as two of the basic physical textile parameters.

Finally, bacterial adhesion was analysed according to the SIST EN ISO 20743:2007 standard, Figure 2. In this method, the bacterial strains of *E. coli* were first incubated overnight. After this, the test solution was prepared at a concentration of 0.5 according to McFarland. Then 19.6 ml of the 0.9 % saline solution was mixed with 0.4 ml of prepared test suspension. 0.2 ml of the mixed solution was added to the individual cotton and polyester sample and afterwards incubated for 24 hours at 37°C. After incubation, the inoculated textile samples were placed in vials which contained neutralisation solution SCDLP (7 g polysorbate 80, 3 g lecithin, 5 g nutrient broth/1000 ml 0.9% saline solution). Vials containing textile samples and neutralisation solution SCDLP were then shaken for 5 minutes at 10.000 rpm. This was followed by serial dilution, solid media inoculation and incubation (24 hours, 37°C).

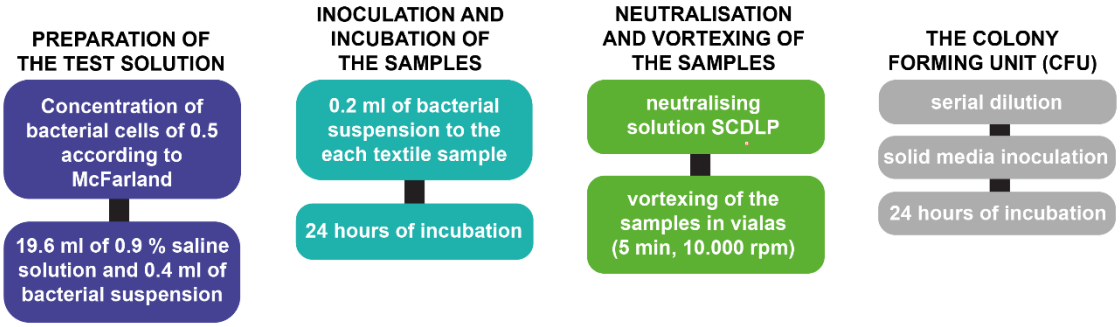


Figure 2: Protocol of the standard SIST EN ISO 20743:2007

3. RESULTS

Figure 3A shows the FTIR spectra of the studied cotton and polyester fabrics. The characteristic absorption bands of cellulose in the fingerprint region (1500–800 cm-¹), which correspond to the C-O-C, C-H and C-O vibrations, can be clearly recognised in the spectrum of the cotton fabric. In addition, a broad absorption band in the range of 3700–3000 cm^{-1} is attributed to the O-H stretching vibrations of adsorbed water, while the absorption band at 1640 cm^{-1} corresponds to the bending vibrations of the –OH groups of adsorbed water (Socrates, 2001).

In contrast, the FTIR spectrum of the polyester fabric shows a strong and distinct absorption band at 1720 cm $^{-1}$, which corresponds to the C=O stretching vibrations of the ester carbonyl group. It is accompanied by C-O and C-O-C vibrations in the range of 1090–1375 cm^{-1} as well as C-H and C-C stretching vibrations of the benzene ring in the range of 790–850 cm^{-1}. A weaker band at 3430 cm-¹ corresponds to the intermolecular O-H bond. It is noteworthy that the O-H stretching band in polyester is significantly weaker than the broad and intense O-H adsorption at ~3400 cm^{-1} observed in cotton (Socrates, 2021).

This clear difference in spectral characteristics emphasises the contrast between the hydrophilic nature of cotton and the hydrophobic character of polyester. Indeed, the abundance of hydroxyl groups (-OH) in cotton enables strong hydrogen bonding with water and makes it very absorbent. In contrast, the dominance of ester bonds (-COO-) and aromatic rings in polyester leads to a rather non-polar, hydrophobic surface that limits water absorption.

Figure 3B shows the physical parameters of the studied woven samples. The thickness and mass per unit area were lower for polyester fabric compared to cotton, which is both reasonable and expected. This difference is due to the finer polyester yarn in the weft (25 tex) and the coarser cotton yarn (60 tex). With constant warp and weft yarn density in the weaving process, the polyester fabric had 44% less mass per unit area than the cotton fabric.

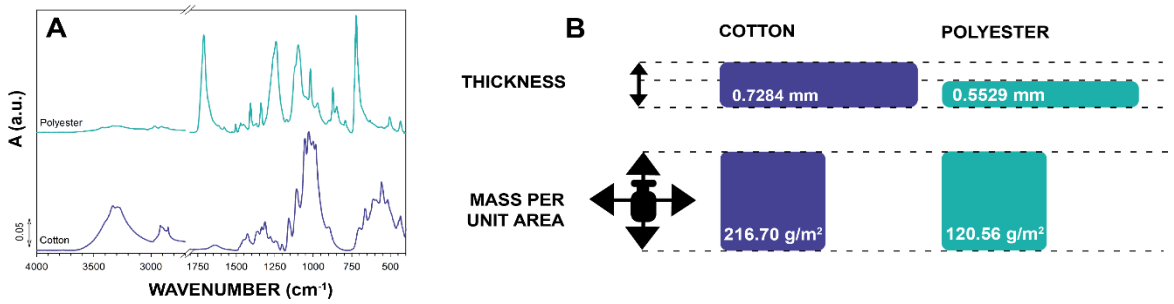


Figure 3: A. FTIR spectra analyses; B. Schematic representation of the values of the investigated physical textile parameters

The results of the bacterial adhesion tests show that the test organism *E. coli* adhered more strongly to the polyester sample (7.070.22 log CFU/ml) than to cotton (4.910.80 log CFU/ml), Figure 4. This result agrees with the study by Koziarz, which concludes that hydrophobic textile materials have a greater affinity for *E. coli* 3300 than hydrophilic materials (Koziarz, 1998). The stronger adhesion to polyester can be attributed to the hydrophobic surface of the material, which enables stronger binding of the bacteria due to van der Waals forces and a limited interaction with moisture. This observation is in line with the results of Møllebjerg et al. who found that more bacterial cells (*S. hominis* DSM 20328, *S. epidermidis* DSM 20044, *M. luteus* DSM 20030 and *C. jeikeium* DSM 7171) adhere to polyester than to hydrophilic cotton (Møllebjerg, 2021).

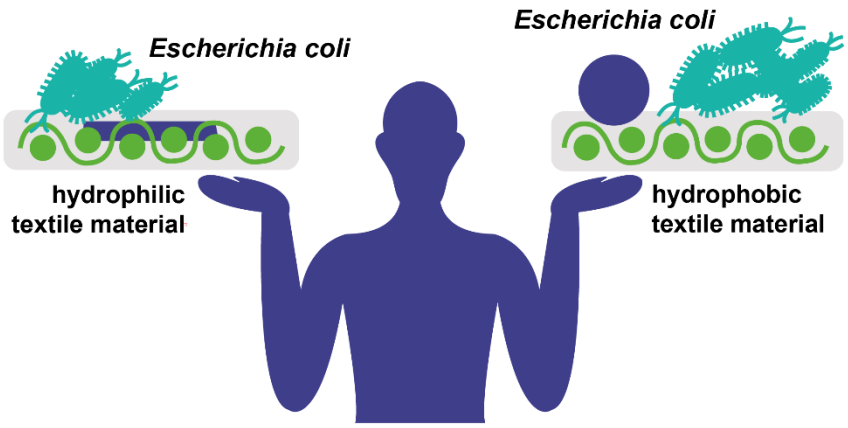


Figure 4: *E. coli* adhesion to hydrophilic cotton and hydrophobic polyester fabric

4. CONCLUSIONS

In this study, *E. coli* (a common member of the human microbiota) was found to adhere more strongly to the hydrophobic polyester sample than to the hydrophilic cotton sample, highlighting the role of material properties in bacterial adhesion. Given the complexity of bacterial adhesion to textiles, an interdisciplinary approach is essential to gain a more comprehensive understanding of the phenomenon

5. ADDITIONAL

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6. REFERENCES

Basu, A., Basu, S., Bandyopadhyay, S. and Chowdhury, R. 2015. "Optimization of evaporative extraction of natural emulsifier cum surfactant from Sapindus mukorossi—Characterization and cost analysis." Industrial Crops and Products (77): 920–931.

Caenn, R., Darley, H. C. H. and Gray, G. R. 2011. Composition and Properties of Drilling and Completion Fluids. Waltham: Gulf Professional Publishing.

Čuk, N., Simončič, B., Fink, R. and Tomšič, B. 2024 "Bacterial Adhesion to Natural and Synthetic Fibre-Forming Polymers: Influence of Material Properties." Polymers (16): 1−30.

Missirlis, Y. F. and Katsikogianni, M. 2007. "Theoretical and Experimental Approaches of Bacteria-Biomaterial Interactions." Materwiss Werksttech (38): 983–994.

Čuk, N., Simončič, B., Fink, R. and Tomšič, B. 2024. "Unveiling the impact of cotton surface free energy on bacterial adhesion capacity." In Book of proceedings: magic world of textiles: 11th International Textile, Clothing & Design Conference [also] ITC&DC, October 6th to October 9th, 2024, Dubrovnik, Croatia., edited by Zvonko Dragčević, Anica Hursa Šajatović and Ivana Špelić, 39−44. Zagreb: University of Zagreb, Faculty of Textile Technology.

Koziarz, J. 1998. "Adhesion and immobilization of bacteria on hydrophobic cloths." Master's Thesis, Ottawa-Carleton Institute of Biology, Ottawa.

Møllebjerg, A., Palmén, L.G., Gori, K., Meyer, R. L. 2021. "The Bacterial Life Cycle in Textiles is Governed by Fiber Hydrophobicity." Microbiol Spectr 9 (2).

Nielsen, C. K., Kjems, J., Mygind, Snabe, T. and Meyer R. L. 2016. "Effects of Tween 80 on Growth and Biofilm Formation in Laboratory Media". Frontiers in Microbiology (7): 1–10.

Socrates G., Infrared Characteristic Group Frequencies. Tables and Charts, John Wiley & Sons Ltd, 2001. https://doi.org/10.1016/0003-2670(94)80274-2.

Żenkiewicz, M. 2007. "Methods for the calculation of surface free energy of solids." Journal of Achievements of Materials and Manufacturing Engineering 24 (1): 137–145.

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POSTER PRESENTATION

ENVIRONMENTALLY FRIENDLY TiO_2/GRAPHITIC CARBON NITRIDE NANOCOMPOSITE FOR MULTIFUNCTIONAL COTTON FABRIC

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Abstract: *This study aims at the synthesis of environmentally friendly TiO_2/graphitic carbon nitride (gCN) nanocomposite used for the functionalisation of cotton (CO) to achieve multifunctional UV protection and photocatalytic dye degradation. The CO modified with TiO_2/gCN nanocomposite was prepared by the synthesis of TiO_2 using an environmentally friendly precipitating agent (acetic acid) in the presence of CO and pre-synthesised gCN at room temperature. The UV protection factor of CO modified with TiO_2/gCN was significantly higher than that of CO modified with TiO_2 or gCN alone. In addition, the CO modified with TiO_2/gCN showed superior degradation efficiency of the Rhodamine B dye, which was attributed to the effective reduction of the band gap energy and the lower recombination of charge carriers in the semiconductor nanocomposite.*

Keywords*: Textile functionalization, Titanium dioxide (TiO_2), Graphitic carbon nitride (gCN), UV protection, Photocatalytic activity.*

1. INTRODUCTION

Multifunctional technical textiles are categorised as advanced high-tech textile materials that are used in many different industries as protective, medical, electronic, bio-, agro-, geo- and aerotextiles as well as sports textiles. They are characterised by the simultaneous expression of multiple functional properties, such as photocatalytic activity, self-cleaning activity and protection against ultraviolet (UV) radiation (Hassan, 2019). Their production is based on the incorporation of chemical finishing agents and other active components with different structures, which change the chemical and morphological properties of the textile fibres on the surface and/or in the mass. A major technological breakthrough in their development was the integration of nanotechnology, which made it possible to incorporate various nanomaterials into textile fibres. This made it possible to achieve special textile properties that could not be obtained by conventional chemical modification processes (Hassan, 2019). However, many of the current nanotechnology processes for the chemical modification of textiles are not based on the principles of environmentally friendly development.

Among the various approaches to chemical surface modification of textile fibres, nanocomposite coatings containing metal oxides are widely used, with titanium dioxide (TiO_2) being the most commonly used material. TiO_2 is known as the „golden“ photocatalyst and is favoured for its semiconducting properties, which give textiles photocatalytic self-cleaning, antimicrobial activity, UV protection and improved thermal stability (Rashid, 2021). Photocatalytic activity is directly induced by exposure to UV light, which excites electrons from the valence band (VB) to the conduction band (CB), creating holes in the VB. Both electrons and holes are charge carriers that engage in redox reactions with oxygen and water on the TiO_2 surface, generating highly reactive oxygen species (ROS). The ROS can then interact with adsorbed pollutants, such as dyes in wastewater, leading to their degradation into carbon dioxide and water (Rashid, 2021; Nur, 2022). Despite its advantages, the use of TiO_2 in textile finishing is limited due to its wide band gap (E_g), which restricts its activity to UV light.

To improve the photocatalytic performance of TiO_2 in the presence of visible light, various approaches are being pursued, such as doping with noble metals or preparation of semiconductor nanocomposites using narrow band gap semiconductors (Rashid, 2021). A promising material in this regard is graphitic carbon nitride (gCN), a novel, sustainable carbon-based photocatalyst. gCN has unique optical and electronic properties, high physico-chemical

and thermal stability, excellent corrosion resistance, and low-cost fabrication. Due to its narrow band gap, it is photocatalytically active under visible light up to wavelength of around 460 nm (Vasiljević, 2021). When illuminated, the electrons in the VB are excited to CB, leaving holes in the VB. However, due to the energy levels of the VB edge, reactive oxygen species (ROS) are only generated by electrons, while the photo-generated holes are directly involved in the degradation of organic pollutants (Su, 2017).

The aim of this research is to in-situ synthesize TiO_2/gCN nanocomposite for the chemical modification of cotton fabric (CO). The research focuses on investigating the UV protection properties of the modified CO as well as its potential to photodegrade Rhodamine B (RhB) dye in aqueous solution. It is hypothesized that the incorporation of TiO_2/gCN nanocomposite into the CO fabric would provide improved UV protection and effective decolorization of the RhB dye solution.

2. EXPERIMENTAL

2.1 Materials

Chemically bleached 100% cotton fabric (CO) with a mass per unit area of 120 g/m^2 (Tekstina d.o.o., Ajdovščina, Slovenia) was used for this study. Titanium(IV) isopropoxide(TTIP; ≥ 97.8% concentration), isopropanol (iPrOH; ≥ 99% concentration) and acetic acid (AA; 99% concentration), all products from Sigma Aldrich (USA), were used to prepare TiO_2 nanoparticles (NPs). The layered particles of graphitic carbon nitride (gCN) were synthesized at the National Institute of Chemistry, Slovenia – Department of Materials Chemistry. Rhodamine B (RhB; Sigma Aldrich, USA) was used as dye.

2.2 Preparation of chemically modified cotton samples

The following method was used to produce chemically modified CO with a two-component composite TiO_2/gCN (sample CO(TiO_2/gCN)). In a beaker, 2 g of the previously synthesized gCN was dissolved in 98 g iPrOH and sonicated for 2 hours. A solution containing 12 g TTIP, 68 g iPrOH and 20 g AA was then added to the beaker and the mixture was placed on a magnetic stirrer with continued sonication. CO was added while stirring, followed by dropwise addition of 200 g distilled water. The solution was then sonicated and stirred for a further 2 hours at room temperature. After completion of sonication, magnetic stirring was continued for 15 minutes to ensure complete synthesis. After synthesis, the samples were squeezed with a 95 ± 2% wet pick-up, air dried and cured at 150 °C for 5 minutes. The functionalized CO samples were then rinsed three times with distilled water for 1 minute each time and dried in air. For comparison, single-component gCN and TiO_2 were applied to CO under identical conditions to produce CO(gCN) and CO(TiO_2) samples, respectively.

2.3 Characterization

The Ti concentration in CO(TiO_2) and CO(TiO_2/gCN) samples was determined using inductively coupled plasma mass spectrometry (ICP-MS).

The transmission spectra of the CO samples were recorded in a wavelength (λ) range 200–800 nm using a Lambda 800+ UV/Vis spectrophotometer (Perkin Elmer, Great Britain). A minimum thirteen measurements were performed for each sample and the average value of transmittance (T) at each λ was calculated. The average transmission spectra were converted into absorption spectra using the following equation:

$$A = -\log T \quad (1)$$

where A represents absorbance. From the absorption spectra, the optical bang gap energies (E_g) of the chemically modified CO samples were determined using Tauc relation (Karkare, 2015):

$$(\alpha\, h\, \nu)^2 = K(h\, \nu - E_g) \quad (2)$$

where α is the energy-dependent absorption coefficient, equal to 2.303 x A, h is Planck constant, ν is the frequency of the radiation, and K is a constant.

According to Planck's radiation law, the energy (*E*) of radiation is equal to:

$$E = \mathrm{h}\,v = \frac{1240}{\lambda} \quad (3)$$

The values of E_g are obtained through extrapolation to $\alpha = 0$ (Karkare, 2015).

The UV protection factor (UPF) of CO samples was determined according to the Standard EN 13758-1:2001. Transmission was calculated at UVA from 315 to 400 nm and UVB from 280 to 315 nm regions. The UPF was calculated using the following equation (SIST EN 13758-1:2002):

$$\mathrm{UPF} = \frac{\sum_{290}^{400} \mathrm{E}(\lambda) x \varepsilon(\lambda) x \Delta(\lambda)}{\sum_{290}^{400} \mathrm{E}(\lambda) x \varepsilon(\lambda) x \mathrm{T}(\lambda) x \Delta(\lambda)} \quad (4)$$

where E*(λ)* represents the solar spectral irradiance*, ε(λ)* represents the relative erythemal effectiveness, *Δ(λ)* represents the wavelength interval, and T*(λ)* is the spectral transmittance at the *λ*.

The UPF rating and protection categories were determined based on UPF values, following the Australian/ New Zealand Standard for Sun-Protective Clothing— Evaluation and Classification (AS/NZS 4399, 2020). UPF values of 15 correspond to the »minimum protection« category, values of 30 to the »good protection« category, and values of 50 to the »excellent protection« category.

The photocatalytic activity of the samples was assessed by evaluating the degradation of the aqueous 0,02 mM RhB solution under daylight using Xenotest Alpha instrument equipped with a visible xenon arc lamp (radiation settings, 0.8–2.5 kVA, and extended radiation range, 300–400 nm). The CO samples (0.8 cm x 4.1 cm) were immersed in 3 ml of a RhB solution in cuvettes, that were initially kept in the dark for 30 minutes to achieve adsorption-desorption equilibrium. The samples were then irradiated for a total of 180 minutes, with measurements taken at 30 minute intervals. At each interval, the A of the RhB solution was measured at the maximum absorption wavelength (λ_{max} = 552.93 nm). The corresponding dye concentration in the solution was determined using previously established calibration curves.

The photocatalytic degradation of RhB dye was quantified by calculating the concentration ratio of C_t to C_0, where C_t represents the dye concentration at a given time of irradiation and C_0 represents the initial dye concentration after the adsorption-desorption equilibrium. Based on these results, the apparent rate constant (K_{app}) of the photocatalytic reaction was determined as a measure of the dyes photocatalytic degradation efficiency, assuming pseudo-first-order kinetic behaviour, as described by the following equation (Shafique, 2022):

$$\ln \frac{C_t}{C_0} = -\mathrm{K_{app}}\,t \quad (5)$$

where t is the illumination time.

3. RESULTS WITH DISCUSSION

The results of the ICP-MS analysis showed that the presence of gCN increased the amount of Ti in the nanocomposite from 4900 mg/kg for the CO(TiO_2) sample to 5700 mg/kg for the CO(TiO_2/gCN) sample.

The absorption spectra of the studied samples are presented in Figure 1a. The CO(UN) sample exhibited the lowest light absorption across the range of 200 nm to 800 nm. The presence of gCN in CO(gCN) sample led to a slight increase in the absorption of UV and visible light, especially at wavelengths below 450 nm. The incorporation of TiO_2 to the CO(TiO_2) sample led to a significant increase in UV absorption especially at wavelengths below 350 nm. However, when both TiO_2 and gCN were combined in the CO(TiO_2/gCN) sample, a significant increase in absorbance was observed in both the UV and visible ranges, indicating a compatibility of both components in the nanocomposite.

The Tauc plots (Figure 1 b) obtained from the absorption spectra show that the incorporation of both TiO_2 and gCN into a nanocomposite ($CO(TiO_2/gCN)$ sample) resulted to a reduction in the E_g compared to gCN (CO(gCN) sample) or TiO_2 ($CO(TiO_2)$ sample) alone. Specifically, the E_g of TiO_2 in the $CO(TiO_2)$ sample was 3.5 eV, while that of gCN in CO(gCN) sample was 2.9 eV, however, for the $CO(TiO_2/gCN)$ sample, the E_g values are 3.3 and 2.7 eV, respectively. These results indicate that the bathochromic shift of light absorbance was achieved in the semiconductor nanocomposite.

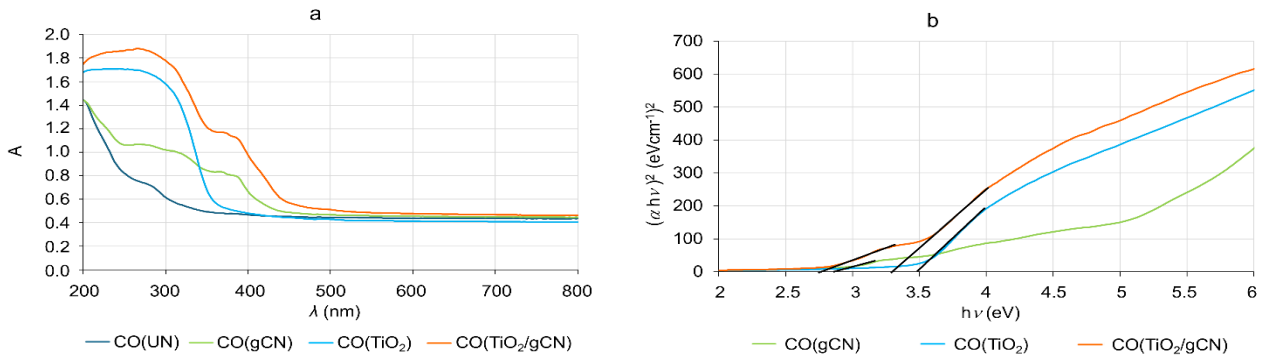


Figure 1: Absorbance (A) of untreated and chemically modified samples (a) and Tauc plots of chemically modified samples (black lines determine the E_g values on x exis) (b)

The UV protection properties (Figure 2) of the chemically modified CO samples were determined using the transmission spectra in the 280–400 nm range. The results show that CO(UN) sample exhibits the highest light transmittance in the 280 nm to 400 nm range, resulting in the lowest UV-A and UV-B blocking capabilities, and a UPF that does not meet the minimum protection threshold as per the Australian/New Zealand Standard. Although the transmittance of the CO(gCN) sample was reduce by more than half compared to CO(UN), it still fails to achieve the minimum required UPF. The $CO(TiO_2)$ sample demonstrates very low transmittance in the UV-B range, followed by a sharp increase in the UV-A range, as the energy of these rays is too low to be absorbed by TiO_2, which also reflected in the UV blocking values, which are higher in the case of UV-B than UV-A. According to the standard, the UPF of $CO(TiO_2)$ equal to 20.5 is classified as minimal. In contrast, the $CO(TiO_2/gCN)$ sample exhibits the lowest transmittance, the highest UV-A and UV-B blocking, and the highest UPF value equal to 43.3, which is classified as good. This further confirms the compatibility between TiO_2 and gCN in the nanocomposite.

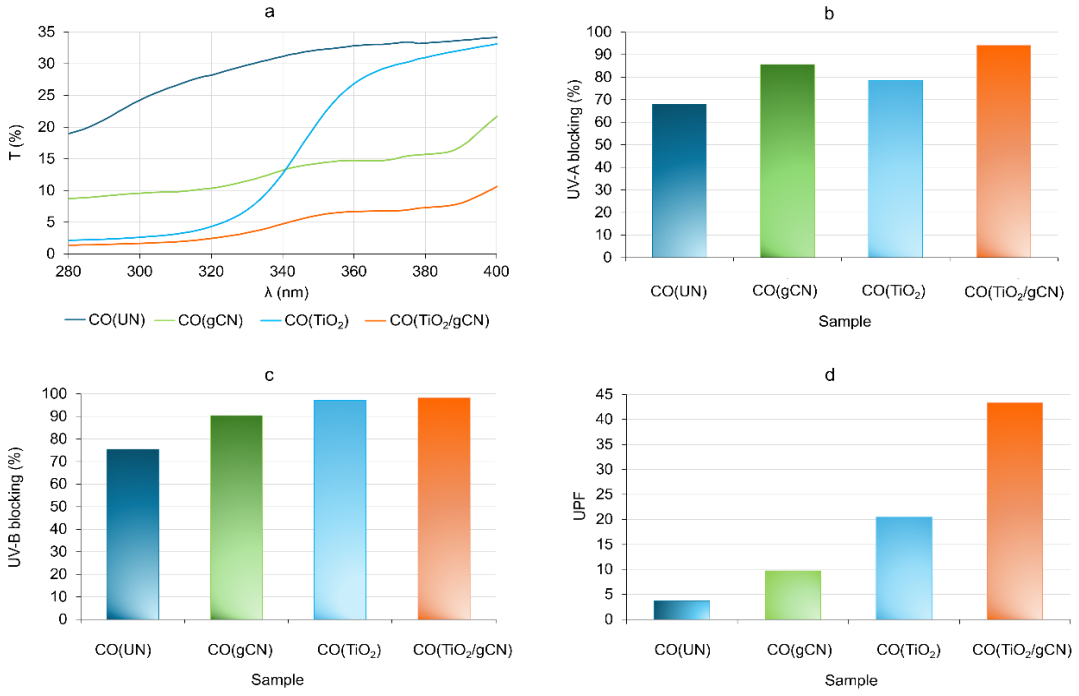


Figure 2: Transmittance of untreated and chemically modified samples (a), blocking of UV-A light (b), UV-B light (c), and UPF values (d)

The results of the photocatalytic degradation of the RhB dye solution (Figure 3) indicate that CO itself has no photocatalytic activity. Among the chemically modified samples, the CO(gCN) sample shows the slowest and least efficient decolorization of the RhB dye. The CO(TiO_2) sample shows a slightly faster decolorization, reaching nearly 100% after 180 minutes. As expected, the CO(TiO_2/gCN) sample shows the highest photocatalytic activity, as evidenced by the fastest decolorization of the RhB dye solution and the highest degree of decolorization. This behaviour highlights the superior photocatalytic performance of the semiconductor nanocomposite. Additionally, the reduction in E_g of semiconductor nanocomposite compared to single-component CO(TiO_2) sample enhanced photocatalytic activity under visible light irradiation.

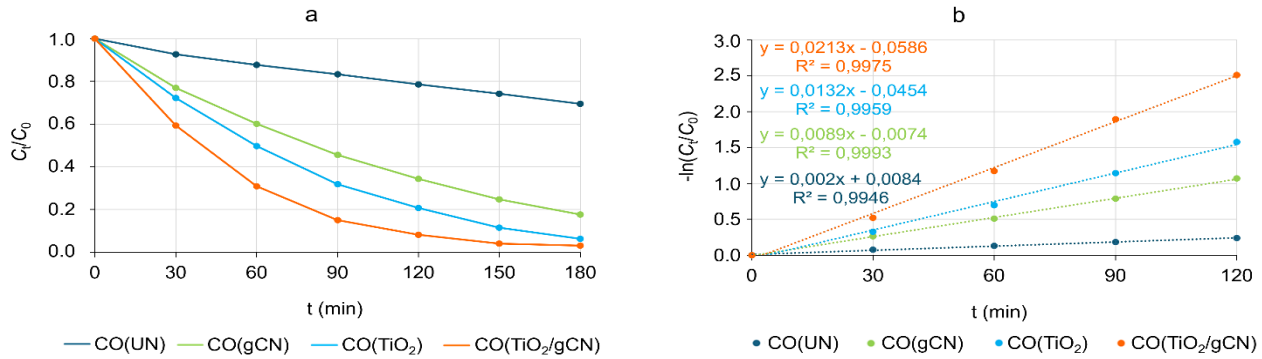


Figure 3: Decolorization rate (a) and first-order kinetic plot (b) of the RhB dye solution at different irradiation times in the presence of untreated and chemically modified samples

4. CONCLUSION

In this study, an environmentally friendly method was successfully applied to functionalize cotton fabric (CO) with TiO_2/gCN nanocomposites to impart multifunctional properties, i.e enhanced UV protection and photocatalytic activity. CO modified with TiO_2/gCN nanocomposite reflects more than twice the UPF compared to CO modified with single TiO_2 and gCN components.

The highest and fastest decolorization rate of the RhB dye solution was observed for the CO modified with TiO_2/gCN nanocomposite. This increased photocatalytic activity can be attributed to the formation of a semiconductor nanocomposite, which reduces the E_g of TiO_2 and gCN compared to the single-components. These results confirm the excellent compatibility of TiO_2 and gCN in the semiconductor nanocomposite.

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5. REFERENCES

Hassan, B. S., Islam, G. M. N. and Haque A. N. M. A. 2019. Applications of Nanotechnology in Textiles: A Review. *Advance Research in Textile Engineering* 4: 1038.

Karkare, M. M. 2015. The Direct transition and not Indirect transition, is more favourable for Band Gap calculation of Anatase TiO_2 nanoparticles. *International Journal of Scientific & Engineering Research* 6:12.

Nur, A.S.M., Sultana, M., Mondal, A., Islam, S., Robel, F.N., Islam, A. and Sumi, S.A. 2022. A review on the development of elemental and codoped TiO_2 photocatalysts for enhanced dye degradation under UV–vis irradiation. *Journal of Water Process Engineering* 47:102728.

Rashid, M.M., Simončič, B. and Tomšič, B. 2021. Recent advances in TiO_2-functionalized textile surfaces. *Surfaces and Interfaces*, *22*, 100890.

Shafique, M., Mahr, M.S., Yaseen, M. and Bhatti, H. N. 2022. CQD/TiO_2 nanocomposite photocatalyst for efficient visible light-driven purification of wastewater containing methyl orange dye. *Materials Chemistry and Physics* 278: 125583.

SIST EN 13758-1:2002. Textiles - Solar UV protective properties - Part 1: Method of test for apparel fabrics. Geneva : International Organization for Standardization, 12 p.

Su, Y., Chen, P., Wang, F., Zhang, Q., Chen, T., Wang, Y., Yao, K., Lv, W. and Liu, G. 2017. Decoration of TiO_2/g-C_3N_4 Z-scheme by carbon dots as a novel photocatalyst with improved visible-light photocatalytic performance for the degradation of enrofloxacin. *RSC Advances* 7: 34096.

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POSTER PRESENTATION

DEVELOPMENT OF SELF-CLEANING VISCOSE FABRIC FUNCTIONALIZED WITH A TITANIUM DIOXIDE-COUPLED REDUCED GRAPHENE OXIDE IN COMBINATION WITH CHITOSAN

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Abstract: *In this work, viscose fabric was functionalized with a TiO_2-coupled reduced graphene oxide (rGO) in combination with chitosan to achieve multifunctional UV protection and self-cleaning properties, with a focus on the application process. TiO_2 was applied via a hydrothermal treatment following two approaches: (i) deposition of TiO_2 sol-gel precursor followed by chitosan and rGO and (ii) prior application of chitosan and rGO followed by TiO_2 sol-gel precursor deposition. Scanning electron microscopy (SEM) showed differences in film formation between the two approaches. UV protection and photocatalytic activity were improved when TiO_2 was applied after chitosan and rGO. This resulted in minimum UV protection and superior Rhodamine B degradation. These results underline the importance of the coating sequence for optimising the functional properties for advanced textile applications.*

Keywords: *Textile functionalisation, Titanium dioxide (TiO_2), Reduced graphene oxide (rGO), UV protection, Self-cleaning.*

1. INTRODUCTION

The functionalisation of textiles has developed into an important chemical finishing process that enables production of textiles with advanced protective properties. Among the various functionalising agents, titanium dioxide (TiO_2) is one of the most studied photocatalysts due to its chemical stability, relatively low toxicity and cost-effectiveness. These properties make TiO_2 very suitable for the modification of textile surfaces, especially for UV protection, photocatalytically induced self-cleaning and antimicrobial activity (Ijaz, 2021; Peiris, 2021; Rashid, 2021). However, a major disadvantage of TiO_2 in textile finishing is its limited photoactivity in visible light and the insufficient durability of the applied coatings. To improve the photocatalytic performance of TiO_2 in the presence of visible light, it is often modified with precious metals and other photocatalytic materials (Jeon, 2020). Graphene and its derivatives, such as graphene oxide (GO) and reduced graphene oxide (rGO), have attracted considerable attention due to their unique physicochemical properties. Graphene consists of a monolayer of sp^2-hybridised carbon atoms arranged in a hexagonal lattice, which gives it a high specific surface area, exceptional adsorption capacity and excellent electrical conductivity. Thanks to these properties, graphene and its derivatives can act as electron transport mediators, adsorbents, photosensitizers, photostabilisers, photocatalysts and co-catalysts in TiO_2-based nanocomposites. In addition, the incorporation of graphene alongside TiO_2 has been shown to improve the hydrophobicity, UV protection, self-cleaning ability and antimicrobial (antibacterial and antifungal) properties of textiles, while attenuating potentially cytotoxic effects (Stan, 2019).

TiO_2 nanoparticles are usually applied to textiles using techniques such as dip coating, sol-gel processes or sputtering (Rashid, 2021). However, their weak interaction with the functional groups of the textile fibres often leads to insufficient adhesion, resulting in poor durability under mechanical stress and repeated washing. Various strategies are used to improve the stability of the coating, including the use of binders or crosslinkers, surface finishing and plasma treatment. Among the crosslinkers, chitosan has shown promise in improving the durability of TiO_2 coatings. As a biopolymer with inherent biocompatibility and non-toxicity, chitosan not only improves adhesion, but also provides additional antimicrobial functions due to the amine groups ($–NH_2$), which can act as a bio-barrier against microbial growth (Rouhani Shirvan, 2019). However, the incorporation of crosslinkers can

alter the photocatalytic efficiency of TiO_2 and impair its functional performance. Therefore, careful optimisation of the application process is crucial to achieve a balance between durability, photocatalytic activity and additional functional properties.

The main objective of this research is the functionalisation of viscose fabric with TiO_2-coupled rGO in combination with chitosan to achieve multifunctional UV protection and self-cleaning properties. Particular attention is paid to the influence of the application process on the performance of the coating. In this context, TiO_2 is applied using a hydrothermal approach in two different steps: (i) first the deposition of the TiO_2 sol-gel precursor followed by the application of chitosan and rGO, and (ii) the prior application of chitosan and rGO followed by the deposition of the TiO_2 sol-gel precursor. This comparative approach aims to investigate the influence of the layer sequence on the structural integrity and functional properties of the resulting coatings.

2. EXPERIMENTAL

2.1 Materials

Titanium tetraisopropoxide (TTIP, ≥97.0% concentration), reduced graphene oxide powder (rGO), 1,2,3,4-butanetetracarboxylic acid (BTCA, 99% concentration), sodium hypophosphite (SHP) and glacial acetic acid were purchased from Sigma Aldrich (United States). Chitosan (DD=95%, η=159 mPa·s) was purchased from Chitoclear, Primex, Iceland. Ethanol (≥99.8% concentration), Rhodamine Blue (RhB) organic dye, and 1.0 mM acetic acid were purchased from Honeywell Research Chemicals (Seetze, Germany) and CARLO ERBA Reagents S.A.S (Barcelona, Spain), respectively. A plain100% viscose fabric with a weight of 110 g/m^2 (warp density: 44 threads/cm; weft density: 34 threads/cm) was used. All reagents are of analytical grade and were used without further purification.

2.2 Preparation of TTIP sol and chitosan/rGO finishing bath

A uniform TTIP sol was prepared by dispersing 4% TTIP in an ethanol solution. A small amount of glacial acetic acid was added to the solutions and magnetically stirred for about one hour to perform hydrolysis. Additionally, a 1% chitosan–water solution was prepared with the addition of 1% glacial acetic acid and left magnetically stirred overnight. Prior to finishing, 2% BTCA and 2% of SHP was slowly added to a chitosan–water solution and left to stir, until completely dissolved. Afterwards, rGO powder was added in a concentration of 1 mg/ml and ultrasonicated for 30 minutes to achieve complete and uniform dispersion of rGO powder in a chitosan/BTCA/SHP solution.

2.3 Functionalisation of viscose fabric by TTIP and chitosan/rGO

The functionalisation process was carried out in two approaches. In the first approach, TTIP sol was applied to cotton fabric using the pad-dry method with a wet pick-up of 120 ± 5% and then dried at 100 °C for 5 minutes. A chitosan/rGO finishing bath was then applied under the same conditions, resulting in the sample CV_TiO_2-rGO/Ch. To investigate the influence of the deposition order on the final properties, in a second approach, chitosan/rGO was applied, followed by the deposition of the TTIP sol, resulting in the sample CV_Ch/TiO_2- rGO.In both cases, the treated fabrics were subjected to hydrothermal treatment at 120 °C for 1 hour with constant stirring using an infrared drying machine (Daelim Starlet-2 DL 6000 Plus). The liquor to-goods ratio was maintained at 1:50 throughout the process. After hydrothermal treatment, the samples were rinsed with distilled water and air dried.

For comparative analysis, additional samples were prepared by applying individually TTIP sol and TTIP/chitosan onto viscose fabric. The samples are coded CV_TiO_2 and CV_TiO_2/Ch respectively.

2.4 Characterization

To investigate the surface morphology of the studied samples, scanning electron microscope (SEM) JSM-6060 LV (Jeol, Japan) was used.

The transmittance of the functionalized samples was recorded in a 250–780 nm wavelength range using a Lambda 800+ UV/Vis spectrophotometer (Perkin Elmer, Great Britain). UV protection factor (UPF) was determined according to the Standard EN 13758-1:2001.

The photocatalytic self-cleaning activity of the samples was investigated based on the degradation of the Rhodamine B (RhB, Sigma Aldrich) dye under daylight. Functionalized cotton samples were placed in 4 ml of a 0.2 mMl RhB solution (Sigma Aldrich, USA) and irradiated with daylight using Q-SUN Xe-3-HSE chamber

(Q-Lab, Great Britain) for 4 hours at 30 min intervals. The absorbance (A) of the RhB solution was measured at λ_{max} of 552.93 nm. Prior to measurements, the calibration curve of the dye concentration (C) vs. absorbance was obtained, allowing the determination of the remaining RhB dye in the solution after irradiation. Accordingly, the discolouration of the RhB dye was expressed as a ratio between C_t and C_0, representing the RhB concentrations after time "t" of irradiation and the initial RhB concentration before (time "0") irradiation.

3. RESULTS WITH DISCUSSION

Figure 1 shows SEM images of the investigated samples, which illustrate the morphological changes caused by the nanocoating. The untreated viscose fibres (CV_UN) have a relatively smooth surface with clearly visible characteristic longitudinal grooves. After application of the nanocoating, a continuous film can be seen on the fibre surface of both the CV_TiO_2/Ch-rGO and CV_Ch-rGO/TiO_2 samples, indicating successful deposition. However, local cracks in the coating can be observed in the CV_Ch-rGO/TiO_2 sample, which indicates possible differences in film formation or adhesion strength in relation to the application approach.

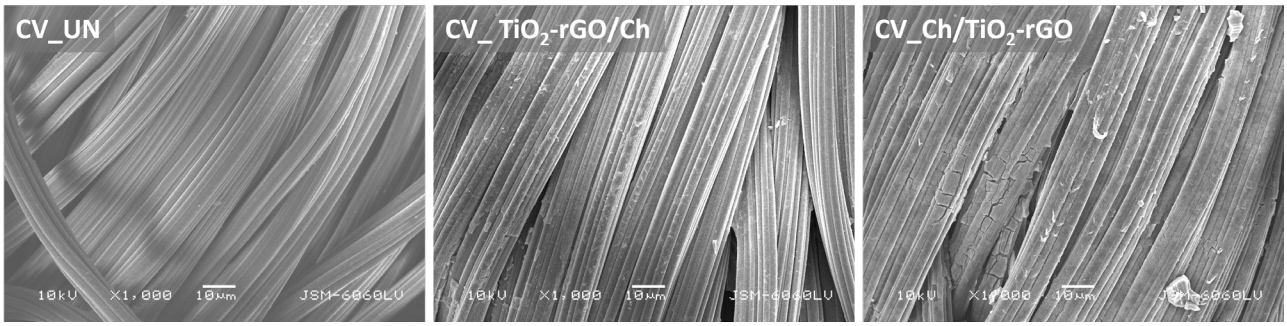


Figure 1: SEM images of the studied viscose fibres

The deposition of TiO_2 significantly decreased transmission of UVA and UVB light, thus increasing UVA and UVB blocking properties, resulting in a 4.5-fold increase in UPF compared to the CV_UN sample (Figre 2 A and B). Accordingly, a UPF of 23 was achieved, which fulfils the requirements for minimum UV protection according to the Australian/New Zealand Standard for Sun-Protective Clothing—Evaluation and Classification (AS/NZS 4399, 2020). In contrast, prior application of TiO_2-rGO followed by chitosan reduced the UV blocking effect, resulting in a UPF value of 12.5, which is below the protection threshold. However, when TiO_2-rGO was applied to the fabric subsequently to the chitosan deposition, the UPF increased to 15.6, which is high enough to fulfil the standard for minimum UV protection.

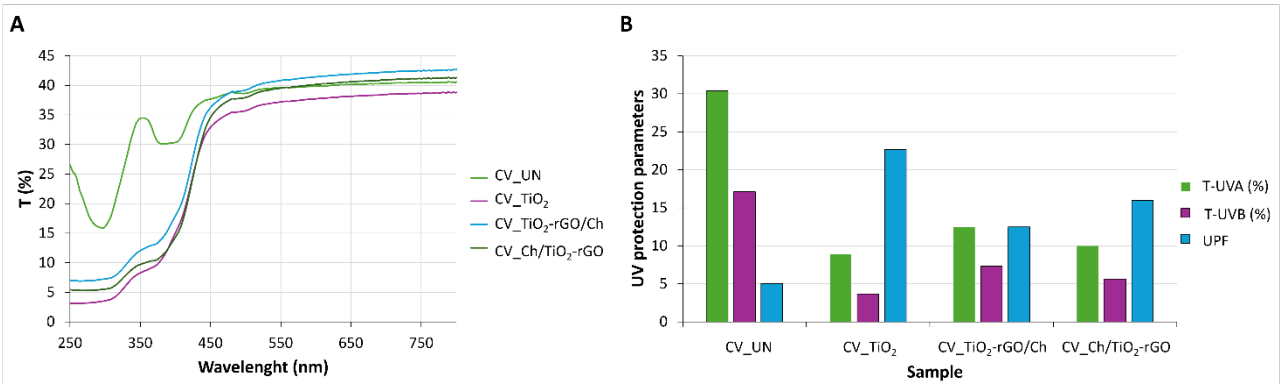


Figure 2: UV transmission spectra of the studied viscose fibres (A) and corresponding UV protection parameters (B)

In contrast to the UV protection properties, coupling TiO_2 with rGO in the presence of chitosan improved the

photocatalytic self-cleaning activity, regardless of the application approach (Figure 3). However, between the two approaches studied, again the CV_Ch/TiO_2-rGO with subsequent application of TiO_2 proved better performance. This improvement in self-cleaning activity can be attributed to the presence of rGO, which plays a crucial role in facilitating charge separation and electron transfer. According to literature, the coupling of TiO_2 with rGO promotes a more efficient transfer of photogenerated electrons from the conduction band of TiO_2 to the neighbouring rGO surface, where they subsequently reduce O_2 molecules and generate superoxide radicals (). At the same time, the corresponding holes in the valence band of TiO_2 interact with the hydroxyl groups (–OH) on the surface, which leads to the formation of highly reactive hydroxyl radicals (•OH). These reactive oxygen species (ROS) then degrade the adsorbed RhB dye molecules on the TiO_2/rGO surface and thus increase the overall photocatalytic efficiency (Alwan 2022; Yu, 2018).

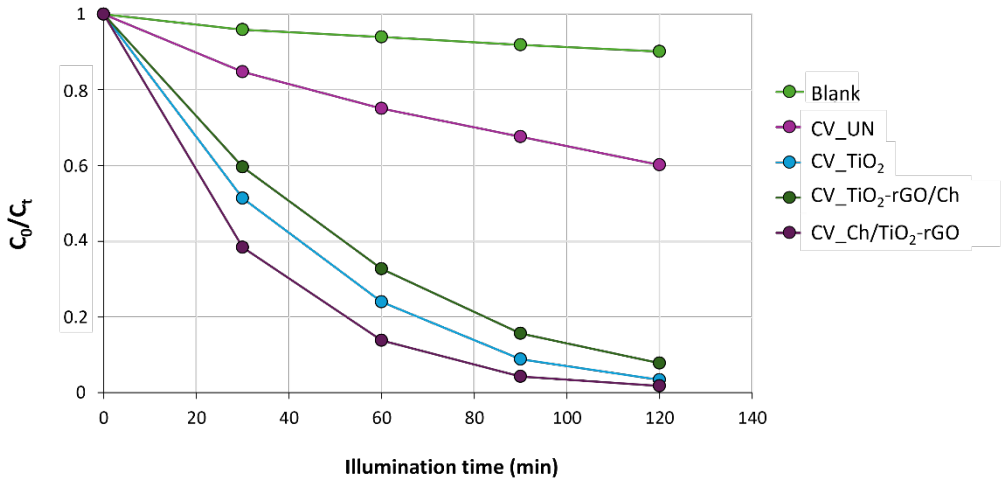


Figure 3: Discolouration of the RhB dye over time under irradiation of the tested samples

4. CONCLUSIONS

In the study, a viscose fabric was successfully functionalized with TiO_2-coupled rGO in the presence of chitosan to achieve multifunctional UV protection and self-cleaning properties. While the coupling of TiO_2 with rGO in the presence of chitosan impaired the UV protection activity, it improved the photocatalytic self-cleaning activity by enhancing charge separation and ROS formation. Among the investigated approaches, the subsequent TiO_2-rGO coupling in the presence of previously applied chitosan proved to be better. These results underline the importance of optimising the coating strategy to achieve a balance between multifunctional UV protection and photocatalytic self-cleaning efficiency.

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5. REFERENCES

Alwan, S. H., Salem, K.H. and Alshamsi, H.A. 2022. Visible light-driven photocatalytic degradation of Rhodamine B dye onto TiO2/rGO nanocomposites, Materials Today Communication 33: 104558.
Ijaz, M. and Zafar, M. 2021. Titanium dioxide nanostructures as efficient photocatalyst: Progress, challenges and perspective. International Journal of Energy Resourch 45: 3569–3589.
Jeon, J. P., Kweon, D. H., Jang, B. J, Ju, M. J. and Baek, J. B. 2020. Enhancing the Photocatalytic Activity of TiO2 Catalysts. Advanced Sustainable Systems 4: 2000197.
Peiris, S., de Silva, H.B., Ranasinghe, K.N., Bandara, S. V. and Perera, I.R. 2021. Recent development and future prospects of TiO2 photocatalysis. Journal of the Chinese Chemical Society 68: 738–769.
Rashid, M. M., Simončič, B. and Tomšič, B. 2021. Recent advances in TiO2-functionalized textile surfaces. Surfaces and Interfaces 22: 100890.
Rouhani Shirvan, A., Shakeri and Bashari, A. 2019. Recent advances in application of chitosan and its derivatives in functional finishing of textiles. In: The Impact and Prospects of Green Chemistry for Textile Technology, edited by Shahid-ul-Islam and Butola B.S., 107–33, Cambridge, UK: Woodhead Publishing
Stan, M. S., Nica, I. C., Popa, M., Chifiriuc, M. C., Iordache, O., Dumitrescu, I., et al. 2019. Reduced graphene oxide/TiO2 nanocomposites coating of cotton fabrics with antibacterial and self-cleaning properties. Journal of Industrial Textiles 49: 277–93.
Yu, L., Wang, L., Sun, X. and Ye, D. 2018. Enhanced photocatalytic activity of rGO/ TiO2 for the decomposition of formaldehyde under visible light irradiation, Journal of Environmental Science 73: 138–146.

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POSTER PRESENTATION

FABRICATION OF DURABLE ELECTROCONDUCTIVE FIBROUS COMPOSITES FOR WEARABLE ELECTRONICS

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Abstract: *The aim of this study was, firstly, to synthesise titanium carbide ($Ti_3C_2T_x$ MXene) nanosheets in two different sizes according to the pre-optimised procedure from two-sized Ti_3AlC_2 MAX phase precursors, using a sustainable synthesis approach. MXenes' surface morphologies were inspected by Scanning Electron Microscopy (SEM). Secondly, the synthesised nanosheets were applied onto cotton fabric by dip-padding procedure and protected with three different compounds, i.e., modified acrylate resin (MAR), waterborne polyurethane resin (WPR) and biantennary oligoglycine peptide (TEC), which was confirmed by Fourier Transform Infrared (FTIR) spectroscopy. Finally, MXene-functionalised/protected samples were washed up to 20 washing cycles and characterised by measuring their electrical resistance, changes in surface morphologies and water contact angles. Based on these results, WPR provided the most suitable protection of MXenes on cotton fabric, followed by MAR, balancing high conductivity with long-term stability. TEC is not recommended for MXene protection due to its low durable performance against harsh washing conditions.*

Keywords: *MXene, electroconductivity, washing durability, flexibility, wearable electronics*

1. INTRODUCTION

Wearable electronic systems typically require conductive tracks to form electrical interconnections between components. Recently, a new family of two-dimensional (2D) materials, the transition metal carbide and nitride, called MXenes, have shown great promise as potential compounds for this purpose on account of their high electrical conductivity (up to 20,000 S/cm), tuneable surface chemistry, high strength and stiffness, good hydrophilicity, scalable solution synthesis (kg batches), sufficient environmental stability, biocompatibility, aqueous solution processing without surfactants addition, etc. (Wang et al., 2019).

It is widely known that the morphological structures of MXenes, especially their size distribution, when applied to textile surfaces, strongly influence the textiles' final properties (Wang et al., 2021). Herein, the larger nanoflakes lead to higher electrical conductivity and mechanical strength than smaller ones. Moreover, fibrous materials modified with larger MXenes usually have a higher loading percentage and, thus, higher electrical conductivity. At the same time, large flakes can affect the fibres' flexibility negatively, as well as reduce the fibres-MXene adhesion, and, consequently, cause low wear and/or wash durability during long-term usage.

Due to the inhomogeneity and roughness of textiles as well as the small sheet size and weak interlayer interaction between MXene sheets, the MXenes employment often does not lead to permanent effects on the textile surfaces during daily use - limited wash durability (Ojstršek et al., 2021). Moreover, it is necessary for MXene to avoid its restack and oxidisation upon exposure to water, mechanical forces and high temperatures, which can hinder its relative capacitance and stability. Thus, diverse polymers can be applied as encapsulants to prevent oxidation and peeling off the conductive tracks without negligible effect on the fabrics' comfort, flexibility and wearability, which is the aim of the presented study.

2. EXPERIMENTAL

2.1 Materials

An industrially bleached plain-waived cotton fabric was used for the trials with a mass/unit area of 92.7 ± 0.6 g/m^2, warp density of 51 threads/cm, weft density of 44 threads/cm, and thickness of 0.18 mm. Two sizes of $Ti_3C_2T_x$ MXene flakes were synthesised, small- (S) and large-size (L), from 1 g of Ti_3AlC_2 MAX precursor powders (in two sizes, 40 and 100 μm) by a pre-optimised top-down minimally intensive layer delamination (MILD) approach as detailly described in (Jug et al., 2025), obtaining a stable dark green supernatant solution with pH 6 with a swelling clay precipitate.

2.2 Application of small- and large-sized MXene nanosheets and their protection

The individual cotton (Co) fabric sample (2×2 cm^2) was dipped three times into 10 mL MXene aqueous dispersion (10 mg/mL) for 5 min, followed by an intermediate/final vacuum-assisted drying at 60 °C, preparing two samples (CoS and CoL). Afterwards, individual polymer, i.e., modified acrylate resin (MAR), waterborne polyurethane resin (WPR) or 2-tailed tectomer (TEC), was applied over MXene-functionalised fabrics using pre-optimised pad-drying. In addition, MXene-functionalised and MXene-coated/protected cotton fabrics were washed up to 20 times (washing cycles) at a temperature of 40 °C for 30 min, using standard reference detergent in a concentration of 1 g/L and a liquor-to-fabric weight ratio of 50:1, with the aim to evaluate fabrics' washing durability. After each washing cycle, the samples were rinsed in tap water for 1 min and then dried at 60 °C for 20 min.

2.3 Analytical procedures

Scanning Electron Microscopy (SEM) was applied by means of a Zeiss Gemini Supra 35 VP Scanning Electron Microscope (Carl Zeiss NTS GmbH), with a maximum scan resolution of up to 1.5 nm at 1 kV, for the inspection of morphologies of synthesised MXene nanosheets and MXene-functionalised samples. In addition, the size distribution was carried out from SEM micrographs of at least 100 randomly chosen nanosheets, employing ImageJ, an image-processing program. Fourier Transform Infra-Red (FTIR) spectroscopic measurements of MXene-functionalised/protected samples were performed using a Spectrum GX spectrophotometer (Perkin Elmer) with a Golden Gate ATR attachment and a diamond crystal. A two-point probe multimeter 34410A 6 1/2 Digit (Agilent Technologies) was used for measuring the electrical resistance of samples across the entire surface area between two consistently sealed connections before and after 5, 10, 15 and 20 washing cycles. The Water Contact Angle (WCA) of MXene-functionalised/protected samples before and after 20 wash cycles was performed by means of the goniometer OCA 35 (DataPhysics Instruments) using the sessile drop technique.

3. RESULTS AND DISCUSSION

3.1 SEM analysis of MXenes

The morphological structures of two different MXenes flakes are presented in Figure 1 together with the size distribution diagrams.

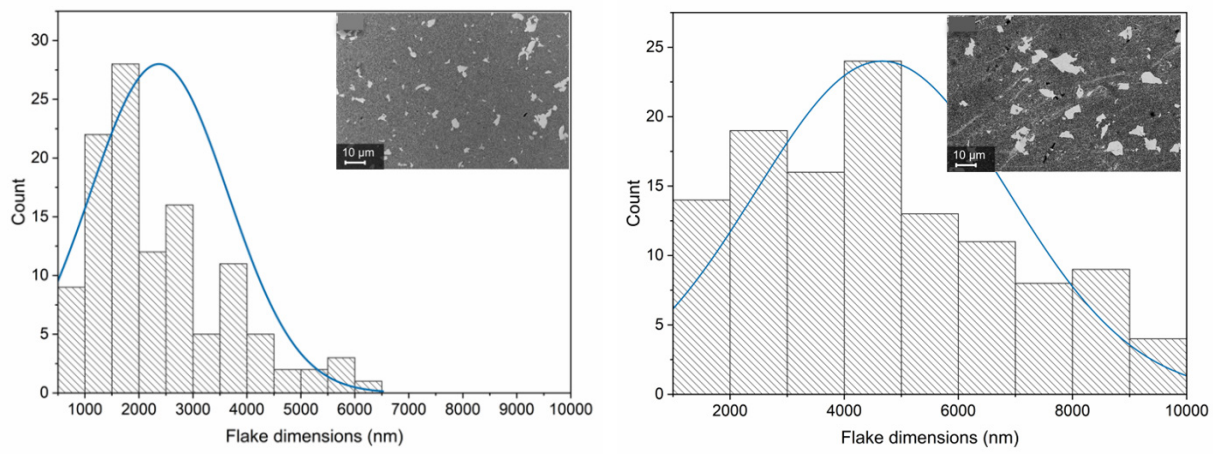


Figure 1: SEM images of MXenes and corresponding average flake-size distribution histograms: small flakes (left); and large flakes (right)

SEM micrographs in Figure 1 revealed the successful synthesis of MXenes flakes with well-defined sharp edges. Approximately twice as small MXene flakes in lateral size can be observed on the left micrograph as compared to the flakes on the right, employing similar etching conditions due to two different initial sizes of used MAX phase precursors. Thus, the flakes with an average diameter of 2373 nm (left) and 4663 nm (right) were determined from the flake-size distribution histograms. As explained in (Wang et al., 2021), the larger the flake size is, the smaller the interfacial resistance between the flakes, implying higher overall MXenes' electrical conductivity and, consecutively, higher electrical conductivity of MXene-decorated fabric.

3.2 FTIR analysis of MXene/polymer-coated samples

Figure 2 depicts the FTIR results of selected large-sized MXene-functionalised/protected samples.

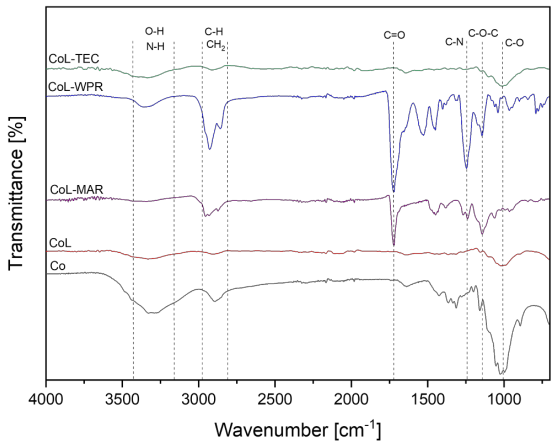


Figure 2: FTIR spectra of untreated cotton (Co), MXene-functionalised (CoL) and MXene-functionalised/protected samples (CoL-MAR, CoL-WPR and CoL-TEC)

As noticed from Figure 1, the pristine cotton fabric shows a broad peak around 3200-3400 cm^{-1}, which was attributed to the stretching of the O–H groups; the peak near 2890 cm^{-1} was assigned to the band of C–H stretching vibrations, and the peak at 1210 cm^{-1} was the stretching of the C–O bond (Lv et al., 2018). After the application of MXenes, the characteristic peaks for cotton are lowered. A similar was perceived for the TEC-protected sample, implying that the MXene peak dominates over characteristic peptide peaks of TEC. Additionally, the MXene-modified/WPR-protected cotton spectrum has completely attenuated cotton peaks and shown absorption bands corresponding to N–H (3340 cm^{-1}), C–H (2920 cm^{-1}), C=O (1720 cm^{-1}), C–N (1240 cm^{-1}), and C–O–C (1100–1250 cm^{-1}) bonds, significant for WPR. For the sample protected with MAR, the most prominent peak appears at ~1720 cm^{-1} (C=O), at ~1140 cm^{-1} (C–O in the ester groups), and at 2950–2860 cm^{-1} (C–H) (Salih et al., 2015).

3.3 Washing durability of MXene/polymer-coated samples

In order to evaluate the effectiveness of three selected compounds (MAR, WPR and TEC) for the protection of MXenes onto cotton fabric against peeling off and oxidation due to the combined action of water, temperature and mechanical forces, MXene-functionalised/polymer-protected samples were washed up to 20 cycles and characterised in terms of electrical resistance measurement (Figure 3) and WCAs determination (Figure 4).

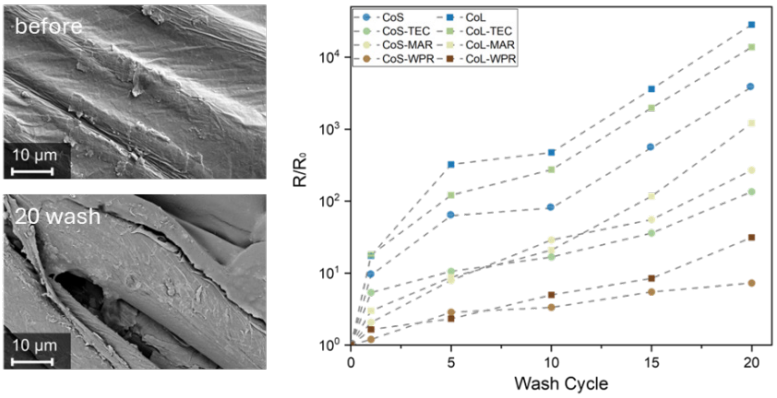


Figure 3: SEM micrographs of CoL sample before and after 20 washing cycles (left); and the electrical resistance of MXene/polymer-coated samples relative to the initial value after 5, 10, 15 and 20 washes (right)

The morphological characteristics of the selected MXene-coated fabric, i.e., CoL sample (Figure 3 - left), exhibited rough and rugged areas, indicating a tight coating of MXene nanosheets around the fibres and filled spaces between them. After 20 washings, the MXenes remained on the surface, although significant cracks were noticed, increasing the electrical resistivity tremendously (up to 2494 Ω·cm). Therefore, the surface of MXene-coated samples was further protected with the selected three polymers.

Both WPR-protected samples, CoS-WPR and CoL-WPR, exhibited a minimal raising of resistance after 5 washes, i.e., for 4.99% and 3.34 %, respectively, compared to their starting values (Figure 3 - right). Moreover, WPR protective coating maintained the electrical resistance of the fabrics effectively at a satisfactory level even after 20 washings. A similar trend was observed in MAR-treated samples with adequate protection during the early washing cycles, with a resistivity of 12.81 Ω·cm (CoS-MAR) and 6.34 Ω·cm (CoL-MAR) after five washes. Nevertheless, if the number of washing cycles exceeds 10, the resistivity rapidly escalates and can eventually reach the resistance level of untreated raw samples, losing electrical conductivity. The least effective protective compound was TEC, wherein the electrical resistivity was significantly dependent on the flake sizes of applied MXenes.

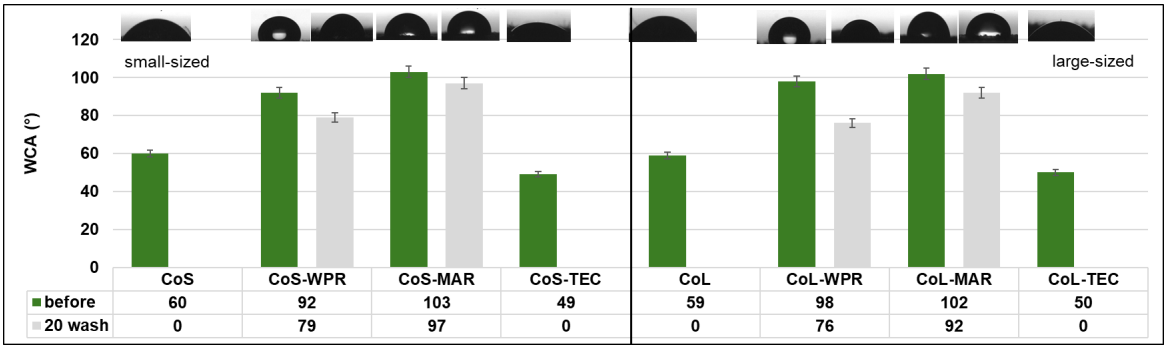


Figure 4: WCA of MXene-coated and MXnene/polymer-coated samples before and after 20 washings

The WCA analysis (Figure 4) gives contact angles of ~60 ° for MXene-coated unprotected (CoS and CoL) samples, presumably on account of the inherent hydrophilic nature of both MXenes and the cotton. On the contrary, the MXene-functionalised/MAR- or WPR-protected samples had excellent hydrophobic properties with high contact angles of around 100°, regardless of the MXene nanosheet's lateral size. The protected samples remained hydrophobic even after 20 washing cycles, decreasing the WCA for 6° (CoS-MAR), 10° (CoL-MAR), 13° (CoS-WPR) and 22° (CoL-WPR), which demonstrates the robustness and efficacy of the coating in preserving the surface's hydrophobic properties. Meanwhile, TEC was the least effective compound for the protection of MXenes against washings since the water drop spread immediately after surface contact after 20 washes. Consequently, water quickly penetrates through the pores during repeated washings, causing a loss of conductivity, as previously confirmed by an enlargement in electrical resistance.

4. CONCLUSION

In the presented study, $Ti_3C_2T_x$ MXene flaxes in two sizes were prepared successfully employing two-sized Ti_3AlC_2 MAX phase precursors. Both the small- and large-sized $Ti_3C_2T_x$ MXene nanosheets (in lateral size) were furthermore evenly applied onto cotton fabric by the pre-optimised dip-padding procedure. The larger MXene flakes imply higher electrical conductivity but lower adhesion and a greater tendency to oxidation. Thus, three different protective compounds were applied to MXene-functionalised fabric, and two of them (WPR and MAR) significantly enhanced the fabric' hydrophobicity even after 20 washing cycles, expanding the potential applications of MXene-decorated fabrics in smart textile applications by providing good durability of electroconductive functionalisation. TEC is not recommended for MXene protection due to its low adhesion and poor hydrophobic performance.

5. ACKNOWLEDGEMENTS

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6. REFERENCES:

Jug, L., Hribernik, S., Ojstršek, A. “Synergic effect of large MXene nanosheets and protective coatings on improved electroconductivity and wash durability of MXene/polymer-modified cotton fabric.” *Progress in Organic Coatings* 200 (2025) 109062.
Lv, N., Wang, X., Peng, S., Luo, L., Zhou, R. “Superhydrophobic/superoleophilic cotton-oil absorbent: preparation and its application in oil/water separation.” *RSC advances* 8 (2018) 30257−30264.
Ojstršek, A., Plohl, O., Gorgieva, S., Kurečič, M., Jančič, U., Hribernik, S., Fakin, D. “Metallisation of Textiles and Protection of Conductive Layers: An Overview of Application Techniques.” *Sensors* 21 (2021) 3508.
Salih, A.M., Ahmad, M.B., Ibrahim, N.A., Dahlan, K.Z.H.M., Tajau, R., Mahmood, M.H., Yunus, W.M.Z.W. “Synthesis of Radiation Curable Palm Oil–Based Epoxy Acrylate: NMR and FTIR Spectroscopic Investigations.” *Molecules* 20 (2015) 14191−14211.
Wang, Q.-W., Zhang, H.-B., Liu, J., Zhao, S., Xie, X., Liu, L., Yang, R., Koratkar, N., Yu, Z.-Z. “Multifunctional and Water-Resistant MXene-Decorated Polyester Textiles with Outstanding Electromagnetic Interference Shielding and Joule Heating Performances.” *Advanced Functional Materials* 29 (2019) 1806819.
Wang, X., Fan, X., Li, M., Zhu, W., Xue, J., Ye, F., Cheng, L. “Structure and electromagnetic properties of $Ti_3C_2T_x$ MXene derived from Ti_3AlC_2 with different microstructures.” *Ceramics International* 47 (2021) 13628–13634.

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POSTER PRESENTATION

ECO-FRIENDLY HYDROPHOBIC TEXTILES: A SHIFT FROM PFAS TO SUSTAINABLE BIO-POLYMERS

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Abstract: *Identifying efficient and long-lasting textile coatings that can serve as alternatives to toxic per- and polyfluoroalkyl substances (PFAS) is essential for a future free from harmful fluorinated chemicals. For this purpose, a hydrophobic cotton (CO) and polyester (PES) textile fabric was produced using natural biopolymers in the form of microcapsules. The CO and PES samples were coated with dippaddry process and the fabric visual appearance, colour measurements, thickness, morphology and hydrophobicity were evaluated before and after coating. The visual appearance of the fabric did not change significantly with the application of coating, which was confirmed by CIELAB colour measurements. The increase in thickness of the fabric was minimal. The water contact angle increased from highly hydrophilic (<10°) to hydrophobic (above 120°) after the coating application. The research showed that with the use of biopolymers which are environmentally and human health friendly, hydrophobicity of natural and synthetic textile fabrics can be achieved.*

Keywords: *water-repellence, hydrophobicity, biopolymers, biomaterials, coatings, textile*

1. INTRODUCTION

Per- and polyfluoroalkyl substances (PFAS) are a large group of more than 4700 (OECD, 2018) synthetic compounds characterized by the presence of strong carbon-fluorine (C-F) bonds, that provide exceptional thermal, chemical, and mechanical stability (Li, 2018). Simultaneous hydrophobic and oleophobic properties make PFAS highly valuable in various industrial applications, such as personal care products, cosmetics, cleaning products, textile coatings for stain and water repellency, food contact materials, adhesives, non-stick pans, medical devices, various membranes, fire-fighting foams, etc. (Panieri, 2022; Gluge, 2020; Gaines, 2023; Kleinman, 2021). However, due to their chemical composition, these compounds are very persistent in the environment, difficult to degrade, and tend to bioaccumulate, leading to significant concerns about potential adverse effects on human health and ecosystems (Wee, 2023). They have been detected in groundwater, surface water and soil worldwide, raising alarms about their longterm effects on the environmental and human exposure (Merino, 2016; Ahrens, 2014; EPA, 2023). People get exposed to PFAS through various pathways, including contaminated water and soil, food chain accumulation, household dust, and others (Karaskova, 2016; Worley, 2017; Lin, 2020; Sadia, 2023; Smalling, 2023), which has been linked to numerous health problems, including reproductive problems, endocrine disruption, immune system effects, infertility, developmental problems in children, weakened immune system, higher cholesterol levels and increased cancer risk (Panieri, 2022; Fenton, 2021; Blake, 2018; EPA, 2023; Bartell, 2021). Because of extensive evidence linking PFAS to serious health effects, addressing PFAS contamination is critical to protect not only the environment but also public health. In response, significant regulatory measures and limitations have been implemented worldwide. Authorities are monitoring the use, manufacture, and disposal of PFAS compounds, and have specified allowable levels of certain PFAS substances in water, soil and air to minimize their release into the environment and reduce associated health risks (EPA, 2023). In addition, regulations have limited the production and use of other PFAS compounds, such as perfluorooctanoic acid (PFOA) and perfluoroctanesulfonic acid (PFOS) (EPA, 2023). Current initiatives aim to completely eliminate the use of PFAS by banning the production and sale of PFAS-containing textiles and proposing bans or restrictions on up to 12,000 different compounds (NY State department of environmental conservation, 2023; ChemRadar, 2024; Spyrakis, 2023). As a result, industries, including the textile sector, are being urged to find PFAS-free alternatives, that can provide similar benefits without the associated risks, to comply with these regulations. Current synthetic

alternatives to PFAS, such as silicones (Jin, 2018), alkylamines (Lin, 2021), acrylates (Messerschmidt, 2018) and melamine (Zheng, 2020), still have their own environmental concerns. These synthetic compounds may still leave a chemical footprint and may not completely solve the problem of pollution and toxicity. A better and more sustainable option would be to move towards the use of natural, renewable materials, which would provide the desired properties without the harmful environmental impact. The literature review showed, that using biomaterials, hydrophobicity can be achieved either by using low surface energy compounds or by increasing surface roughness (Shahid, 2022). To reduce surface energy, natural compounds such as fatty acids and their salts (Shahid, 2022), or natural waxes like beeswax and carnauba wax have been used (Shahid, 2022). Surface roughening has been achieved through enzyme etching or by applying various nanostructures derived from natural materials (Shahid, 2022), which mimic the lotus leaf effect. Combinations of both approaches can be used to achieve higher levels of hydrophobicity. However, the literature review showed that most of these formulations still involve various chemicals and/or solvents, indicating that the formulations are not completely biomaterial-based and can still pose a level of environment burden and health risks. To address these concerns, it is preferable to use solely natural biomaterials, which can be either chemically modified to achieve hydrophobic properties if they are inherently hydrophilic, or by combining multiple biomaterials to achieve synergistic effects. This is especially promising due to growing interest in biodegradable polymers, derived from renewable sources.

The same approach to hydrophobic coatings development is also used in the Horizon Europe PROPLANET project. Within the project, natural biopolymer-based hydrophobic coatings for textile applications are being developed in alignment with the Safe and sustainable by Design (SsbD) principles to ensure the use of safer and more sustainable materials. One of the ways the project aims to achieve that is by using natural biomaterials in the form of microcapsules (Figure 1).

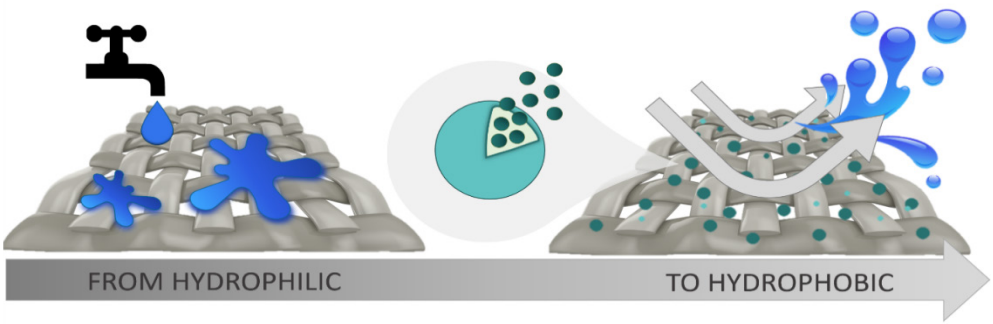


Figure 1: Schematic presentation of a hydrophilic fabric and a hydrophobic fabric achieved with application of coating with microcapsules.

2. EXPERIMENTAL

2.1 Materials

Bleached and mercerized plain weave 100% cotton (CO) woven fabric (185 g/m2, warp density 26 threads/cm, weft density 24 threads/cm) from Europrint (Ajdovščina, Slovenia) and polyester (PES) fabric (185 g/m2, warp density 21 threads/cm, weft density 17 threads/cm) fabric from Svet Metraže (Ljubljana, Slovenia) were used as substrates for the coating. A suspension of biopolymer-based microcapsules (MC) was prepared using a combination of natural biopolymers. For all of the experiments in the research Milli-Q pure water was used.

2.2 Methods

2.2.1 Sample preparation

CO and PES fabric samples measuring approximately 35x40 cm were used for coating application, which was carried out using the dippaddry process. The samples were immersed into glass impregnation bath containing coating solution and then squeezed between the rollers of a two-roller foulard (Mathis, Switzerland) to achieve a wet pick up of 80 %, and dried in a laboratory continuous dryer (Mathis, Switzerland) at 40 °C for 5 minutes. The coating formulation was developed as a part of the PROPLANET project and its manufacturing process is protected by the project's intellectual property.

2.2.2 Analysis

Colour measurements
Colour coordinate (CIE L*a*b*) values of the samples were measured using the Datacolor Spectro 1050 reflectance spectrophotometer (Datacolor, Luzern, Switzerland). Measurements were made with a d/8° measurement geometry, under D65 illumination, 10° standard observer, with specular reflectance included, with a 9-mm aperture. Four layers of the sample were used for the measurements and an average of five measurements was reported.

Sample thickness
The thickness of the samples was measured with digital caliper Mitutoyo ID-C112X (Mitutoyo, Japan) with an 8 mm stem diameter and ≤ 1.5N measuring force. Five measurements of each sample were taken, and the average value was reported.

Scanning electron microscopy (SEM)
The surface morphology of the samples was analysed using scanning electron microscope JSM-6060 LV (Jeol, Japan). Prior to observation the samples were coated with a thin layer of gold. The coated samples were observed directly after coating. SEM micrographs were taken at a beam voltage 10kV, working distance 16 mm, 30 beam spot size and a magnification of 50x.

Water contact angles (WCA)
The water repellence of the control (uncoated) and coated samples was evaluated by measuring WCA. For this analysis, tensiometer Theta T200 (Biolab Scientific, Gothenburg, Sweden) was used. The static contact angle was determined at 5 seconds after the beginning of the measurement.

3. RESULTS WITH DISCUSSION

The presented research aimed to achieve hydrophobic CO and PES textile substrates by using only natural biopolymers. Our purpose was not only to replace PFAS with other fluorinated compounds, which are currently in broad use and are being phased out by various regulations, but to use only natural substances which are renewable, biodegradable, can be recycled and are not harmful for the environment and human health.

Since it is crucial for practical applications that the coating not only enhances functionality of textiles, but also preserves the fabric's original properties and appearance, while ensuring suitability for use and handling, we first checked the visual appearance of the samples. This involved visual assessment and hand-feel, determining the sample thickness and measuring the colour values. To effectively compare the properties of fabrics, we determined the properties of both untreated (control) and coated fabrics. The visual differences between the untreated and coated CO and PES were minimal (Figure 2a-d). The handfeel of the coated samples was similar to the control ones, although there was a subtle feel of coating presence on the fabric, determined by slightly more textured and stiffer surface. To determine the colour differences quantitatively, CIE L*a*b* colour values of the control and coated CO and PES samples were measured. The results show (Figure 2) that the lightness values (CIE L*) of both control samples are slightly higher than of the belonging coated samples, meaning that by application of the coating, the samples become slightly darker. The values of the green–red colour coordinates (CIE a*) are on the red side of the colour coordinate for CO and PES samples, control and coated ones. After the coating application the values decrease for both CO and PES fabric, which is more evident in the case of cotton samples, meaning that the coated samples are less red than the uncoated ones. The values of the blue–yellow coordinate are on

the blue side of the colour coordinate for all four samples. The biggest difference in the CIE b* values are seen between control and coated cotton sample, where the CIE b* value decreases from -15.95 to -5.59 after coating application, meaning that the samples become less blue. This is also noticeable with the naked eye, as coated CO sample is slightly less blue and more yellow than the control one. This small difference in colour values is due to the thin layer of coating that does not significantly affect the sample's appearance. This is also evident from the results of thickness measurements (Figure 2) which show, that with coating application, the thickness increases minimally, by 0,05 mm for CO and by 0,01 mm for PES.

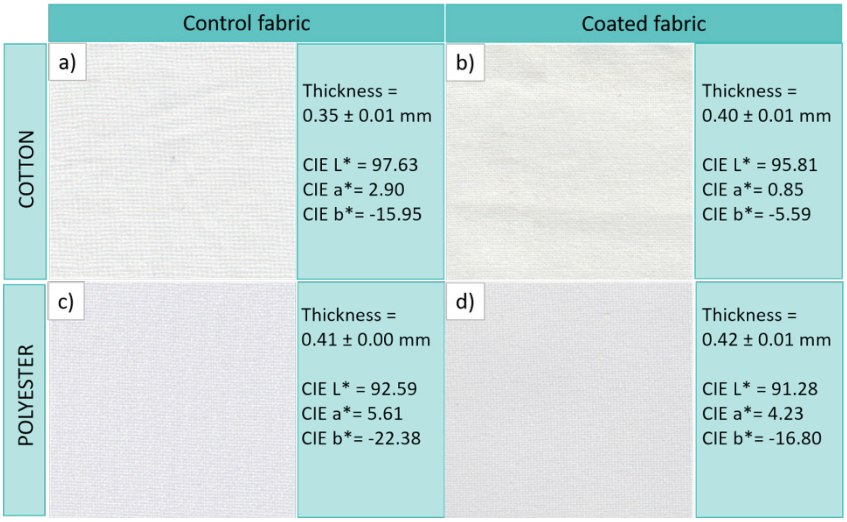


Figure 2: Visual appearance, thickness and CIE L*a*b* values of the control and coated CO and PES.

According to the results above, the coating has minimal influence on the original properties of CO and PES fabric. To check more precisely how the application of coating influences the surface morphology of the fabric, SEM analysis was carried out. SEM micrograph of coated sample (Figure 3b) shows the presence of microcapsules, which are spherical and mostly evenly distributed over the surface of the fabric, with some individual aggregates observed. How their presence influences the water repellency of the coated material in comparison to the control sample, was determined through measuring the static contact angle with water. The hydrophobicity of material is achieved when the water droplets do not spread or wet its surface. The boundary between wetting and repellency is defined by the contact angle of the liquid droplet on the textile substrate. If the contact angle is less than 90°, the textile is wettable, but if the contact angle is greater than 90°, the textile substrate is repellent. In other words, an increase in the contact angle means an increase in repellency (Law, 2014). Our measurements showed that the untreated samples are highly hydrophilic, to the extent that it is not possible to determine a measurable WCA with the standardized procedure. Therefore, the WCA was determined as <10° (Figure 3c). After the coating application the WCA increased to above 120°, meaning that the samples are hydrophobic (Figure 3d), which is also evident from the WCA images.

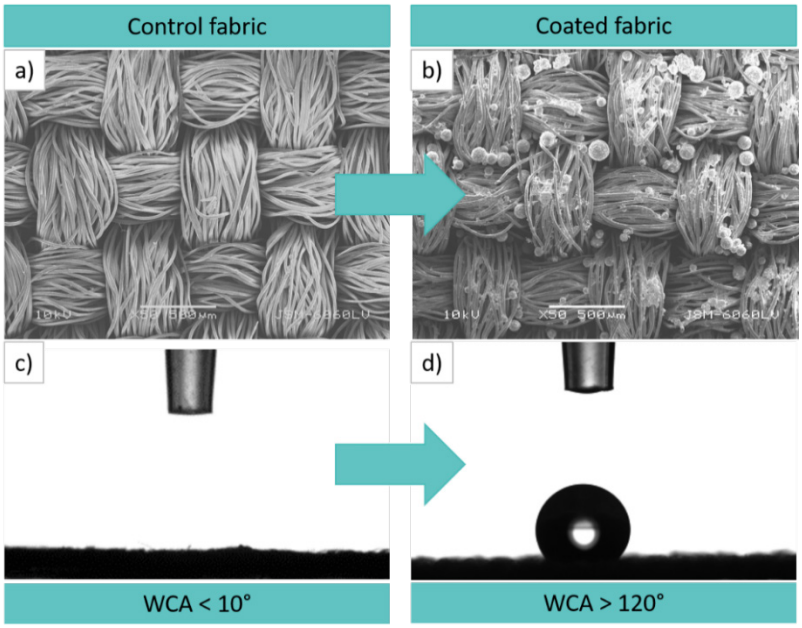


Figure 3: SEM micrographs of a) control PES fabric and b) coated PES fabric at magnification 50x and WCA value with the image of droplet of c) control and d) coated PES fabric.

4. CONCLUSIONS

The aim of this research was to produce hydrophobic textile fabric using natural, biodegradable compounds that are safe for human health and environment. Our innovative coating was developed using natural biopolymers in the form of microcapsules. Application of the coating did not significantly alter the appearance, colour or thickness of the CO and PES fabrics. SEM micrographs showed an even distribution of the microcapsules across the fabric surface. The WCA values increased from < 10° for untreated fabric to above 120° for coated fabric, which is comparable to commercial hydrophobic coatings. Unlike fluorine-based coatings, the developed formulation is non-toxic, biodegradable and safe for the environment and human health. In conclusion, this research has shown that hydrophobic properties of textile fabrics can be achieved using biopolymers as renewable sources in an environmentally friendly, sustainable way, which is a much safer alternative to traditional PFAS. Additional analysis has to be performed to determine the coating's durability in comparison with commercial coatings, as this will be crucial for assessing their long-term performance, effectiveness and viability in practical applications.

5. REFERENCES

Ahrens, L., Bundschuh, M. 2014. "Fate and effects of poly- and perfluoroalkyl substances in the aquatic environment: a review". Environmental Toxicology and Chemistry 33(9): 1921-1929.

Bartell, S. M., Vieira, V. M. 2021. "Critical review on PFOA, kidney cancer, and testicular cancer." Journal of the Air & Waste Management Association 71(6): 663-679.

Blake, B. E, Pinney, S. M, Hines, E. P., et al. 2018. "Associations between longitudinal serum perfluoroalkyl substance (PFAS) levels and measures of thyroid hormone, kidney function, and body mass index in the Fernald Community Cohort." Environmental pollution 242: 894-904.

ChemRadar. 2024. "Japan proposes to designate 138 perfluorinated compounds as Class I Specified Chemical Substances". URL: https://www.chemradar.com/news/detail/dz1n895bhdz4 (last accessed on 30.1.2025).

Gaines, L. 2023. "Historical and current usage of per- and polyfluoroalkyl substances (PFAS): A literature review." Am J Ind Med. 66: 353–378.

Gluge, J. et al. 2020. "An overview of the uses of per- and polyfluoroalkyl substances (PFAS)." Environ. Sci.: Processes Impacts 22: 2345.

EPA – United Stated Environmental protection Agency. Our Current Understanding of the Human Health and Environmental Risks of PFAS. URL: https://www.epa.gov/pfas/our-current-understanding-human-health-and-environmental-risks-pfas (last accessed on 19.12.2023).

Fenton, S. E., et al. 2021. "Per-and polyfluoroalkyl substance toxicity and human health review: Current state of knowledge and strategies for informing future research." Environmental toxicology and chemistry 40(3): 606-630.

Jin, H., Xu, W. 2018. “The Preparation and Properties of Fluoroacrylate-Modified Polysiloxane as a Fabric Coating Agent.” Coatings 8: 31.
Karásková, P., et al. 2016. “Perfluorinated alkyl substances (PFASs) in household dust in Central Europe and North America.” Environment international 94: 315-324.
Kleinman, M.T., Stevenson, E. D. 2021. “Introduction to the 51st Annual A&WMA Critical Review: PFOA and Cancer.” Journal of the Air & Waste Management Association 71: 661-662.
Law, K-Y. 2014. “Definitions for Hydrophilicity, Hydrophobicity, and Superhydrophobicity: Getting the Basics Right.” The Journal of Physical Chemistry Letters 5(4): 686-688.
Li, Y., Oliver, P. D., Kookana S. R. 2018. “A critical analysis of published data to discern the role of soil and sediment properties in determining sorption of per and polyfluoroalkyl substances (PFASs).” Science of the Total Environment 628-629: 110-120.
Lin, Y., Jiang, J. J., Rodenburg, L. A., et al. 2020. “Perfluoroalkyl substances in sediments from the Bering Sea to the western Arctic: Source and pathway analysis.” Environment international 139: 105699.
Lin, T. C., Lee, D. J. 2021. “Cotton fabrics modified with tannic acid/long-chain alkylamine grafting for oil/water separation.” Journal of the Taiwan Institute of Chemical Engineers 127: 367-375.
Merino, N., Qu, Y., Deeb, A., R., Hawley, E., R., Hoffmann, M. R., Mahendra, S. 2016. “Degradation and Removal Methods for Perfluoroalkyl and Polyfluoroalkyl Substances in Water.” Environmental Engineering Science 33(9): 615-649.
Messerschmidt, M. et al. 2018. “Fluorocarbon-Free Dual-Action Textile Finishes Based on Covalently Attached Thermoresponsive Block Copolymer Brush Coatings.” ACS Appl. Mater. Interfaces 10: 40088−40099.
New York State Department of Environmental Conservation. 2023. »PFAS in apparel law.« URL: https://dec.ny.gov/environmental-protection/help-for-businesses/pfas-in-apparel-law (last accessed on 30.1.2025)
OECD, Toward a new comprehensive global database of per- and polyfluoroalkyl substances (PFASs): Summary report on updating the OECD 2007 list of per- and polyfluoroalkyl substances (PFASs). 2018, Environment Directorate.
Panieri, E., Baralic, K., Djukic-Cosic, D., Buha Djordjevic, A., Saso, L. 2022. “PFAS molecules: a major concern for the human health and the environment.” Toxics 10(2): 44.
Sadia, M., Nollen, I., Helmus, R., Laak, T. L., Béen, F., Praetorius, A., van Wezel, A. P. 2023. “Occurrence, Fate, and Related Health Risks of PFAS in Raw and Produced Drinking Water.” Environmental Science Technology 57(8): 3062–3074.
Shahid, M., Maiti, S., Adivarekar, R. V., Liu, S. 2022. “Biomaterial based fabrication of superhydrophobic textiles – A review.” Materials today chemistry 24: 100940.
Smalling, K. L., Romanok, K. M., et al. 2023. “Per- and polyfluoroalkyl substances (PFAS) in United States tap water: comparison of underserved private-well and public-supply exposures and associated health implications.” Environment International 178: 108033.
Spyrakis, F., Dragani, T. A. 2023. “The EU’s per-and Polyfluoroalkyl substances (PFAS) ban: A case of policy over science.” Toxics, 11(9): 721.
Wee, S. Y., Aris, A. Z. 2023. “Environmental impacts, exposure pathways, and health effects of PFOA and PFOS.” Ecotoxicology and Environmental Safety 267: 115663.
Worley, R. R., Moore, S. M., Tierney, B. C., et al. 2017. “Per-and polyfluoroalkyl substances in human serum and urine samples from a residentially exposed community.” Environment international 106: 135-143.
Zheng, G., Salamova, A. 2020. “Are Melamine and Its Derivatives the Alternatives for Per- and Polyfluoroalkyl Substance (PFAS) Fabric Treatments in Infant Clothes?” Environ. Sci. Technol. 54: 10207-10216.

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POSTER PRESENTATION

SUSTAINABLE FLAME RETARDANT SOLUTIONS: TUNING AMMONIUM PHYTATE CONCENTRATION FOR SILK COATINGS

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Abstract: *A novel green flame retardant, ammonium phytate (APA), was synthesised and applied in various concentrations to silk fabrics to optimise flame resistance while maintaining the physical and mechanical properties of the fabric. Its performance was compared to the well-known green flame retardant phytic acid (PA). Both PA and APA were applied in concentrations ranging from 1 % to 20 % (in 5 % increments) using the pad-dry-cure method. Flame retardancy was determined by vertical flammability tests, while flexural rigidity, air permeability, breaking strength and elongation at break were evaluated to determine the effects of flame retardants on the physical and mechanical properties of the fabric. The results showed that APA exhibited superior flame retardant effect compared to PA. Concentrations above 5 % ensured effective protection without excessive stiffness and mechanical degradation, making APA a promising alternative for environmentally friendly flame retardant textile applications.*

Keywords: *silk, green flame retardant, ammonium phytate, phytic acid, vertical flammability test, mechanical properties*

1. INTRODUCTION

Silk, a natural and biodegradable fibre, is valued for its luxurious texture and sustainability, making it useful not only for apparel but also in various economic sectors as a high-end material. However, its inherent flammability limits its use in fields where fire safety is crucial, such as protective clothing, home textiles, and the preservation of historical fabrics, as its combustion can not only cause material damage but also pose a risk to human safety (Zhang, 2024). Enhancing the flame retardancy of silk fibres is therefore essential.

In the past, halogen-based flame retardants were the most commonly used due to their exceptional efficiency in inhibiting combustion. However, further research has shown that the combustion of such materials produces toxic compounds, including dioxins, furans and other halogenated acids, which pose a serious risk to human health and contribute significantly to environmental pollution (Lu, 2002). Growing environmental awareness and stricter sustainability regulations in the industry have driven research into the development and application of safer and more sustainable flame retardants. As a result, new synthesis and application processes based on phosphorus and nitrogen compounds have been developed to effectively inhibit combustion without generating harmful by-products (Alongi, 2014; Salmeia, 2016).

Phosphorus and nitrogen based flame retardants of natural origin play a crucial role in the development of sustainable flame retardant finishes. Of these, phytic acid (PA), which occurs naturally in cereal grains, pulses and nuts, is particularly noteworthy. Due to its high phosphorus content, it has already been recognised as an effective flame retardant in the textile industry (Cheng, 2016; Cheng, 2023; Wu, 2024; Zhang, 2018). Its salt, ammonium phytate (APA), which is synthesised from phytic acid and urea, has an even greater flame retardant potential due to the synergistic interaction between phosphorus and nitrogen (Feng, 2017). This combination increases char formation and thermal stability, improving the overall efficiency in preventing combustion compared to PA alone (Feng, 2017; Cheng, 2022).

While APA has already been used on cotton fibres, to the best of our knowledge, its efficacy on silk fibres has not yet been investigated. Therefore, this study aims to optimize the concentration of APA on silk fibres and evaluate its flame retardant effect in comparison to PA, potentially enhancing flame retardancy through the combined effect of phosphorus and nitrogen.

2. EXPERIMENTAL

2.1 Materials

As a model textile substrate a 100 % degummed silk fabric with a weight of 65 g/m^2 was used throughout the experiments. Phytic acid (PA) and urea were purchased from Sigma Aldrich.

2.2 Synthesis of ammonium phytate (APA)

APA was synthesised in the laboratories of the National institute of Chemistry (Slovenia) according to the procedure described by (Feng, 2017). Briefly, PA (7.723 mL, 0.015 mol) and urea (5.405 g, 0.09 mol) were mixed, stirred, and heated for 60 min at 110 °C and 15 min at 120 °C, yielding a light brown liquid. The product was freeze-dried, purified with ethanol, and APA was obtained as a brownish solid.

2.3 Flame retardant finishing of silk fabric

The finishing of silk fabrics was carried out using the pad-dry-cure method. First, finishing baths were prepared with different concentrations of APA and PA in water, ranging from 1 % to 20 % (w/w) in 5 % increments. The fabric samples were immersed in the corresponding finishing solution, wrung out with a two-roll padder. This process was carried out twice to achieve a wet pick-up of 210 ± 5 %, and then the samples were dried in a laboratory dryer at 100 °C for 90 s. Based on the concentration of the flame retardant used, the samples were coded as SE_PAx or SE_APAx, where x is the percentage of PA or APA used. The untreated silk fabric was coded as SE_0.

2.4 Characterization

The flammability of the silk samples analysed was tested on vertically suspended samples using the standard flammability test DIN 53906.The fabric samples (15 x 9 cm, warp direction) were exposed to a propane gas flame for 4 seconds. The after-flame and after-glow times were recorded, with three measurements taken per sample and the mean values were calculated. Tear length was determined by suspending a 50 g weight from one end of the sample while the opposite end was fixed. The tear length was calculated as the difference between the original length of the sample and the remaining untorn length.

In order to determine the influence of the PA and APA coating on the mechanical-physical properties of the treated silk samples compared to the untreated sample, measurements of bending rigidity, breaking strength, elongation at break and air permeability were carried out. The flexural rigidity was determined in accordance with ASTM standard D-1388-64. The measurements of breaking strength and elongation at break were carried out using an Instron 5567 dynamometer according to the SIST ISO 5081:1996 standard method. For each silk sample, ten measurements were carried out in the warp direction at a tearing speed of 100 mm/min and a measuring length of 100 mm. The air permeability was measured with an Air-Tronic B (Mesdan, Italy) according to the SIST EN ISO 9237:1999 standard.

3. RESULTS AND DISCUSSION

The results of flame retardant properties of silk fabrics functionalized with APA compared to PA at different concentrations are summarised in Table 1 and Figure 1. Untreated silk burned vigorously and without residue, with after-flame and after-glow times of 7.0 s and 5.9 s, respectively. In contrast, the application of APA completely stopped the spread of flame and resulted in after-flame and after-glow times of 0 s, even at the lowest concentration tested, which was comparable to the flame retardant effect of PA.

However, when comparing the flame retardant effect of APA with that of PA at the same concentrations, APA exhibited significantly better results than PA. While the tear length of the SE_APA1 sample (1 % APA) was comparable to that of the SE_PA1 sample (1 % PA), increasing the APA concentration resulted in a 20–26 % reduction of the tear length compared to the corresponding PA samples. The reduced tear length clearly demonstrates the enhanced flame retardant effect of APA and thus the increased thermal stability of APA-functionalised silk samples, which is attributed to the synergistic effect of phosphorus and nitrogen within the APA structure. In contrast, the flame retardant effect of PA is based solely on phosphorus, which means less intensive protection of the silk against thermal degradation.

A char length of less than 150 mm is usually required for effective flame retardancy, with 100 mm being the preferred threshold for high-performance flame retardant textiles (NFPA 701: Standard Methods of Fire Tests for Flame Propagation of Textiles and Films). The samples treated with APA at concentrations above 5 % not only inhibited combustion during flame removal, but also exhibited a significantly reduced tear length, ensuring compliance with this flame retardant standard.

Table 1: After-flame ($t_{after\text{-}flame}$) and after-glow time ($t_{after\text{-}glow}$) of the studied samples and corresponding tear length (l_{tear}) determined according to the DIN 53906 standard method.

Sample code	*Flame retardant*	*C* **(%)**	$t_{after\text{-}flame}$ **(s)**	$t_{after\text{-}glow}$ **(s)**	l_{tear} **(cm)**
SE_0	/	/	7.0	5.9	15.0
SE_PA1	PA	1	0	0	10.5
SE_PA5		5	0	0	10.8
SE_PA10		10	0	0	10.9
SE_PA15		15	0	0	9.9
SE_PA20		20	0	0	9.0
SE_APA1	APA	1	0	0	10.9
SE_APA5		5	0	0	8.6
SE_APA10		10	0	0	8.4
SE_APA15		15	0	0	7.9
SE_APA20		20	0	0	6.7

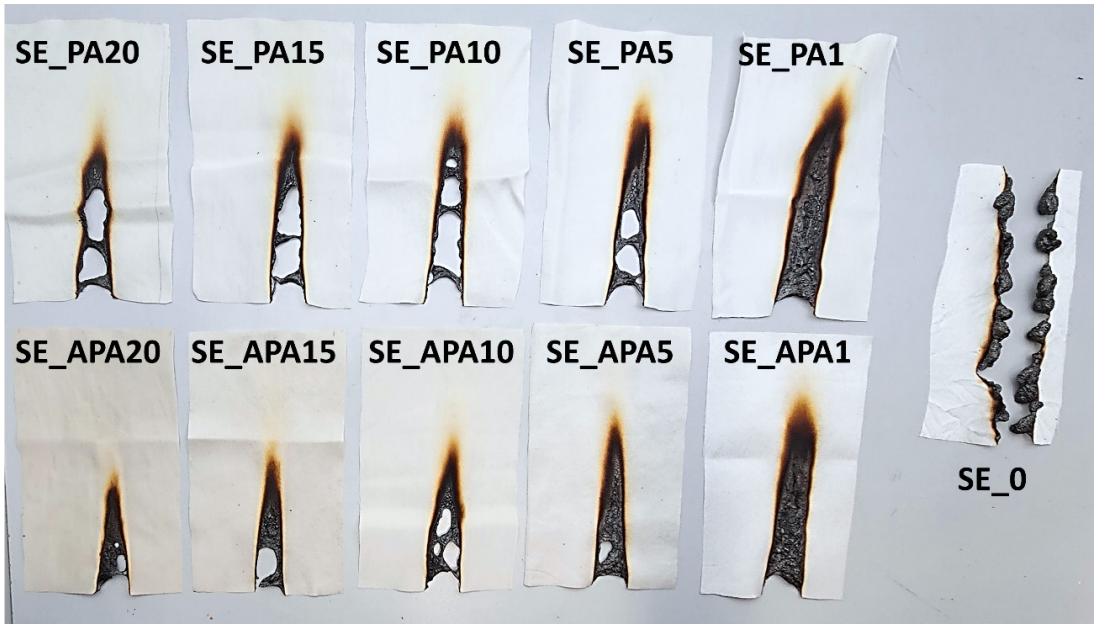


Figure 1: Photos of untreated and PA- or APA-functionalised samples, showing the remaining residual char after the vertical flame spread test.

When chemically modifying textiles, it is crucial to consider not only the functional performance, but also the effects on the intrinsic physical and mechanical properties. Therefore, handling properties (Figure 2), air permeability (Figure 3) and tensile properties (Figure 4) were evaluated.

Figure 2 shows the results of stiffness, including areal density, bending length and total flexural rigidity. The areal density increased with higher concentrations of finishing agents, which was expected due to the increased dry content on the fibres (Figure 2a). Bending length increased for SE_PA5 and SE_APA5 samples, indicating initial stiffening, but decreased at higher concentrations, although areal density continued to increase (Figure 2b). The highest stiffness was observed with SE_PA5 and SE_APA5, while SE_PA20 and SE_APA20 had the lowest bending lengths, similar to untreated silk (SE_0). The reason for this could be ascribed to the increase of areal density. However, PA-functionalised samples exhibited lower bending lengths than APA-treated samples despite higher areal density. Therefore, the main reason for the decrease in bending lengths, could be ascribed to the moisture-absorbing properties of PA. Namely, the silk samples functionalized with PA felt significantly more moist than the samples functionalized with APA. As moisture acts as a natural lubricant, this probably contributed to the lower bending length of the PA-treated samples. As a result, PA-functionalised samples exhibited lower overall flexural rigidity compared to APA-functionalised samples at the same flame retardant concentration (Figure 2c).

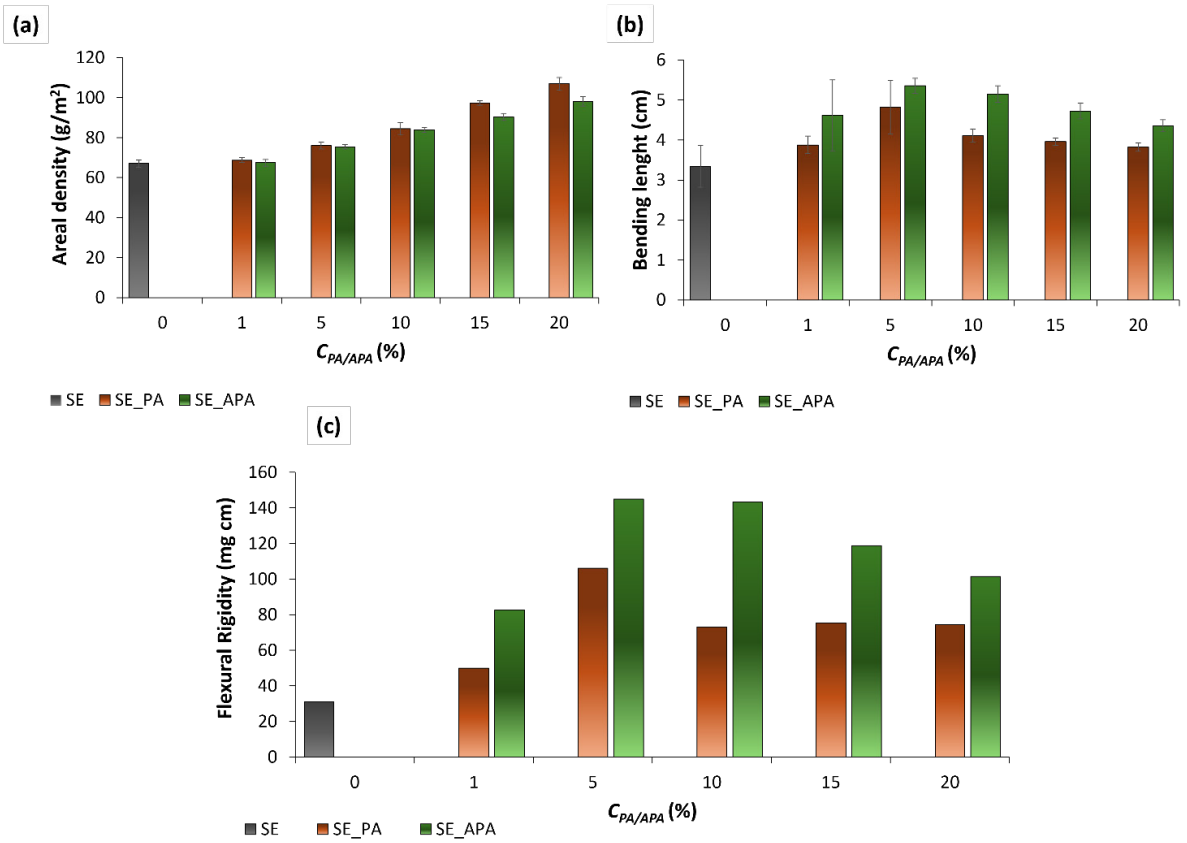


Figure 2: Areal density (a) and bending length (b) of untreated ($C_{PA/APA}$ = 0 %) and PA- or APA-functionalised samples over the studied concentration range ($C_{PA/APA}$ = 1–20 %) and their corresponding flexural rigidity (c).

Figure 3 shows the results of air permeability for silk fabrics functionalized with PA and APA. The air permeability initially decreases at 1 % but gradually increases up to 10 %. Beyond that, at 15 % and 20 %, the trend became inconsistent, with differences between PA- and APA-treated samples. High standard deviations indicate considerable variability within the sample sets, probably due to the heterogeneous distribution of flame retardants leading to localised pore blockage. However, the untreated silk (SE_0) also exhibits high variability, suggesting that inherent irregularities in the fabric also contribute to the variations in air permeability. Consequently, this variability limits the ability to draw firm conclusions about the exact influence of PA and APA at higher concentrations. Nevertheless, a general trend can be recognised which indicate that the air permeability tends to recover at higher concentrations compared to the initial drop at 1 %.

The functionalisation of silk with studied flame retardants had different effects on the tensile properties of the silk fabric (Figure 4). While functionalisation with APA did not significantly affect either the breaking strength or the elongation at break, even at higher concentrations (> 10 %), the application of PA led to a significant deterioration of these properties. In fact, both breaking strength (Figure 4a) and elongation at break (Figure 4b) showed a decreasing trend with increasing PA concentration, indicating a weakening effect of PA on the mechanical integrity of the silk fabric. One possible reason for this is the higher moisture absorption of PA compared to APA, which was observed during handling of the tested samples. This could have contributed to a softening effect that disturbed the hydrogen bonds within the silk fibroin network, leading to a decrease in cohesion between the silk protein chains, and thus a reduction in tensile properties.

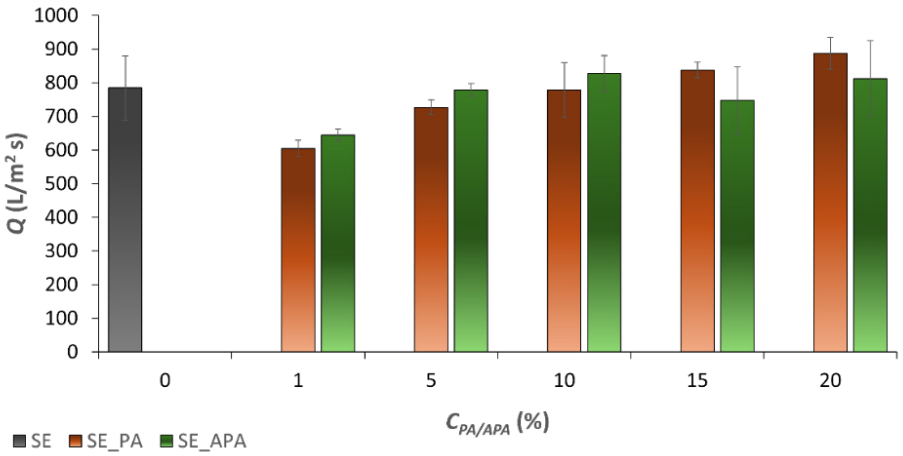


Figure 3: Air permeability (Q) of untreated ($C_{PA/APA}$ = 0 %) and PA- or APA-functionalised samples over the studied concentration range ($C_{PA/APA}$ = 1–20 %).

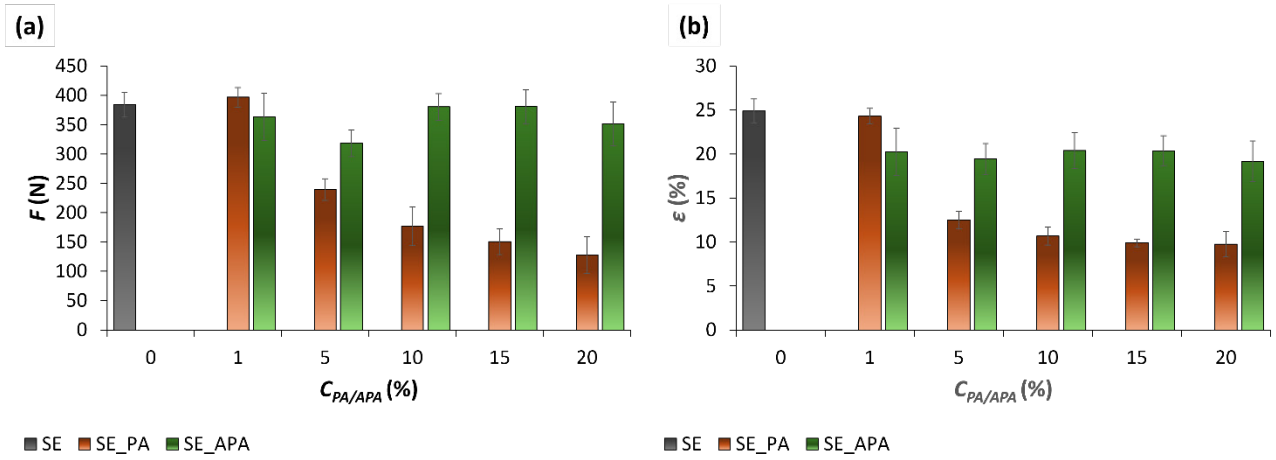


Figure 4: Breaking strenght (F) (a) and elongation at break (ε) (b) of untreated ($C_{PA/APA}$ = 0 %) and PA- or APA-functionalised samples over the studied concentration range ($C_{PA/APA}$ = 1–20 %).

4. CONCLUSIONS

The study shows that APA effectively improved the flame retardancy of silk, with showing superior performance compared to PA, due to the synergistic effect of phosphorus and nitrogen. The latter was demonstrated in a 20–26 % reduction in tear length after the vertical flammability test. While APA-functionalised fabrics maintained better mechanical integrity, PA weakened the fabric due to higher moisture absorption. Air permeability showed variability, likely due to the uneven distribution of the flame retardants as well as inherent irregularities in the fabric. To achieve optimal balance between flame retardancy and fabric integrity APA concentration of 5 % and higher is recommended, ensuring effective protection of silk from thermal degradation without excessive stiffness or mechanical degradation.

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5. REFERENCES

Zhang, Y., Xing, T., Huang, Z., He, A., Luo, Y., Hong, Y., Wang, M., Shi, Z., Tong, A., Qiao, S., Ke, G., Zhao, T., Chen, F. in Xu, W. An innovative strategy towards highly efficient flame-retardant silk. Chemical Engineering Journal, 2024, 489, 151356.
Lu, S.-Y. in Hamerton, I. Recent developments in the chemistry of halogen-free flame retardant polymers. Progress in Polymer Science, 2002, 27, 1661–1712.
Salmeia, K. A., Gaan, S. in Malucelli, G. Recent Advances for Flame Retardancy of Textiles Based on Phosphorus Chemistry. Polymers, 2016, 8, 319.
Alongi, J., Carosio, F. in Malucelli, G. Current emerging techniques to impart flame retardancy to fabrics: An overview. Polymer Degradation and Stability, 2014, 106, 138-149.
Feng, Y., Zhou, Y., Li, D., He, S., Zhang, F. in Zhang, G. A plant-based reactive ammonium phytate for use as a flame-retardant for cotton fabric. Carbohydrate Polymers, 2017, 175, 636–644.
Cheng, X.-W., Song, J.-Y., Cui, M.-L., Dong, S. in Guan, J.-P. Reactive phytate-based intumescent flame-retardant toward sustainable and durable functional coating of silk fabric. Materials Today Sustainability, 2023, 24, 100528.
Zhang, X., Zhou, X.-Y., Cheng, X.-W. in Tang, R.-C. Phytic acid as an eco-friendly flame retardant for silk/wool blend: A comparative study with fluorotitanate and fluorozirconate. Journal of Cleaner Production, 2018, 198, 1044-1052.
Wu, C., Lu, L.-X., Wu, Z.-X., Cheng, X.-W. in Guan, J.-P. Fully biobased approach for sustainable flame retardancy, antibacterial and anti-UV modification of silk fabric. Industrial Crops & Products, 2024, 222, 119557.
Cheng, X.-W., Guan, J.-P., Tang, R.-C. in Liu, K.-Q. Phytic acid as a bio-based phosphorus flame retardant for poly(lactic acid) nonwoven fabric. Journal of Cleaner Production, 2016, 124, 114-119.
Cheng, X.-W., Wang, Z.-Y., Jin, W.-J. in Guan, J.-P. Covalent flame-retardant functionalization of wool fabric using ammonium phytate with improved washing durability. Industrial Crops & Products, 2022, 187, 115332.

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POSTER PRESENTATION

KOMBUCHA-EXTRACT-MEDIATED GREEN SYNTHESIS OF SILVER NANOPARTICLES FOR ANTIBACTERIAL SILK TEXTILES

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Abstract: *In this study, Kombucha extract was introduced as a green reducing and stabilising agent for the in situ biosynthesis of silver nanoparticles (Ag NPs) on silk fabric. The silk fabric was first treated with a 2.0 mM $AgNO_3$ aqueous solution, followed by treatment with Kombucha extract for 1, 2 and 4 hours at 35 °C. UV-Vis spectroscopy confirmed the successful formation of the Ag NPs by detecting characteristic SPR peaks. Regardless of the synthesis time, the functionalized samples showed significant antimicrobial activity against Escherichia coli and Staphylococcus aureus without the formation of a distinctive inhibition zone, indicating minimal diffusion of the nanoparticles. The findings highlight the feasibility of Kombucha-mediated Ag NPs functionalization for sustainable development of antimicrobial silk textiles.*

Keywords: *silk, green in situ biosynthesis, silver nanoparticles, Kombucha extract, antimicrobial activity*

1. INTRODUCTION

The antimicrobial functionalisation of textiles is crucial, not only to prevent the growth of microorganisms responsible for unpleasant odours and to maintain personal hygiene, but above all to protect against pathogenic microorganisms (Morais, 2016; Windler, 2013). Due to their large surface area and ability to retain moisture, textile fibres provide an ideal environment for colonisation by microorganisms and pose a potential risk for the transmission of bacteria, fungi and viruses from person to person (Balasubramaniam, 2020). Studies on nosocomial pathogens indicate that various bacterial, fungal and viral species can persist for weeks on natural and synthetic textile surfaces, making contaminated textiles a potential vector for infection transmission (Kampf, 2020).

Silver nanoparticles (Ag NPs) are among the most commonly used antimicrobial agents for textile applications due to their broad spectrum of activity. However, the conventional synthesis of Ag NPs often uses toxic chemicals and produces hazardous by-products, leading to concerns about risks to the environment and human health. In response, biosynthesis methods have emerged as a sustainable alternative, utilising biological entities such as plant extracts, microorganisms and biomolecules to reduce silver ions (Ag^+) into metallic nanoparticles. Compared to conventional synthesis methods, biosynthesis offers advantages such as lower toxicity, cost efficiency and improved biocompatibility, making it particularly attractive for biomedical and textile applications (Radetić, 2013; Rai, 2009; Simončič, 2017).

Kombucha extract, a product of tea fermentation rich in polyphenols, organic acids and microbial metabolites (Abaci, 2022; Jayabalan, 2014) has recently been explored as a reducing and stabilising agent for the synthesis of Ag NPs, which demonstrated excellent antibacterial activity against *S. aureus* and *E. coli* (Shanmugavel, 2017). The bioactive compounds in Kombucha facilitate the formation of nanoparticles while influencing their size, morphology and stability. By optimising synthesis parameters such as pH, temperature and reaction time, the antimicrobial efficacy and functional properties of Ag-NPs synthesised from Kombucha can be improved (El-Fallal, 2023). However, to the best of our knowledge, previous studies have focused exclusively on *ex situ* synthesis, and the direct *in situ* synthesis of Ag NPs on textile substrates has not yet been explored .

This study aims to develop a green *in situ* Ag NPs synthesis approach for the antimicrobial functionalisation of textiles using Kombucha extract as a natural reducing agent. The antimicrobial efficacy of the synthesised Ag NPs

will be systematically evaluated on silk fabrics, thus contributing to the development of sustainable antimicrobial textile materials.

2. EXPERIMENTAL

2.1 Materials

Throughout the experiments, a 100% degummed silk fabric with a weight of 65 g/m^2 was used. Silver nitrate ($AgNO_3$) was purchased from Sigma Aldrich. Kombucha SCOBY (Symbiotic colony of bacteria and yeasts) starting culture was purchased by a local producer Fermentarnica d.o.o. (Slovenia).

2.2 Preparation of kombucha extract

The Kombucha SCOBY sample was activated accordingly. A growth medium of black tea (5 g/L) and sucrose (80 g/L) was prepared by boiling for 5 minutes and then allowed to cool to room temperature. Subsequently, 900 ml of the tea broth was inoculated with Kombucha pellicle fragments (3.7 % w/v, wet weight basis) and 10 % (v/v) liquid broth of the activated tea fungus. The mixture was incubated for 14 days under dark, static conditions at room temperature. After the incubation period, the Kombucha biomass extract was filtered to remove microbial spores and other solid residues.

2.3 In situ synthesis of Ag NPs

The silk samples were immersed in a 2.0 mM aqueous solution of $AgNO_3$ at a fabric-to-liquid ratio of 1:25 and stirred for 10 minutes at 30 °C using the Starlet-2 DL-6000 Plus infrared dyeing device (DaeLim Starlet Co., Ltd., Korea) to ensure uniform dispersion and adsorption of Ag^+ ions on the silk fibres. The Kombucha extract was slightly alkalized with 1 M NaOH before being gradually added to the $AgNO_3$ solution containing the silk samples, with the final fabric-to-liquid ratio adjusted to 1:50. The samples were then stirred at 30 °C for a further 1, 2 or 4 hours, rinsed thoroughly with distilled water and air-dried at room temperature. Based on the synthesis time the samples were coded as SE_Ag-1, SE_Ag-2 and SE_Ag-4.

2.4 Characterization

The surface morphology of the studied samples was studied by scanning electron microscope (SEM) JSM-6060 LV (Jeol, Japan).

The reflectance and transmittance of the studied samples was recorded in a 250–780 nm wavelength range using a Lambda 800+ UV/Vis spectrophotometer (Perkin Elmer, Great Britain). From the reflectance (R) values of the samples obtained at different wavelengths, the colour strength (K/S) was calculated as follows:

$$K/S = \frac{(1-R)^2}{2R} \qquad (1)$$

From the transmittance values UV protection factor (UPF) was determined according to the Standard EN 13758-1:2001.

The antibacterial activity of the analysed samples was determined by evaluating the dehydrogenase enzyme activity using iodonitrotetrazolium chloride (INT) for *Escherichia coli* ATCC 35218 and *Staphylococcus aureus* ATCC 29213. A bacterial suspension with a concentration of 1 × 10^6 CFU/ml was applied to the samples in a microtitre plate and then incubated at 37°C for 24 hours. After incubation, the samples were washed with 2 mL of 0.9% NaCl to remove non-adherent bacteria. Subsequently, 0.5 mL of a 0.5 mg/mL INT solution was added, and the plate was incubated at 37°C for 2 hours to allow INT reduction. To dissolve the formed formazan, 0.5 mL of DMSO (dimethyl sulfoxide) was added and the optical density (OD) was measured at 490 nm. Based on the OD values, the antibacterial activity (AA) of the studied samples was determined as follows:

$$AA = \frac{(OD_{UN} - OD_F)}{OD_F} \times 100\ [\%] \qquad (2)$$

where OD_{UN} is the OD at 490 nm determined for the untreated silk sample and OD_F is the OD at 490 nm determined for the functionalised silk sample.

In addition, the leaching properties of the functionalized samples were assessed by evaluating the zone of inhibition using the Kirby-Bauer method. A 0.1 mL suspension of the tested bacterial species at a concentration of 1.5×10^8 CFU/mL was evenly distributed on Tryptic Soy Agar (TSA) plates. A disc-shaped sample was then placed on each plate and incubated at 37°C for 24 hours, after which the zone of inhibition was measured.

3. RESULTS AND DISCUSSION

The *in situ* synthesis of Ag NPs by Kombucha extract led to notable changes in the surface morphology of the silk fibres. As can be seen in the SEM images in Figure 1, the untreated silk fibres have a smooth and cylindrical structure. In contrast, after functionalisation with Ag NPs, thin, ribbon-like structures were loosely attached to the fibre surface regardless of the synthesis time. However, no clear deposition of nanoparticles on the fibre surfaces can be seen at the magnification applied.

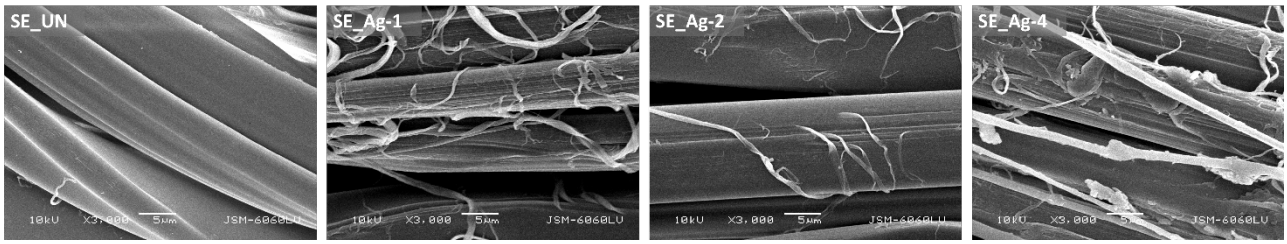


Figure 1: SEM images of silk samples at 3000x magnification showing morphological differences before and after the in situ synthesis of Ag NPs.

UV-Vis spectroscopy was used to confirm the presence of Ag NPs on the surface of silk fibres, as it is one of the most commonly used techniques to characterise Ag NPs by surface plasmon resonance (SPR). The UV-Vis absorption spectra of the colloidal Ag NPs solutions obtained after removal of the silk samples (Figure 2a) show two broad absorption bands: the first centred at around 360 nm and the second at 440 nm. The presence of these distinct SPR peaks indicates the formation of spherical Ag-NPs, as reported in previous studies (Laouini, 2021). The band at 360 nm can be attributed to smaller nanoparticles, while the broader peak at 440 nm indicates the presence of larger nanoparticles or their aggregation. Increasing the synthesis time resulted in a slight increase in 440 nm peak intensity while maintaining its position, indicating that the morphology of Ag NPs in the colloidal solution was not affected by the synthesis duration.

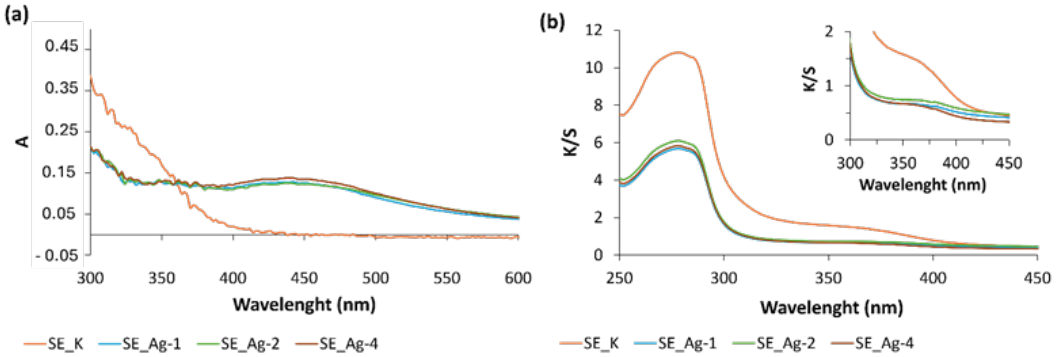


Figure 2: UV-Vis absorption spectra of Kombucha extract and colloidal Ag solutions after treatment of silk samples (a) and colour strength (K/S) spectra of silk samples treated with Kombucha extract (SE_K) and functionalized with in situ synthesised Ag NPs(b).

The colour strength (K/S) spectra (Figure 2b) of the sample treated with Kombucha extract (SE_K) showed two intense absorption peaks at 280 nm and 360 nm, which can be attributed to polyphenolic compounds and other metabolites in the extract. After the *in situ* synthesis of Ag NPs, a significant decrease in the intensity of both peaks was observed in the K/S spectra of samples SE_Ag-1, SE_Ag-2 and SE_Ag-4. This decrease clearly indicates the consumption of the compounds responsible for the reduction during the formation of the nanoparticles and confirms the role of the extract as a reducing agent. Furthermore, a shift of the peak from 360 nm to 372 nm was clearly observed after the synthesis of the Ag nanoparticles. Such a shift is typically associated with the formation of silver nanoparticle aggregates or the SPR effect, which can cause changes in the absorption bands depending on the size and aggregation of the nanoparticles. Interestingly, the spectral changes were not significantly influenced by the synthesis time, suggesting that the duration of synthesis does not play a crucial role in the optical properties of the resulting Ag NPs.

Next, the self-sterilising performance of the silk fabric samples tested was evaluated and the results are shown in Figure 3. After 24 hours of contact with the Gramme-negative *E. coli* and Gramme-positive *S. aureus* bacteria, the Ag NPs on the functionalised silk fibres significantly reduced the enzyme activity of dehydrogenase, resulting in a sharp decrease in the optical density (OD) of the INT indicator. This reduction led to a remarkable antibacterial activity with a growth inhibition of about 80% for *E. coli* and about 69% for *S. aureus.* The slightly lower activity against S. aureus can be attributed to the structural differences in the cell membranes between Gramme-negative and Gramme-positive bacteria. However, a gradual increase in antibacterial activity against *S. aureus* was observed with longer synthesis time.

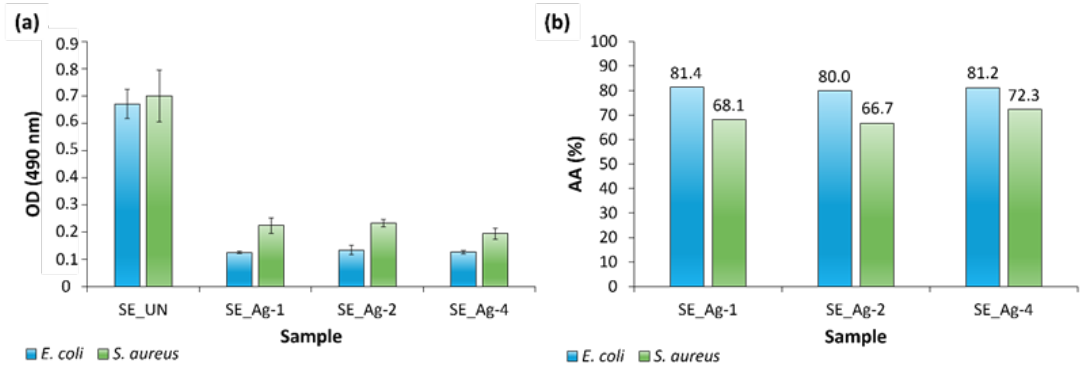


Figure 3: Optical density (OD) at 490 nm indicating the dehydrogenase enzyme activity on the surface of the studied samples after inoculation with *E. coli* or *S. aureus* bacteria (a), and corresponding antibacterial activity (AA) of the samples (b).

To assess the leaching properties of the biosynthesised Ag NPs, a qualitative evaluation was performed using the Kirby-Bauer method (Figure 4). Regardless of the synthesis time, none of the tested samples exhibited an inhibition zone, indicating that the concentration of Ag NPs was not sufficient to effectively inhibit bacterial growth of *E. coli* or *S. aureus* by diffusion-based mechanisms. These results are promising as they demonstrate the potential of Kombucha-mediated Ag NP functionalisation for the development of silk-based antimicrobial textiles while minimising unintended effects on beneficial skin microflora.

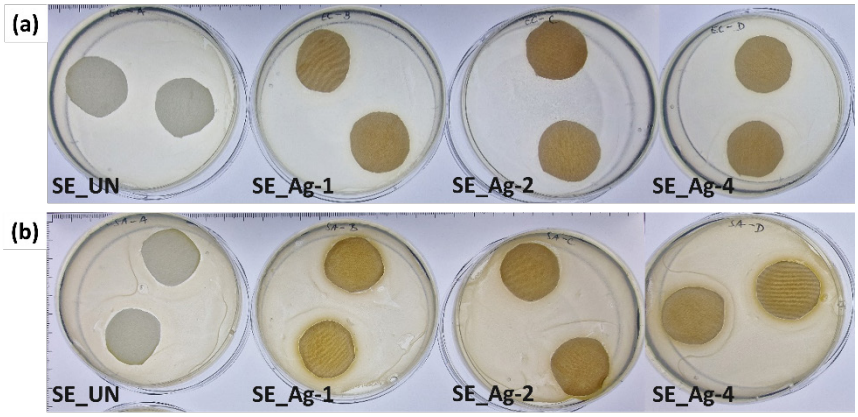


Figure 4: Growth of *E. coli* (a) and *S. aureus* (b) on the agar plates according to Kirby-Bauer method.

4. CONCLUSIONS

The use of Kombucha extract enabled the successful *in situ* biosynthesis of Ag NPs as confirmed by UV-Vis spectroscopy. The results showed characteristic SPR peaks indicative of nanoparticle formation, with spectral shifts in the K/S spectra further demonstrating the role of the extract as a reducing agent. Antibacterial tests showed significant self-sterilising properties of the functionalized silk, with growth inhibition of up to 80% against *E. coli* and 69% against *S. aureus*, with a slight increase in efficacy against *S. aureus* with longer synthesis time. In addition, no significant leaching of Ag-NPs was observed, indicating a minimal Ag concentration in the immediate environment of the functionalized samples. These results underline the potential of Kombucha extract-synthesised Ag NPs for the sustainable development of antimicrobial silk textiles.

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5. REFERENCES

Abaci, N., Senol Deniz, F.S., and Orhan, I.E. 2022.Kombucha – An Ancient Fermented Beverage with Desired Bioactivities: A Narrowed Review. Food Chem X 14: 100302.

Balasubramaniam, B., Prateek, Ranjan, S., Saraf, M., Kar, P., Singh, S.P., Thakur, V.K., Singh, A. and Gupta, R.A. 2020. Antibacterial and antiviral functional materials: Chemistry and biological activity toward tackling COVID-19-like pandemics. ACS Pharmacology & Translational Science 4 (1): 8–54.

El-Fallal, A.A., Elfayoumy, R.A., and El-Zahed, M.M. 2023. Antibacterial activity of biosynthesized zinc oxide nanoparticles using Kombucha extract. SN Applied Sciences 5 (12): 332.

Jayabalan, R., Malbaša, R.V., Lončar, E.S., Vitas, J.S., and Sathishkumar, M. 2014. A review on Kombucha Tea—Microbiology, composition, fermentation, beneficial effects, toxicity, and tea fungus. Comprehensive Reviews in Food Science and Food Safety 13 (6): 538–550.

Kampf, G. 2020. How long can nosocomial pathogens survive on textiles? A systematic review. GMS Hygiene and Infection Control 15: Doc10.

Laouini, S.E., Bouafia, A., Soldatov, A.V., Algarni, H., Tedjani, M.L., Ali, G.A.M., and Barhoum, A. 2021. Green synthesized Ag/Ag□O nanoparticles using aqueous leaves extracts of Phoenix Dactylifera L. and their azo dye photodegradation. Membranes 11 (7): 468.

Morais, D.S., Guedes, R.M., and Lopes, M.A. 2016. Antimicrobial approaches for textiles: From research to market. Materials 9 (7): 498.

Rai, M., Yadav, A., and Gade, A. 2009. Silver nanoparticles as a new generation of antimicrobials. Biotechnology Advances 27 (1): 76–83.

Radetić, M. 2013. Functionalization of textile materials with silver nanoparticles. Journal of Materials Science 48 (1): 95–107.
Shanmugavel, M., Nandhini, N.T., Supriya, B., Vasantharaj, S., Inbasekaran, S., and Gnanamani, A. 2017. Kombucha fungus mediated silver nanoparticles and their biological activities. International Journal on Applied Bioengineering 11 (2): 22–26.
Simončič, B., and Tomšič, B. 2017. Recent concepts of antimicrobial textile finishes. In Textile Finishing: Recent Developments and Future Trends, edited by K.L. Mittal and T. Bahners, 1–68. Beverly: Scrivener Publishing.
Windler, L., Height, M., and Nowack, B. 2013. Comparative evaluation of antimicrobials for textile applications. Environment International 53 (1): 62–73.

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POSTER PRESENTATION

FUNCTIONALIZATION OF SILK WITH GREEN CHITOSAN–ALOE VERA–ESSENTIAL OIL COMPOSITE FOR MEDICAL APPLICATION

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Abstract: *This study combines chitosan, aloe vera (AV) and citronella essential oil (EO) to functionalise silk fabrics for advanced medical textile applications. A chitosan-AV-EO mixture was applied to the fabric together with β-cyclodextrin (β-CD) via the pad dry cure method. Scanning electron microscopy (SEM) was used to analyse the morphology of the fabric, while moisture content, antibacterial activity and leaching properties were evaluated to determine functional performance. The results demonstrate the potential of this composite for wound healing applications, as it exhibits improved moisture retention and effective antibacterial activity against Gramme-negative bacteria. Further optimisation of AV and EO concentrations is required to improve efficacy against Gramme-positive bacteria. The incorporation of β-CD helped to limit the leaching of AV and EO, potentially prolonging antimicrobial activity and minimising cytotoxicity.*

Keywords: *silk, medical textile, chitosan-based composite, moisture content, antibacterial activity*

1. INTRODUCTION

A wound is defined as any disruption of the continuity of the skin and underlying tissue that impairs the protective function of the skin and exposes deeper structures to mechanical damage, desiccation, radiation, thermal influences and microbial contamination (Rajendran, 2011). Wounds can result from trauma, pathological conditions or surgical procedures, making effective treatment a crucial aspect of medical care.

Wound treatment has evolved considerably in the past, from traditional methods such as cotton gauze and saline to modern wound dressings. Conventional dressings are often unable to effectively regulate moisture and pH, which can delay healing. In contrast, modern materials are designed to better retain moisture, maintain pH balance and optimise gas exchange, creating a more favourable healing environment. Moreover, the use of biocompatible materials and bioactive compounds is crucial to promote tissue regeneration and infection control (Rajendran, 2011).

Chitosan-based hydrogels are considered one of the most promising materials for wound dressings due to their biocompatibility, biodegradability and remarkable antimicrobial and antioxidant properties. These advantages are due to the presence of hydroxyl (-OH) and amino (-NH_2) groups in the chitosan molecular structure, which can donate electrons to neutralise free radicals (Hong, 2024). The antimicrobial activity of chitosan is primarily attributed to the protonation of the amino groups in acidic pH environments (below pH 6.5). This allows chitosan to interact with the negatively charged surfaces of microbial cell membranes, disrupting their integrity and ultimately causing cell death (Simončič, 2017). In addition, chitosan-based hydrogels can be easily modified to incorporate various bioactive agents such as aloe vera extract and essential oils (Amaral, 2024; Milanesi, 2021). These two natural antimicrobial substances further enhance the antimicrobial and antioxidant properties of chitosan. Essential oils from citrus fruits, for example, which are rich in limonene and flavonoids, contribute to the antibacterial, antioxidant and anti-inflammatory effect, while aloe vera extract moisturises, soothes the skin and has an anti-inflammatory effect. In addition, aloe vera stimulates collagen production and promotes the proliferation of fibroblasts, which supports tissue regeneration during wound healing (Ishfaq, 2021; Liang, 2021; Maduna, 2023).

Driven by a sustainable approach to improve the quality of biomaterials while minimising the environmental impact, this study focused on the integration of chitosan, aloe vera extract and citronella essential oil to develop advanced medical textiles with enhanced antimicrobial, antioxidant and wound healing properties. By combining these bioactive components, the aim was to create a functional textile material that promotes an optimal healing environment, supports tissue regeneration and provides a biocompatible, environmentally friendly alternative for wound treatment.

2. EXPERIMENTAL

2.1 Materials

Degummed 100% silk fabric (65 g/m²) was selected as the base material. Chitosan (degree of deacetylation: 95%, viscosity: 159 mPa·s) was sourced from Chitoclear, Primex (Iceland). Butanetetracarboxylic acid (BTCA, 99%) was used as a chitosan crosslinker, while sodium hypophosphite (SHP) served as the crosslinking initiator, both obtained from Sigma-Aldrich (USA). To maintain an acidic pH, glacial acetic acid (Sigma-Aldrich, USA) was used. Aloe *barbadensis* leaf powder (AV) concentrate (200:1) was supplied by Natural Loti (Slovenia). Citronella Java essential oil (EO) and β-cyclodextrin (β-CD) for essential oil encapsulation were both purchased from Sigma-Aldrich (USA).

2.2 Preparation of the finishing bath

A 1% chitosan solution was prepared by dissolving chitosan in water with the addition of 1% glacial acetic acid and magnetic stirring overnight. Subsequently, 2% BTCA and 2% SHP were gradually added to the chitosan solution and stirred until completely dissolved. Before the finishing process, 0.4% aloe vera (AV) powder was dissolved in the chitosan solution. In addition, a mixture of 0.33% β-CD and 0.33% essential oil (EO) was added to the chitosan/AV solution to obtain the final chitosan/AV/EO formulation. Prior to addition, β-CD and EO were finely ground using a mortar and pestle to facilitate encapsulation of the EO in the β-CD cavity.

2.3 Functionalisation of the silk fabric

The functionalisation of silk fabric was carried out using the pad-dry-cure method. The silk fabric samples were immersed in the chitosan/AV/EO solution at room temperature for 1 minute and then passed through a double roller padder to achieve a wet pick-up of 120 ± 5%. The treated samples were then dried at 100 °C for 1 minute and cured at 150 °C for 5 minutes (sample code: SE_Ch+AV+EO). For comparison, a chitosan/AV solution and only chitosan were applied to the samples under the same conditions, resulting in samples SE_Ch+AV and SE_Ch, respectively.

2.4 Characterization

The surface morphology of the studied samples was studied by scanning electron microscope (SEM) JSM-6060 LV (Jeol, Japan).

Moisture content (MC) was measured according to AATCC Test Method 20A-2008 Fibre Analysis: Quantitative. A moisture analyser MLB-C (Kern & SOHN GmbH, Germany) was used for this purpose. The samples were pre-conditioned for 24 hours at 65 ± 2% relative humidity at 20 °C and 40 °C before measurement. They were then placed in the moisture analyser and dried at 100 °C until a constant mass was achieved. MC was calculated using the following equation

$$MC = \left(\frac{m_0 - m_f}{m_0}\right) \times 100\ [\%], \qquad (1)$$

where m_0 represents the initial mass of the pre-conditioned sample and m_f the final mass of the sample after drying. The *MC* values were given as the average of five independent measurements. Based on the *MC* values determined, the contribution to moisture content (C_{MC}) was calculated using the equation:

$$C_{MC} = \left(\frac{MC_F - MC_{UN}}{MC_{UN}}\right) \times 100[\%] \qquad (2)$$

where MC_F is the moisture content of the functionalised samples, and MC_{UN} is the moisture content of the untreated sample, determined under the same conditions.

The antibacterial activity of the studied samples was evaluated by measuring the dehydrogenase enzyme activity using iodonitrotetrazolium chloride (INT) against *Escherichia coli* ATCC 35218 (E. coli) and *Staphylococcus aureus* ATCC 29213 (*S. aureus*). A bacterial suspension with a concentration of 1×10^6 CFU/ml was applied to the samples in a microtiter plate and incubated at 37 °C for 24 hours. After incubation, the samples were rinsed with 2 mL of 0.9% NaCl to remove non-adherent bacteria. Subsequently, 0.5 mL of a 0.5 mg/ml INT solution was added and the plate was incubated for a further 2 hours at 37 °C to facilitate INT reduction. To dissolve the resulting formazan, 0.5 mL of dimethyl sulfoxide (DMSO) was added, and the optical density (OD) was measured at 490 nm. The antibacterial activity (A) of the functionalized samples was calculated using the following equation:

$$\mathrm{A} = \frac{(OD_{UN} - OD_F)}{OD_F} \times 100\ [\%] \qquad (3)$$

where OD_{UN} is the OD at 490 nm determined for the untreated silk sample and OD_F is the OD at 490 nm determined for the functionalised silk sample.

To assess the potential release of antimicrobial agents from the functionalized samples, the zone of inhibition was determined using the Kirby-Bauer disk diffusion method. A 0.1 mL bacterial suspension (1.5×1081.5 \times 10^81.5×108 CFU/mL) of the tested species was evenly spread onto Tryptic Soy Agar (TSA) plates. A disc-shaped fabric sample was placed on each plate, followed by incubation at 37 °C for 24 hours. The antimicrobial efficacy was then evaluated by measuring the diameter of the inhibition zone surrounding the sample.

3. RESULTS AND DISCUSSION

Figure 1 shows the SEM images of the studied samples. The application of chitosan and chitosan– AV had no significant effect on the morphology of the silk fibres. The SEM images of the corresponding SE_Ch and SE_Ch+AV samples show a smooth, cylindrical structure comparable to that of the untreated SE fibres, indicating that the functionalisation process preserved the original fibre integrity. In contrast, the SEM images of SE_Ch+AV+EO show the presence of small surface deposits on the silk fibres, which can be attributed to the formation of the EO-/β-CD complex. This implies a successful encapsulation of the EO within the β-CD cavities, possibly contributing to the functional properties of the treated textile.

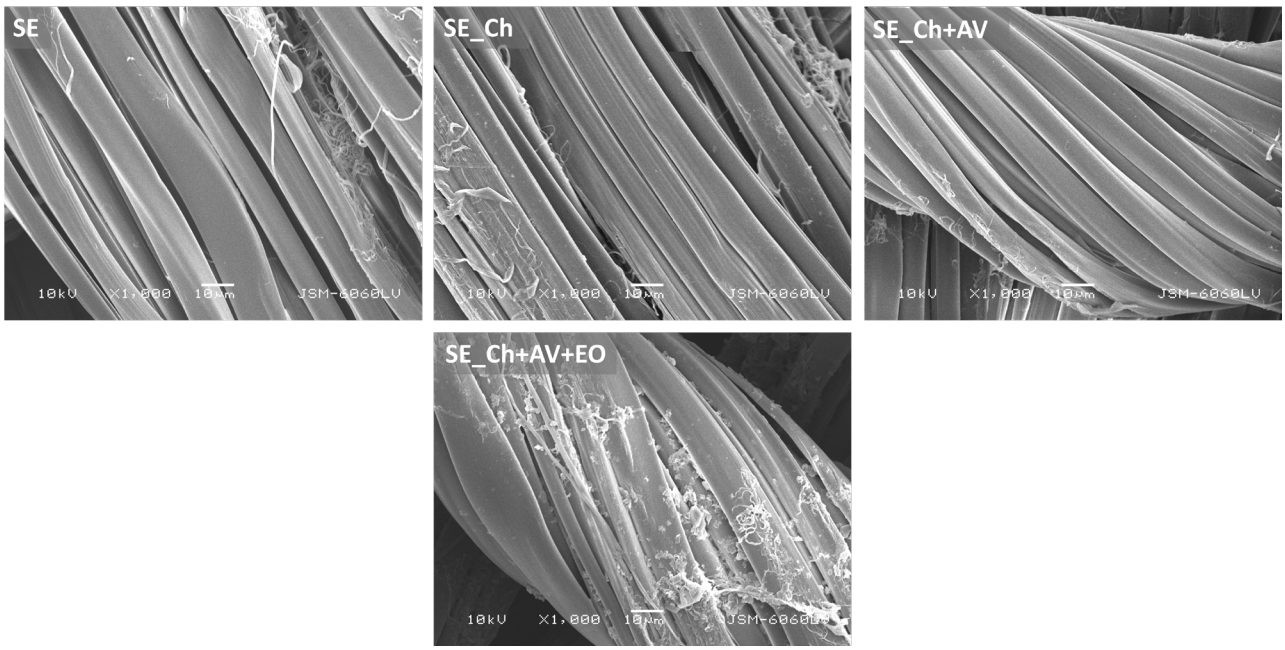


Figure 1: SEM images of the studied silk samples obtained at 1000x magnification.

Compared to untreated silk fabric (SE), the application of chitosan significantly increased the moisture content (*MC*), with further increase observed by the addition of AV extract (Figure 3a). The presence of EO in the chitosan–AV composite had no further effect on MC, suggesting that it was successfully encapsulated without altering the moisture properties of the SE_Ch+AV sample. A more detailed analysis of the contribution of the bioactive components to the *MC* (C_{MC}) is shown in Figure 3b. The incorporation of chitosan resulted in a 28% increase in C_{MC}, while the addition of AV and EO increased C_{MC} by a further 10–12%. These results confirm the positive moisturising effect of AV in combination with chitosan, independent of the presence of EO.

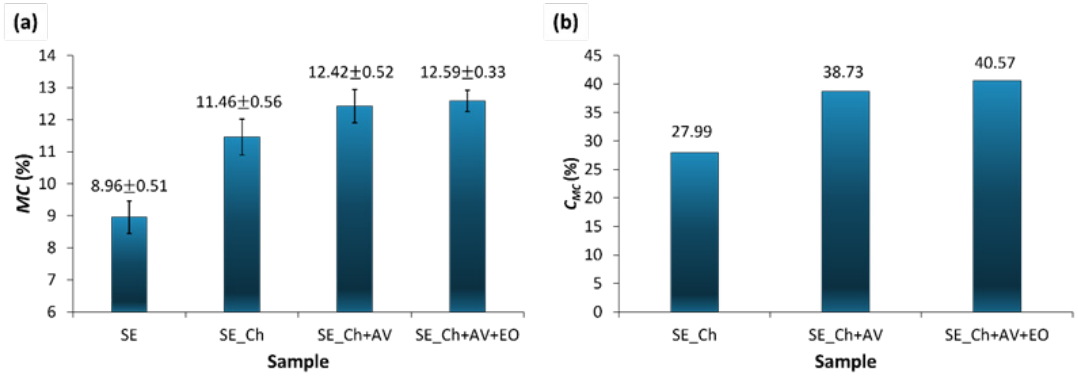


Figure 2: Moisture content (*MC*) of the studied silk samples (a) and corresponding contribution of the bioactive components to the *MC* (C_{MC}) of the silk fibres (b)

In addition to its moisturizing effect, the application of bioactive components imparted certain antibacterial activity against both model bacteria, *E. coli* and *S. aureus*. The SE_Ch sample exhibited good 76 % antibacterial activity against *E. coli*, which was further slightly enhanced by the addition of AV and EO bioactive components. In contrast, only a moderate antibacterial effect was observed against *S. aureus*, with a 50 % reduction in bacterial growth. This difference can be attributed to structural variations in the cell membranes of Gram-negative and Gram-positive bacteria. Therefore, further optimization of the concentration of bioactive components is necessary to enhance antibacterial efficacy against Gram-positive bacteria.

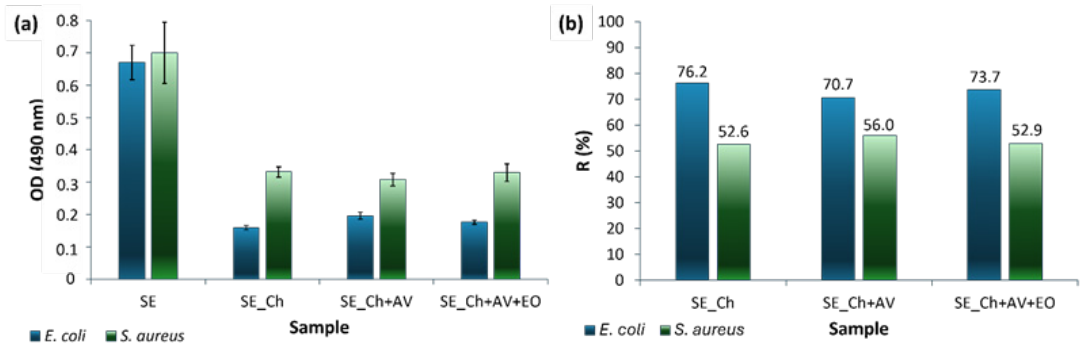


Figure 3: Optical density (OD) of the iodonitrotetrazolium chloride solution at 490 nm reflecting the activity of the enzyme dehydrogenase on the sample surfaces after inoculation with *E. coli* or S. *aureus* (a) and the corresponding antibacterial activity (R) (b).

The leaching properties of AV and EO from the functionalized SE_Ch+AV and SE_Ch+AV+EO samples were investigated using the Kirby-Bauer method against *E. coli* (Figure 4). Notably, only the SE_Ch+AV sample showed a minimal inhibition zone of 1.0–2.0 mm, indicating a controlled release of AV from the chitosan matrix. This release was suppressed when the EO/β-CD complex was introduced, confirming the successful encapsulation of EO in the hydrophobic interior of the β-CD. In addition, the hydrophilic exterior of the β-CD likely served as an anchoring site for AV, which also limited its leaching. Such controlled release behaviour is beneficial for wound healing as it may prolong antimicrobial activity while minimising potential cytotoxicity to surrounding healthy tissue.

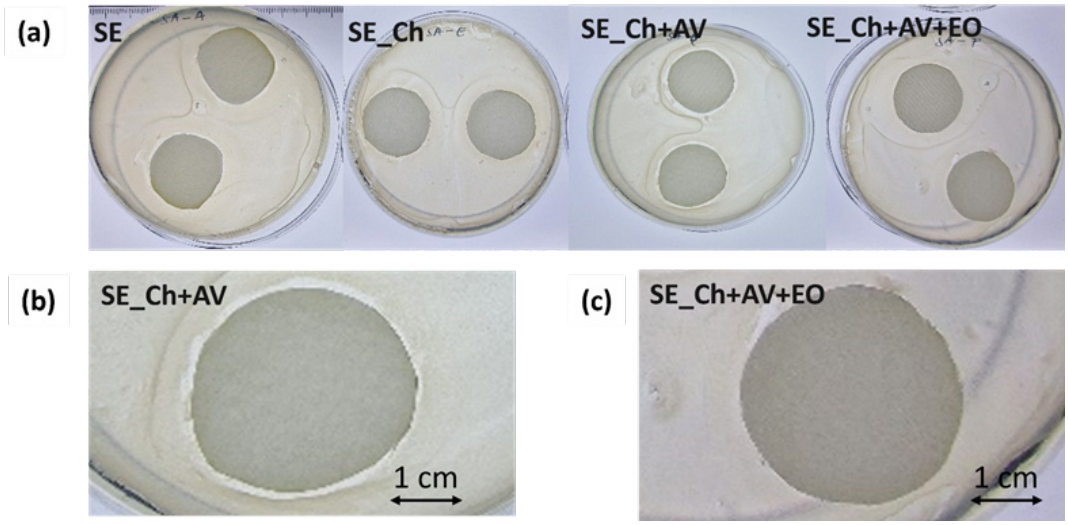


Figure 4: Evaluation of bioactive component release from studied samples using the Kirby-Bauer method against *E. coli*: (a) Inhibition zones, (b) Enlarged view of the inhibition zone for SE_Ch+AV, and (c) Absence of an inhibition zone for SE_Ch+AV+EO.

4. CONCLUSIONS

Functionalisation of the silk fibres with chitosan, AV and EO preserved the original fibre morphology, with only the SE_Ch+AV+EO sample showing small surface deposits, confirming the successful encapsulation of EO in β-CD. Chitosan significantly increased the moisture content, which was further enhanced by AV, while the addition of EO did not affect the achieved moistening effect. The treated fibres showed good antibacterial activity against *E. coli*, while the effect against *S. aureus* remained moderate. The limited diffusion of AV and EO from the β-CD complex suggests a controlled release, possibly prolonging antimicrobial activity while minimising cytotoxicity. Future research should focus on optimising AV and EO concentrations in the studied composite to improve antibacterial efficacy against both bacterial strains.

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5. REFERENCES

Amaral, V. A., Santana, V. L., Lisboa, E. S., Martins, F. S., Chaud, M. V., de Albuquerque-Júnior, R. L. C., Santana, W., Santos, C., Santos, A. de J., Cardoso, J. C., Souto, E. B., and Severino, P. 2024. "Chitosan Membranes Incorporating Aloe Vera Glycolic Extract with Joint Synthesis of Silver Nanoparticles for the Treatment of Skin Lesions." Drug Delivery and Translational Research. https://doi.org/10.1007/s13346-024-01683-x.

Hong, F., Qiu, P., Wang, Y., Ren, P., Liu, J., Zhao, J., and Gou, D. 2024. "Chitosan-Based Hydrogels: From Preparation to Applications, a Review." Food Chemistry: X 21: 101095.

Ishfaq, M., Akhtar, B., Muhammad, F., Sharif, A., Akhtar, M. F., Hamid, I., Sohail, K., and Muhammad, H. 2021. "Antioxidant and Wound Healing Potential of Essential Oil from Citrus reticulata Peel and Its Chemical Characterization." Current Pharmaceutical Biotechnology 22 (8): 1114–1121.

Liang, J.H., Cui, L.L., Li, J.K., Guan, S.M., Zhang, K. and Li, J.A. 2021. "Aloe Vera: A Medicinal Plant Used in Skin Wound Healing." Tissue Engineering Part B: Reviews 27 (5): 455–474.

Maduna, L. and Patnaik, A. 2023. "A Review of Wound Dressings Treated with Aloe Vera and Its Application on Natural Fabrics." Journal of Natural Fibers 20 (1): 2190190.

Milanesi, G., Vigani, B., Rossi, S., Sandri, G., and Mele, E. 2021. "Chitosan-Coated Poly(lactic acid) Nanofibres Loaded with Essential Oils for Wound Healing." Polymers 13 (16): 2582.

Rajendran, S. R., and Anand, S. C. 2011. "Hi-Tech Textiles for Interactive Wound Therapies." In Handbook of Medical Textiles, edited by V. T. Bartels, 38–79. Cambridge: Woodhead Publishing Limited.

Simončič, B., and Tomšič, B. 2017. "Recent concepts of antimicrobial textile finishes." In Textile Finishing: Recent Developments and Future Trends, edited by K.L. Mittal and T. Bahners, 1–68. Beverly: Scrivener Publishing.

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POSTER PRESENTATION

APPLICATION OF INCLUSION COMPLEXES B-CYCLODEXTRIN-CITRUS ESSENTIAL OIL IN THE PRINTING PROCEDURE ON COTTON FABRIC

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Abstract: *The paper investigated the possibility of creating inclusion complexes β-cyclodextrin lemon essential oil and their application by means of textile printing processes on 100% cellulose fabrics in plain weave. After textile printing, half of the samples were subjected to a washing process according to EN ISO 6330:2012 with a detergent without the addition of optical brighteners to determine the durability of the print and the binding of the inclusion complexes of β-cyclodextrin and lemon essential oil to the material. The physico-chemical and morphological properties of the samples were analyzed using the following analytical methods: Fourier Transform Infrared Spectrophotometry (FTIR) and Scanning Electron Microscopy (FE-SEM). In addition to the above, in order to tentatively establish the binding of inclusion complexes of β-cyclodextrin and essential lemon oil to cotton cellulose using printing paste, a subjective method for olfactometric determination of the intensity of odor release in a certain period of time was also used. Based on the results obtained, it can be seen that the inclusion complexes β-cyclodextrin and lemon essential oil are successfully bound to cellulose material by printing method. The application of the finished textile product is intended to serve as protection against mosquitoes and other insects, so printing with the addition of inclusion complexes β-cyclodextrin and essential lemon oil could be used on bed linen and interior decorative fabrics.*

Keywords: *inclusion complex β-cyclodextrin-essential oil, cotton fabric, textile printing, Fourier transform infrared spectrometry (FTIR), Scanning Electron Microscopy (FE-SEM)*

1. INTRODUCTION

Cotton is the most commonly used natural fiber in the world and is very reactive due to its molecular structure, as there are -OH groups at one end of the polymer chain, while an aldehyde group -CHO is present at the other end of the chain. The cellulose ring has a saddle-shaped structure, and in such a structure the bonds between the atoms are the least strained and this shape is the most energetically favorable, and given the position of the cellulose rings, the -OH groups are in the equatorial plane (Andrassy 2005). With the accelerated progress and development of technology, new textile materials are being developed that can be used in various areas of interest and improve the quality of life. One of the most important areas of research in the last decade has been the use of cyclodextrins and essential oils due to their non-toxicity and biodegradability. These unique properties enable a wide range of applications in the textile industry, especially in the field of textile processing, where their application to textiles aims to achieve certain functional properties such as odor absorption, UV protection, antimicrobial protection, insect protection, release of fragrance or active ingredients for skin care and the like (Knittel 2000, Szejtli 2003, Voncina 2013). Cyclodextrins (CD) are cyclic oligosaccharides with a specific hollow truncated cone structure that enables them to form inclusion complexes with hydrophobic molecules. In inclusion complexes, the cavity of the cyclodextrin molecule acts as a “host” and the complexing hydrophobic molecule as a “guest”. The dimensions of the “guest” molecule or one of its parts must be compatible with the dimensions of the cyclodextrin cavity in order for the complex to form. Cyclodextrin consists of glucopyranose units linked together by α-1,4-glycosidic bonds. Most commonly used in industry are α-, β- and γ-CD, which consist of 6, 7 and 8 glucose units (Eastburn 1994, Martin del Valle 2004, Voncina 2013). Of particular importance are the applications of β-cyclodextrin, which is often used in combination with various textile materials and chemical agents to bind active ingredients. The binding of cyclodextrin to cotton material can be achieved in various ways by cross-linking cyclodextrin with cotton, wool and polyester and polyamide fibers using polycarboxylic acids (1,2,3,4-butanetetracarboxylic

acid (BTCA), citric acid (CA) and others) as well as aggressive or harmful chemicals such as cyanuric chloride to modify cyclodextrin or epichlorohydrin as cross-linking agents (Voncina 2013). Research found that cyclodextrin covalently bound to cellulose retains the ability to form complexes and the complexed active ingredient is released after contact with the skin (Haji 2020). The use of cyclodextrin in textile printing brings new possibilities for improving the quality, sustainability and functionality of textile products. As water-soluble molecules, cyclodextrins have the ability to form inclusion complexes with pigments, which significantly increases their fixation on textile fibers and thus improves the wash and light resistance of the print (Cie 2015, Elgammal 2016, Wan 2016). These properties not only contribute to an increase in color strength and resistance print , but also enable the development of functional textile products that release odors in a controlled manner under the influence of heat or moisture, for example. Research in the field of textile printing is still limited, but has recently intensified. In 1996, Knittel and colleagues investigated the use of cyclodextrin derivatives as a substitute for urea (Knittel 1996). Further research has shown that a monochlorotriazinyl derivative of β-cyclodextrin improves dye fixation on a blend of wool and polyester fabrics, and its effects on rheological properties, colour strength and fastness have been investigated (Erkan 2018, Hebeish 2006). Ibrahim et al. have focused their research on the pre-modification of the wool component in fabrics made from a blend of wool and polyester using monochlorotriazinyl-β-cyclodextrin. For printing on textiles, they used disperse dyes complexed with β-cyclodextrin, which achieved highly efficient printing with excellent UV protection properties and a significant improvement in print fastness properties (Ibrahim 2009). More recent research has focused on the use of cyclodextrin in environmentally friendly printing processes. Zhao et al. found, for example, that the modification of cotton fabrics with β-cyclodextrin during printing improves the adsorption of natural dyes, resulting in more intense shades and better color fastness. The mechanical properties of the processed materials are significantly improved, with greater crease resistance being achieved (Zhao 2017). Further development and research in this area could lead to innovative solutions that meet the increasing demands for sustainability and functionality of textile products. Therefore, this paper represents one of the innovative approaches for the application of essential oils, such as citrus oil, which forms an inclusion complex with β-cyclodextrin bound to cotton. This technology allows the textile materials to gradually and continuously release fragrances and active ingredients, adding value to the product. The aim of this work is to investigate the potential of using cyclodextrins and essential oils in textile processing, with a focus on achieving favorable functional properties of the material and the environmental benefits that this approach brings.

2. EXPERIMENTAL

In this work, textile printing was carried out on 100% cotton fabric, with a surface weight of 150 g/m², a warp to weft ratio of 36/27 [ASTM D3775-07] and a yarn count of 60/2; 34/1 Nm. The print paste contained β-cyclodextrin (CycloLab R&D Ltd.) and lemon essential oil (ELEMENTS), a synthetic thickener (Printperfect 226 EC) and natural pomegranate pigment (Sutlović 2020). The printing process was conducted by manual screen-printing, using the following tools: a manual lab-type flat screen-printing table, a wooden-handled polyurethane blade squeegee of 60 durometer hardness, and an aluminium 40 × 50 cm screen with a mesh of 62 threads/cm^2. Considering that the applied method was hand screen-printing, the squeegee angle was kept between 7-10°, with optimal pressure to assure uniform transfer of the printing paste to the surface of a textile substrate. The printed samples were then dried and fixed in a laboratory stretch dryer (Benz) at a temperature of 150 ºC for 6 minutes. Table 1 shows the composition of the prepared printing pastes and the legend of the cotton sample labels used.

Table 1. Presentation of the composition of the prepared printing pastes and the legend of the sample labels

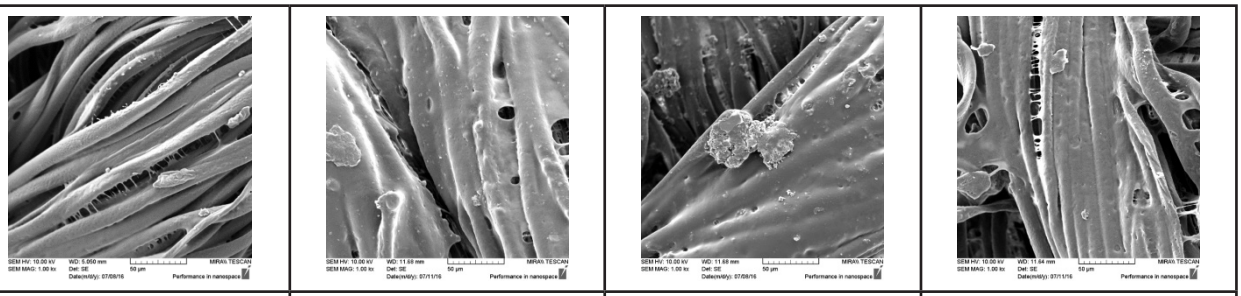
PRINTING PASTE 1		PRINITING PASTE 2	
30 g synthetic thickener		30 g synthetic thickener	
4 mL pigment solution: 100 mL soft water, 1 g pomegranate pigment		5 mL pigment solution: 100 mL soft water, 10 g β-cyclodextrin, 25 mL lemon essential oil	
	4 mL pigment solution: 100 mL soft water, 10 g β-cyclodextrin, 25 mL lemon essential oil, 1 g pomegranate pigment		
	3 µl lemon essential oil		
SAMPLE LABEL			
CDfree	Samples printed with paste 1	**CD2**	Samples printed with paste 2
Cdfree_1xHLWD	Paste 1 was used to print the sample and the sample was subjected to one wash cycle.	**CD2_1xHLWD**	Paste 2 was used to print the sample and the sample was subjected to one wash cycle.

After printing, a wash cycle was carried out in accordance with standard EN ISO 6330:2012 [ISO 6330:2012] using a detergent without the addition of optical brighteners at a ratio of 1:20 to test the durability of the print on cellulose material.

Physico-chemical changes in cotton samples were investigated using Fourier transform infrared spectroscopy in the attenuated total reflectance technique (FTIR-ATR) (Perkin Elmer, Spectrum 100 software). Four scans with a resolution of 4 cm^{-1} between 4000 cm^{-1} and 380 cm^{-1} were performed for each sample, and the spectra obtained were processed using the Spectrum 100 software package, Perkin Elmer. The samples were scanned with a high-resolution scanning electron microscope (FE-SEM), Tescan, MIRA\\LMU, Czech Republic, at different magnifications to examine the morphological surface characteristics and to confirm the bonding of the β-cyclodextrin particles to the cellulose material. Prior to scanning, all samples were coated with a gold-palladium mixture in an SC7620 Sputter Coater Emitech Steamer. The rate of discharge from the inclusive complexes was measured subjectively by periodically testing the sample scent intensity. The samples were individually packed in plastic bags and left there for 7 days. They were tested by an 8-member committee, which rated the samples with an odour intensity of 1 to 5 (1 – no odour; 5 – intense odour). After the first day of testing, the samples were left strictly separated outdoors at room temperature. The tests were repeated after 3, 8 and 10 days.

3. RESULTS WITH DISCUSSION

Figure 1 shows the morphological characterization of the surface of the samples performed with a high-resolution scanning electron microscope (FE-SEM Tescan, MIRA\\LMU, Czech Republic).



a) CDfree | b) Cdfree_ 1xHLWD | c) CD2 | d) CD2 1xHLWD

Figure 1. Morphological characterization of the sample surface using FE-SEM at a magnification of 1000x

The surface morphology of the cotton sample printed with paste without β-cyclodextrin-essence oil inclusion complexes (Figure 1 a) and b)) clearly shows the presence of printing paste before (Cdfree) and after the wash cycle (Cdfree_ 1xHLWD). On the surface of the cellulose sample treated with printing paste 2 (CD2) (Figure 1 c) and d)), the presence of β-cyclodextrin-essence oil inclusion complexes before (CD2) and after the wash cycle (CD2_1xHLWD) is visible in addition to the printing paste, indicating their successful bonding. However, larger clusters of anglomerated particles of the inclusion complexes are visible on the CD2 sample, while the presence of inclusion complexes in the printing paste is visible after the wash cycle. This was also confirmed on a physico-chemical level by FTIR analysis of the samples using the ATR technique.

Figures 2 and 3 show the spectral bands of the printed samples, which had an inclusion complex of β-cyclodextrin and essential oil in their structure with the addition of natural pomegranate pigment. From the obtained spectral curves, it can be clearly seen that the sample has prominent peaks at a wavenumber of 1660 cm-1, indicating the presence of alkenes (C=C), which are a component of lemon essential oil. Stronger peaks in the range 2874 cm-1 to 2931 cm-1, corresponding to the stretching and vibration of C-H, have been found and which belong to a series of alkanes in lemon essential oil (Schulz 2002) and are absent in the spectral bands of cotton, pomegranate crystals and beta-cyclodextrin (Grgac 2022). A sharp peak at 1729 cm-1 indicates the presence of vinyl hydrocarbons, which are also found in citrus essential oils. In addition to the aforementioned changes in the spectral bands of the printed samples compared to the bands of the lemon essential oil used, changes are visible due to the presence of β-CD, which has very similar peaks to cellulose and enhances the signal of individual groups in the cellulose itself. The influence of dyes on printed cotton materials is very difficult to analyze, but it can be assumed that the pomegranate dye has influenced the elongation and amplification of the signal in the range of 1259 cm-1 to 1025 cm-1 resulting from stretching within the C-O groups of cellulose.

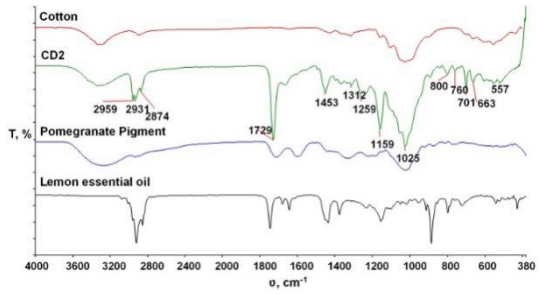


Figure 2. Spectra of cotton samples, CD2, pomegranate pigment, citrus essential oil (lemon essential oil) recorded on an FTIR-ATR spectrometer

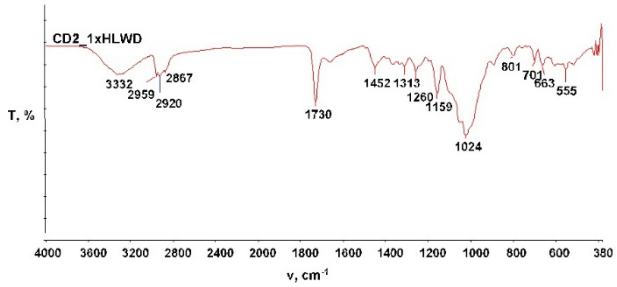


Figure 3. Spectrum of sample CD2 after maintenance cycle (CD2_1xHLWD)

Olfactometric determination of odor intensity on the first day of testing showed that the CDfree and CDfree _1xHLWD samples had no odor because they were not printed with a paste containing inclusion complexes of β-cyclodextrin and lemon essential oil. The CD2 samples were rated 5 by all examinees on the first day, and the same sample that was washed was rated 5 by 6 examinees and 4 by 2 examinees, indicating an intense odor. The tests on the third day showed the greatest decrease in odor in the sample with an average rating of 3.8 for the CD2 sample and 3.4 for the CD2_1xHLWD sample. After eight days in the air, the CD2_1xHLWD samples had a lower odor intensity (average value of 2.4) than the CD2 samples (average value of 3.1). After the 10th day, the samples washed after textile printing CD2_1xHLWD had a slightly lower odor intensity (with an average value of 2.4) than the samples that were not washed with CD2 (with an average value of 2.8). Based on all the recorded results of the subjective odor evaluation, we can conclude that the odor of the CD2 samples is gradually released over the course of 10 days, with the indication that it also remained present in the CD2_1xHLWD sample. This method of olfactometric investigation is subjective and depends on various parameters of the investigator, so the results obtained only serve as possible guidelines for further development of such samples.

4. CONCLUSIONS

In the middle of the last century, research was intensified to incorporate the principles of green chemistry into textile finishing processes, with the aim of achieving multifunctionality through the use of fabrics and processes that are considered biodegradable, non-toxic, environmentally friendly and economically acceptable. The development has not been smooth in the past and is still not smooth today, as a number of problems related to the stable bonding of various substances to textile substrates, which are mostly made of cellulose, occur on a daily basis. The aim of this work was to obtain a multifunctional material printed with a printing paste with the addition of β-cyclodextrin inclusion complexes and citrus essential oil using pomegranate as a natural dye. The success of the printing method for the stable binding inclusion complexes β-cyclodextrin essential oil lemon with cellulose was confirmed by characterising the surface morphology of the printed cellulose sample, where the presence of particles of the inclusion complexes of β-cyclodextrinand lemon essential oil is visible before and after the washing cycle. Physico-chemical changes of the printed samples with the addition of β-cyclodextrin-lemon essential oil inclusion complexes were monitored through the spectral bands obtained by recording the samples on an FTIR spectrometer in the ATR technique and clearly indicate the presence of a peak at the wave number 1660 cm^{-1}, which indicates the existence of alkenes (C=C), which are part of citrus essential oil. Stronger peaks were also recorded in the range of 2830 cm^{-1} to 2960 cm^{-1} corresponding to the stretching and vibration of C-H present in a series of alkanes in citrus essential oil. The olfactometric determination of the odor intensity showed that the odor remains in good intensity even after 10 days of aging of the samples, while the odor intensity decreases in the printed, washed sample, but is still present. Based on the results obtained, the success of binding the inclusion complexes of β-cyclodextrin and lemon essential oil to the cellulose material by printing is evident, and the research conducted provided valuable insights for the further development of multifunctional durable textile finishing.

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6. REFERENCES

Andrassy, M. and Čunko, R. 2005. Vlakna. Čakovec: ZRINSKI d. d.

Cie, C. 2015. Ink jet textile printing. New York: Elsevier.

Eastburn, S.D. and Tao, B.Y. 1994. „Applications of modified cyclodextrins.“ Biotechnol advances. 12 (2): 325–339.

Elgammal, M., Schneider, R. and Gradzielski, M. 2016. „Development of self-curable hybrid pigment inks by miniemulsion polymerization for inkjet printing of cotton fabrics.“ Dyes and Pigments. 133: 467-478.

Erkan, G., Sengül, K., Akkaş, M. and Büyükpoyraz, S. 2018. „Pigment printing of cotton fabrics with cyclodextrin and bifunctional reactive dye.“ Fascicle of textiles, Leatherwork. 19 (2): 43-48.

Grgac, S.F., Jablan, J., Inić, S., Malinar, R., Kovaček, I., Čorak, I. 2022. „The Effect of Ultrasonic Treatment on the Binding of the Inclusion Complex β-Cyclodextrin-peppermint Oil with Cellulose Material.“ Materials. 15: 470. https://doi.org/10.3390/ma15020470

Haji, A. 2020. „Functional Finishing of Textiles with β-Cyclodextrin.“ In Frontiers of Textile Materials: Polymers, Nanomaterials, Enzymes, and Advanced Modification Techniques, edited by Mohd Shabbir, Shakeel Ahmed, Javed N. Sheikh, 87–116. Beverly, Massachusetts, USA: Scrivener Publishing LLC.

Hebeish, A. A., Ragheb, A. A., Nassar, S. H., Allam, E. E. and El Thalouth, J. A. 2006. „Technological evaluation of reactive cyclodextrin in cotton printing with reactive and natural dyes.“ Journal of applied polymer science. 102 (1): 338-347.

Ibrahim, N. A. and El-Zairy, E. M. R. 2009. „Union disperse printing and UV-protecting of wool/polyester blend using a reactive β-cyclodextrin.“ Carbohydrate Polymers. 76 (2): 244-249.

Knittel, D. and Schollmeyer, E. 2000. „Technologies for a new century. Surface modification of fibres.“ Journal of the Textile Institute. 91 (3): 151-165.

Knittel, D. and Schollmeyer, E. 1996. „Beitraege zum Reaktivdruck-Substitution von Harnstoff.“ Textilveredlung. 31: 153-156.

Martin del Valle, E.M. 2004. „Cyclodextrins and their uses: a review.“ Process Biochemistry. 39 (9): 1033–1046.

Szejtli, J. 2003. „Cyclodextrins in the Textile Industry.“ Starch/Stärke. 55 (5): 191-196.

Voncina, B. and Vivod, V. 2013. Cyclodextrins in textile finishing. URL: https://www.intechopen.com/chapters/42001 (last accessed on 15. 01. 2025.).

Wan, T., Chen, D. and Bai, X. 2016. „Preparation and relative properties of dope-dyed polyurethane modified by β-cyclodextrin.“ Dyes and Pigments. 129: 18-23.
Zhao, C., Wang, C., Chen, K. and Yin, Y. 2017. „Improvement of ink-jet printing performances using β-cyclodextrin forming inclusion complex on cotton fabric.“ Fibers and Polymers. 18 (4): 619-624.
Sutlović, A., Glogar, M. I., Bešlić, S., Brlek, I. 2020. Prirodna bojila za tekstil – doprinos kreativnosti i održivosti, Tekstil. 69 (1-3): 1-10, ISSN: 0492-5882
ISO 6330:2012(en) Textiles — Domestic washing and drying procedures for textile testing
ASTM D3775-07, Standard Test Method for Warp (End) and Filling (Pick) Count of Woven Fabrics
Schulz, H., Schrader, B., Quilitzsch, R. and Steuer, B. 2002. „Quantitative analysis of various citrus oils by ATR/FT-IR and NIR-FT Raman spectroscopy.“ Applied spectroscopy. 56 (1): 117-124.

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POSTER PRESENTATION

FORMATION OF HALOCHROMIC POLYAMIDE/ELASTANE KNITTED FABRIC BY SCREEN PRINTING METHOD

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Abstract: *The possibility of designing a textile sensor that reacts to the pH value by changing its colour was studied in the research. The knitted fabric made of polyamide 6.6/elastane was screen-printed with the indicator dye bromophenol blue (BPB). The sensitivity of the knitted fabric to pH changes was evaluated spectrophotometrically by measuring the CIELAB colour values before and after immersing the printed samples in different buffer solutions, namely pH 2.2, 3, 4, 5, 6, 7, 9 and 11. At the same time, the pH sensitivity of the BPB dye in buffer solutions was also determined. The results showed that the designed halochromic knitted fabric is pH sensitive and the colour change is visible to the naked eye. The BPB dye in the printed samples reacts less strongly to the pH value than the BPB dye in buffer solutions. The halochromic effect of the printed sample is reversible, but the reversibility depends on the number of immersions in buffer solutions.*

Keywords: *polyamide/elastane knitted fabric, halochromism, screen printing, bromophenol blue.*

1. INTRODUCTION

Continuous progress in science and technology is the key to the development of society. In the fields of medicine, health and hygiene, value-added textiles, including smart textiles and wearable technologies, represent an important market segment. In recent years, there has been a great demand for human health monitoring (Sajovic, 2023). This is due to the health issues that people have faced in the last two decades due to the rapid development of the world, climate change and stressful working environments. Monitoring the spread of diseases that lead to more complicated and risky surgical interventions and cures is a less financially beneficial method than monitoring the health of middle-aged people. The letter could serve as a preventive measure for a healthier life in old age. For this reason, the development of chromic materials that respond to changes in the environment such as temperature, UV light and pH with a colour change is crucial as they have potential applications in health monitoring, environmental sensing and wearable technologies. Chromic materials are known as passive smart materials. The colour change is usually reversible and visible to the naked eye (Bamfield, 2018). By applying chromic dyes or pigments to a textile substrate, a textile-based chromic sensor can be produced that can change colour in response to certain changes in the environment (Christie, 2013). Such a dye can change from a colourless to a coloured state, from a coloured to a colourless state or from one colour to another. Dyes that react to pH changes are called halochromic dyes, which also include the indicator dyes.

The manufacture of disposable diapers for newborns and babies is primarily focused on high absorption of urine to keep children dry through day and night. As disposable diapers are a combination of different materials with different functional properties, they all serve the same purpose, which is to provide high absorbency while ensuring comfort and dryness when worn (Brunning, 2020). Due to the moderate biodegradability of disposable diapers (Czarnecka, 2022) and people's environmental awareness (Sachidhanandham, 2020), the use of cloth diapers is increasing year on year. There are disposable diapers on the market that already contain the indicator dye bromophenol blue (Brunning, 2020), which is marketed by manufacturers as an indicator dye for the wetness of the diaper with urine, but we have not seen the indicator dye in cloth diapers. Therefore, we focused our research on the formation of halochromic textiles by applying the halochromic dye bromophenol blue to knitted polyamide 6.6/elastane fabrics using a flat screen-printing process to develop a flexible textile sensor. If the colour of such a diaper changes, parents could be warned that the wet diaper should be replaced with a dry diaper.

In the study, polyamide 6.6/elastane knitted fabric was screen-printed with the indicator dye bromophenol blue. The time required for the printed fabric to change colour after immersion in buffer solutions with different pH values was recorded. In addition, the reversibility of the colour change after repeated immersion of the printed samples in buffer solutions with a pH value of 2.2 and 7 was determined.

2. EXPERIMENTAL

2.1 Knitted fabric

White knitted fabric made of 91 % polyamide 6.6 and 9 % elastane with a density of 20 wales/cm and 28 courses/cm and mass per surface area of 200 g/m^2 producer of Inplet pletiva, d.o.o., Sevnica, Slovenia.

2.1 Dye

In the research indicator dye 3,'3",5,'5"- Tetrabromophenol Sulfonephthalein or Bromophenol blue (BPB) with empirical formula of $C_{19}H_{10}Br_4O_5S$ and molecular mass of 669.96 g/mol (Sigma-Aldrich, USA) was used. The structural formula of the dye is presented in Figure 1.

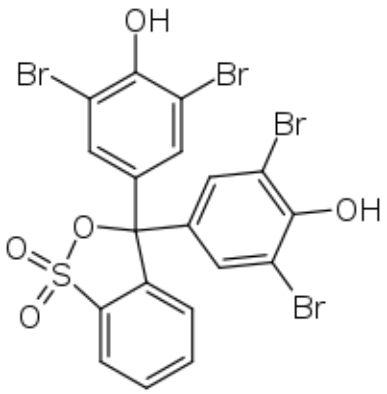


Figure 1: Bromophenol blue dye

2.2 Thickening agent and auxiliaries

The following chemicals were used to produce the printing paste: thickening agent Prisulon DCA 130 (CHT, Switzerland), which is a polygalactomannan ether, urea (Acrosorganics, The Netherlands) which is a hydrotropic agent and increases the solubility of the dye, tiodiglycol Glyezyin A (BASF, Germany) to improve the solubility of the dye and ammonium sulphate $(NH_4)_2SO_4$ (Fluka, The Netherlands) which is responsible for the acidic medium of the printing paste were used in the study. The McIlvain buffer system was used to prepare buffer solutions with a pH of 2.2, 3, 4, 5, 6 and 7, which required 0.2 M solution of disodium hydrogen phosphate (Na_2HPO_4) and 0.1 M solution of citric acid ($C_6H_8O_7$). Buffer solutions already prepared by Kefo, Slovenia, were used for pH 9 and 11.

2.3 Preparation of knitted fabric for printing

The knitted fabric was soaped with 0.5 g/L non-ionic soaping agent Etolat OA138 (Orka, Ljubljana) in a Gorenje WA 844T household washing machine at 40 °C, using a washing programme for synthetics with a duration of 59 minutes and 800 rpm. After washing, two rinses were carried out at 30 °C for 20 minutes at 800 rpm. The washed knitwear was dried in the Gorenje D72GBL drying machine at a lower temperature using the drying programme for synthetics.

2.4 Preparation of the printing paste

Printing paste was prepared according to the receipt written in Table 1.

Table 1: Composition of the printing paste

Ingredient	Concentration (g/kg)
dye BPB	3
urea	50
H_2O, cold, distilled	57
H_2O, boiling, disilled	280
Glyezin A	50
Prisulon DCA 130 13%	500
$(NH_4)_2$ SO_4 1 : 2	60

2.1 Printing and aftertreatments

Samples of knitted fabric were printed with the use of electromagnetic laboratory printing machine Mini MFD R 390, (J. Zimmer, Austria) using the following parameters: diameter of the printing knife of 4 mm, speed of the printing knife passes of 80%, degree of magnetic pressure of 3, number of printing knife passes of 2. The fabric samples were printed with a blank flat screen stencil, with a mesh size of 77 threads/cm. After printing, the samples were dried at 100 °C for 1 minute and steaming normally for 20 min at 100–102 °C in a laboratory Ink jet textile steamer. The wet fastness of the printed samples of PA6 was increased by cold reserving with 1.5 g/L Cibatex PA (Huntsman, Germany) at pH 3.5–4 with 60% CH_3COOH (Sigma Aldrich Chemie, Germany) for 10 min. Then the samples were rinsed with cold water, soaped with 1 g/L Tinegal W (Huntsman, Germany) for 15 min at 50 °C and rinsed with warm and then cold water at the end. The samples were then dried at 100 °C for 1 minute.

2.2 Methods of testing

Spectrophotometric measurements

The colour of the printed samples was measured with a Datacolor Spectro 1050 (Datacolor, USA) spectrophotometer and CIELAB colour space. Measurements were made in the range 400–700 nm with a d/8° measurement geometry, under D_{65} illumination, 10° standard observer, with specular reflectance included with a 9-mm aperture. Four layers of the sample were used for the measurements. An average of 10 measurements was taken for each sample. The CIELAB values were determined on unprinted and printed samples. The colour strength (*K/S*) was calculated from the reflectance values according to the Kubelka-Munk equation (1):

$$\frac{K}{S} = \frac{(1-R)^2}{2R} \qquad (1)$$

where *K* is absorption coefficient, *S* is scattering coefficient and *R* is the reflectance factor.

Determination of the pH sensitivity of the printed samples to the colour change

The colour response of the printed samples to pH was determined after the samples were immersed in buffer solutions with different pH values, namely 2.2, 3, 4, 5, 6, 7, 9 and 11. After 15 minutes, all samples were removed from the buffer solutions, air-dried and analysed spectrophotometrically by measuring CIELAB values and reflectance in the range of 400–700 nm.

Determination of the pH sensitivity of the dye in buffer solutions

A stock solution of BPB dye was prepared by dissolving 0.022 g of BPB in 10 ml of distilled water. 0.3 ml of the BPB solution was added to 20 ml of buffer solutions with different pH values and the absorbance spectrum of the BPB dye was recorded with the Lambda 850+ UV-Vis spectrophotometer (Perkin Elmer, GB) in the range of 400–700 nm.

Determination of the reversibility of the pH-sensitive dye on printed samples

Before the printed sample was immersed in the buffer solution, the CIELAB values of the sample were measured. Five measurements were taken, and the result represents the average value. The sample was then immersed in a buffer solution with a pH value of 2.2, in which the strongest colour change was observed. The samples were left in the solution for 15 minutes and then allowed to air dry before the CIELAB values were measured. Five CIELAB readings were taken on the dry sample, and the result represents the average value. The same sample was then immersed in a pH 7 buffer for 15 minutes, air dried and the CIELAB values were measured again, taking 5 measurements of the CIELAB values. The process of immersing the printed sample in the pH 2.2 buffer and then in pH 7 buffer was repeated 9 times.

3. RESULTS AND DISCUSSION

The CIELAB values of the printed samples before (S) and after immersion (S_pH) in buffer solutions with different pH values are summarised in Table 1. It can be seen from the values that the colour of the S_pH samples has changed compared to the S sample. While the CIE L^* values of the S_pH samples do not change significantly compared to the S sample, the CIE a^* values decrease sharply and become negative in buffers with pH 2.2, 3 and 4 and then become positive again as the pH value increases. This means that the samples turn green at lower pH values (from pH 2.2 to pH 4) or become less green and redder as the pH increases from pH 5 to pH 11. The CIE b^* values of the S_pH sample become less negative after immersion in the buffers of pH 2.2, 3 and 4 and almost reach the CIE b* values of the S sample when the pH increases from pH 5 to pH 11. This means that the S_pH samples immersed in the buffers pH 2.2, 3, 4 and 5 become less blue and more yellow, but when the pH increases from 6 to 11, they become slightly bluer than the S sample. The chroma of the S_pH samples decreases after immersion in buffers of pH 2.2, 3, 4 and 5, indicating that the colour of the samples is less saturated, but increases again as the pH increases from 6 to 11, indicating that the colour of the samples is more saturated. The calculated colour difference (ΔE^*_{ab}) between the S and S_pH samples decreases with increasing pH from 2.2 to 11. This means that a pH-sensitive knitted fabric has been successfully designed. Since the highest colour difference ΔE^*_{ab} = 37.81) was achieved at the lowest pH value of 2.2, this means that the colour change is clearly visible even to the naked eye. The colour change of the printed samples after immersion in the buffer solutions was also visible to the naked eye in buffers with a pH value of 2.2 (ΔE^*_{ab} = 37.81) to pH 5 (ΔE^*_{ab} = 2.22). The reversibility of the colour on samples printed with BPB dye is shown in Figure 2.

Table 1: CIELAB colur values, chroma (C^*_{ab}) and hue (h_{ab}) of the printed samples before (S) and after immersion (S_pH) in buffer solutions with different pH values

Sample	L^*	a^*	b^*	C^*_{ab}	h_{ab} (°)	DE^*_{ab}
S	58.27	1.83	-43.51	43.55	272.40	/
S_pH 2.2	59.75	-11.86	-8.30	14.48	214.98	37.81
S_pH 3	58.02	-9.23	-20.38	22.37	245.62	25.64
S_pH 4	57.22	-3.44	-34.59	34.76	264.33	10.41
S_pH 5	57.05	0.68	-42.06	42.06	270.92	2.22
S_pH 6	57.34	2.15	-44.32	44.37	272.77	1.27
S_pH 7	57.21	2.50	-45.16	45.23	273.17	2.07
S_pH 9	57.48	2.41	-44.32	44.39	273.10	1.27
S_pH 11	57.77	2.17	-44.60	44.65	272.78	1.25

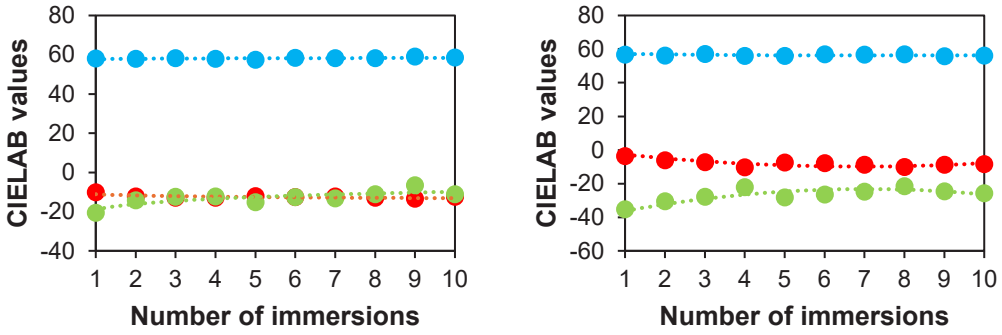


Figure 2: Changes of CIELAB values before and after different number of immersions into buffer solution of pH 2.2 (left) and pH 7 (right). CIE *L**, CIE *a**, CIE *b**

Figure 2 shows that the colour change on the printed fabric is reversible. It varies with the number of immersions in the buffer solution. The CIELAB colour values after immersing the samples first in the pH 2.2 buffer solution and then in pH 7 buffer solution show that the reversibility is maintained but varies with the number of immersions.

In Figure 3 the K/S values versus wavelength of printed samples before and after immersion into buffer solutions of different pH values are presented. In can be seen a significant decrease in the *K/S* value at 600 nm for the samples immersed in buffer solutions with a pH of 2.2 and 3, and an increase in the *K/S* value at 600 nm for the samples immersed in buffer solutions from pH 4 to pH 11, compared to the sample before immersion (Figure 3). At 450 nm, an additional increase in the *K/S* values of the printed samples immersed in buffer solutions from pH 2.2 to pH 4 is observed.

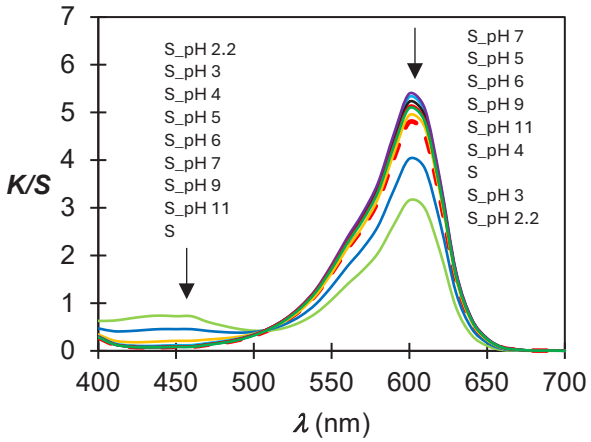


Figure 3: *K/S* values of the printed samples as a function of the wavelength before immersion in buffer solutions with different pH values and after immersion.
S, S_pH 2.2, S_pH 3, S_pH 4, S_pH 5, S_pH 6, S_pH 7, S_pH 9, S_pH 11

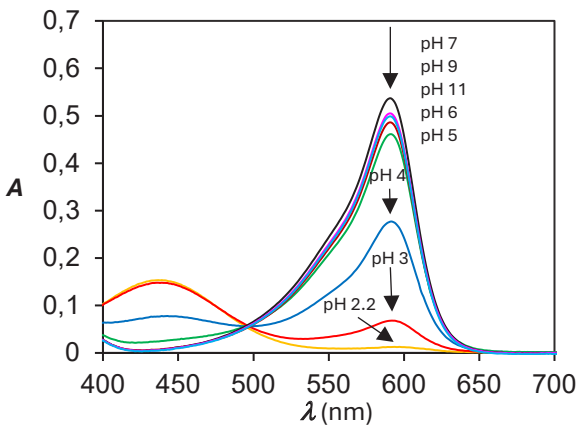


Figure 4: Absorption spectra of BPB dye in buffer solutions of different pH values
pH 2.2, pH 3, pH 4, pH 5, pH 6, pH 7, pH 9, pH 11

In contrast to the pH sensitivity of the BPB dye bound to the knitted fabric, the sensitivity of the BPB dye in buffer solutions is different (Figure 4), as a comparison between Figure 3 and Figure 4 shows. The BPB dye reacts more strongly to pH changes in the buffer solution (Figure 4) than the dye bound to the knitted fabric (Figure 3). The BPB dye reacts more strongly to the pH value in the solution than on the knitted fabric. This is due to the formation of dye-fibre interactions, which hinder the protonation and deprotonation of the dye, compared to the dye in the

buffer solution, whose protonation and deprotonation are less hindered. When the pH was lowered from pH 4 to pH 2.2, there was a hypochromatic change in the absorption maximum of the BPB dye at 591 nm and the appearance of a new peak at 440 nm. The latter indicates that the dye is changing into a protonated form, resulting in a colour change from blue-violet to yellow-green. When the BPB dye is bound to the knitted fabric and then immersed in buffer solutions with different pH values, a decrease in the *K/S* value at 600 nm can be observed in Figure 3 when the pH drops from 4 to pH 2.2, and an increase in the *K/S* value at 450 nm can be observed. The latter shows that the dye BPB bound to the knitted fabric is sensitive to pH but reacts worse to pH than when the dye is present in buffer solutions. The pH sensitivity of a BPB dye bound to knitted fabric depends not only on the strength of the dye-fibre interactions and thus the ability of the dye to protonate or deprotonate, but also on the wetting speed of the textile with the buffer solution (Van den Schueren, 2012). Since the wetting speed of textiles with the buffer solution depends mainly on the composition of the textile, the construction parameters of the textile (density and thickness of the textile, fineness of the yarns and number of yarn turns) (Van der Schueren, 2010) and the finishes that can reduce the hydrophilicity of the material (Stojkoski, 2020). In our case, the printed knitted fabrics were wetted in 15 to 20 seconds, while the colour change was observed after 15-20 minutes.

4. CONCLUSION

In the study, a pH-sensitive textile sensor was created by applying the dye bromophenol blue to a polyamide/elastane knitted fabric that reacts in the studied pH range from pH 2.2 to pH 11 and whose colour change is visible to the naked eye. Direct flat screen printing is a suitable method for developing pH-sensitive textiles with the indicator dye bromophenol blue. The colour reaction of the indicator dye used in the buffer solution differs from that of the dye bound to the knitted fabric, whereby the dye-fibre interactions, which hinder the protonation or deprotonation of the indicator dye bromophenol blue, are of decisive importance.

5. REFERENCES

Bamfield, P. 2001. *Chromic Phenomena: Technological Applications of Colour Chemistry*. Cambridge: Royal Society of Chemistry, pp. 1–8.

Brunning, A. The chemistry of disposable nappies: absorbency, wetness indicators and waste. URL: https://www.compoundchem.com/2020/01/14/nappies/(last accessed on 31.1.2025).

Christie, R.M. 2013. Chromic materials for technical textile applications. In *Advances in the Dyeing and Finishing of Technical Textiles*. pp. 3–36., Oxford, Cambridge, Philadelphia, New Delhi: Woodhead Publishing.

Czarnecka, E., Walczak, M., Kumar, G., Piechota, G. and Nowaczyk, J. 2022. Degradation of biodegradable diapers as an element circular economy in waste containing various plastics. *Journal of Cleaner Production*. *377*, 134426.

Sachidhanandham, A., and Priyanka, M. 2020. A review on convenience and pollution caused by baby diapers. *Science and Technology Development Journal*. *23*(3): 699–712.

Sajovic, I., Kert, M., and Boh Podgornik, B. 2023. Smart textiles: A review and bibliometric mapping. *Applied Sciences*. *13*(18): 10489.

Stojkoski V. and Kert M. 2020. Design of pH responsive textile as a sensor material for acid rain. *Polymers*.12(10), 2251.

Van der Schueren, L. and De Clerck, K. 2010. The use for pH-indicator dyes for pH-sensitive textile materials. *Textile Research Journal*. 80(7): 590–603.

Van der Schueren, L. and De Clerck, K. 2012. Coloration and application of pH-sensitive dyes on textile materials. *Coloration Tehnology*. 128(2): 82–90.

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POSTER PRESENTATION

DURABILITY OF THERMOCHROMIC INK PRINTED ON TEXTILE

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Abstract: *This study examines the stability of screen-printed thermochromic ink on textiles under various environmental conditions. RED 37C Thermochromic WB Screen ink was printed on cotton fabric using a semi-automatic INO Print 2002 E-70 machine. The durability of prints was assessed through optical density and CIELab* colorimetric measurements before and after exposure to moist-heat (80°C, 65% RH, 48h), xenon lamp light (48h), and dry rubbing (500 strokes). Results showed minimal optical density changes after moist-heat treatment, while light exposure and dry rubbing significantly affected magenta, reducing its optical density by nearly 50%. Colorimetric analysis revealed a substantial colour difference after light exposure, making the shift highly visible. Dry rubbing also caused noticeable changes. The textile itself remained largely unaffected. Findings confirm the sensitivity of thermochromic ink to environmental factors, particularly light, emphasizing the need for improved formulations for enhanced durability.*

Keywords: *Thermochromic ink, optical density, colour change, light fastness, moist-heat treatment, dry rubbing.*

1. INTRODUCTION

Chromisem refers to the alteration of colour, and substances capable of demonstrating this phenomenon are termed chromic materials (Bamfield, 2010). Thermochromism is the phenomenon observed in thermochromic materials, where the colour changes in response to temperature variations. Thermochromic materials offer innovative possibilities for various applications, including textiles. These dynamic materials enable both functional and aesthetic enhancements, making them ideal for smart textiles used in fashion, healthcare, functional clothing, and safety industries (Vu et al., 2024). By integrating thermochromic inks through printing techniques, textiles can exhibit temperature-sensitive visual changes, providing interactive and practical solutions.

The two major types of thermochromic-active materials are leuco dye-based composites and thermochromic liquid crystals (Seeboth and Lotzsch, 2008). Leuco dyes are a prominent class of organic thermochromic compounds. They undergo reversible colour changes due to temperature-induced isomerization, transitioning between colourless and coloured forms (Vu et al., 2024). However, the leuco dye-based thermochromic system is highly sensitive to UV radiation, as colour transformation may also occur when exposed to UV, which can break the lactone ring (Nagare et al., 2024). Organic thermochromic materials, whether leuco dye-based or thermochromic liquid crystals, are known for their low stability against light, chemicals, and high temperatures (Strižić Jakovljević et al., 2020). Friškovec et al. (2013) reported poor light fastness and stability at high temperatures. Similarly, Cabral et al. (2020) highlighted poor light fastness, though they also noted good rub and wash stability of thermochromic pigments screen-printed on a 50% cotton and 50% polyester substrate. The performance and durability of thermochromic inks printed on textiles, particularly their long-term usability under various conditions, were further studied by Cabral et al. (2023). They found out that although washing and rubbing can cause varying degrees of lightening in the sample colours, the results emphasized the poor light stability of thermochromic ink screen printed on polyamide/elastane textile.

In our study thermochromic ink was screen printed onto textile, made from pure cotton. The objective of our research was to determine the stability of the prints under light exposure, moist-heat treatment, and dry rubbing.

2. EXPERIMENTAL

2.1 Materials

The thermochromic ink used for printing onto textiles was RED 37C Thermochromic WB Screen, produced by Special FX Creative (Good Life Innovations Ltd. Newhaven, UK). It is a reversible thermochromic water based ink that appears red at room temperature and becomes colourless at high temperatures. By using a heat source of 47ºC or above the ink becomes transparent and reveals what is beneath printed surface. For printing the INO Print 2002 E-70 screen printing machine (GrafcoAST, Camalò di Povegliano, Italy), a semi-automatic screen printing machine was used. A textile printing substrate used was knitted cotton fabric of 150 g/m^2 basis weight. In Figure 1 the printed sample is seen.

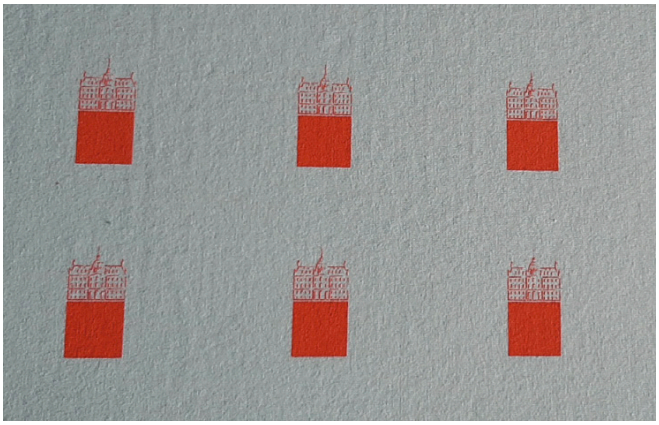


Figure 1: Printed textile sample

2.2 Methods

Printed textile was aged using standard techniques for accelerated aging: moist-heat based on standard SIST ISO 5630-3 and aging with a Xenon lamp based on standard ISO 105-B02. Moist-heat treatment was performed at temperature of 80°C and 65% relative humidity. The light fastness test was conducted by exposing a textile specimen to artificial light under specified conditions: 35°C chamber temperature, 50°C black standard temperature, 35% relative humidity. For determination of the light fastness a Xenotest Alpha (Atlas, USA) was used. The apparatus simulates and accelerates the natural weathering process, providing reliable results concerning the long-term behaviour of materials. In both cases, the exposure times was 48 h.
The dry rub fastness test was performed using a rubbing device Param RT-01 (Labthink Instruments Co., Medford, MA, USA), according to the ASTM D5264-98 standard (mass of weights: 900 g; speed: 106 cpm). The printed textile was rubbed against the unprinted paper in 500 strokes. The colour change was determined using spectrophotometric measurements.

Spectrophotometric measurements were conducted on the printed textile before and after exposure to the previously mentioned treatments. The optical density (OD) of the prints, which is a measure of the light absorbance of a material, was measured using a Gretag Matcbeth D19C densitometer (X-Rite, Grand Rapids, MI, USA). The colorimetric properties of the print were determined using X-Rite Eye-One i1Pro (X-Rite, Grand Rapits, MI, USA) spectrophotometer (measurement geometry: 45/0, observation angle: 10°, light source: D65 and 3.6 mm measuring aperture). The colour difference (ΔE*ab) was calculated according to Eq. (1). The colorimetric value of print before treatment was taken as a reference.

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad (1)$$

In the Eq. 1 $\Delta L^* = L^*_0 - L^*_T$; $\Delta a^* = a^*_0 - a^*_T$; $\Delta b^* = b^*_0 - b^*_T$ are the differences calculated for untreated (0) and treated (T) print.

3. RESULTS WITH DISCUSSION

By measuring the optical density and colorimetric properties of the print, the durability of thermochromic ink can be evaluated.

3.1 Optical density

Results of measured change in the optical density of printed thermochromic ink after exposure to different environmental factors are shown in Figure 2. In the subtractive CMYK model the red colour is created by combining magenta (M) and yellow (Y) inks. Optical density measurements are reported as contributions of C, M, Y, and K, even if some of these values (like cyan (C) or black (K)) are zero for pure red. Measurements of the optical density of prints after exposure to various treatments revealed differing effects on the CMYK colours. The optical density values under the influence of moist-heat treatment remain almost unchanged, with magenta and yellow showing a negligible change of -0.07. Exposure to light and dry-rubbing have a greater impact. After both treatments, the largest change is observed in magenta, where the optical density value is nearly halved, while for yellow and black, it decreases by 25% and 30%, respectively. Visual assessment showed that the differences are barely visible to the naked eye.

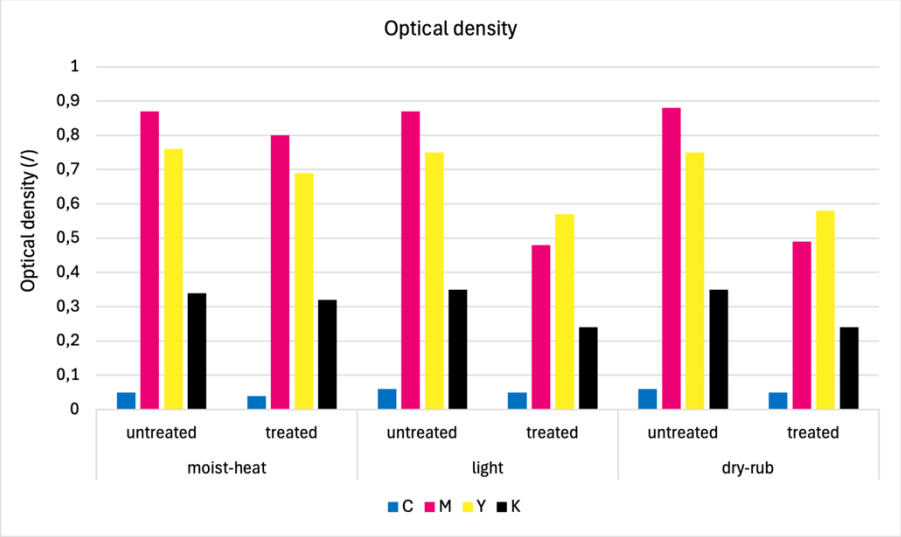


Figure 2: Optical density of printed thermochromic ink before and after different treatments

3.2 Colorimetric properties

Among colorimetric properties, the CIELAB colour coordinates *L*, a** and *b** were determined. In Table 1 values measured before and after treatments are presented.

Table 1: Colorimetric values *L*, a** and *b** of the textile and print determined before treatment and 48 hours after, given as mean value and standard deviation.

	Untreated		Moist-heat		Light		Dry-rub
	textile	**print**	**textile**	**print**	**textile**	**print**	**print**
L*	92.10 (0.22)	61.95 (0.48)	91.25 (0.34)	64.01 (0.45)	91.92 (0.49)	71.30 (0.31)	62.76 (0.22)
a*	2.14 (0.01)	56.35 (0.90)	2.13 (0.54)	52.78 (0.50)	1.27 (0.03)	34.79 (0.61)	53.83 (0.66)
b*	-6.37 (0.12)	29.72 (0.82)	-4.03 (0.08)	27.09 (0.45)	-2.66 (0.14)	28.39 (0.88)	27.20 (0.51)

Colorimetric values changed after moist-heta treatment, with lightness (*L**) changing less than the other two components. The greatest change was observed in the *a** component. In Figure 3 the colour differences, ΔE^*_{ab} between the printed thermochromic ink before and after exposure to different treatments is presented. The colour difference ΔE^*_{ab} is greater than 3, indicating that it is visible. Increased temperature also affects the textile itself, with the *b** component showing the most significant change. For the textile, the colour difference is smaller, below 3, meaning it is still visible and can partially contribute to the observed colour difference of the print. Colorimetric values changed significantly after light exposure. By far, the greatest change was observed in the *a** component, while lightness, *L** also changed considerably, whereas the *b** component changed the least (Table 1). The colour difference, ΔE^*_{ab} of 24.4 is unacceptably high and disruptive. Despite the large difference in colorimetric values after light exposure, the standard deviation remains low, indicating uniform colour changes in the print under light exposure. Light exposure has only a minor impact on the colorimetric properties of the textile itself, with slight changes noted only in the *b** component. The influence of the textile on changes in the colorimetric properties of the print after light exposure is negligible. The textile is also resistant to dry rubbing, with no change in its colour. The colorimetric differences on the print are visible, after rubbing, slight changes were observed in the *a** and *b** components. The colour difference, ΔE^*_{ab} after dry-rub of the printed thermochromic ink on the textile is 4.20, making it clearly visible and noticeable.

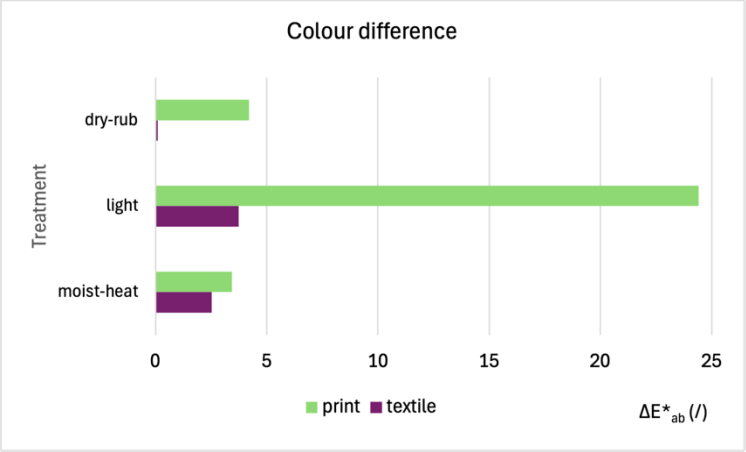


Figure 3: Colour difference of textile and printed thermochromic ink after different treatments

4. CONCLUSIONS

The results indicate that the durability of thermochromic ink printed onto the textile varies depending on the environmental factors to which it is exposed. Our research confirmed that thermochromic ink is sensitive to external factors, particularly light. Moist-heat treatment causes minor colour shifts and negligible changes in the optical density of magenta and yellow. However, exposure to light and dry rubbing significantly affect the ink, particularly magenta, whose optical density is nearly halved. The light exposure leads to the most noticeable changes, particularly in the *a** component, and lightness, leading to disruptive colour change. Dry rubbing also results in visible alterations. The textile itself remains largely unaffected by different treatments. Overall, the findings emphasize the need for careful consideration of environmental factors when using thermochromic inks on textiles, as exposure to heat, light, and friction can influence both optical and colorimetric properties.

5. ACKNOWLEDGEMENT:

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6. REFERENCES:

Bamfield, P., 2010. Chromic phenomena: technological applications of colour chemistry. Cambridge: Royal Society of Chemistry, pp. 75–95.
Cabral, I., Souto, A.P., and Worbin, L., 2020. Experimental work: Thermochromic Leuco dyes. In: I. Cabral, A.P. Souto, and L. Worbin, eds. Dynamic Light Filters: Smart Materials Applied to Textile Design. Cham: Springer International Publishing, pp.33–63.
Cabral, I., Santiago, D., and Steffens, F., 2023. Chromic textiles: Colour fastness properties and irreversible colour change behaviour of textiles screen printed with thermochromic, photochromic and hydrochromic colourants. Coloration Technology, 139(2), pp.200-208.
Friškovec, M., Kulčar, R., and Klanjšek Gunde, M., 2013. Light fastness and high-temperature stability of thermochromic printing inks. Coloration Technology, 129, pp. 214-222.
Nagare, S.M., Hakami, A., Biswas, P.K., et al., 2024. A review of thermochromic materials for coating applications: production, protection, and degradation of organic thermochromic materials. Journal of Coatings Technology and Research. https://doi.org/10.1007/s11998-024-00982-9
Seeboth, A. and Lötzsch, D., 2008. Thermochromic phenomena in polymers. Shrewsbury: Smithers Rapra Technology.
Strižić Jakovljević, M., Kulčar, R., Friškovec, M., Lozo, B., and Klanjšek Gunde, M., 2020. Light fastness of liquid crystal-based thermochromic printing inks. Dyes and Pigments, 180, p.108482.
Vu N.T., Nguyen, M.T., Hoan, X.N., Duc Nguyen, D., Chung, W., Chang, S.W. and Duc La, D., 2024. Exploring the potential of organic thermochromic materials in textile applications. Journal of Materials Science, 59, pp.14924–14947.

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POSTER PRESENTATION

THE AUXETIC PROPERTIES OF WOVEN FABRIC

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Abstract: *Auxetic woven fabrics exhibit a negative Poisson's ratio (NPR), which means that they expand laterally when stretched. This unique property improves energy absorption and flexibility and makes them valuable for various applications. In this study, the auxetic behaviour of woven fabrics is investigated by analysing how the jacquard pattern and the weft density influence the Poisson's ratio. Two different patterns were created to weave fabrics in a complex double and double weft weave, using elastic and non-elastic yarns in the weft at three different weft densities. The results show that both the pattern and the weave contribute to NPR at different weft densities. A higher weft density leads to a more stable auxetic behaviour over a larger strain range, while a lower weft density increases the auxetic effects but with lower strain persistence. These results emphasise the potential of auxetic woven fabrics for applications in sportswear, compression garments and flexible textiles.*

Keywords: *Poisson's ratio, auxetic woven fabric, PBT, jacquard patterns, weave, density*

1. INTRODUCTION

An auxetic woven fabric is a fabric with negative Poisson's ratio (NPR), which means that when it is stretched in one direction, it expands laterally (in the perpendicular direction) instead of contracting like most conventional fabrics. Compared to conventional materials, the negative Poisson's ratio gives auxetic textiles special properties, improved properties such as mechanical properties, ductility, fracture toughness, energy absorption capacity and the like, which offer more application possibilities (EEvans, K. 1991). Most early research on auxetic textiles focused on knitted fabrics as they are inherently stretchable and flexible, but woven fabrics have become an increasingly important field of research as they exhibit different mechanical properties and structural behaviour compared to knitted fabrics. There are two main approaches to the production of auxetic woven fabric. One uses auxetic fibres or yarns and the other uses conventional yarns, focusing on the geometric arrangement of the fabric structures to achieve auxetic behaviour (Zulifqar et al., 2017; Cao et al., 2019; Széles, 2023). The production of auxetic woven fabrics from conventional yarns with lower thickness and better formability that can be easily formed into garments is still a major challenge for weaving specialists (Zulifqar et al., 2017; Cao et al., 2019; Széles, 2023).

To investigate the auxetic potential of woven fabrics for apparel purposes, we produced two jacquard patterns in three different weft densities. We used elastic PBT yarns and inelastic CO yarns in the weft and investigated how the different patterns and weft densities impact the Poisson's ratio. The auxetic behaviour is evaluated based on the woven structure, pattern shape and weave of the fabric including the variable density factor.

2. EXPERIMENTAL

2.1 Materials and methods

Six fabric samples were designed by using the Arahne CAD programme for weaving (Arahne d.o.o., Slovenia). They were woven on the same cotton warp (2 x 8 tex), with the same settings and conditions, on the Minifaber weaving machine with electronic Jacquard T.I.S. (Minifaber, Italy). To achieve an auxetic and aesthetic effect of the fabric, we chose two patterns (Fig. 1). We used diagonal geometric patterns to achieve a better auxetic effect. The warp density was 40 threads/cm, the weft density varied between 35, 40 and 45 threads/cm for Sample 1 and

25, 30 and 35 threads/cm for Sample 2. Sample 1 fabrics were woven in a complex double 6-end twill weave (Fig. 1 - left), Sample 2 were woven in weft-backed weave of 4-end twill and plain weave (Fig. 1 – right), both woven with a 1:1 sequence (1 white PBT multifilament 2 x 7.8 tex : CO, 2x8 tex). After weaving, the fabrics were heat treated with steam to gain the elastic potential of the PBT weft threads. The different densities for the Sample 1 and Sample 2 were chosen because the woven structures are very different and the Sample 2 could not be woven with a weft density of more than 35 threads/cm, as the laboratory weaving machine is not equipped with a warp let-off motion that would allow this.

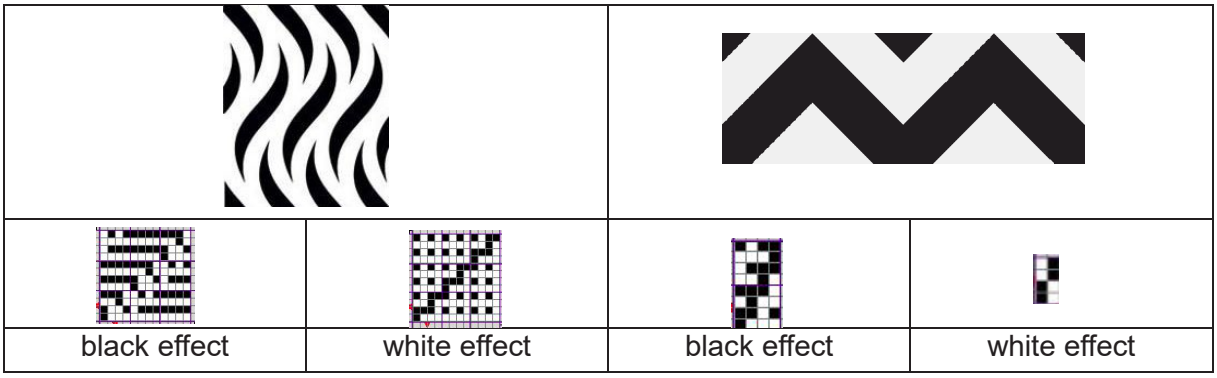


Figure1: Pattern and weave for Sample 1(left), pattern and weave for Sample 2 (right)

The tensile tests, which we recorded with a camera, were performed along the elastic range (weft direction) on an Instron 5567. The capacity of the load cell used was 500 N, the gauge length and tensile speed were set to 150 mm and 50 mm min^{-1} respectively. The results were analysed with images taken every 3 seconds.

3. RESULTS WITH DISCUSSION

The results of the Poisson's ratio values and the corresponding longitudinal strain of Sample 1 and Sample 2 with three different densities.

Table 1: Poisson's ratio values and corresponding longitudinal strains of fabrics with three different densities

Sample	Maximum negative Poisson's ratio	Corresponding longitudinal strain (%)	Poisson's ratio is negative up to longitudinal strain (%)
Sample 1_45	-0,76	6,67	60,00
Sample 1_40	-0,29	11,67	53,33
Sample 1_35	-1,51	1,67	41,67
Sample 2_35	-0,76	3,33	15,00
Sample 2_30	-1,43	1,67	23,33
Sample 2_25	-2,17	1,67	26,67

The results (Table 1) show that both samples exhibit auxetic behaviour (negative Poisson's ratio) at different weft densities, but the extent of this effect is different.

Sample 1 (at 45, 40, 35 threads/cm) generally maintains auxetic behaviour over a wider strain range than Sample 2. For Sample 2, the maximum negative Poisson's ratios are higher (indicating stronger auxetic behaviour), but this effect is rather short-lived, especially when the weft density decreases. For Sample 1, the negative Poisson's ratio decreases with decreasing weft density, but the fabric retains its auxetic behaviour over a wider strain range. For Sample 2, the negative Poisson's ratio becomes stronger (more negative) with decreasing weft density, but the auxetic behaviour is only maintained for a shorter range of longitudinal strain.

Figures 2 and 3 illustrate the variation in Poisson's ratio with increasing longitudinal strain for different patterns, weave structures and weft densities. The results confirm that the weave pattern and weft density significantly influence the auxetic properties. Higher weft densities contribute to a more stable auxetic effect over a wider strain range, while lower weft densities enhance auxetic behaviour but only at lower strains.

Sample 1 with complex double 6-end twill weave shows a strong initial auxetic effect, especially at the lower weft densities (35 threads/cm). However, the auxetic effect decreases after about 50% longitudinal strain.

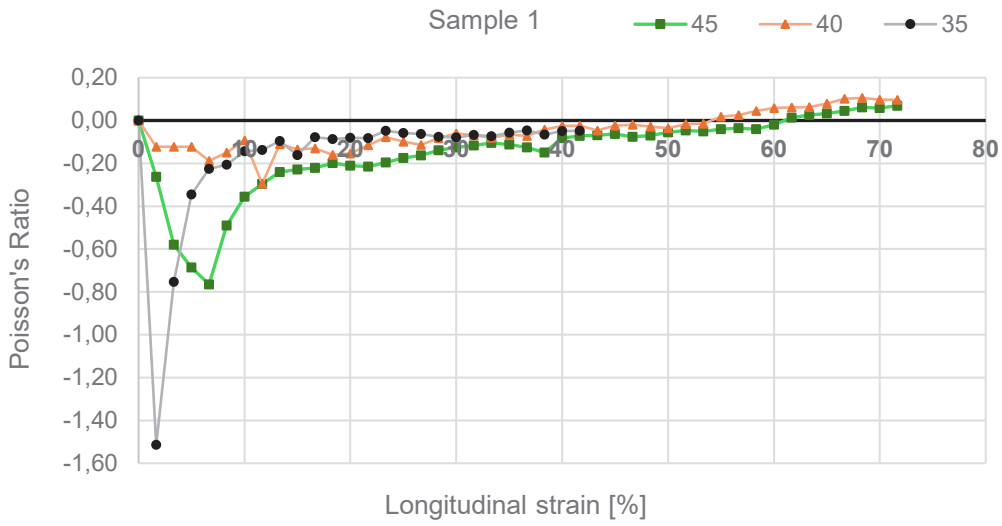


Figure 2: Poisson`s ratio vs. longitudinal strain curve of Sample 1 at three different weft densities

Sample 2 with double structure (4-end twill and plain) (Figure 3) exhibits a more stable auxetic response compared to Sample 1, whereby the values fluctuate slightly but remain predominantly negative, but the auxetic response disappears after about 15% – 20% longitudinal strain. The highest auxetic response is observed in the fabric with a lower weft density (25 threads/cm).

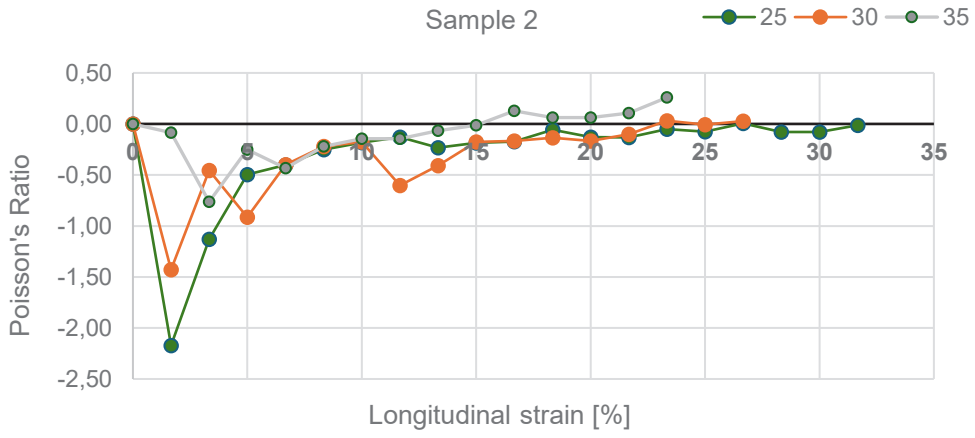


Figure 3: Poisson`s ratio vs. longitudinal strain curve of sample 2 at three different weft densities

3.1 Influence of weft density on the auxetic properties

Higher weft densities (Sample 1_ 45, 40 threads/cm) show a more stable auxetic behaviour with a wider range of deformations. Sample 1 shows the best auxetic response at a 45 threads/cm weft density. It does not have the maximum value of the negative Poisson's ratio, but with a value of -0.4 at 10 % strain and with values around -0.2 at 25 % strain, it offers adequate auxetic properties of the fabrics. In contrast to the Sample 1 with the lowest

density of 35 threads/cm, which shows the highest negative Poisson's ratio at 2.5% elongation, which already decreases rapidly at 5% elongation.

When comparing Figure 2 and Figure 3, we can see clear differences in the auxetic behaviour of the fabrics, which can be attributed to the different structure and weft density. The Sample 2 fabrics with a lower weft density (25, 30 threads/cm) shows a stronger auxetic effect with a limited range of strain (negative Poisson's ratio value of -0.5 to -1 at 5% strain and with values around -0.2 at 10-20% strain).

Weft density affects the auxetic potential of fabrics, but this is also strongly related to the woven structure of the fabric. The weave, which determines the number of interlacing points or the flotation of the threads, together with the thread density, determines the frictional surfaces between the threads, which prevent them from moving freely and taking up a new position during stretching of the fabric. Sample 1, woven in a non-stitched double weave, which allows greater shrinkage of the fabric immediately after heat treatment and consequently a higher auxetic potential than Sample 2, with a more compact weft structure.

4. CONCLUSIONS

For high performance applications (sportswear, activewear, sports compression or adaptive clothing), Sample 1 with a density of 45 threads/cm is the most suitable option with a maximum NPR of -0.76 and an extensive strain range of up to 60%. It offers both high auxetic behavior and good stretchability, which are crucial for comfort and fit in these applications. For moderate performance and low stretch, such as maternity wear, leggings and underwear, Sample 1 with a density of 40 threads/cm with a moderate NPR of -0.29 and a strain range of up to 53.33% would be suitable. Sample 2 with densities of 35, 30 and 25 threads/cm with strong auxetic effects but limited stretchability (due to low longitudinal strain) are more suitable for compression garments, medical textiles or other applications where controlled deformation is desired but high stretchability is not required. Regardless of the pattern, the general trend shows that higher weft density fabrics have more stable auxetic properties over larger strain ranges, while lower density fabrics have more pronounced but shorter-lived auxetic effects.

5. REFERENCES

Ken E Evans, Auxetic polymers: a new range of materials, Endeavour, Volume 15, Issue 4, 1991, Pages 170-174, ISSN 0160-9327, https://doi.org/10.1016/0160-9327(91)90123-S.

Zulifqar A, Hua T, Hu H. Development of uni-stretch woven fabrics with zero and negative Poisson's ratio. Textile Research Journal. 2018;88(18):2076-2092. doi:10.1177/0040517517715095

Cao H, Zulifqar A, Hua T, Hu H. Bi-stretch auxetic woven fabrics based on foldable geometry. Textile Research Journal. 2019;89(13):2694-2712. doi:10.1177/0040517518798646

Széles, Levente and Horvath, Richard and Cveticanin, Livija, Design and Parameter Dependency Assessment of a Novel Doubly Re-Entrant Auxetic Honeycomb. Available at SSRN: https://ssrn.com/abstract=4595331 or http://dx.doi.org/10.2139/ssrn.4595331

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INNOVATIVE CHEMICAL TEXTILE PROCESSING

ORAL PRESENTATION

HYDROPHILICITY AND CAPILARITY OF COTTON FABRIC CATIONIZED DURING MERCERIZATION PROCESS

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Abstract: *Cationization of cotton is an alternative method to improve the adsorption of anionic dyes and auxiliaries as it changes the surface charge of the fibres. In this study, the hydrophilicity and capillarity of cationized cotton fabrics during mercerization were investigated after different ageing times of the cationic compound (1, 5 and 24 hours) in order to shorten the process time. It was found that cationization changes the zeta potential, hydrophilicity and capillarity of the cotton fabric. The standard cotton fabric gets wet quickly and absorbs liquid, but remains wet for a long time, while it dries quickly after cationization. Therefore, the standard fabric is characterized as a "moisture management fabric" and the cationized fabric as "fast absorbing and fast drying fabric". In terms of optimising the cationization process, it has been shown that ageing for 5 hours is sufficient to achieve similar properties to ageing for 24 hours, which significantly shortens the cationization process.*

Keywords: *hydrophilicity, capillarity, cationization during mercerization, CHPTAC, zeta potential, MMT*

1. INTRODUCTION

The cationization of cotton is an alternative method for improving the adsorption of anionic dyes and auxiliaries, which leads to a change in the surface charge of the fibres (Figure 1). Epihalohydrins are the most commonly used cationic agents, namely epoxypropyltrimethylammonium chloride (EPTAC) and 3-chloro-2-hydroxy-propyltrimethylammonium chloride (CHPTAC), while amines and quaternary ammonium compounds can be also used. This modification can be carried out by exhaustion and padding as a pre- or after-treatment technique (Lewis 1997, Hauser 2001, Hashem 2003, 2006, Aktek 2017) or during the mercerization process (Grancarić 2004, Tarbuk 2014, 2024).

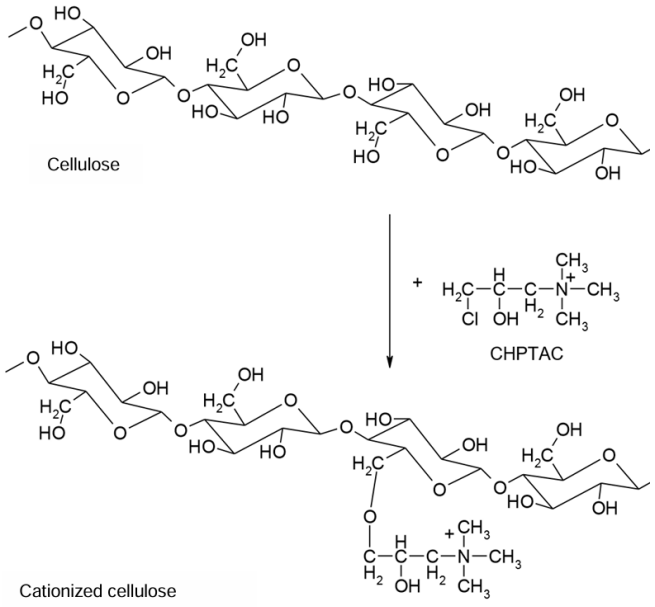


Figure 1: Cationization of cotton cellulose with CHPTAC

The main difference between the two techniques is the result of the subsequent dyeing process. If cationization is performed in the pre- or after-treatment, the surface groups are blocked and the subsequent dyeing process are not uniform. If cationization is carried out during the mercerization process, a change in the cellulose crystal lattice occurs due to mercerization (Soljačić 1968), and a novel cellulose is formed in which the cationic compound is evenly distributed between the cellulose chains (Tarbuk 2014), so that the dyeing is uniform (Tarbuk 2014, 2016, Sutlović 2021, Čorak 2022).

This technique was introduced in 2003 by the research group of Grancarić, Tarbuk and Dekanić in the slack mercerization of yarn (Grancarić 2004) and further developed in 2009 in the mercerization without tension on the jigger, resulting in a new cotton cellulose published in 2014 (Tarbuk), which has all the advantages of the two processes mentioned above. Apart from the articles by these authors, no published articles on cationization during the mercerization process were found. This modification completely changes the dye-cellulose system, resulting in uniform dyeing after the dyeing process with natural, direct, acid and metal complex, vat and reactive dyes and in inkjet printing, with no salt required (Tarbuk 2024). However, the cationization process involves a 24-hour ageing time. Therefore, this study investigated the hydrophilicity and capillarity of cationized cotton fabrics during mercerization after different ageing times of the cationic compound (1, 5 and 24 hours) with the aim of shortening the process time.

2. MATERIAL AND METHODS

The standard cotton fabric for ISO 2267:1986 type 10A by wfk-Testgewebe was used in this research. It is chemically bleached fabric of 100% cotton, plain weave, mass per unit area 170 g/m^2, the warp and weft density 27/27 threads per cm, and the fineness of the yarn 29.5/29.5 tex, label ST.

Cationization during mercerization was carried out according to Tarbuk (2014) using 3-chloro-2-hydroxypropyl trimethylammonium chloride (CHPTAC, Sigma Aldrich) with the change in aging time. A two-step procedure on a jigger machine with 0% tenacity was performed at room temperature: 1. mercerization in a bath with 24% NaOH, 8 g/L Subitol MLF, and 2. alkaline cotton fabric before fixation (hot rinsing) was cationization in a bath with 50 g/L CHPTAC, sealed and left at room temperature to age 1, 5 or 24 h, followed by hot rinsing and neutralization in 5% acetic acid then cold rinsed to achieve a neutral pH and air dried. The samples were labelled as C1, C5 and C24 depending on the ageing time.

To confirm the change in surface charge, the electrokinetic potential (zeta potential, ZP) was measured using the current flow method with a Brookhaven-Paar Electrokinetic analyzer (EKA) with a stamp cell in 0.001 M KCl as electrolyte. The measurements were carried out in the range of pH values 3 to 10, and zeta potential was calculated according to the Helmholtz–Smoluchowsky equation (Grancarić 2005).

Hydrophilicity and capillarity of the modified cotton were tested using the following standard test methods:

AATCC TM 79-2010e2(2018)e3, Test Method for Absorbency of Textiles (»Drop test«),

AATCC TM 197-2022, Vertical Wicking Rate of Textiles: to Specified Distances (»Vertical test«) and

AATCC TM 195-2011e2(2017)e5, Liquid Moisture Management Properties of Textile Fabric on Moisture Management Tester (MMT; SDL Atlas, USA).

3. RESULTS AND DISCUSSION

In this work, the possibility of shortening the process time of cationization of cotton during mercerization was investigated. For this purpose, the cotton was cationized during mercerization with different ageing times (1, 5 and 24 hours) of the short-chain quaternary ammonium salt, an epihalohydrin, 3-chloro-2-hydroxypropyl trimethylammonium chloride (CHPTAC) and its zeta potential, hydrophilicity and capillarity were investigated.

The results of zeta potential of standard and cationized cotton fabrics *vs.* pH value of 0.001 M KCl are shown in Figure 2.

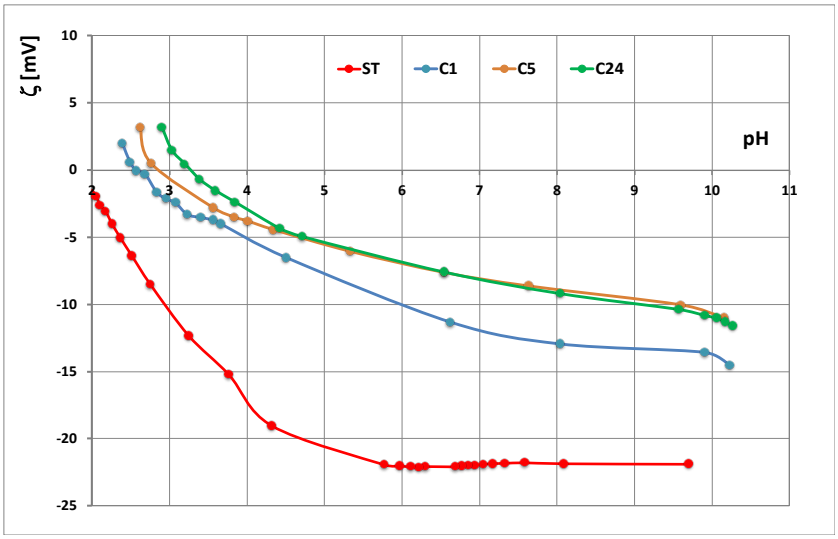


Figure 2: Zeta potential of standard and cationized cotton fabrics vs. pH value of 0.001 M KCl

The results of the zeta potential (Figure 2) show that the standard cotton fabric (ST) has a negative charge, which is due to the dissociation of the hydroxyl groups of the cotton cellulose. The electrical charge of the cotton has changed significantly due to cationization with CHPTAC, which was introduced into the open cellulose structure during mercerization and binds covalently to the available groups. The binding of CHPTAC creates the new amino groups, which also dissociate, giving the cotton fibre a more positive charge.

The efficiency of the cationization process at different ageing times, monitored by measuring the zeta potential, shows that 24-hour ageing is not necessary. At 24-hour (C24) and 5-hour (C5) ageing, the zeta potential is similar.

The results of hydrophilicity, capillarity and moisture management properties of cotton cationized during mercerization, are presented in Tables 1 and 2, and Figure 3.

Table 1: The absorbency (»Drop test« according to AATCC TM 79-2018) and the vertical wicking rate (W) in time for a short distance, d=20 mm (»Vertical test« according to AATCC TM 197-2022) of standard and cationized cotton fabrics

Fabric			
	t* (s)** ***(Drop test)	***t* (s)** ***(Short distance: d=20 mm)***	***W* (mm/s)**
ST	0	117.33	0.171
C1	0	44.61	0.448
C5	0	62.16	0.322
C24	0	52.46	0.381

The results of the “drop test” (Table 1) of 0 s for the absorption of all fabrics show that the hydrophilicity was retained after modification. However, the wetting time (WT) in Table 2, which was measured with the MMT device, reveals the difference in the wetting behaviour between the fabrics. Table 1 shows the vertical wicking rate for a short distance (d=20 mm), as the 150 mm mark was not reached in 30 min. It can be seen that all cationized

fabrics absorb liquid faster than unmodified standard fabric (ST). The time and the distance waterfront reached in 30 min are shown in Figure 3. From the slope of the curves in Figure 3 and the time of the vertical wicking test for a short distance, it can be seen that for a distance of 20 mm, standard cotton fabrics (ST) required 117 s and cationized cotton fabrics less than 62 s, and the wicking rate is calculated accordingly.

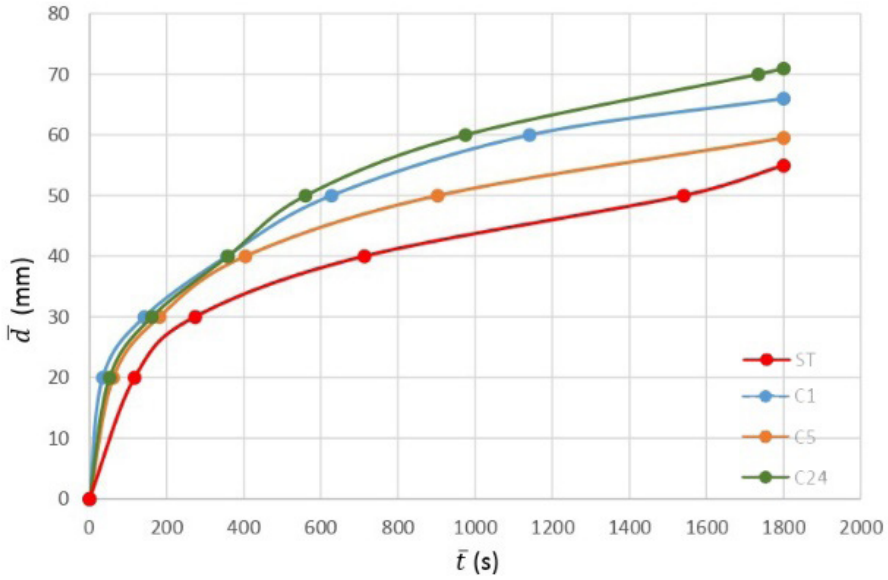


Figure 3: Distance (*d*) waterfront as a function of time (*t*) in a 30-minute vertical wicking test on standard and cationized cotton fabrics

The absorption rate (AR) in Table 2 represents the average absorption of liquid moisture for the top and bottom of the sample. The results in Table 2 that it is about 20 %/s for ST and it changes to 60-70 %/s during the cationizations. These results, again, indicate better capillarity of C1, C5 and C24 than ST. For this reason, the spreading speed (SS), which represents the speed of surface wetting from the centre of the sample to the maximum wetting radius, is faster on cationic surfaces than on standard surface (2.8 mm/s for ST to 3.7 mm/s for C1, C5, C24). The results of the vertical test confirm these results (Table 1). Within 30 minutes, the water penetrates 55 mm in ST fabric and up to 71 mm for C24 fabric due to capillarity (Figure 3).

Table 2: Moisture Management Test results on the ST and cationized cotton fabrics

Fabric	WT-T (s)	WT-B (s)	AR-T (%/s)	AR-B (%/s)	MWR-T (mm)	MWR-B (mm)	SS-T (mm/s)	SS-B (mm/s)	R (%)	OMMC
ST	4.96	3.61	19.78	22.51	23.33	23.33	2.89	2.74	419.26	0.67
C1	3.15	3.34	70.22	58.08	20	20	3.76	3.62	81.09	0.49
C5	3.20	3.37	71.46	58.19	20	20	3.70	3.58	89.34	0.50
C24	3.13	3.37	69.65	63.97	20	20	3.72	3.56	13.62	0.43

*WT – wetting time; AR – absorption rate; MWR – maximum wetted radius; SS – spreading speed; R – accumulative one-way transport capability; OMMC – overall (liquid) moisture management capability; at any quantity: T – top surface; B – bottom surface.

Accumulative one-way transport capability (R) in Table 2 represents the difference between the area of the liquid moisture content curves of the top and bottom surfaces of a specimen with respect to time. For ST it is 419.26%, which means that water content on top surface is much higher than on bottom indicating a high absorbency. Cationization significantly lowers accumulative one-way transport capability, which indicates that the water content on the top surface is no longer much higher than on the fabric bottom surface. This suggests that the liquid introduced to the bottom surface is slowly transferred to the top surface (Nemcokova *et al* 2015). Overall (liquid) moisture management capability (OMMC) is calculated by combining three measured performance characteristics: the absorption rate on the bottom surface, the one-way liquid transport capability, and the maximum spreading speed on the bottom surface. It represents an index of the overall capability of a fabric to transport liquid moisture (AATCC TM 195). It is very good for the TS fabric, whereas OMMC in only good for cationized fabrics.

The ST fabric gets wet quickly and absorbs liquid, which quickly reaches the bottom side of the fabric, but the fabric remains wet for a long time. Therefore, the ST fabric is characterized as “moisture management fabric”. After cationization, the properties change and the liquid is absorbed extremely quickly, but also dries very quickly. Since all cationized fabrics have fast wetting, absorption and spreading, large spreading area, but poor one-way transport the cationized fabrics are characterized as “fast absorbing and fast drying fabrics”.

4. CONCLUSION

Cationization during mercerization changes the hydrophilicity and capillarity of the cotton fabric. A high number of –OH and –COOH groups gives cotton fabrics a negative zeta potential. Cationization has changed the surface charge; -NH_2 groups leads to a more positive charge. The ST fabric gets wet quickly and absorbs liquid, but remains wet for a long time. After cationization, it dries very quickly. Therefore, the ST fabric is characterized as “moisture management fabric”, while cationized fabrics are “fast absorbing and fast drying fabrics”.

With regard to the optimization of the cationization process, it could be shown that an aging of 5 hours is sufficient for CHPTAC and that an aging of 24 hours (as in the literature) is not necessary, which considerably shortens the cationization process.

5. ACKNOWLEDGEMENT

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6. REFERENCES

Aktek, T., Millat, A. K. M. M. (2017) “Salt free dyeing of cotton fiber—A critical review”. Int J Text Sci 6 (2), pp. 21-33.

Čorak, I., Brlek, I., Sutlović, A., Tarbuk, A. (2022) “Natural Dyeing of Modified Cotton Fabric with Cochineal Dye”. Molecules 27 (3), 1100, pp. 1-13.

Grancarić, A. M., Tarbuk, A., Dekanić, T. (2004) “Elektropozitivan pamuk”. Tekstil 53 (2), pp. 47-51.

Grancaric, A. M., Tarbuk, A., Pušić, T. (2005) “Electrokinetic properties of textile fabrics”. Coloration Technology 121 (4), pp. 221–227.

Hashem, M., Hauser, P., Smith B. (2003) “Reaction Efficiency for Cellulose Cationization Using 3-Chloro-2-Hydroxypropyl Trimethyl Ammonium Chloride”. Textile Research Journal 73 (11), pp. 1017-1023.

Hashem, M. M. (2006) “Development of a one-stage process for pretreatment and cationisation of cotton fabric”. Coloration Technology 122 (3), pp. 135–144.

Hauser, P. J., Tabba, A. H. (2001). “Improving the environmental and economic aspects of cotton dyeing using a cationised cotton”. Coloration Technology 117 (5), pp. 282–288.

Lewis, D. M., McIlroy, K. A. (1997) “The chemical modification of cellulosic fibres to enhance dyeability”. Review of Progress in Coloration and Related Topics 27 (1), pp. 5–17.

Nemcokova, R., Glombikova, V., Komarkova, P. (2015) “Study on Liquid Moisture Transport of Knitted Fabrics by Means of MMT”. AUTEX Research Journal 15 (4), pp. 233-242.

Soljačić, I., Žerdik, M. (1968). “Mercerizacija pamuka”. Tekstil, 17, 495-518.

Sutlović, A., Glogar, M. I., Čorak, I., Tarbuk, A. (2021) “Trichromatic Vat Dyeing of Cationized Cotton”. Materials 14 (19), 5731, pp. 1-17.

Tarbuk, A. (2024) “The sustainability of the cotton cationization during the mercerization process”. Journal of Chemists, Technologists and Environmentalists 5 (1), pp. 1–13.
Tarbuk, A., Grancarić, A. M., Leskovac, M. (2014) “Novel cotton cellulose by cationisation during the mercerisation process—part 1: chemical and morphological changes”. Cellulose 21 (3), pp. 2167–2179.
Tarbuk, A., Grancarić, A. M., Leskovac, M. (2014) “Novel cotton cellulose by cationization during mercerization—part 2: the interface phenomena”. Cellulose 21 (3), pp. 2089–2099.
Tarbuk, A., Sutlović, A., Dekanić, T., Grancarić, A. M., Zdjelarević, I. (2016) “Ultra-Deep Black Cationized Cotton by Metal-Complex Dyeing”. In 16th World Textile Conference AUTEX 2016 – Proceedings, edited by Barbara Simončič, Brigita Tomšič, Marija Gorjanc, pp. 5.3.(1-7), Ljubljana, University of Ljubljana, Faculty of Sciences and Engineering, Department of Textiles, Graphic Arts and Design.

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ORAL PRESENTATION

THE ROLE OF TRISODIUM PHOSPHATE IN ENHANCING ACIDIC DYEING OF NYLON FABRICS

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Abstract: *Nylon fabrics are dyed in acidic environments through ionic bonding, where positively charged amino groups on the fabric interact with the negatively charged sulfonate groups of acidic dyes. The optimal pH range for the nylon dyeing process is between 4 and 6, and acetic acid (AA) is commonly employed to regulate and achieve this pH level. However, even at low concentrations, AA alone can cause a rapid decrease in the dye bath pH. Such abrupt pH reductions can lead to color inconsistencies and dye breaks, particularly in large-scale textile production where fabrics are dyed in bulk. This study proposes the use of trisodium phosphate (TSP) as a buffering agent in conjunction with AA to mitigate these challenges. The incorporation of TSP facilitates a more controlled and gradual decline in pH, thereby preventing the fabric from rapidly adsorbing the dye in an uncontrolled manner. By enabling the fabric to adsorb the majority of the dye before reaching the optimal pH levels, the remaining dye can be evenly fixed onto the fabric, minimizing the risk of color irregularities and ensuring a more uniform dyeing outcome.*

Keywords: *Trisodium Phosphate, TSP, Nylon, Acidic Dyeing, Buffering Effect, pH Control*

1. INTRODUCTION

Nylon is a polyamide polymer which has positively charged amino ($-NH_3^+$) groups and negatively charged carboxyl ($-COO^-$) groups similar to other protein fibers such as wool and silk (Kertess, 1949). These categories of fibers are generally dyed in an acidic environment with various acid dyes (Kim, 2011). A decrease in pH in the dye bath leads to a greater positive charge on the fiber, as the ionization of the carboxyl group diminishes, and the amino groups undergo increased protonation. The fabric, enriched with positively charged amino ($-NH_3^+$) groups, becomes highly receptive to bonding with the dye's negatively charged sulfonates (-SO3□). Amino groups of the fiber form ionic bonds with anionic dye molecules (Dawson, 1981). As the number of amino groups increases, the fabric's capacity to adsorb dye molecules is enhanced.

Acetic acid is a commonly used chemical in the acidic dyeing of nylon fibers. It is used to decrease the pH value of the dye bath and to achieve acidity. An acidic medium is necessary to get strong ionic bonds between dye molecules and the fibers, so maintaining the range of pH 4–6 is crucial (Dawson, 1981). This necessitates the use of acetic acid as a pH-regulating chemical.

Acidic conditions are essential for dyeing nylon with acid dyes; however, due to the strong affinity of these dyes for nylon fabrics, it is crucial to maintain strict control over the dye bath. Two primary factors influence the dye adsorption capacity of nylon fabric: temperature and pH. As the temperature rises, the fabric‘s ability to adsorb dye increases. Similarly, a decrease in pH enhances dye adsorption. If the pH decreases too rapidly, the dye penetrates the fabric quickly, leading to a situation where the reaction rate surpasses the diffusion rate. This discrepancy can result in color unevenness and dye breaks. Therefore, for optimal and controlled dyeing, it is essential to regulate both temperature and pH throughout the dyeing process.

The use of buffers in the dyeing process has a critical importance in achieving high-quality products. Buffers stabilize the pH and prevent sudden chain reactions in the dyeing medium. The pH stabilization allows the dye to diffuse and penetrate the fabric slowly, preventing color inconsistencies and irregularities (Soleimani-Gorgani, 2006).

Trisodium phosphate (TSP), Na_3PO_4, is a compound commonly used as a buffer in reactive and disperse dye applications (Subramanian, 1932, Lee, 2006). It creates a strong alkaline solution when dissolved in water and dissociates into sodium ions (Na^+) and phosphate ions (PO_4^{3-}). The phosphate ion acts as a weak base and can react with water to bind hydrogen ions (H^+) or neutralize excess hydroxide ions (OH^-) in the solution. The buffering capacity of TSP is achieved through the conversion of phosphate ions (PO_4^{3-}) into dihydrogen phosphate ($H_2PO_4^-$), and hydrogen phosphate (HPO_4^{2-}) forms in the solution. These transformations help maintain the balance of the solution's pH. When acid (H^+ ions) is added to the solution, phosphate ions bind to these H^+ ions and convert into dihydrogen phosphate ions. These reactions help prevent a further decrease in pH (Dawson, 1981, Maulik, 2022).

Lin et al. (FB, 2007) investigated the relationship between the pH values of the dye bath and the dye exhaustion rate of the fiber. They also examined the effects of various acids and pH-sliding agents used to gradually reduce the pH of the bath through heating, to control the dyeing process of nylon fibers with metal complex acid dyes. They showed nearly 10% and 15% decreases in dye exhaustion when the final pH value was set between 5~6 and 6~7, respectively, compared to the pH value at 4.5. Between different combinations of agents, the acetic acid-based pH-sliding agent demonstrated superior performance in achieving uniform dyeing of nylon fabrics compared to the others. In another study, reactive dyeing of nylon fiber was investigated with the use of TSP as a buffer to arrange pH values for optimum dye exhaustion, and fixation by Lee et al (Lee, 2006). They revealed that all reactive dyes are applicable at pH 5-6, but for enhanced fixation efficiency, the sulphato-ethylsulphone groups should be converted to vinylsulphone before dyeing with trisodium phosphate.

While TSP can serve as a buffering agent in different applications, it is not commonly used for dyeing nylon fibers under acidic dyeing conditions. This study aims to ensure the homogeneous distribution of dye on nylon fabric surfaces by using trisodium phosphate (TSP) alongside acetic acid during dyeing with acidic dyes. The method focuses on gradually lowering the pH of the dye bath, thereby preventing sudden pH changes that could lead to dye breaks.

2. MATERIALS AND METHOD

2.1 Materials

All chemicals used in the experiments were purchased commercially from Sigma Aldrich, with the same quality as those used in large-scale dyeing at the facility. Knitted nylon 6 fabrics, each weighing 10 grams and composition of 95% nylon and 5% elastane, were used from the fabrics that customers of Ideateks Textile sent to our factory to be dyed. The two acidic dyes used in this work were supplied by Setaş Chemical Industry Inc.; one of the dyes was 1:2 pre-metalized acid dye C.I Acid Blue 193, which has two sulfonate groups, and the other C.I Acid Blue 62, which is monosulfonated. As a pH-regulating chemical, acetic acid (AA, 99%) and as a buffer trisodium-phosphate (TSP, 96%) were used. Ultra-pure water was used in all experiments.

2.2 Method

2.2.1 Dyeing Procedure

Nylon 6 fabric was dyed in sealed, stainless steel dyeing vessels of 150 cm^3 capacity, housed in a Rapid Eco Dyer ECO-24 laboratory-scale dyeing machine. The dyeing method used is shown in Figure 1. The dyeing procedure consists of two experiments: 1. Dyeing with only AA, 2. Dyeing with AA+TSP. Both processes were carried out with 1% (owf) acid dyes and varied amounts of acetic acid between 0-2.3 g/L maintaining a material-to-liquor ratio at 1:10. In the second experiment, additionally, 1 g/L trisodium phosphate was used. The dyeing started at 35°C and the temperature was raised to 105°C with a degree of 2°C/min and dyeing was continued further for 50 minutes. The temperature was gradually lowered, first to 70°C and then to 45°C, to complete the dyeing process. The dyed fabrics were removed and washed by passing them through three warm water baths before being left to dry.

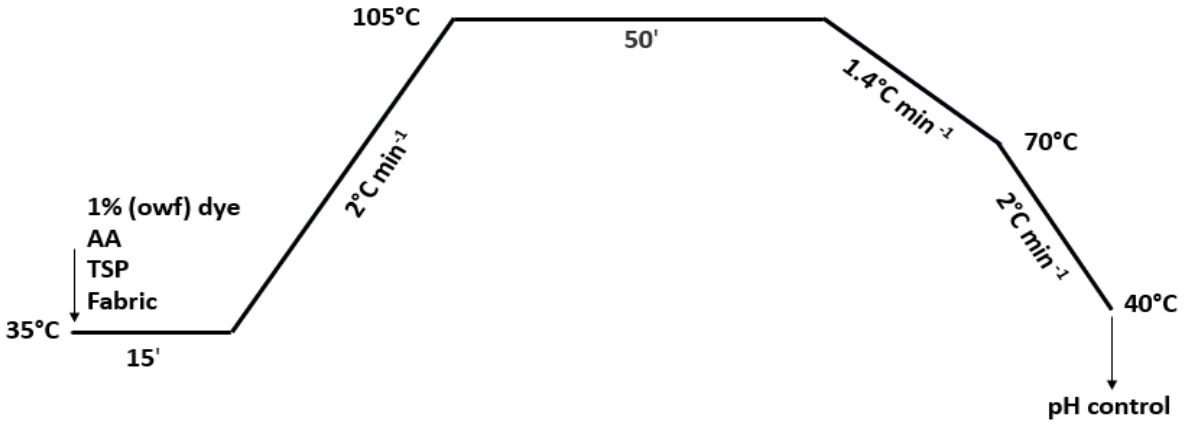


Figure 1: Dyeing procedure

2.2.2 Measurement and Analysis

The pH values of each dye bath were recorded using a REX PH310F pH meter, following the completion of the dyeing process. The amount of dye absorbed by the fabrics was measured using an X-Rite Ci7800 spectrophotometer interfaced to a PC using D65 illumination, 10° standard observer with specular component excluded and UV component included. Each fabric was folded in half to create two layers, and the average of two readings was recorded for each measurement.

3. RESULTS AND DISCUSSION

The effect of TSP on the pH of the dye bath and herewith dye adsorption of the nylon fabric were studied with two different acid dyes. One of the monosulfonated C.I Acid Blue 62 and the other is disulfonated 1:2 pre-metalized acid dye C.I Acid Blue 193.

In the first experiment, two separate dyeing processes were performed using Acid Blue 62 dye. In the first process, 1 g/L TSP was added to the dye bath, while AA was introduced in varying concentrations from 0 to 2.3 g/L. Following the completion of dyeing in each bath with different AA levels, the pH of the dye bath was measured. After the nylon fabrics from each dye bath were washed and dried, the amount of dye adsorbed in the process using 1% dye was determined. In the second experiment, the same procedures were repeated using Acid Blue 193 dye.

For both experiments, the pH variations of the dye baths based on the amount of AA are shown in Figure 2. In the graphs, the blue curve represents the pH change when TSP is used in addition to AA, while the red curve shows the pH change when only AA is used. As observed in both dyeing experiments, TSP prevented the sudden drop in the dye bath pH from around 9 to 4-5, ensuring a more gradual decrease instead.

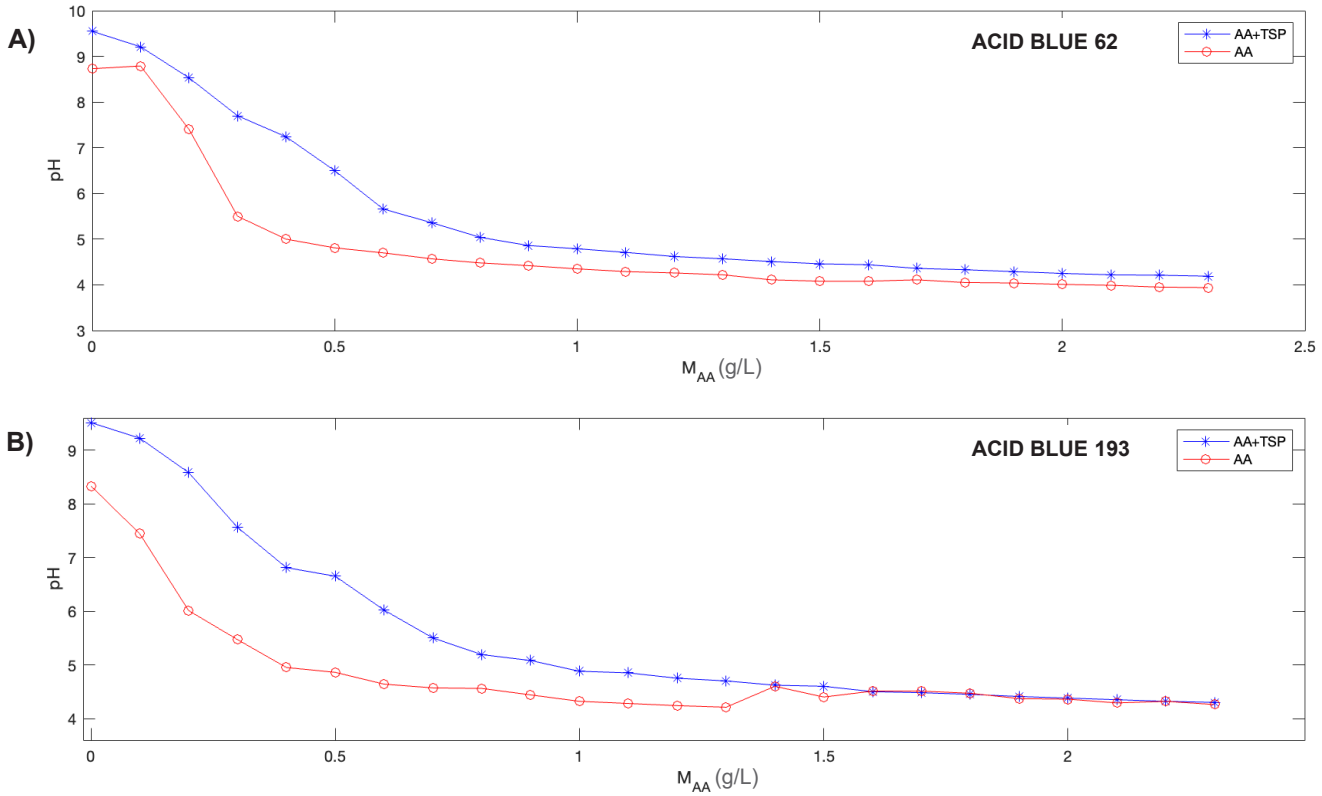


Figure 2: The pH change of the dye bath depending on the amount of AA (MAA) considering the presence or absence of TSP for A) Acid Blue 62 and B) Acid Blue 193

The dye adsorption of nylon fabrics based on the amount of AA is presented in Figure 3 and Figure 4 for Acid Blue 62 and Acid Blue 193, respectively. As observed from the graphs, for both dyes, when only AA is used, the fabric rapidly adsorbs a large portion of the dye even at very low AA concentrations. Since most of the dye uptake occurs at this stage, increasing the AA amount further does not result in a significant change in the adsorption percentage. When TSP is used alongside AA in the dyeing process, dye uptake occurs gradually up to a certain AA concentration. In environments where the pH is acidic enough for the reaction to occur, a significant percentage of the dye is gradually adsorbed by the fabric. This gradual adsorption helps prevent potential dye breaks and color inconsistencies. The images of the dyed fabrics in Figure 3 and Figure 4 support this observation. Images B.1 and B.2 show the dye adsorption at AA concentrations of 0 and 2.3 g/L, respectively, when TSP is used. Images C.1 and C.2 show the dye adsorption at AA concentrations of 0 and 2.3 g/L, respectively, when only AA is used. As observed, when only AA is used, there is no significant difference in the fabric colors at the beginning and end points, whereas when TSP is used, it is evident that less dye is adsorbed at the starting point compared to the endpoint.

When comparing the two dyes, it was observed that in the case of Acid Blue 193, the dye adsorption onto the nylon fabric was significantly lower than that of Acid Blue 62 when only AA was used. This can be explained by the disulfonated nature of Acid Blue 193. As the sulfonation degree of the dye increases, the fabric‘s ability to adsorb the dye decreases (Chantler, 1969). However, this issue can be mitigated by using TSP, as clearly shown in the graph provided in Figure 4, image A.

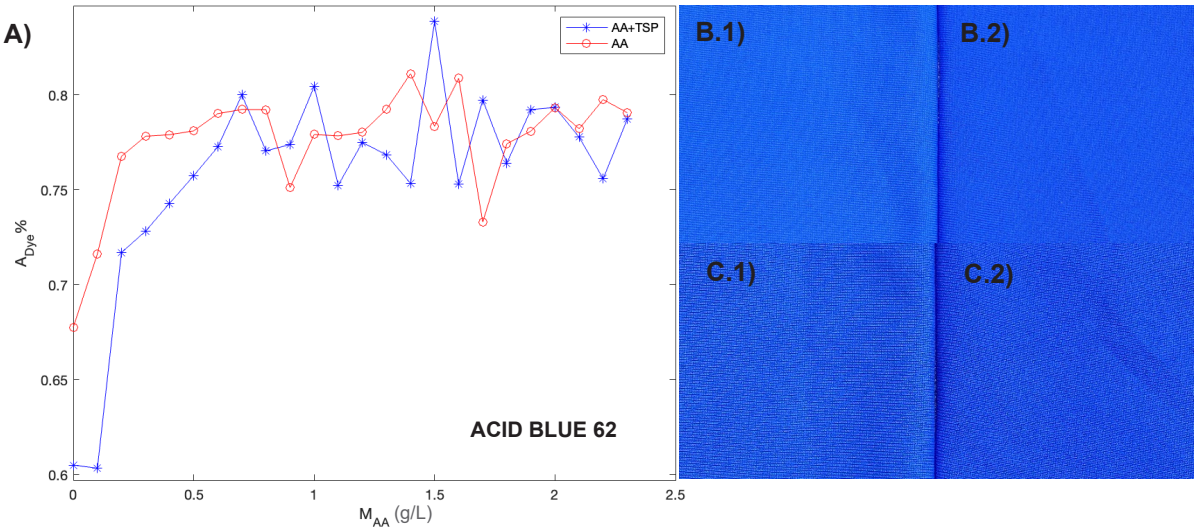


Figure 3: A) The change of dye adsorption of the fabrics depending on amount of AA (MAA) considering the presence or absence of TSP for Acid Blue 62; the dyed fabrics for the presence of 1 g/L TSP with B.1) no AA B.2) 2.3 g/L AA; the dyed fabrics for the absence of TSP with C.1) no AA C.2) 2.3 g/L AA

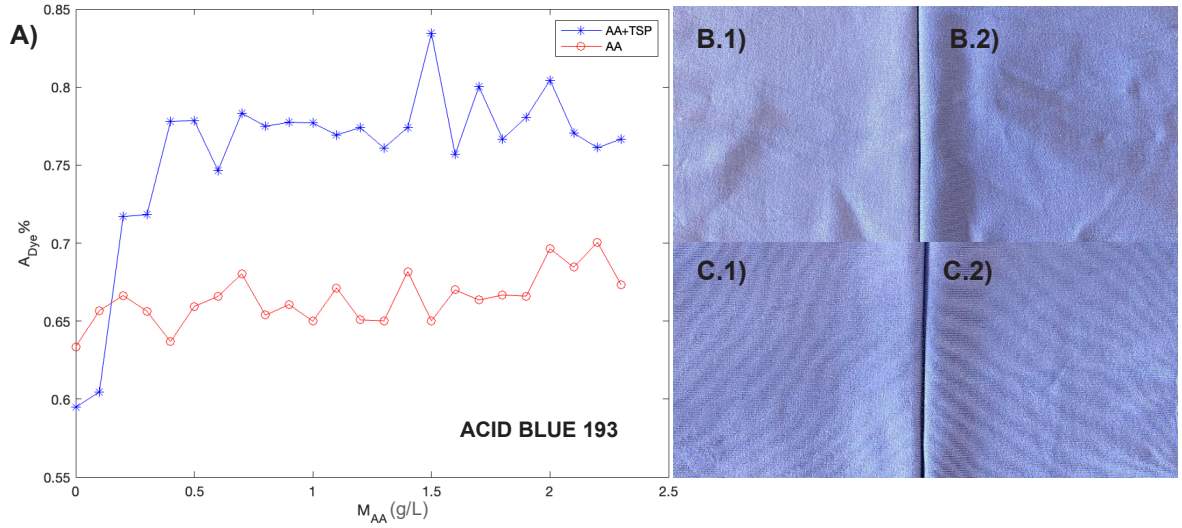


Figure 4: A) The change of dye adsorption of the fabrics depending on amount of AA (MAA) considering the presence or absence of TSP for Acid Blue 193; the dyed fabrics for the presence of 1 g/L TSP with B.1) no AA B.2) 2.3 g/L AA; the dyed fabrics for the absence of TSP with C.1) no AA C.2) 2.3 g/L AA

4. CONCLUSIONS

In this study, we propose the use of trisodium phosphate (TSP) to prevent dye breaks and color inconsistencies, which are common challenges in large-scale nylon fabric dyeing. Acting as a buffering agent during the dyeing process, TSP prevents the abrupt drop in pH from approximately 9 to the optimal range of 4–6. Instead, it ensures a gradual pH reduction, allowing the nylon fabric to progressively adsorb the dye, leading to uniform adsorption across the entire fabric surface. Furthermore, the use of TSP effectively prevented the low adsorption rates observed in dyeings using AA alone with 1:2 premetallized dyes containing disulfonated groups. By incorporating TSP, adsorption percentages comparable to those of monosulfonated dyes were achieved, enhancing dye uptake efficiency.

5. REFERENCES

Chantler, M. D., Partlett, G. A., & Whiteside, J. A. B. 1969. “Prospects and Problems in the Dyeing and Finishing of Differential□dyeing Nylon 6.6 Yarns.” Journal of the Society of Dyers and Colourists 85 (12): 621-629.
Dawson, T. L. 1981. “pH and its importance in textile coloration.” Journal of the Society of Dyers and Colourists 97 (3): 115-125.
FB, L., & CK, L. 2007. “Dyeing optimization with metal complex acid dyes for nylon fabrics.” Journal of textile engineering 53 (3): 117-122.
Kertess, A. F., Potts, S., HOWLETT, F., & LUXMORE, J. 1949. “The Properties and Uses of Nylon Fabrics.” Journal of the Textile Institute Proceedings 40 (4): 388-393.
Kim, S. D., Lee, H. Y., Choi, Y. J., & Lee, J. L. 2011. “Dyeing characteristics of Nylon, cotton and N/C mixture fabrics with reactive-disperse dyes containing a sulphatoethylsulphone group.” Fibers and Polymers 12: 932-938.
Lee, B. S., Lee, J. A., Lee, K. S., Park, J. H., & Kim, S. D. 2006. “Dyeing Properties of Nylon Fabric with Reactive Dyes Having Different Reactive Group.” Textile Coloration and Finishing 18 (5): 1-7.
Maulik, S. R., Bhattacharya, A., Roy, P. P., & Maiti, K. 2022. “Reactive Dye and Its Advancements.” Textile Dyes and Pigments: A Green Chemistry Approach 17-44.
Soleimani-Gorgani, A., & Taylor, J. A. 2006. “Dyeing of nylon with reactive dyes. Part 1. The effect of changes in dye structure on the dyeing of nylon with reactive dyes.” Dyes and pigments 68 (2-3): 109-117.
Subramanian, D. R., Venkataraman, A., & Bhat, N. V. 1982. “Studies on Dyeing and mechanical properties of Nylon 6 filaments subjected to swelling treatments.” Journal of Applied Polymer Science 27 (11): 4149-4159.

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POSTER PRESENTATION

COMPARISON OF INKJET PRINTING WITH REACTIVE DYES ON COTTON FABRIC IMPREGNATED WITH ALGINATE OR POLYACRYLATE THICKENER

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Abstract: *For successful inkjet printing on cotton fabric, the fabric must be pretreated. The pretreatment consists of impregnating the fabric with a thickener solution that also contains all the chemicals needed to fix the dyes to the fibres. In our study, natural alginate and synthetic polyacrylate thickeners were applied to the fabric by impregnation. The fabrics were printed using the Mimaki Tx2-1600 digital printer with the reactive dyes cyan, magenta, yellow and black. The printed fabrics were steamed normally for 10 minutes, then washed, soaped and dried.*
The colour values, the colour depth and the dye penetration of the printed samples were compared. It was found that printing was successful with both preparation, although the colour depth was higher with the alginate thickener. It was also confirmed that the type of thickener in the pretreatment paste had no effect on the colour fastness on washing.

Key words: *digital printing, reactive dyes, thickener, colour values, colour fastness.*

1. INTRODUCTION

Digital printing is the latest, but already fully established textile printing technology. Dyes in the form of tiny droplets of dye solutions (ink) are sprayed onto the fabric through numerous micrometer-sized nozzles (Ujiie, 2006).

Reactive, disperse, acid and pigment dyes in the form of ink are used for digital textile printing. The dyes must match the textile substrate, bond physically and chemically with the fibres, fix sufficiently and have the required fastness properties.

Reactive dyes are a group of dyes with brilliant shades and good fastness properties that chemically bind to textile fibres. They are most commonly used for printing on cellulose fibres and are also suitable for printing on silk, wool and polyamide (Soleimani-Gorgani, 2005). They are anionic, as one or more sulphonate groups are bound to the dye molecule (dye−SO_3-). Reactive dyes can bind to the hydroxyl groups of cellulose via the reactive system and form covalent bonds under alkaline conditions, usually by nucleophilic bimolecular substitution or nucleophilic addition mechanisms (Šostar-Turk, 1998).

The textile material to be printed must be prepared accordingly before printing, and the dye must be fixed, washed and dried after printing. Absorption and capillary forces in the fibres cause spreading and deteriorate the contour quality. Therefore, the fabric must be impregnated with a thickening agent and suitable fixing agents before printing. The composition of the impregnating bath and the steaming time have a strong influence on the adsorption and fixation of reactive dye on cotton (Yuen, 2005, Yang 2004).

For printing on cotton, low-viscosity alginate thickeners in low concentrations are used, in which auxiliaries, oxidizing agents and alkalis are dissolved (Quiao, 2022, Eser, 2012). Some producers also recommend synthetic polyacrylate thickeners for printing of reactive dyes (Miles, 1994. Bezema, technical documentation, 2000).

Sodium alginates are important thickeners for reactive dyes because the extent of interaction is very small. This is due to the absence of primary hydroxyl groups and to the repulsion or the dye anions by the ionised carboxyl groups of the polymer under alkaline conditions (Miles, 1994).
Polyacrylate thickeners have several carboxylic acid groups which are ionised on addition of alkali. The resultant mutual repulsion of negatively charged centres causes extension of polymer chains and substantial increases in viscosity. The polyacid is usually neutralised by ammonia so that, during the drying, the free acid is largely re-formed (Figure 1) (Miles, 1994).

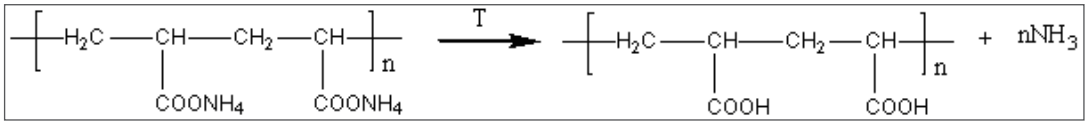


Figure 1: Ionic and acid form of polyacrylate.

After printing and drying, the dyes are fixed on the textile. During fixation, the dyes diffuse from the thickening film into the interior of the fibre and bind there. The most common fixation process is one-step normal steaming at 100–103°C. Fixation is followed by washing with cold and warm water to remove non-fixed dyes, thickeners and chemical additives (Ujiie, 2006).

The aim of this study was to investigate whether reactive dyes can be digitally printed on cotton fabric pretreated with alginate or polyacrylate thickener.
The CIE L*a*b* colour values, the colour depth (K/S) and the dye penetration (P) were compared on differently pretreated fabrics printed with four basic colours under the same conditions. The colour fastness of the prints to washing was also measured.

2 METHODS

2.1 Materials

100% cotton plain woven fabrics 156 g/m^2 from the manufacturer Tekstina d.d. Ajdovščina, Slovenia, was used.

2.2 Preparing the textiles for printing

The fabrics were pretreated with an alginate thickening preparation (A) or a polyacrylate thickening preparation (PAC). The recipes are listed in Tables 1 and 2.

The following chemicals were used: CHT alginate EHV (Bezema, Switzerland), alginate thickener; Clear D/27 (Minerva, Italy), polyacrylate thickener; sodium hydrogen carbonate ($NaHCO_3$) (Kemika, Zagreb, Croatia); urea ($CO(NH_2)_2$) (J.T. Baker, Netherlands), hydrotropic agent, Rapidoprint XR (Bezema, Switzerland), sodium m-nitrobenzenesulfonate, oxidising agent; citric acid ($C_6H_8O_7$) (Kemika, Zagreb, Croatia).
The fabrics were impregnated with a laboratory two-roller padder (Mathis, Switzerland) with an impregnation effect of 88 %. The impregnated samples were air dried at room temperature.

Table 1: Recipe for the preparation of the alginate (A) and polyacrylate (PAC) thickener.

Additive	Amount (g)	
	A	PAC
CHT-alginat EHV 4 %	400	-
Clear D/27	-	26
Distilled H_2O	525	889
$NaHCO_3$	25	25
$CO(NH_2)_2$	50	50
Rapidoprint XR	10	10
Total	1000	1000

2.3 Printing, fixation and after-treatment

Printing was done with a digital piezo DOD printer TextileJet Tx2-1600 from Mimaki with a resolution of 720 dpi and reactive dyes Jettex R (DyStar, England). The patterns were pre-processed as squares in Adobe Photoshop. 100% cyan (C), 100% yellow (Y), 100% magenta (M) and 100% black (K) were printed.
The printed fabrics were fixed in a laboratory steamer DHE 20675 (Werner Mathis AG, Switzerland) in 90% saturated steam at 102°C for 10 minutes.
After fixation, the fabric was first rinsed with cold water to remove residual thickeners, chemicals and some unfixed dyes, then with warm water and finally with hot water. The next step was soaping for five minutes at 100 °C with 1 g/l CIBAPON R detergent (CIBA, Switzerland) to remove all remaining dye residues. After soaping, the samples were rinsed with warm and cold water and air-dried at room temperature.

2.4 Analyses

The colour coordinates CIE L*a*b* and the reflectance R (%) of the printed samples were measured with a spectrophotometer SF 600 PLUS-CT (Datacolor International, Switzerland). Ten measurements were taken for each colour on each print. The measurements were taken on the front and back of the printed fabric. The measurement conditions were: standard light D65, standard observer 10°, device geometry d/8°, measuring range 400–700 nm, four fabric layers and a measuring aperture of 20 mm.

The colour difference (ΔE*) was calculated from the CIE colour coordinates L*a*b* according to equation 1:

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

where ΔL* is the difference in lightness, Δa* is the difference on the red-green axis and Δb* is the difference on the yellow-blue axis.
The colour depth values (K/S) of the prints were calculated from the reflectance measurements using equation 2:

$$\frac{K}{S} = \frac{(1-R)^2}{2R} \quad (2)$$

where K is the absorption coefficient (depending on the dye concentration), S is the scattering coefficient and R is the reflectance of the sample at a specific wavelength (R = 0 – 1).
The penetration coefficient, P, indicates the amount of dye that has reached the back of the fabric. It was calculated according to equation 3:

$$P = \frac{\frac{K}{S}\,(\text{back})}{(0{,}5 * [\frac{K}{S}\,(\text{front}) + \frac{K}{S}\,(\text{back})])} \text{ x } 100\ [\%] \quad (3)$$

where K/S(front) is the colour depth on the front side of the sample and K/S(back) is the colour depth on the back side of the sample.

Colour fastness to washing was determined according to the standard ISO 105-C01:1989 – Textiles – Colour fastness tests - Part C01: Colour fastness to washing: Test 1. The samples were washed in a Launder-ometer LDH-HT B-S (Atlas Electric Devices, USA).

3. RESULTS AND DISCUSSION

Table 2 shows the results of the CIE L*a*b* colour values of cyan, magenta, yellow and black (CMYK) prints on cotton fabric impregnated with different preparations. The L*a*b* values are close although the calculated colour differences, ΔE*, show that the colours printed on differently pretreated fabrics differ significantly.

Table 2: CIE L*a*b* values of CMYK prints on cotton fabrics impregnated with alginate (A) or polyacrylate (PAC) thickener and colour differences, ΔE*, between differently pretreated fabrics.

Thickener	Colour	L*	a*	b*	ΔE*
A	C	51,25	-32,08	-31,87	-
	M	44,9	54,32	-7,56	-
	Y	84,16	-5,55	90,3	-
	K	22,52	-5,95	-6,8	-
PAC	C	52,67	-32,49	-31,97	1,48
	M	47,55	53,58	-8,97	3,09
	Y	85,37	-4,64	87,7	3,01
	K	26,33	-6,6	-7,43	3,92

Figure 2 shows that the colour depths (K/S) are higher on fabric impregnated with alginate than with acrylate thickener for all colours.

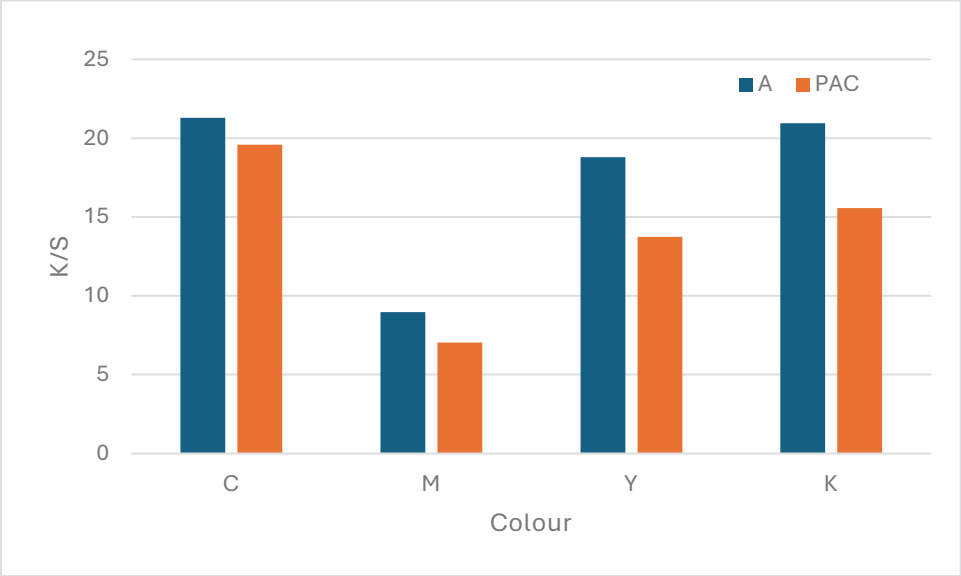


Figure 2: K/S values of CMYK prints on cotton fabrics impregnated with alginate (A) or polyacrylate (PAC) thickener

Figure 3 shows the degree of penetration of the CMYK colours. The values are similar at all colours.

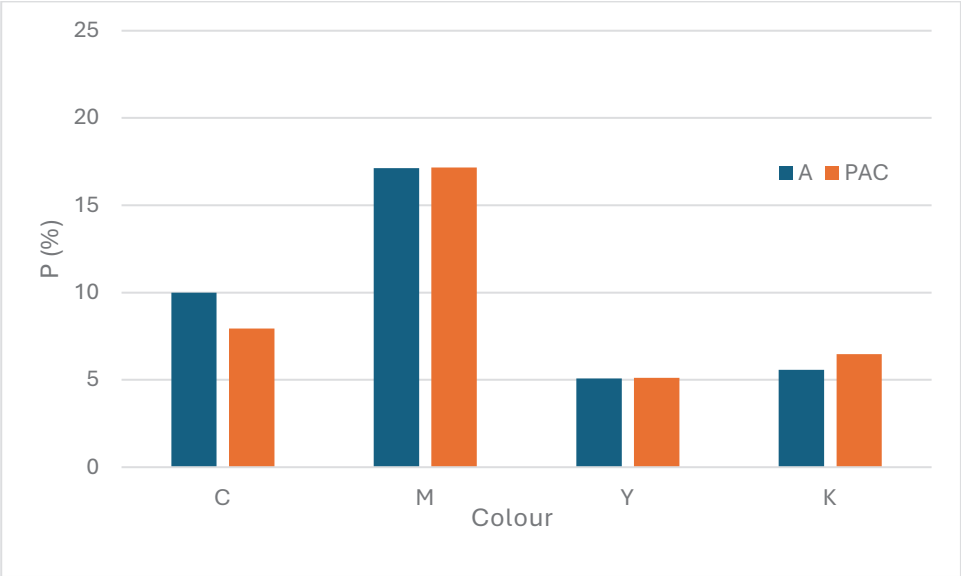


Figure 3: Penetration degree (P) of CMYK prints on cotton fabrics impregnated with alginate (A) or polyacrylate (PAC) thickener

Table 3 shows the colour fastness values of the prints when washed at 60°C. The colour changes and the ratings for dye transfer to cotton and wool are good for all samples and show no difference between differently pretreated fabrics. Polyamide adjacent fabric are similar for all dyes and fabrics. The ratings range from 3 to 4-5. The staining on the adjacent fabrics is relatively low, indicating that the washed-out dye does not stain the adjacent fabrics.

Table 3: Wash fastness values at 60°C of prints on cotton fabrics impregnated with alginate (A) or polyacrylate (PAC) thickener

Pre-treatment	Colour	Washing Fastness		
		Colour Change	Staining of Cotton	Staining of Wool
A	C	4	4	3
	M	5	4	4
	Y	5	4	4
	K	4	4	4
PAC	C	4	4	2
	M	4	4	4
	Y	5	4	4
	K	5	4	4

4. CONCLUSIONS

Cotton fabrics impregnated with polyacrylate thickener can be successfully printed digitally with reactive dyes, although the colour tones achieved are slightly lower than those obtained with cotton fabrics impregnated with alginate thickener. The colour differences are not very high, but are visible by naked eye. Penetration values are similar for both thickeners. The wash fastnesses are good in both cases.

We can conclude that reactive dyes react and bind to the cotton fabric in the same way at both thickeners. The explanation for lower K/S values at PAC is its transformation into acidic form during drying. This lowers the pH value of the environment and reduces the degree of reaction of reactive dyes with cellulose.

5. REFERENCES

Eser, B., Özgüney, A. T. and Özerdem, A. 2012. "Investigation of the Usage of Different Thickening Agents in Ink-Jet Printing with Reactive Dyes." *Industria Textila* 63(2): 85–90.
Miles, L. W. C. 1994. *Textile Printing.* Society of Dyers and Colourists, Bradford, England.
Qiao, X., Fang, K., Liu, X., Gong, J., Zhang, S., Wang, J. and Zhang, M. 2022. "Different Influences of Hydroxypropyl Methyl Cellulose Pretreatment on Surface Properties of Cotton and Polyamide in Inkjet Printing." *Progress in Organic Coatings* 165: 1–9.
Soleimani-Gorgani, A. and Taylor, J. A. 2006. "Dyeing of Nylon with Reactive Dyes. Part 1. The Effect of Changes in Dye Structure on the Dyeing of Nylon with Reactive Dyes." *Dyes and Pigments* 68: 109–117.
Šostar, S. and Schneider, R. 1998. "Guar Gum as an Environment-Friendly Alternative Thickener in Printing with Reactive Dyes." *Dyes and Pigments* 39(4): 211–221.
Ujiie, H. 2006. *Digital Printing of Textiles.* The Textile Institute, CRC Press, Woodhead Publishing Ltd., Cambridge, England.
Yuen, C. W. M., Ku, S. K. A., Choi, P. S. R. and Kan, C. W. 2005. "Factors Affecting the Color Yield of an Ink-Jet Printed Cotton Fabric." *Textile Research Journal* 75(4): 319–325.
Yang, Y. and Naarani, V. 2004. "Effect of Steaming Conditions on Colour and Consistency of Ink-Jet Printed Cotton Using Reactive Dyes." *Coloration Technology* 120: 127–131.

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POSTER PRESENTATION

TRIALS OF DRY-AIR FIXATION OF DIGITALLY PRINTED REACTIVE DYES ON COTTON FABRICS

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Abstract: *The possibility of dry-air fixation of reactive dyes on textile substrates was investigated. The fabrics were impregnated with an alkaline solution of alginate thickener containing different amount of urea. The objective was to determine the optimal pretreatment for achieving high-quality prints. The fabrics were printed in the primary colours; cyan, magenta, yellow, black and subsequently analysed for colour depth (K/S), CIELAB colour values, and print sharpness. Additionally, the colour fastnesses of the prints to washing, rubbing (crock test), and light were measured. The results indicated that steam fixation provides significantly better print quality, demonstrating that dry-air fixation is insufficient for optimal results in digital printing with reactive dyes. An increased amount of urea in the pretreatment improved printing results in certain cases.*

Key words: *digital textile printing, reactive dyes, dry-air fixation, mercerized cotton, colour fastness.*

1. INTRODUCTION

Cotton fabrics can be digitally printed with pigments or reactive dyes (Miles, 1994). Because inks are non-viscous water solutions, they easily spread along fibres as a consequence of capillary forces, compromising the sharpness of contours. To prevent this, the fabric should be treated with a thickening agent and appropriate fixing agents before printing. For printing on cotton, low-viscosity alginate thickeners in low concentrations are used, in which auxiliaries, oxidizing agents, and alkalis are dissolved (Qiao, 2022; Eser, 2012). After printing, the dye must undergo fixation, washing, and drying. During fixation, the dyes diffuse from the thickening film into the interior of the fibre and bind there. The most common fixation process is one-step normal steaming at 100–103°C. Fixation is followed by washing with cold and warm water to remove non-fixed dyes, thickeners, and chemical additives (Ujiie, 2006). The composition of the impregnating bath and the steaming time have a strong influence on the adsorption and fixation of reactive dye on cotton (Yuen, 2005; Yang, 2004; Hamaky, 2007). Experiments on the fixation of reactive dyes with dry heat have also been published (Yasukawa et al., 2008).

Since steamers are not available in many places where digital printing is performed, we were interested in whether cotton samples digitally printed with reactive dyes could be fixed using dry heat, i.e., without the use of a steamer Standard inks from a selected manufacturer were used. The fabric was pretreated with finishes containing different concentrations of urea, which increases the possibility of dye reactions with fibers during dry heat fixation.

The CIE L*a*b* colour values, the colour depth (K/S) were compared on fabrics printed with four basic colours and differently fixed. The colour fastness of the prints to washing, light and rubbing was also measured.

2. METHODS

2.1 Materials

Singed, desized, scoured, bleached and mercerized 100% cotton plain fabrics 156 g/m^2 from the manufacturer Tekstina d.d. Ajdovščina, Slovenia, was used.

2.2 Preparing the textiles for printing

Three alginate thickening pretreatment solutions with different concentration of urea were prepared. The recipes are presented in Table 1.

The following chemicals were used: CHT alginate EHV (Bezema, Switzerland), alginate thickener; sodium hydrogen carbonate ($NaHCO_3$) (Kemika, Zagreb, Croatia); urea ($CO(NH_2)_2$) (J.T. Baker, Netherlands), hydrotropic agent, Rapidoprint XR (Bezema, Switzerland), sodium m-nitrobenzenesulfonate, oxidising agent.

The pretreatment solutions were padded onto cotton fabircs using a laboratory two-roller padder (Mathis, Switzerland) with a pick-up of 75%. The pretreated samples were air dried at room temperature.

Table 1: Recipe for the alginate pretreatments.

Additive	Amount [g]		
	A1	A2	A3
CHT-alginat EHV 4 %	400	400	400
CO(NH□)□	50	100	150
Rapidoprint XR	10	10	10
$NaHCO_3$	26	26	26
Distilled H_2O	514	464	414
Total	1000	1000	1000

2.3 Printing, fixation and after-treatment

Printing was performed using a digital piezo DOD printer TextileJet Tx2-1600 from Mimaki with a resolution of 720 dpi and reactive dyes Jettex R (DyStar, England). The patterns were printed as squares of 10x10 cm and lines of 1 mm. 100% cyan (C), 100% yellow (Y), 100% magenta (M) and 100% black (K) were printed.

The printed fabrics were fixed in a laboratory steamer DHE 20675 (Werner Mathis AG, Switzerland) in 90% saturated steam at 102°C for 10 minutes or in a stenter dryer (W. Mathis AG, Switzerland) for 5 minutes at 150 °C. After fixation, the fabrics were first rinsed with cold water to remove residual thickeners, chemicals and some unfixed dyes, then with warm water and finally with hot water. The next step was soaping for five minutes at 100 °C with 1 g/l CIBAPON R detergent (CIBA, Switzerland) to remove all remaining dye residues. After soaping, the samples were rinsed with warm and cold water and air-dried at room temperature.

2.4 Analyses

The colour coordinates CIE L*a*b* and the reflectance R (%) of the printed samples were measured with a spectrophotometer SF 600 PLUS-CT (Datacolor International, Switzerland). Ten measurements were taken for each colour on each print. The measurement conditions were: Standard light D65, standard observer 10°, device geometry d/8°, measuring range 400–700 nm, four fabric layers and a measuring aperture of 20 mm.

The colour difference (ΔE*) was calculated from the CIE colour coordinates L*a*b* according to equation 1:

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

where ΔL* is the difference in lightness, Δa* is the difference on the red-green axis and Δb* is the difference on the yellow-blue axis.

The colour depth values (K/S) of the prints were calculated from the reflectance measurements using equation 2:

$$\frac{K}{S} = \frac{(1-R)^2}{2R} \quad (2)$$

where K is the absorption coefficient (depending on the dye concentration), S is the scattering coefficient and R is the reflectance of the sample at a specific wavelength (R = 0 – 1).

Colour fastness to washing at 40 °C was determined according to the standard ISO 105-C01:1989 – Textiles – Colour fastness tests - Part C01: Colour fastness to washing: Test 1. The samples were washed in a Launder-ometer LDH-HT B-S (Atlas Electric Devices, USA).

Light fastness was determined according to the standard SIST EN ISO 105-B02:2014 – Colour fastness to artificial light: Xenon arc lamp test on a Xenotest Alpha (Atlas, USA).

Rub fastness was determined according to the standard SIST EN ISO 105-X12:2002 – Colour fastness to rubbing. Rubbing was carried out using a Crockmeter (Electronic Crockmeter; SDL Atlas, USA)

3. RESULTS AND DISCUSSION

Table 2 shows the results of the CIE L*a*b* colour values of CMYK prints on cotton fabric impregnated with different preparations. Figure 1 represents the K/S values of printed samples. Colour differences show that colors vary the most depending on the fixation method. Samples fixed with steam have lower lightness (L*) and higher a* and b* values than samples fixed with dry air. This means that significantly less dye bonded to the fabric with hot air treatment than with steam. The unbound, printed dyes were removed during washing and fixation. The colour differences between steam-fixed and dry-air-fixed samples are very large and visible to the naked eye. This is also confirmed by the K/S values (Figure 1), which indicate the colour depth. For all steamed samples, the values are much higher than for those treated with dry air.

The type of pretreatment has a much smaller effect on colours than the fixation method. With an increasing concentration of urea, the K/S values rise for C, M and Y. For K, however, the K/S values are highest with the A2 finish, which has a medium urea concentration.

Table 2: CIE L*a*b* values of prints and colour differences (ΔE*) between steamed prints on preparation A1.

Colour	Fixation	Pre-treat-ment	L*	a*	b*	ΔE*
C	steam	A1	58,15	-28,69	-24,38	
		A2	55,21	-30,72	-26,04	3,94
		A3	55,27	-32,01	-26,63	4,94
	dry air	A1	77,5	-14,68	-5,69	30,33
		A2	76,9	-15,87	-6,77	28,74
		A3	76,48	-17,53	-8,13	26,92
M	steam	A1	54,16	50,46	-0,9	
		A2	53,91	50,95	-1,35	0,71
		A3	54,09	52,97	-1,9	2,71
	dry air	A1	74,39	22,47	-1,95	34,55
		A2	73	24,81	-2,92	31,89
		A3	72,93	26,42	-2,58	30,55
Y	steam	A1	81,17	2,51	78,23	
		A2	79,61	2,77	75,03	3,58
		A3	80,84	3,98	76,56	2,25
	dry air	A1	84,26	-6,03	52,56	27,24
		A2	84,39	-6,24	60,6	19,94
		A3	84,28	-5,4	60,21	19,92
K	steam	A1	22,5	-0,84	-1,97	
		A2	20,28	-1,09	-1,81	2,25
		A3	20,92	-1,15	-1,93	1,61
	dry air	A1	30,83	-4,83	-2,53	9,25
		A2	24,91	-3,56	-2,06	3,64
		A3	26,96	-3,84	-1,7	5,38

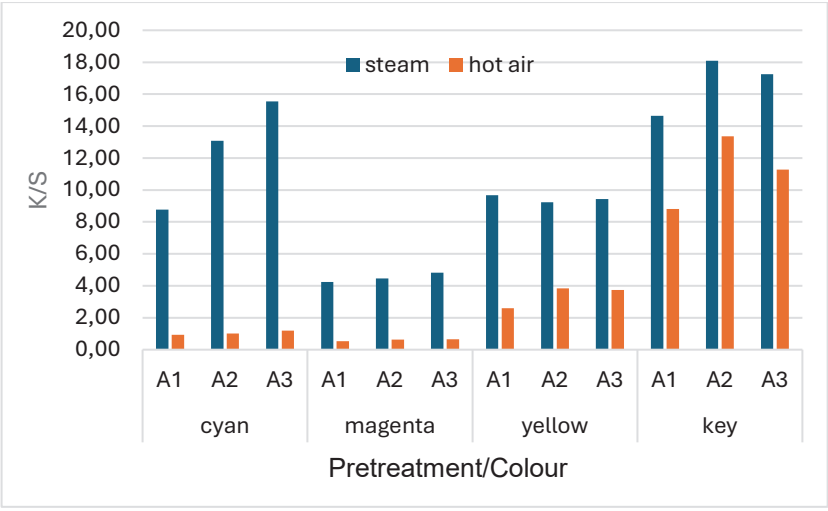


Figure 1: K/S values of printed samples impregnated with A1, A2 or A3 preparation, fixed in steam or dry air.

Table 3 lists the measured line thickness values, illustrating the printing accuracy on the examined samples. In the case of steam fixation, the line widths are slightly larger than desired, while with dry-air fixation, they are equal to or less than 1 mm. The largest deviation is observed in the sample pretreated with A3 and steamed, exceeding the expected width by 0.4 mm.

Table 3: Width of a 1 mm line printed on differently pretreated and fixed fabrics with magenta

Fixation	Pre-treatment	Line width [mm]
Steam	A1	1,2
	A2	1,2
	A3	1,4
Dry air	A1	1,2
	A2	0,9
	A3	1

Table 4 presents the ratings of colour tone changes in the samples, and of colour transfer to cotton (Co) and wool (Wo), both measured after washing at 40 °C. Table 5 includes the ratings of colour fastness of the prints to dry and wet rubbing, as well as the assessments of colour fastness to light exposure.

At colour fastness to washing at 40 °C both the ratings for colour tone changes and the ratings for colour transfer to cotton and wool were good, ranging between values 4 and 5.

The colour fastness ratings of prints to dry and wet rubbing are similar for both dry-air and steam fixation. Better results were observed for yellow samples, while cyan and black samples performed worse, as expected, since darker shades are more visible than lighter ones.

The colour fastness ratings of prints to light clearly show that the values are significantly lower for dry-air-fixed samples compared to steam-fixed ones. This is because, with a smaller amount of dye on the fibres, any degradation due to light exposure is more noticeable. Slightly poorer results were observed for samples pretreated with A3.

Table 4: Wash fastness values of samples printed on different preparation and fixed with steam or dry air.

Colour	Fixation	Pre-treatment	Washing fastness		
			Colour change	Staining CO	Staining Wo
C	steam	A1	/	4	5
		A2	4/5	4	5
		A3	4/5	4	5
	dry air	A1	5	5	5
		A2	5	5	5
		A3	4/5	5	5
M	steam	A1	5	5	5
		A2	4/5	5	5
		A3	5	5	5
	dry air	A1	5	5	5
		A2	5	5	5
		A3	5	5	5
Y	steam	A1	5	5	5
		A2	5	5	5
		A3	5	5	5
	dry air	A1	5	5	5
		A2	5	5	5
		A3	5	5	5
K	steam	A1	5	4	5
		A2	4/5	4	5
		A3	5	4/5	5
	dry air	A1	5	4/5	5
		A2	5	5	5
		A3	5	4/5	5

Table 5: Colour fastness values to wet and dry rubbing and light.

Colour	Fixation	Pre-treatment	Colour fastness		
			Dry rubbing	Wet rubbing	Light
C	steam	A1	2	3/4	4
		A2	1/2	4/5	5
		A3	1/2	4/5	5
	dry air	A1	4	4/5	1
		A2	4/5	5	2
		A3	4	4	2
M	steam	A1	2	4/5	3
		A2	4/5	4/5	4
		A3	3	4/5	4
	dry air	A1	4	4/5	1
		A2	4/5	3/4	1
		A3	3	4	1
Y	steam	A1	3	4/5	5
		A2	5	4/5	5
		A3	3	4/5	4
	dry air	A1	5	4/5	2
		A2	3	4/5	2
		A3	3/4	4/5	2
K	steam	A1	3	5	4
		A2	2	4/5	4
		A3	1/2	4/5	4
	dry air	A1	4	4/5	3
		A2	1/2	4/5	3
		A3	3	4/5	3

4. CONCLUSIONS

The investigation revealed that in digital printing with reactive dyes, fixation cannot be achieved with dry air, as the samples appear too light, the color depth is low, and fastness, especially to light and rubbing, is poor. Dye migration into the fibers is minimal in the absence of moisture, resulting in less dye reacting with the fibres. Even an increased amount of urea in the preparation is not sufficient to achieve adequate fibre dyeing in dry conditions. Moreover, a higher urea concentration negatively affects print accuracy at steaming.

5. REFERENCES

El Hamaky, Y. H., Tawfeek, S., and Gaber, S. 2007. “Printing Cotton Fabrics with Reactive Dyes of High Reactivity from an Acidic Printing Paste.” Coloration Technology 123(6): 365–373.
Miles, L. W. C. 1994. “Textile Printing.” In Textile Printing, edited by L. W. C. Miles, Bradford: Society of Dyers and Colourists.
Qiao, X., Fang, K., Liu, X., Gong, J., Zhang, S., Wang, J., and Zhang, M. 2022. “Different Influences of Hydroxypropyl Methyl Cellulose Pretreatment on Surface Properties of Cotton and Polyamide in Inkjet Printing.” Progress in Organic Coatings 165: 1–9.
Ujiie, H. 2006. “Digital Printing of Textiles.” In Digital Printing of Textiles, edited by H. Ujiie, Cambridge: The Textile Institute, CRC Press, Woodhead Publishing Ltd.
Yang, Y., and Naarani, V. 2004. “Effect of Steaming Conditions on Colour and Consistency of Ink-Jet Printed Cotton Using Reactive Dyes.” Coloration Technology 120: 127–131.
Yasukawa, R. 2008. “Dye Fixation Process in Ink-Jet Printing of Cotton Fabric by Reactive Dye.” Sen-I Gakkaishi 64(5): AA113–AA117.
Yuen, C. W. M., Ku, S. K. A., Choi, P. S. R., and Kan, C. W. 2005. “Factors Affecting the Color Yield of an Ink-Jet Printed Cotton Fabric.” Textile Research Journal 75(4): 319–325.

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POSTER PRESENTATION

COLOURFASTNESS PROPERTIES OF DIGITALLY PRINTED PIGMENTS ON COTTON/LYCRA KNITTED FABRIC

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Abstract: *The study investigated the colour fastness properties of digitally printed pigments on white and black cotton/Lycra knitted fabric. Four process colours, namely cyan, magenta, yellow and black, were printed on white fabric, while white and then cyan, magenta and yellow were printed on black fabric. The Epson SureColor F2200 inkjet printer was used for printing. After printing, samples were air-dried and cured using a hot press. The colour of the printed samples was evaluated spectrophotometrically using the CIELAB colour space. The colour fastness of the printed samples to rubbing, washing, hot pressing, perspiration and light was tested according to the applicable SIST EN ISO standards and visually evaluated using a grey scale and a blue wool scale, respectively. The results showed that the background colour (white or black) of the knitted fabric influenced the colour of the printed samples. The influence was more pronounced with black fabric than with white fabric. In general, the printed samples had excellent colour fastness to light, very good to excellent colour fastness to washing, hot pressing and perspiration and slightly lower colour fastness to rubbing.*

Keywords: *digital printing, pigments, cotton/Lycra knitted fabric, colour fastness.*

1. INTRODUCTION

Textile printing has undergone significant changes over the centuries, from outdated analogue processes (Miles, 2003) to modern digital processes (Tyler, 2005). Although rotary and flat screen printing are still the leading printing techniques, they have been largely superseded by digital printing in recent years. Digital printing is based on a combination of creative innovation, environmental efforts and technical improvements that allow companies to be flexible and meet the demands of a rapidly evolving market with speed and accuracy, while remaining true to their commitment to environmental responsibility. Digital textile printers enable designers and manufacturers to produce high-quality prints with vibrant colours, sharp details and smooth transitions. A focus on sustainability, customisation and digital innovation are the trends that will be responsible for the next wave of growth in the textile industry. Growing consumer awareness and high consumer expectations will translate into more environmentally friendly products (Global textile times, 2025). The digital textile printing market is forecast to reach USD 7.46 billion by 2030, with a compound annual growth rate (CAGR) of 12.4% over the period 2024-2030 (Industry ARC, 2025).

A detailed review of the available literature revealed that disperse, reactive and acid dyes as well as pigments are predominantly used in digital printing (Thakker, 2024). The colour fastness of printed textiles depends on both the concentration of the dye or pigment in the printing inks and the printed textiles (Glogar, 2022) and the presence of suitable chemicals on the pretreated textiles (Ding, 2021), which are responsible for the swelling of the textiles and the rapid penetration of the dye into the fibres (Kan, 2012), the formation of the dye-fibre bond and its strength during the fixing process. In addition, the appropriate post-treatment process is determined by the removal of unfixed dye from the textiles and thus the improvement of the wet fastness properties of the printed textiles. No study was found in the published articles investigating the most common colour fastness properties on white and black knitted fabrics digitally printed with pigments. The aim of this study is therefore to investigate the colour fastness of cotton/Lycra blended knitted fabrics printed with four process colours, namely yellow, magenta, cyan, black and additionally white, whereby the results obtained can serve as a recommendation for the design of printed products according to customer requirements.

The white and black knitted fabrics were digitally printed using an Epson SureColor F2200 inkjet printer. The colour fastness tests were carried out in accordance with the applicable SIST EN ISO standards. The colour fastness was tested during rubbing, washing, hot pressing, perspiration and lighting. The colour of the prints was evaluated spectrophotometrically using the CIELAB colour space. For black knitted fabric, the influence of the white pigment on the CIELAB colour values of the process colours was also evaluated by determining the colour difference.

2. EXPERIMENTAL

2.1 Knitted fabrics

White (W) and black (B) single jersey knitted fabric made of 90 % cotton and 10 % elastane (Lycra) with a density of 32 (W fabric) or 31 (B fabric) wales/cm and 30 (W fabric) or 28 (B fabric) courses/cm. The W fabric has 151 g/m^2 and the B fabric 208 g/m^2.

2.2 Pigment inks and chemicals

Epson Ultrachrome DG2 cyan (C), magenta (M), yellow (Y), black (K) and white inks were used for printing. The inks are aqueous dispersions of pigments. When printing on dark textiles, the fabric was pre-treated with an aqueous solution of a commercial product T43R1/SC6PTL2 (Epson, USA).

2.3 Preparation of the fabric for printing and printing

Before printing, both the W and B fabrics were washed with 3 g/l anionic washing and wetting agent Subitol AS 6 (CHT, Switzerland) and 2 g/l Na_2CO_3 (Honeywell, Germany) at 60 °C for 30 minutes at a ratio of LR 1:20. After washing, the knitted fabrics were rinsed with warm and cold water and air-dried at room temperature.

The B fabric samples were sprayed with the above-mentioned commercial product in a Pretreat maker 5 device (Gröner Schulze, Germany) before printing. The samples were then dried in a vacuum press at 170 °C for 60 seconds. The digital artwork was created in Adobe Illustrator 2024 and opened in the Digital Factory Apparel v11 programme with a resolution of 300 dpi. Using the Job colour replacement function, the CMYK values for each process colour C, M, Y and K were set to 100 before printing. The prepared artwork was digitally printed on white and pre-treated B samples using an Epson SC-F2200 (Epson, USA) printer. The B samples were first printed with white ink and then with CMYK inks, whereby 90% coverage of the B sample with white ink was selected. The printed samples were then hot-pressed at 170 °C for 60 seconds. Colour fastness tests were carried out after 3 days.

The sample codes are listed in Table 1.

Table 1: Sample codes and their description

Sample code	Description
W and B	white (W) and black (B) knitted fabric, unprinted
W_C	white knitted fabric, printed with 100 % cyan ink
W_M	white knitted fabric, printed with 100 % magenta ink
W_Y	white knitted fabric, printed with 100 % yellow ink
W_K	white knitted fabric, printed with 100 % black ink
B_C	black knitted fabric, printed with 100 % cyan ink
B_M	black knitted fabric, printed with 100 % magenta ink
B_Y	black knitted fabric, printed with 100 % yellow ink

2.4 Test methods

Measurement of colour

The colour of the printed samples was evaluated spectrophotometrically with the Datacolor Spectro 1050 (Datacolor, USA) using the CIELAB colour space. For each sample, 10 measurements were taken at standard illuminant D65, geometry d/8°, including specular reflection, 10° standard observer, 100% UV and an aperture size of 9 mm. The measurements were carried out on samples folded four times. The results represent the average value of 10 measurements. The colour difference (ΔE^*_{ab}) was calculated according to equation 1:

$$\Delta E^*_{ab} = \sqrt{(L^*_b - L^*_s)^2 + (a^*_b - a^*_s)^2 + (b^*_b - b^*_s)^2} \qquad (1)$$

where L^* is the lightness, a^* is the red-green axis, b^* is the yellow-blue axis, the index b is the batch (B sample) and the index s is the standard (W sample).

Colour fastness to rubbing

The rub fastness of the printed samples was tested in accordance with the SIST EN ISO 105-X12:2016 standard using the Crockmeter M238BB (SDL Atlas, USA). The staining of wet or dry adjacent fabrics was visually assessed using a grey scale according to the SIST EN ISO 105-A03:2019 standard, with a grade of 5 indicating excellent colour fastness and a grade of 1 indicating poor colour fastness. Three repetitions of the test were carried out for each sample. The result represents the average value.

Colour fastness to washing

The colour fastness of the printed samples for household and commercial laundry was tested in the GyroWash device (James Heal, UK) in accordance with the SIST EN ISO 105-C06:2012 standard using test method A1S. Colour change was assessed visually using a grey scale (standard SIST EN ISO 105-A02:1993), while staining was also assessed visually using a grey scale (SIST EN ISO 105-A03:2019). Three repetitions of the test were carried out for each sample. The result represents the average value.

Colour fastness to hot pressing

The colour fastness of the printed samples during hot pressing was tested according to the SIST EN ISO 105-X11:1999 standard. The test samples were pressed for 15 seconds at 150 °C using a hot press. The colour change and staining of white wet and white dry fabrics were visually assessed using a grey scale (standards SIST EN ISO 105-A02:1993 and SIST EN ISO 105-A03:2019) Three repetitions of the test were performed for each sample. The result represents the average value.

Colour fastness to perspiration

The colour fastness of the printed samples during hot pressing was tested according to the SIST EN ISO 105-E04:2013 standard. The test samples were pressed for 15 seconds at 150 °C using a hot press. The colour change and staining of adjacent fabrics were visually assessed using a grey scale (standards SIST EN ISO 105-A02:1993 and SIST EN ISO 105-A03:2019) Three repetitions of the test were performed for each sample. The result represents the average value.

Colour fastness to artificial light

The colour fastness of the printed samples after a certain period of exposure to artificial light was tested in accordance with the SIST EN ISO 105-B02:2014 standard. The colour change was assessed visually using a blue wool scale, with a grade of 8 indicating excellent light fastness and a grade of 1 indicating poor light fastness.

Microscopy

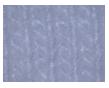
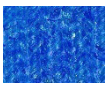
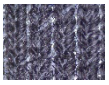
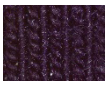
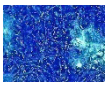
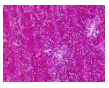
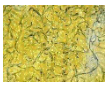
The uniformity of the surface of printed samples was observed under the SMZ800 stereomicroscope (Nikon, Japan) at 50x magnification. In addition, the morphology of the thickening layer of the printed samples was analysed using the scanning electron microscope (SEM) JSM–6060 LV (JEOL, Japan) at 500x magnification.

3. RESULTS AND DISCUSSION

3.1 Colour

Table 2 shows the CIELAB values of the unprinted and printed samples of W and B fabrics. It can be seen that the difference between the colours printed on samples of W and B fabrics is quite large. Although the samples of the B fabric are covered with a layer of white pigment before the other colour pigments are printed, all colours on the samples of the W fabric are lighter than on the B fabric. This is due to the transparency of the pigment system, which cannot completely cover the background colour of the fabric. In addition, a strong visual appearance of the concentrated white pigment on the fabric surface was observed on the B printed samples (see appearance of samples in Table 2), although the white ink cartridges were shaken well before printing, as were the coloured inks. This uneven deposition of the white pigment also affects the colour of the pigment. When calculating the colour difference between the printed fabrics W and B for each process colour, it can be seen that the largest colour difference exists for the Y pigment (ΔE^*_{ab} = 16.59) and the smallest for the C pigment. (ΔE^*_{ab} = 8.70). The latter is understandable as the Y pigment is the lightest and the C pigment the darkest. Table 2 also shows that the brightness of sample B_Y is lower compared to sample W_Y, even though the white pigment was applied to the B fabric before the Y pigment was printed. This indicates that the black colour of the fabric is most likely to show through in the printed areas. The B_Y sample is also greener and less yellow than the W_Y sample, which is also due to the black background colour of the fabric, which allows both layers of colour, white and yellow, to show through. The background colour of the knitted fabric can also be seen in samples B_C and B_M. Sample B_C is darker and less green and less blue than sample W_C, while sample B_M is darker, less red and less blue than sample W_M.

Table 2: CIELAB colour values of unprinted and printed samples as well as the calculated colour difference (ΔE^*_{ab}) between the colours C, M and Y on samples of W and B fabrics

Sample name	Sample appearance	CIE *L**	**CIE *a****	**CIE *b****	ΔE^*_{ab}
W		96.15	3.42	-12.31	/
W_C		51.11	-13.68	-42.15	/
W_M		55.43	53.98	-14.40	/
W_Y		87.15	2.85	77.08	/
W_K		32.21	2.03	-2.68	/
B		15.09	-0.56	-0.79	/
B_C		44.91	-12.41	-36.18	8.70
B_M		46.90	47.49	-7.85	12.56
B_Y		75.26	-2.92	67.05	16.59

A more detailed effect of the white pigment on the shade of colour pigment was investigated under stereo microscope. It can be seen from the appearance of samples, presented in Table 2, that the W samples are visually uniformly printed and that the coverage of the background colour of the knitted fabric by the pigment is good. Empty spaces can also be seen between the rows and columns of the knitted fabric, which indicates that the fabric is still sufficiently permeable to air despite being printed with pigments. The latter is confirmed by SEM micrographs (Figure 1).

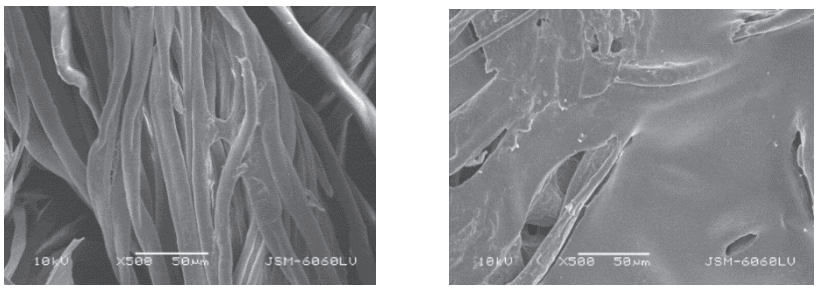


Figure 1: SEM micrographs of W_C sample (left) and B_C sample (right)

The SEM micrographs of the W_C and B_C samples presented in Figure 1 show that the fibres of the B_C sample are fully covered and bonded with a binder layer in which the pigments are entrapped, whereas in the case of the W_C sample there is significantly less binder layer formed, as W samples were not sprayed with a pre-treatment agent before printing, as was the case with the B samples.

3.2 Colour fastness

Table 3 summarises the assessments of the colour fastness of the printed samples to rubbing, washing, hot pressing, perspiration and light.

Table 3: Colour fastness grades of printed samples

Sample	Fastness grade																
	Rubbing				Washing			Hot pressing			Perspiration						Light
	Dry		Wet				Acidic			Alkaline							
	CC_W	CC_C	CC_W	CC_C	SC	SW	CC	SC	SW	CC	SC	SW	CC	SC	SW	CC	CC
W_C	3	3	3	4	4/5	4/5	5	5	5	5	5	5	5	5	5	5	8
W_M	3	3/4	3	4	4/5	4/5	5	4/5	5	5	5	5	5	5	5	5	8
W_Y	4	4	4	4	4/5	4/5	5	5	5	5	5	5	5	5	5	5	8
W_K	5	4/5	4/5	4/5	4/5	4/5	4/5	5	5	5	5	4/5	5	5	5	5	8
B_C	4	4	4	4	4/5	4/5	5	5	5	4/5	4	4	5	4	4/5	5	8
B_M	4	4/5	4/5	4	4/5	4/5	4/5	5	5	5	4/5	4	5	4	4/5	5	8
B_Y	3	3	4/5	4/5	4/5	4/5	5	5	5	5	4/5	4/5	5	4	4/5	4	8

CC_W change in colour along the length of the knitted fabric, CC_C-change in colour across the width of the knitted fabric, SC-staining of cotton fabric, SW-staining of wool fabric, CC-change in colour

In general, the printed samples are less colourfast when rubbed dry than when rubbed wet, both along the length and across the width of the fabric. The fastness of W samples is also worse than that of B ones, regardless of the type of rubbing. It can be concluded from this that during rubbing, more friction occurs between the dry knitted fabric and the dry fabric with which the knitted fabric is rubbed than between the dry knitted fabric and the wet fabric. The higher colour fastness of the B printed samples during rubbing compared to the W printed samples

was attributed to the fact that the B samples were additionally sprayed with an aqueous solution of a binding agent that could improve the fastness. Although the colour fastness of the printed fabrics during rubbing is between 3 and 4/5 on a grey scale, the printed samples exhibit good to very good colour fastness during dry and wet rubbing.

Printed samples have excellent (grade 5) to very good (grade 4/5) colour fastness when washed at 40 °C (Table 3). No colour change (grade 5) or only a slight colour change (grade 4/5) was observed on the washed printed samples compared to the unwashed printed samples. The latter indicates that the pigments are well bonded to the binder layer formed on the cotton fibres in which the pigments are entrapped, or that the adhesion between the binder and the textile fibre is high. SEM micrographs of unwashed printed samples show that fibre adhesion and the formation of a bonding layer is much higher in B printed samples than W printed samples (Figure 1). Furthermore, the printed samples show excellent colour resistant to hot pressing (Table 3), with grey scale grade of 5 in almost all cases. In contrast to the colour fastness grades of the printed samples to hot pressing, the colour fastness grades of printed samples to acid and alkaline perspiration are slightly lower (grades 4 and 4/5). The printed B samples (grade 4 and 4/5) were slightly less colour resistant to acid and alkaline sweat than the printed W samples (rating 5). The latter could be attributed to the poorer colour fastness of the black dye with which the knitted fabric was dyed, which resulted in a detectable staining of white adjacent fabric during testing, whereas no pigment passage to white adjacent fabric could be detectable by naked eye. Moreover, printed samples showed excellent colour fastness to light (grade 8 according to blue wool scale)

4. CONSLUSION

In the study, W and B knitted fabrics were digitally printed using an Epson SC-F2200 printer. It was found that the background colour of the fabric influenced the CIELAB values of the printed samples. As the white ink does not completely cover the background colour of the B knitted fabric, there are colour differences between the printed W and B samples. The printed samples have good to very good colour fastness when wet rubbed and less good colour fastness when dry rubbed. They have very good to excellent colour fastness to washing and hot pressing. The B samples are less fast to perspiration than the W samples, which is due to the lower colour fastness of the black dye used to dye the B samples. Both samples have excellent colour fastness to light.

5. REFERENCES

Ding Y., Zhendong W., Chuanxiong Z., Ruobai X., Wenliang X. 2021. A study on the applicability of pigment digital printing on cotton fabrics. Textile Research Journal 91(19–20): 2283–2293.

Global textile times: 2025 Fabric Printing: Advancements In Textile Technology, Global textile times. URL: https://www.globaltextiletimes.com/opinions/2025-fabric-printing-advancements-in-textile-technology/ (last accessed on 31.1.2025).

Glogar M. I., Dekanić, T., Tarbuk A., Čorak I., Labazan P. 2022. Influence of Cotton Cationization on Pigment Layer Characteristics in Digital Printing. Molecules 27(4)1418: 1–14.

Industry ARC: Digital textile printing market overview, URL: https://www.industryarc.com/Research/Digital-Textile-Printing-Market-Research-501687 (last accessed 31.1.2025).

Kan, C.W, Yuen, C.W.M. 2012. Digital Ink-jet Printing on Textiles. Research Journal of Textile and Apparel 16(2): 1–24.

Miles, L. W. C, 2003. Textile printing: revised second edition. Bradford: Society of Dyers and Colourists.

Thakker A. M., Sun, D. 2024. Inks for digital printing of textiles. The Journal of The Textile Institute 115(12): 2377–2390.

Tyler, D.J. 2005. Textile Digital Printing Technologies. Textile Progress 37(4): 1–65.

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POSTER PRESENTATION

RESEARCH OF THE AMOUNT OF FIBRES FRAGMENTS SHEDDING IN WASHING PROCESS OF A STANDARD 50/50% PES/ COTTON KNITTED FABRIC

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Abstract: *Since the washing process is considered one of the most influential processes in the release of fibre fragments - i.e. water pollution with microplastics - and the data situation is still imprecise and requires a lot of research, the research project InWaShed - MP (IP-2020-02-7575) was also recently carried out. In this project, the properties of PES/cotton 50/50% knitted fabrics were investigated in the washing process. The effects on the fibre fragments were investigated by simulating a washing process (60 °C, 30 min) using two different detergents as well as tap water and distilled water and the change in mass of the tested knitted fabric after 3 washing cycles in relation to the original dry mass was measured. In addition, a filtration of the residual bath was carried out - the mass of the dry residue of the bath filter was determined after three washing cycles with standard detergent and distilled water and reference baths.*

Keywords: *washing process, detergents, microplastics pollution, PES/cotton knitted fabric, gravimetric method*

1. INTRODUCTION

Textiles made of synthetic polymers, of which polyester is the most common, are a significant source of microplastic pollution, as fragments of synthetic fibres are released due to various physical-mechanical and chemical influences during production, use and care during the life cycle and improper disposal at the end of the life cycle of textile products. According to studies (Sherrington 2016), around 35% of the total amount of microplastics released into the oceans comes from the washing of textiles made from synthetic fibres. According to estimates by (UNEP 2018), the total annual amount of microplastics and macroplastics released into the environment through the washing of textiles – clothing - is 0.29 million tonnes or 3.2%. All this points to the problem of the method for determining and assessing the extent of microplastic pollution. To monitor this process and determine the quantities, ISO/EN/HR standards for the determination of the amount of fibre particles released during washing were adopted in 2023, further underlining the importance of this issue (EN ISO 4484-1:2023). Among other global research, the project: Assessment of microplastic shedding from polyester textiles in washing process (IP-2020-02-7575), funded by the Croatian Science Foundation for the period from 1 February 2021 to 31 January 2025, has started to investigate this topic, based on the data that one third of microplastics in wastewater comes from microplastics released from textiles during the washing process. Among the many influences on the phenomenon of fibre fragments detaching from textiles during washing are the nature and composition. Therefore, it is necessary to perform a variety of tests on different types of textile materials using similar methods. In this work, a test was carried out on a 50/50% PES/cotton standard knitted fabric (Farhat 2024) as a continuation of the 100% PES standard knitted fabric (Vinčić 2024) and 100% PES woven fabric (Vinčić 2022) also tested as part of the InWaShed - MP research project (IP-2020-02-7575).

2. EXPERIMENTAL

In the experimental part, the simulation of the washing process (temperature 60 °C, 30 min) was carried out in the Ahiba Turbomat laboratory apparatus with 6 beakers with magnetic stirring of the bath using two different detergents and tap water and distilled water and the change in the mass of the tested fabric after 3 washing cycles in relation to the initial dry mass was measured. In addition, a filtration of the residual bath was carried out - the mass

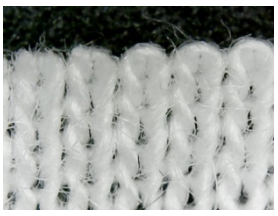
of the dry residue of the bath filter was determined after 3 washing cycles with standard detergent and distilled water and reference baths.

The simulation of the washing process was carried out on a clean standard 50/50% cotton/PES knitted fabric with the addition of standard and Persil universal detergent in distilled and tap water and in distilled and tap water only (without detergent).

2.1 Materials

In the experimental part standard polyester/cotton 50/50% weft knitted fabric was used, the characteristics of which are presented in Table 1.

Table 1: Structural parameters and digital image of standard polyester/cotton 50/50% weft knitted fabric

Paremeter	Specification
Standard fabrics supplier	WFK, Germany
Composition	50/50% PES/cotton
Mass per unit area (g/m^2)	139.5
- horizontal (Dh)	14 stiches/cm
- vertical (Dv)	28 stiches/cm
Dino-Lite microscopic images Magnification 50x	 a) surface  b) cutted edge

2.2 Simulation of washing process

The simulation of the washing process was carried out on the samples of PES/cotton standard weft knitted fabric in Ahiba Turbomat (Datacolor) laboratory apparatus according to the T/t diagram in Figure 1, using Persil and the standard detergent ECE A in different concentrations:

- 1.5 g/L Persil - universal powder detergent (Henkel)
- 1.25 g/L standard detergent ECE Formulation Non Phosphate Reference Detergent (A) without optical brighteners.

The tap water used to wash the Persil detergent had a temperature of 14.50 °dH.

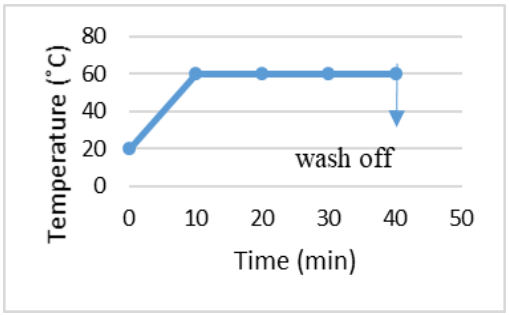


Figure 1: Process diagram of simulated washing process

The washing process was simulated in an AHIBA laboratory apparatus with magnetic stirrer of the bath according to parameters based on the HRN EN ISO 6330:2012 method.

2.3 Methods

In the simulation test of the washing process of clean standard 50/50% PES/cotton knited fabric, standard detergent and distilled water as well as universal detergent in powder form Persil and tap water were used to prepare the bath. Samples 1 and 2 of all tested series were processed without the addition of detergents - i.e. only in tap water or distilled water - and samples 3, 4, 5 and 6 in the bath with the addition of detergents in the water.

The simulation of the washing process was carried out at a temperature of 60 °C, gradually increasing the temperature for 10 minutes and processing (washing) at 60 °C for 30 minutes with magnetic circulation of the bath. After simulating the washing process, the samples were rinsed and dried until they were completely dry. Their mass was then determined and the value of the mass change in relation to the mass of the samples before washing was calculated.

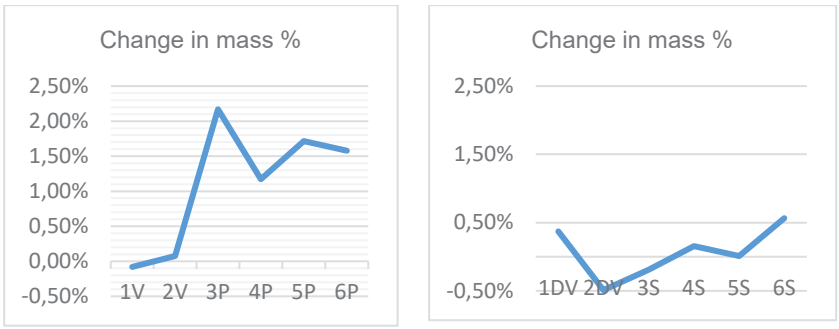
In addition to measuring the mass change, the bath samples were filtered with standard detergent and distilled water after the washing process. The filtration of the collected residual baths and the mass of the filtered dry mass was determined on FilterBio® polyestersulphone filters - 47 mm diameter and 0.22 µm pore size. 3 x 200 ml were separated from each bath sample, i.e. three parallel filtrations were carried out, from which the average values were determined.

3. RESULTS WITH DISCUSSION

The results of the change in mass after the 3rd cycle of the washing process are shown in Figure 2. Based on the variations obtained, the results clearly confirm the complexity and sensitivity of these tests, and it was confirmed that the results are significantly influenced by the type of detergent in combination with the water used. Figure 2 shows the cumulative values of the changes in the mass of the samples, expressed as a percentage in relation to the initial mass (dry mass of the samples before washing). The results obtained are surprising: after the first cycle, a loss of mass was observed for some samples and an increase in mass for others, but after the third washing cycle, these increase values are very large and almost the same for all comparative samples (Figure 3a, samples 3P - 6P). The change in mass of the tested samples washed with Persil after the 3rd wash cycle has a positive

sign, i.e. there was an increase in mass, on average +1.66%. Although the accuracy of the results obtained may be questioned, the increase in the comparative samples is relatively uniform, which could indicate the phenomenon of precipitation of the detergent and/or interaction with the tap water or a systematic error. In any case, further tests should be carried out with the same samples and under the same washing process conditions.

A lower average increase in mass was also observed with standard detergent (+0.13%) (Figure 3b, samples 3S - 6S). The results of the mass of the dry residue of the bath filter after three washing cycles carried out on the residual bath from the wash with standard detergent and distilled water are shown in Figure 3.



a) b)

Figure 2: PES/cotton knitted fabic change in mass after 3rd washing cycles:

a) samples 1V and 2V only in tap water, samples 3P, 4P, 5P and 6P in Persil + tap water
b) samples 1DV and 2DV only in distilled water, samples 3S, 4S, 5S and 6 in Standard detergent ECE + distilled water

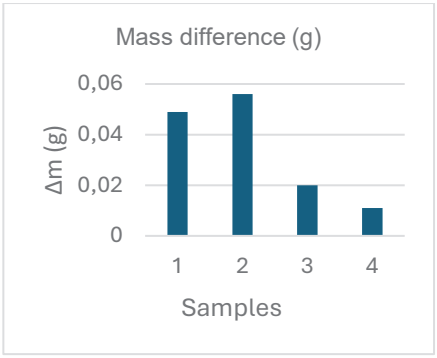


Figure 3: Mass difference of the samples of the dry residue of the bath filter: 1 - standard detergent and distilled water after three washing cycles without knit samples, 2 - referent bath of standard detergent and distilled water (without washing process), 3 - bath after three washing cycles of the knit samples with distilled water, 4 - bath after three washing cycles of the knit samples with standard detergent and distilled water

The results from Figure 3 are interesting and surprising. The largest mass difference was found for reference sample 2 (standard detergent and distilled water – unused bath), followed by the same bath (sample 1) processed under similar conditions (at 60 °C) but without the knitted fabric sample, followed by the remaining bath after washing the knitted fabric in distilled water only (sample 3) and the smallest mass difference for sample 4 – a bath with standard detergent and distilled water after washing the knitted fabric. However, these results could be related to the deposition of detergent on the knitted fabric samples (which can be explained by the average increase in their mass after washing). The cotton content in the blend most likely affects the greater deposition of detergent on the 50/50% PES/cotton knitted fabric, as the cotton fibres have a greater possibility of forming different bonds and have a higher substantivity and absorptivity.

4. CONCLUSIONS

The results of this research provide a better insight into the influence of raw material composition on the release of microparticles, i.e. fibre fragments, which will contribute to a better understanding of their contribution to microplastic pollution and help in the development of new methods and procedures to determine and reduce the emission of microplastics from textile materials. They will also contribute to expanding the database of the InWaShed - MP research project (IP-2020-02-5757), which is funded by the Croatian Science Foundation (HrZZ).

These results, which showed an increase in the mass of the tested samples after three washing cycles, and a comparison with similar tests carried out on 100% PES knitted fabic, indicate the influence of cotton in a blend with polyester. As cotton interacts more readily with the bath due to its absortivity and substantivity during washing (of different compositions), it may indirectly influence the reduced release of PES fibre fragments into the bath, i.e. the wastewater. Although further testing is needed, this could be one of the solutions to reduce the problem, i.e. the amount of fibre microparticles released during washing, i.e. microplastics.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

European Standard EN ISO 4484-1:2023, February 2023.

Farhat, L (2024): Comparison of the release of fiber microparticles in the washing of different standard polyester knits. Final Bc Thesis, University of Zagreb Faculty of Textile Technology.

Sherrington, C. (2016): Plastics in the marine environment, Eunomia, Bristol, UK, http://eunomia.eco/reports/plastics-in-the-marine-environment (Accessed: 25 March 2021).

UNEP (2018): Mapping of global plastics value chain and plastics losses to the environment: with a particular focus on marine environment, United Nations Environment Programme, https://www.unep.org/pt-br/node/27212 (Accessed: 6 May 2021).

Vinčić, A., Pušić, T. et al. (2022) 'Release of PES fibre particles during washing - estimation by reducing the fabric mass and dry mass of the residual bath', in Book of Proceedings of the 10th International Textile, Clothing & Design Conference, ed. By Zvonko Dragčević, Faculty of Textile Technology, University of Zagreb, pp.160-166.

Vinčić, A., Pušić, T. et al. (2024) 'Determination of the amount of released fiber microparticles in the washing of standard polyester knitted fabric', in Book of Proceedings of the 11th International Textile, Clothing & Design Conference, ed. by Anica Hursa Šajatović, Ivana Špelić, Faculty of Textile Technology, University of Zagreb, pp. 143-148.

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INNOVATIVE TEXTILE PROCESSING, DIGITALISATION AND INDUSTRY 5.0

ORAL PRESENTATION

COMPUTERIZED CREATION OF NOVELTY WEAVES

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Abstract: *Traditional weaving textbooks usually present a classification of basic weaves, combined with methods for creation of new weaves. We present new methods of algorithmic creation of weaves, which are nowadays possible thanks to the use of CAD software. We explain these methods as implemented in ArahPaint jacquard drawing program and ArahWeave jacquard weaving CAD. The created weaves vary in use by satisfying specific technical properties, for example crepe weave with desired float length. We also want the weaves to repeat nicely, and be visually regular, free of unwanted stripes.*

Keywords: *weaving jacquard CAD parametric generation*

1. INTRODUCTION

Textile schoolbooks have a long tradition and they all present their own weave classification, accompanied by some step by step instructions for creation of new weaves, by combining the existing ones (Brickett 1934, Giudici 1943, Holyoke 2013, Kienbaum 2016, Rodón i Amigó 1930). This can be done simply by using a basic weave block and rotating it by 90/180/270 degrees, by placing rotated blocks arranged in a regular pattern, by superimposing weaves, by interlacing them, by adding points to existing weave using some rules, etc. In a modern terminology, we would call these instructions algorithms for weave constructions.

We will concentrate on single layer weaves, as multiple layer weaves are usually created on the fly by the designer based on a specific construction need.

Most textile CAD software offers tools to automate these processes. But some push the boundaries even further, and provide additional tools with more complex algorithms, which the old masters could not envision. We will explain some functions, which have been implemented in software packages ArahPaint (Gregorčič 2025) and in ArahWeave (Gregorčič 2025).

Usually we construct a weave with the aim to achieve certain surface effect, while respecting some technical production limitations, like maximum length of floats, weave repeat size (for divisibility), visual appeal (must be balanced without unwanted lines in any direction). One classical example of such a weave construction is crepe weave. It is quite difficult to do for shaft weaving, so even today in the industry they always use the same 3-4 good crepe weaves. For jacquard, we are free to make much larger weaves, so we present an algorithm for creation of crepe weave of any repeat size, intensity level (warp to weft effect) or length of maximum float.

2. MAKING NOVELTY WEAVES BY CAD

1.1 Crepe weaves by random weave mirroring

One approach we use in ArahPaint is to chose a suitable starting motif, then we call the function to create random mirroring layout of the motif, and finally we create the new weave. The advantage of this approach is that we can easily make very large weaves, which match the number of hooks on our jacquard. The bigger the weave, the more regular it will look. Since our base weave was carefully chosen, we do not have any long floats.

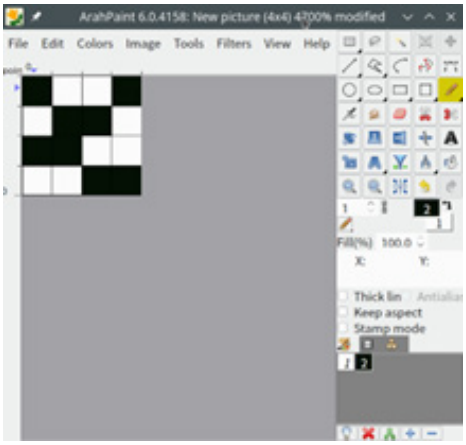


Figure 1: Base weave for expansion by random mirroring

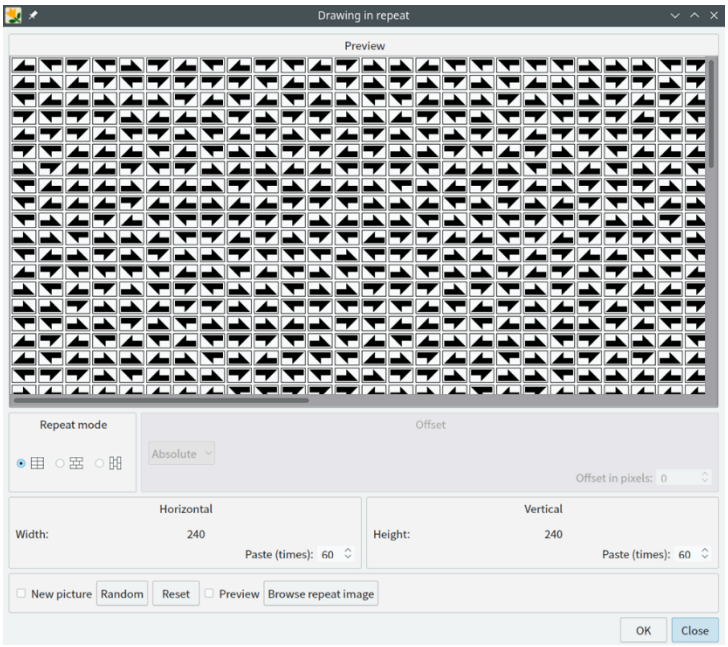


Figure 2: Setting the layout for expansion by random mirroring

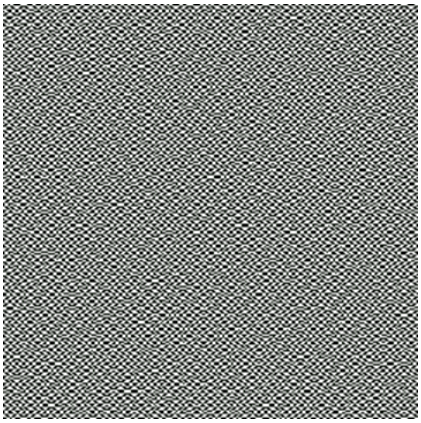


Figure 3: The resulting crepe weave of size 240x240

1.2 Simulating flame yarns by randomly inverting weave areas

Weavers always try to achieve maximum effect using minimal tools. For example, flame yarn is more expensive than regular yarn, and we try to get the effect of flame yarn look just by using special weave. We start with plain weave, and then we use the software to randomly invert sections of single warp and single weft. The starting position is random, and length is also random, but parametric. In areas where the weave was inverted, the yarns weave in the same way, so they are grouped together. As a result, you will get a view of irregular yarn in the fabric. Since the algorithm to place the invert operation works in repeat, there will be no visible defect on the border. Once again, we can easily use this approach to make weaves of any size, so we are sure to use the whole capacity of the jacquard at hand, and we made a design which is hard to copy.

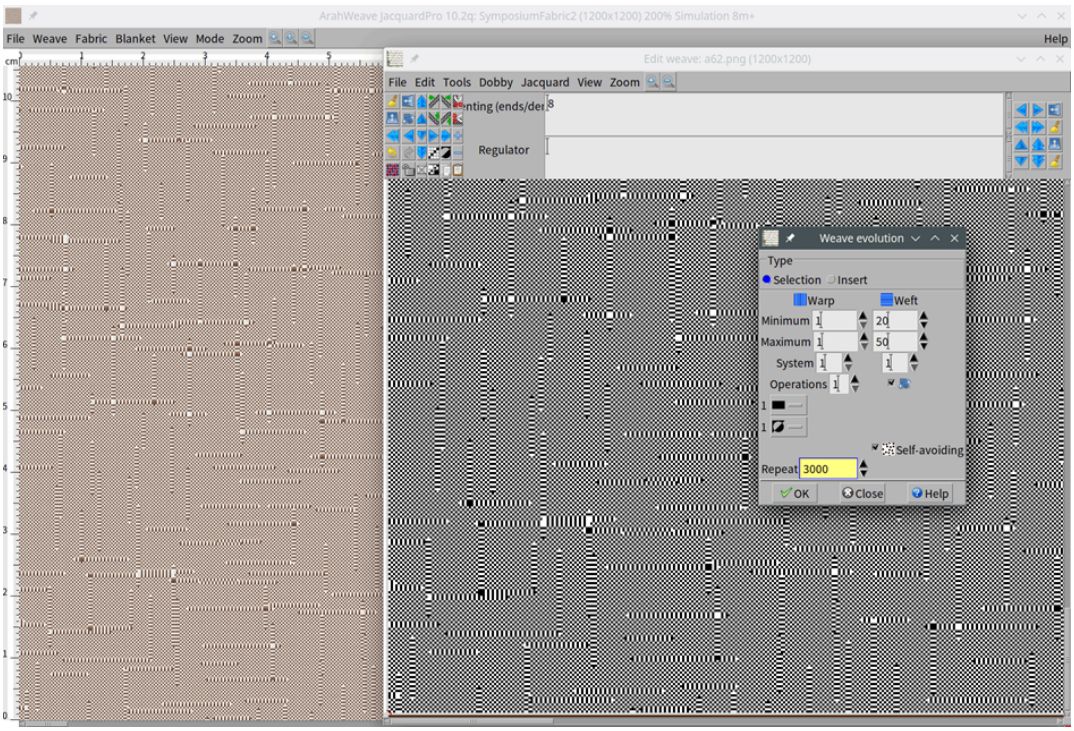


Figure 4: The resulting crepe weave of size 240x240

1.3 Creating irregular crepe by randomly inverting weave areas

In upholstery fabrics, we often wish to create an irregular texture, and generally it is difficult to create a weave or pattern that is free of visual stripes across the repeat. We want the repeat to be invisible to the viewer, but also to have he right amount of irregularity, so that the design is not dull. Once again, we are using the random invert function on plain weave. This time we create 10000 inverted filled rectangles, randomly placed, and with random size between 10 and 200 weave points. Since some junction areas are unpredictable because of the overlapping random operations, we could have areas of long floats. So we also call the function to correct the long float with maximum permitted float of 6 points.

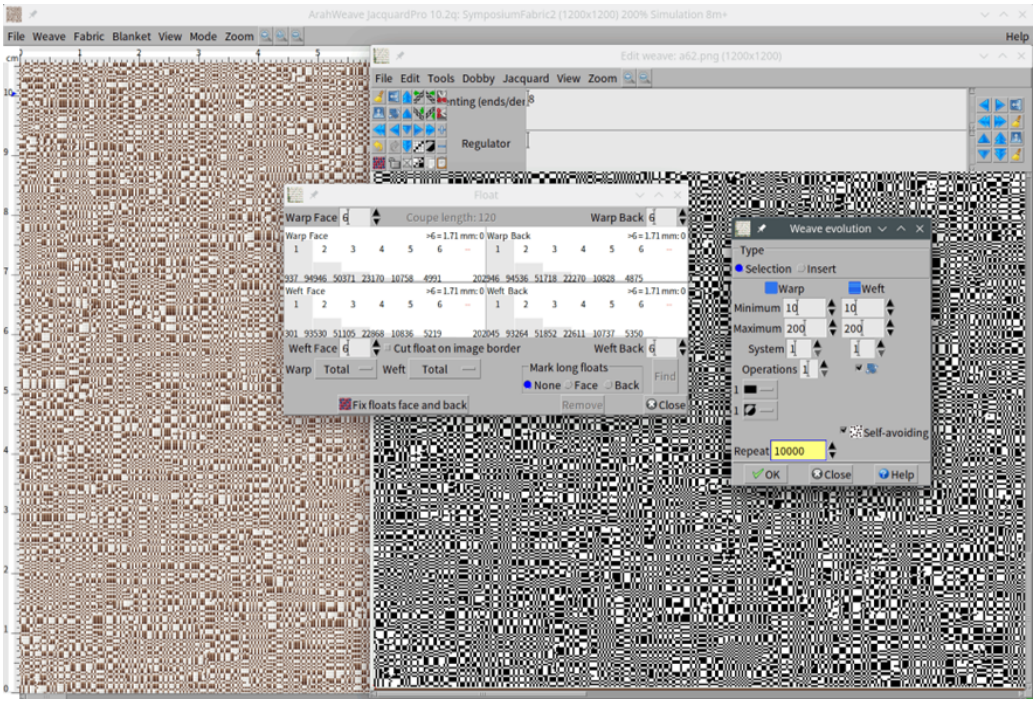


Figure 5: Irregular crepe for upholstery

1.4 Creating crepe weave by random using variable intensity

Another way of creating crepe weaves is to simply define the desired weave size, for example 1200x1200, and warp/weft intensity ratio. In ArahWeave, we define the intensity between 0 and 255, so for mid level crepe, we should use the intensity of 128. Program simply creates a random mix of black and white points with given intensity. In order to use it as a weave, we also define the maximum number of allowed long floats. The value depends on the intended fabric usage and weaving density, in this case we use 3.

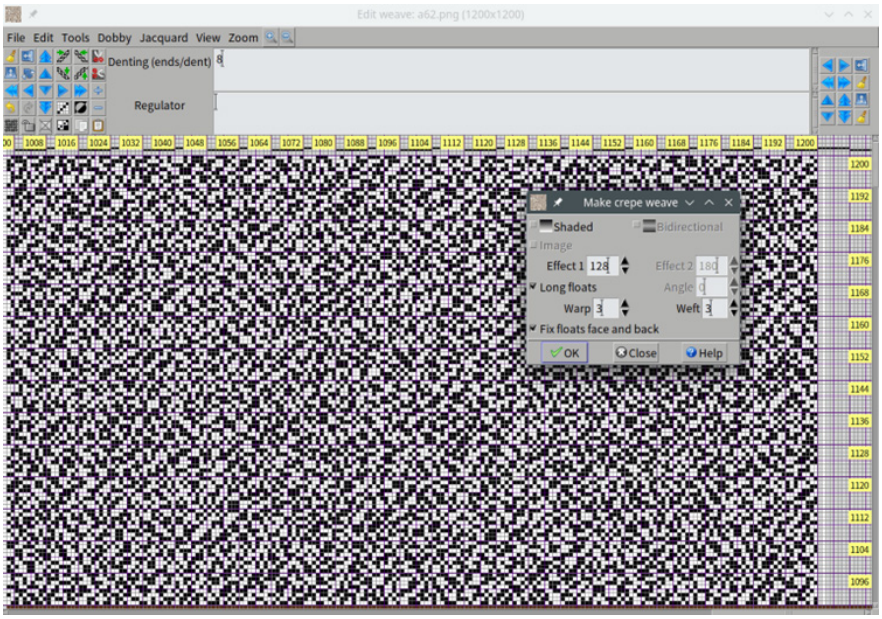


Figure 6: Random crepe weave 1200x1200 with maximum float of 3

Since we have full freedom of setting the intensity of the warp to weft effect, we can push it a little further and directly create gradient effect with the crepe weave, by setting the minimum and maximum effects, we can even make it bidirectional or use an angle. This kind of weave are very appreciated by designers of curtains or shawls, since they can make a weave with the size that matches their design requirements.

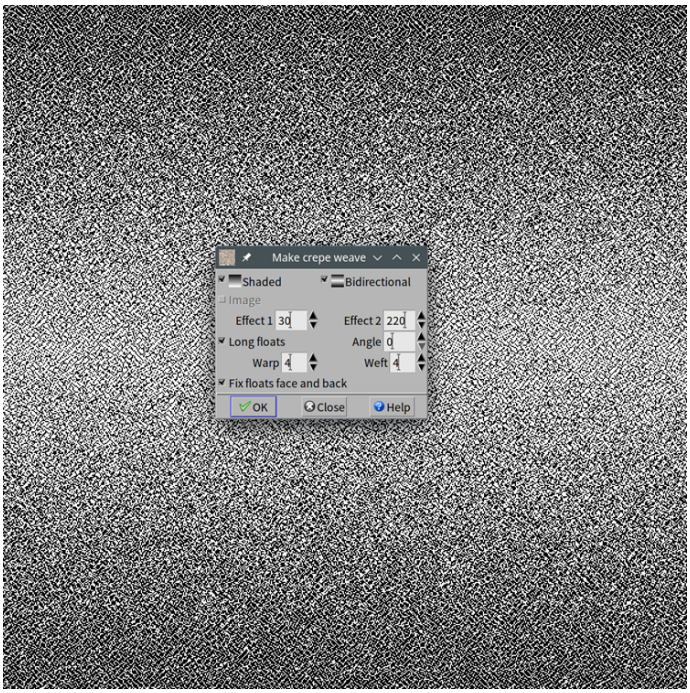


Figure 7: Random shaded crepe weave 600x600 with maximum float of 4

1.5 Creating weaves by motif rotation and zoom

The discovery of this method was a result of our research motif rotation in repeat. Very often, we have a base motif which is in block repeat, and we wish to rotate it by a certain angle, while keeping the repeat property and not deforming the design. Usually we do it by 45 degrees in order to get diamond repeat. Some famous brands like Burberry use a complex interlaced rotated design as a way of protection of their brand and intellectual property. Intuitively we would think that we can rotate the existing repeating image by any angle, but in reality it is only possible for certain well defined angles for square designs. We have programmed this capability in ArahWeave. But we went even a step further, and allowed motif rotation and resize within the ArahPaint drawing program. Using even extremely simple core pattern like plain weave (repeat 2x2), we get a whole group of patterns defined by their angle and rotation. The operation is extremely sensitive, so we can use the decimal points of the parameters to gradually change the pattern appearance. Since the core pattern is so small, we do not get long floats in the resulting image. Surprisingly enough, many of the resulting designs have satin counterpoints placed correctly, as if they were drawn by an actual designer. We said before that arbitrary motif rotation in repeat is not possible, so how can can we use the non-repeating result in weaving? We can repeat it several times and use ArahPaint's function for automatic repeat detection. In many cases the repeat will not be perfect, but it will be close enough to be visually convincing and usable.

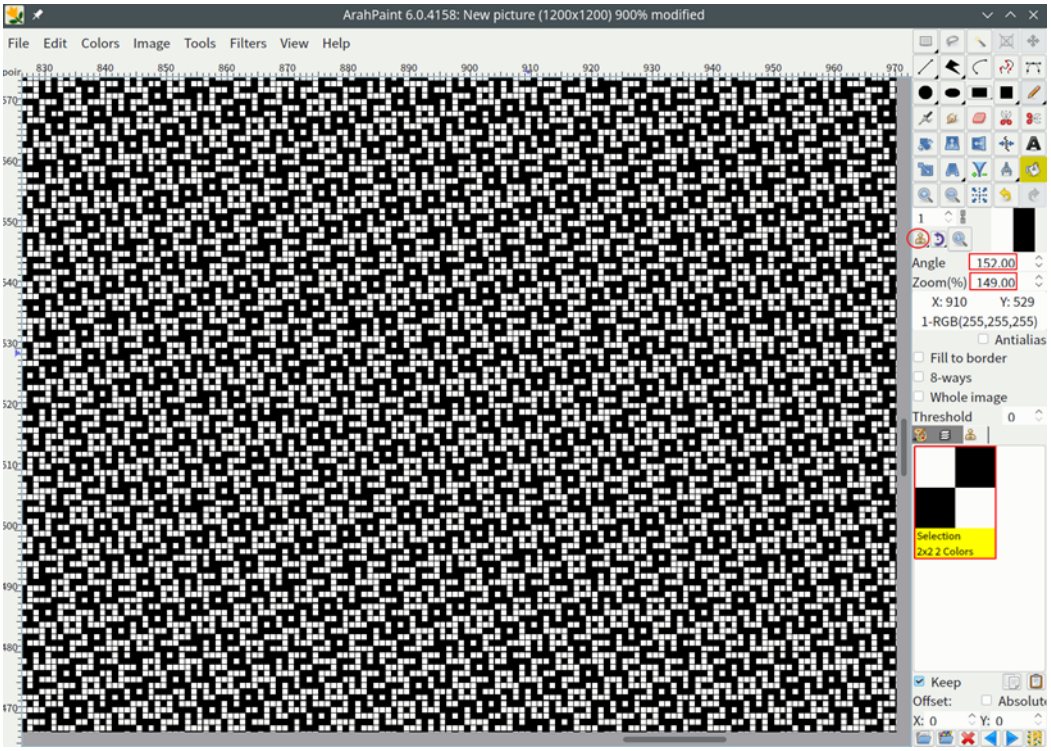


Figure 8: Plain weave rotated by angle 152º and zoomed at 149% generates this pattern

How can simple rotation and zoom create such a rich set of patterns? We are familiar with aliasing problem, where we have to approximate a line of a circle with a limited resolution, and we get jaggies when the line skips the point edge. This pixelization is normally a defect which we can not avoid. But in this case, we use the distribution of these digital errors as design tool, and it creates whole group of pleasing patterns.

ArahWeave is free for download from Arahne's web site, and anyone can play with the angle and zoom to get interesting weaves. Since the space is limited, we can't show more of them, here are some pairs of angle and zoom to try with plain weave: (52º, 149%) (20º, 110%) (19º, 107%) (23º, 0.3%) (29.8º, 124%).

2. CONCLUSION

Graphics designers have fully embraced digital design. They use vector tools, filters, some even write scripts or shaders to get the effect that they want. Many woven designers still work in traditional way, despite working with computer on CAD. Because CAD only mirrors and automates the traditional manual way of image coloring and color to weave substitution. Woven designers can raise their art to the next level, if they start embracing digital generative methods of design and weave creation. Appropriate software can help a lot, since it can take care of long floats and repeat correctness already at level of creation, not as a post-processing step.

3. REFERENCES:

Brickett, C.J. 1934. Textile Designing. Scranton, PA.: International Textbook Company
Giudici, O. 1943. Tessuti di Lana e di Cotone: Analisi e Fabbricazione. Milano: Ulrico Hoepli
Holyoke J. 2013. Digital Jacquard Design. London, New Delhi, New York, Sydney: Bloomsbury
Kienbaum M. B. 2016. Binding Technology of Fabrics: Book 1: Single surface fabrics. Goldkronach: CH-Consulting
Rodón i Amigó P. 1930. Ligamentos Crepes. Badalona: Cataluña Textil
Gregorčič, A., Peterc, D. 2025. ArahWeave User's Manual. URL: https://www.arahne.eu/pdf/aweave-EN.pdf (last accessed on 1.03.2025).
Gregorčič, A. 2025. ArahPaint User's Manual. URL: https://www.arahne.eu/pdf/apaint6-EN.pdf (last accessed on 1.03.2025).

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ORAL PRESENTATION

CREATING A DATABASE FOR OPERATION LIST IN GARMENT PRODUCTION PROCESS

Selma Imamagić[1], Anica Hursa Šajatović[1] and Bosiljka Šaravanja[1]

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Abstract: *Digital transformation is a strategy that incorporates digital technologies into all areas of an organisation. To achieve this, an organisation must go through digitisation and digitalisation processes. Digitisation involves the conversion of information from analogue to digital form, while digitalisation uses digital solutions to make business processes more automated. This paper provides an insight into the digitalisation process in garment production by creating a digital operation list. The list of technological operations of the technological process of sewing a woman medical coat was used as an example. A database for storing information and an application for entering and linking data were also developed. As a result, digital operation list for sewing woman medical coat was gained. In this form, it can become available to all users of the application anytime and anywhere (provided they have an Internet connection) and is unlikely to be lost or damaged.*

Keywords: *operation list, digitalisation, database, application, garment industry.*

1. INTRODUCTION

Today's rapidly changing market needs involving quality products with a variety of categories, materials and designs, pose a major challenge to manufacturing systems. To thrive in such a market, manufacturers must adapt their production processes (Borangiu et al. 2020). As mentioned in *Borangiu et al.* (2020), digital transformation in industry can improve the sustainability and maintainability of manufacturing processes, products, systems and logistics through resource instrumentation and virtualisation as well as data analytics, machine learning and cloud services.

According to *Trzaska et al.* (2021), digital transformation is a process of devising new business applications that integrate all digitised data and digitised applications. It involves the integration of digital technologies into all areas of an organisation creating a new digital business model (TecnoSolutiones). The basic step in the digital transformation process is digitisation (Fig. 1), a process of converting data from analogue to digital format (Savić 2019). The second step in this transformation model is digitalisation, which is defined by *Gartner Glossary* as the use of digital technologies to change the business model and provide new revenue and value-producing opportunities.

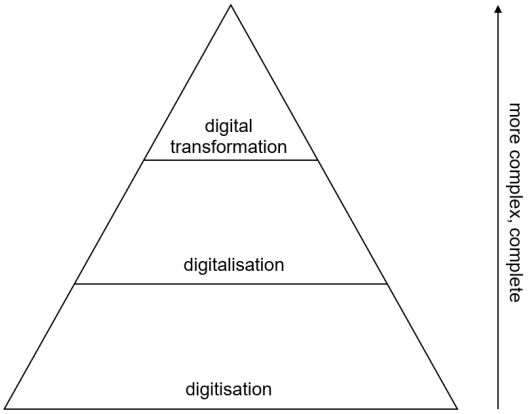


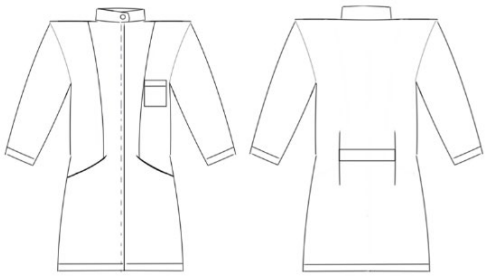
Figure 1: The digital transformation pyramid (O'Leary 2022)

The problem of integrating digital transformation can be seen in the case of small and medium-sized enterprises (SMEs) (Telukdarie et al. 2023). In addition, *Moeuf et al.* (2018) highlighted that these companies use the concept of Industry 4.0, i.e. intelligent digital technologies, mainly for monitoring industrial processes and that there is still a lack of real applications in the field of production planning. With this in mind, this paper gives an example of the creation of a digital operation list for production planning in the garment industry. The importance of digitalisation of this area and the resulting benefits can be found in *Alexopoulos et al.* (2022) and *Jeske et al.* (2021).

2. EXPERIMENTAL PART

2.1 Input data

The aim of this work was to create a digital operation list for a garment. The operation list in garment industry lists the technological operations required to produce a garment and the order in which they are carried out. The following information must be provided for each technological operation: the number of the operation in the performance order, its name, the resources required for its performance, its performance complexity and duration. As an example of the operation list, the list of technological operations for the technological process of sewing the women's medical coat "Vera" was taken from Šaravanja et al. (2024), Fig. 2.



Ope. No.	Operation name	Type of machine	Complexity of operation	Standard operation time (s)
1.	Sew back belt	SNLS	II	38.91
2.	Sew darts on back part and insert back belt	SNLS	II	140.19
3.	Sew hip pocket on front part and topstitch	SNLS	II	56.32
4.	Sew buttonhole	BH Semi_Auto	I	33.67
5.	Fly front construction	SSM	II	112.55
6.	Add covered buttonholes	SNLS	II	230.49
7.	Front part and hip pocket joint	SSM	II	55.98
8.	Front part topstitch	SNLS	II	79.83
9.	Breast patch pocket hem	SNLS	II	6.02
10.	Breast patch pocket attach	SNLS	II	54.97
11.	Shoulder top-stitch	SSM	II	81.26
12.	Insert sleeve	SSM	II	80.90
13.	Sleeve and side seam joint	SSM	II	57.05
14.	Side label seam	SNLS	II	8.61
15.	Collar band make and turn to face (bag out)	SNLS/MNL	II/III	56.94
16.	Stitch collar band to neckline	SNLS	II	35.56
17.	Collar band close and topstitch	SNLS	II	118.34
18.	Bottom hem	SNLS	II	56.34
19.	Sleeve hem	SNLS	II	10.88
TOTAL STANDARD TIME FOR TECHNOLOGICAL PROCESS OF SEWING:				1314.81

a. b.

Figure 2: Women's medical coat "Vera": a- technical drawing, b- operation list (Šaravanja et al. 2024) Three different machines, i.e. resources were used to sew the medical coat shown above: single needle lockstitch machine (SNLS), semi-automatic buttonhole sewing machine (BH Semi-Auto) and special sewing machine (SSM). Manual work (MNL) seen in 15th technological operation was not considered as a separate resource in this paper. In addition, most of technological operation of sewing the "Vera" medical coat are the technological operations of medium performance difficulty, with the exception of the 4th one, which requires skilled worker to perform it.

2.2 Methods

In order to create a digital operation list, it was first necessary to create a database. For this purpose, SQL Server was used. The created database with the name *OperationList*, was filled with the following tables: *Resources*, *Products*, *Complexity*, *Units*, *Operations*, *Technology* and *UsedResources*. These tables are essential for storing data: in this case, information about the technological process of sewing women's medical coat from the corresponding operation list (Fig. 2-b).

The next step was to build a project, i.e. an application using the Python programming language, also called *Operation List*, and connect it to the database that had been created. As a result, it was enabled to store data for the technological process of sewing the "Vera" women's medical coat using the *Operation List* application in the above-mentioned tables of the *OperationList* database.

Figure 3 shows the resource entry field. Here the user of the *Operation List* application can enter the desired data about resources by selecting the *Resource* button. These are:

- resource ID: marker of the resource that is displayed in the digital operation list
- description: full name of the resource
- operating time: time per day in which a resource is accessible (e.g. one shift: 450 minutes)
- row in chart: the position of the resource when creating a diagram (e.g. Gantt chart).

For this paper, the information of three machines required for sewing the medical coat (SNLS, BH Semi_Auto and SSM) were entered. Products, units and complexity data were also entered in the same way (buttons of the same name in the menu bar).

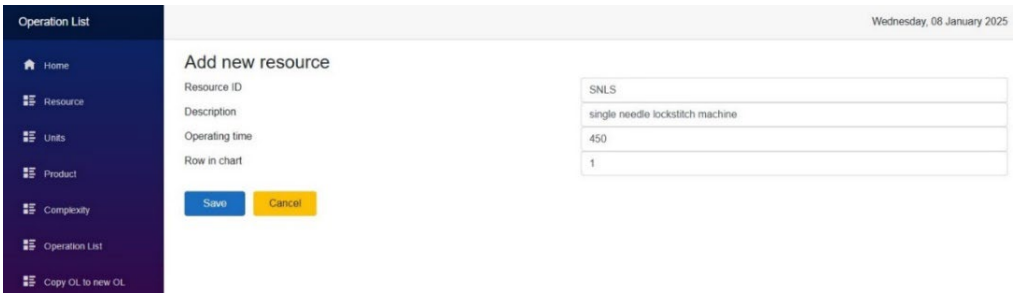


Figure 3: Resource entry filed in the Operation List application

The *Operation List* button in the menu bar is used to define elements of a new digital operation list. The technological operations as well as the type of technology and the resources used to perfom them are defined here.

Figure 4 shows defining first of 19 technological operations required to produce a "Vera" coat. By entering them, this information has been entered directly into the digital operation list that has just been created. Therefore, for each operation it must be defined:

- variant name: name used for possible changes in the production of the same product (e.g. when changing resources, technology, requeired time, sequence of performing etc.)
- product ID: Identification of the product in the database
- technology number: number of the type of technology in the database
- operation number: represents the number of the technological operation in the sequence of their performing (e.g. the first technological operation is defined with the number 10)
- predecessor operation: number of the technological operation that precedes a defined operation (e.g. the first technological operation has no predecessor, so a zero must be entered in this field)
- complexity: Identification of the performance difficulty (e.g. II: medium performance difficulty).

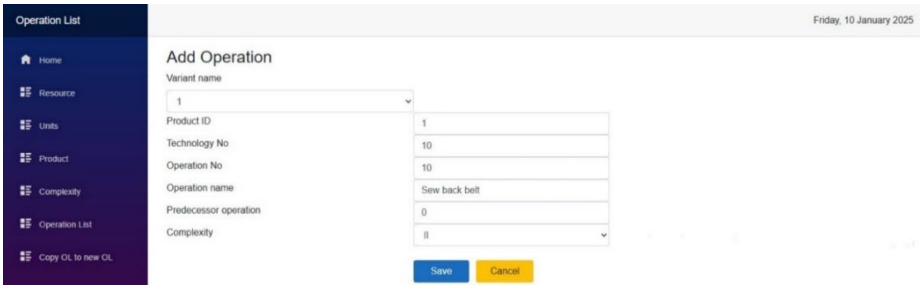


Figure 4: Defining first operation of sewing medical coat “Vera“ in the Operation List application

As a result, a draft version of the digital operation list is created, Fig. 5., where each technological operation can be edited, deleted or added if necessary. By clicking the *Resource* button on the left-hand side of the draft version, each technological operation in this operation list is linked to the associated machine and duration, Fig. 6.

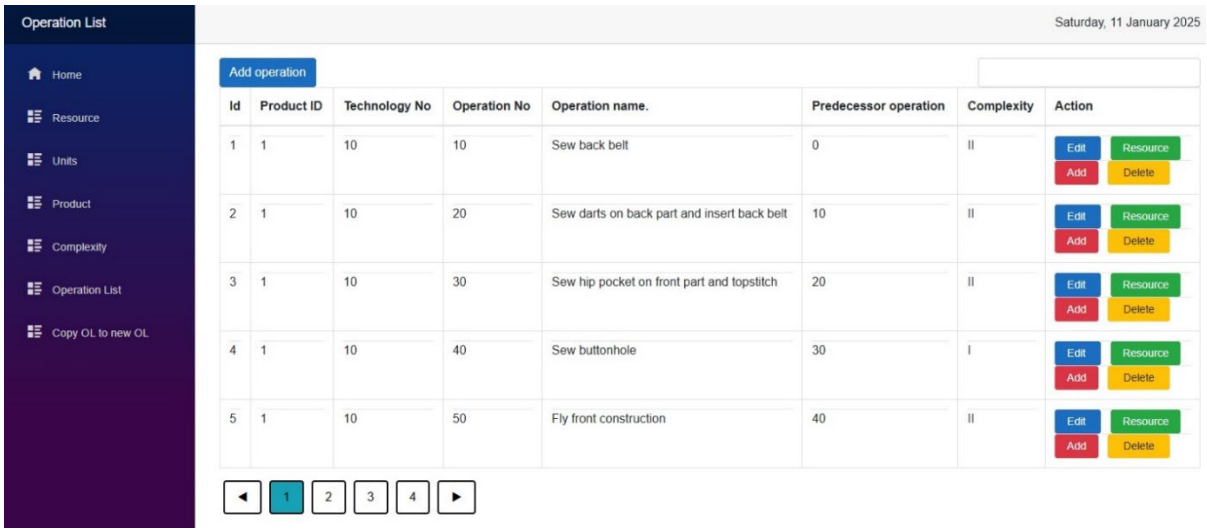


Figure 5: Draft version of digital operation list

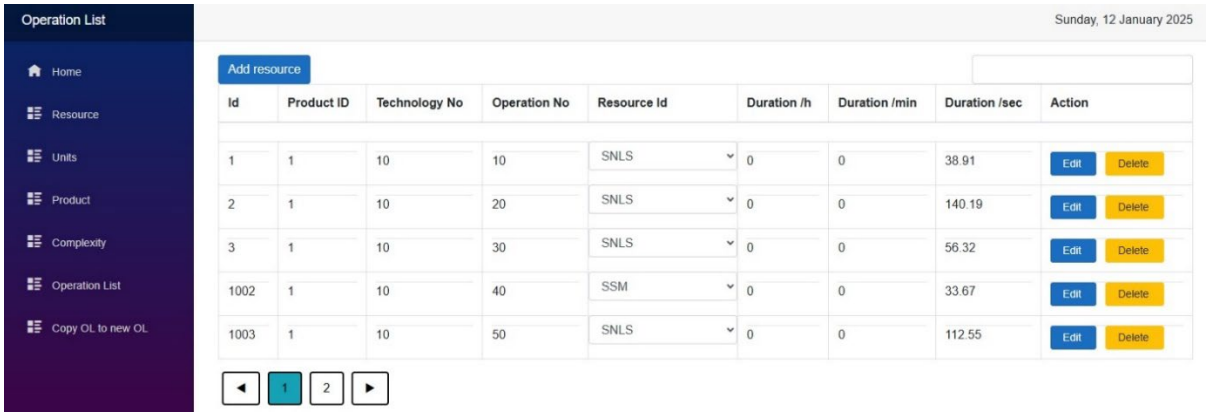


Figure 6: Linking resources and technological operations of tehnological process of sewing “Vera“ medical coat

3. RESULTS WITH DISCUSSION

The result of this paper is a digital operation list (Fig. 7) of a product, in this case the technological process for sewing the “Vera” medical coat, which is available to all users, i.e. the employees of a production company, anytime and anywhere (provided they have an Internet connection). Employees can easily store the required data on resources, products and technologies in the databases with the help of the developed application and later link them in the operation list. Technologists can create new operation lists or use information from existing ones. In addition, digital operation lists can be stored securely and, unlike physical documents, are rarely lost or damaged.

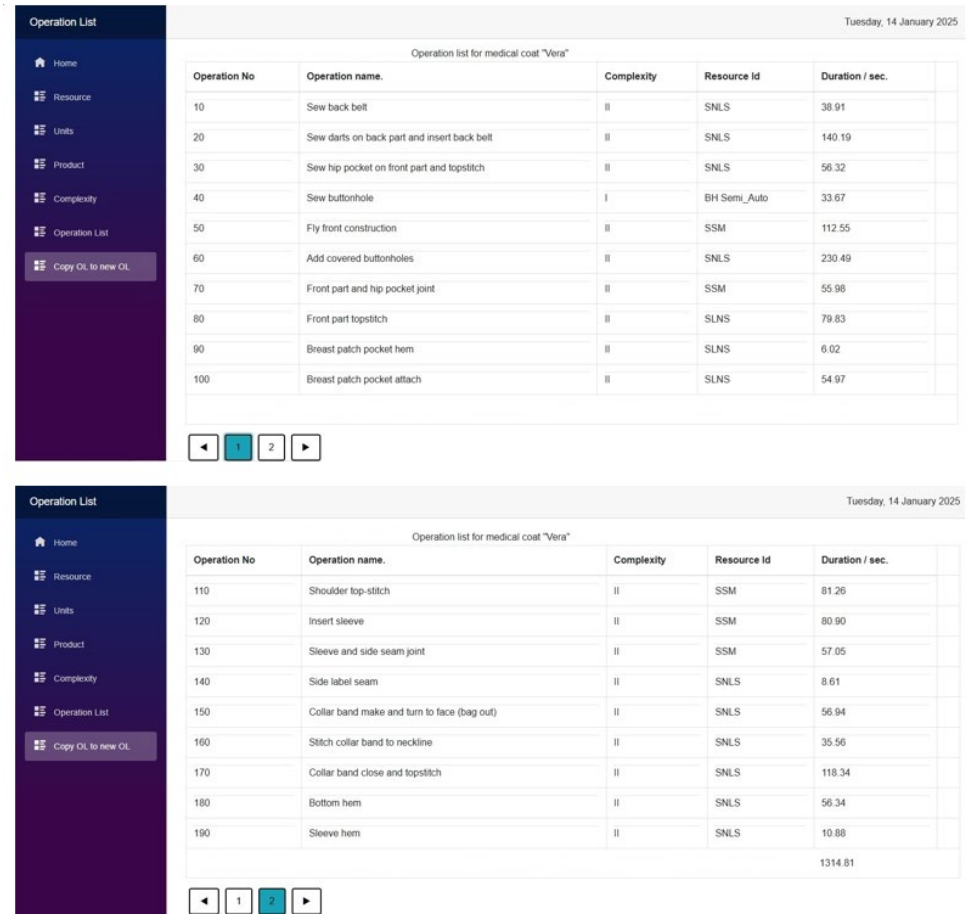


Figure 7: Digital operation list of the technological process of sewing medical coat “Vera“

Digital operation list created in this paper represents one of the steps in the digital transformation of the production process, respectively planning in the garment industry. Considering that in the production planning process exists a lack of application of concepts of Industry 4.0 in SMEs (Moeuf et al. 2018) and that these companies make up 99% of all companies in the EU (European Commission), there is certainly a potential for digitalisation in this field. This includes creating more technical documents using digital technologies and linking them together to digitalise all processes in manufacturing systems. As a result, manufacturing companies will improve their efficiency, resource utilisation and product quality, reduce operating costs and be able to adapt quickly to changes in customer demands and the market (Duraivelu 2022).

Nevertheless, the aim of this paper was to give an insight into the digital documents’ creation (database and application). As regards, there certainly exists the possibility of improving and upgrading created digital operation list or adding other elements, primarily depending on the type of manufacturing.

4. CONCLUSIONS

Digital transformation means integrating digital technologies in all areas of an organisation. It makes it possible to respond to rapidly changing customer behaviour, i.e. expectations and needs, and to remain competitive on the market. The literature review revealed that the integration of this concept is lacking in small and medium-sized enterprises (SMEs), which represent the majority of companies in the EU today.

In this sense, this paper shows an example of the creation of a digital operation list – one of the basic technical documents in production planning in the garment industry. The creation of digital operation list can provide a basis for further researches and improvements of given document as well as and the continuation of digital transformation of the manufacturing process.

5. REFERENCES

Alexopoulos, K., Nikolakis, N. and Xanthakis, E. (2022) 'Digital Transformation of Production Planning and Control in Manufacturing SMEs-The Mold Shop Case', Applied Sciences, 12, pp. 1-14

Borangiu, T., Morariu, O., Răileanu, S., Trentesaux, T., Leitão, P & Barata, J. (2020) 'Digital transformation of manufacturing. Industry of the Future with Cyber-Physical Production Systems', Romanian Journal of Information Science and Technology, 23 (1), pp. 3-37

Duraivelu, K. (2022) 'Digital transformation in manufacturing industry – A comprehensive insight', Materials Today: Proceedings, 68 (6), pp. 1825-1829

European Commission. SME definition. Available at: https://single-market-economy.ec.europa.eu/smes/sme-fundamentals/sme-definition_en (Accessed: 20. 10. 2024)

Gartner Glossary. Digitalization. Available at:
https://www.gartner.com/en/information-technology/glossary/digitalization (Accessed: 18. 10. 2024)

Jeske, T., Würfels, M. And Lennings, F. (2021) 'Development of Digitalization in Production Industry – Impact on Productivity, Management and Human Work', Procedia Computer Science, 180, pp. 371-380

Moeuf, A., Pellerin, R., Lamouri, S., Tamayo, S. and Barbaray, R. (2018) 'The industrial management of SMEs in the era of Industry 4.0', International Journal of Production Research, 56 (3), pp. 1118-1136

O'Leary, D. E. (2022) 'Digitization, Digitalization and Digital Transformation in Accounting, Electronic Commerce and Supply Chains', USC Marshall School of Business Research Paper Series, pp. 1-18

Savić, D. (2019) 'From Digitization, Through Digitalization, to Digital Transformation', Online Searcher, 43 (1), pp. 36-39

Tecno-Soluciones. Digitalization and Digital Transformation What are the differences between them?. Available at: https://tecnosoluciones.com/digitalization-and-digital-transformation-what-are-the-differences-between-them/?lang=en&pdf=51693 (Accessed: 17. 10. 2024)

Telukdarie, A., Dube, T., Matjuta, P. and Philbin, S. (2023) 'The opportunities and challenges of digitalization for SME's', Procedia Computer Science, 217, pp. 689-698

Trzaska, R., Sulich, A., Organa, M., Niemczyk, J. and Jasiński, B. (2021) 'Digitalization Business Strategies in Energy Sector: Solving Problems with Uncertainty under Industry 4.0 Conditions', Energies, 14, pp. 1-21

Šaravanja, B., Imamagić, S., Marković, P. and Hursa Šajatović, A. (2024) "Setting standard time for the technological process of sewing woman's medical coat "Vera"". In Book of Proceedings of the 11th International Textile, Clothing & Design Conference, edited by Hursa Šajatović, A., Špelić, I. et al., 169-174, Zagreb: University of Zagreb, Faculty of Textile Technology

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TEXTILE BASED COMPOSITES AND TECHNICAL TEXTILES

POSTER PRESENTATION

THE INFLUENCE OF THE LAYER STRUCTURE ON THE DURABILITY OF TEXTILE LAMINATES

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Abstract: *The research focuses on two-layer laminates, which are used in the automotive industry for the upholstery of car seats. The investigated laminates are produced in a dry lamination process on a static laminator at a constant pressure of 3 bars. The front side of the laminate consists of a 3D knitted fabric and a multilayer nonwoven fabric, while the back side is made of nonwoven or woven fabric. In this research the influence of the structure of the laminate top side on the durability of the laminate is being investigated in more detail. The results showed that the integration of a three-dimensional knitted fabric has a significant effect on increasing the strength under compressive load with a ball. On the other hand, the three-dimensional knitted fabric in the laminate reduces the delamination force of the laminate.*

Keywords: *laminate, 3D knitted fabric, multilayer nonwoven, dry lamination*

1. INTRODUCTION

The interior of a vehicle can consist of textile laminates. Depending on the number of layers and the technological processes of lamination, textile laminates are divided into several groups (Joshi, M.; Butola, B.S. 2013). Recently, multilayer nonwovens and three-dimensional textiles have been frequently used (Chang, C.W.; Chang, F.C. 2021; Gruyter, D. 2023). In our research, we focused on two-layer laminates, which are used for car seat upholstery and can be found on the top of car seats. These laminates are subjected to the different loads during their use, so their durability is very important (Reis, B. et al. 2022; Yuping, C.; Liu, Y.; Hong, H. 2022). In the study, two-layer laminates were produced, with one of the layers consisting of three-dimensional warp knitted fabric and the other of multilayer nonwoven.

The laminates are produced in a dry lamination process on a static laminator at constant pressure and temperature. A binder in the form of a powder and a thermoplastic web were used for the lamination (Reis, B. et al. 2022; Yuping, C.; Liu, Y.; Hong, H. 2022).

The focus of the research was to investigate the influence of the structure of the individual layers of the laminate (three-dimensional knitted fabric and multilayer nonwoven) on the durability of the laminate.

The research results showed that the integration of a three-dimensional knitted fabric has a significant effect on increasing the strength under compressive load with a ball.

On the other hand, the three-dimensional knitted fabric in the laminate reduces the delamination force of the laminate.

2. EXPERIMENTAL

1.1 Materials

The samples were laminated on a static laminator in a dry process for 15 seconds at a constant pressure of 3 bars and a temperature of 145°C. Sample 1 has a mass of 463 g/m^2 and consists of a three-dimensional knitted fabric (vertical density of 20 rows per cm and horizontal density of 10 columns per cm) and a multilayer nonwoven fabric, and sample 2 with a mass of 413 g/m^2 consists of a three-dimensional knitted fabric and a woven fabric (warp density 32 threads/cm and weft density 10 threads/cm). Samples 3 and 4 have lower masses, 258 g/m^2 and 184 g/m^2.

Samples 3 and 4 consist of a multilayered nonwoven (dry laid on roller carding machine, needle-bonded) and a woven fabric (warp density 32 threads/cm and weft density 10 threads/cm).

A thermoplastic polypropylene mesh fabric was chosen as the binder for the lamination for sample 1 and a polyamide powder for samples 2, 3 and 4 (Figure 1).

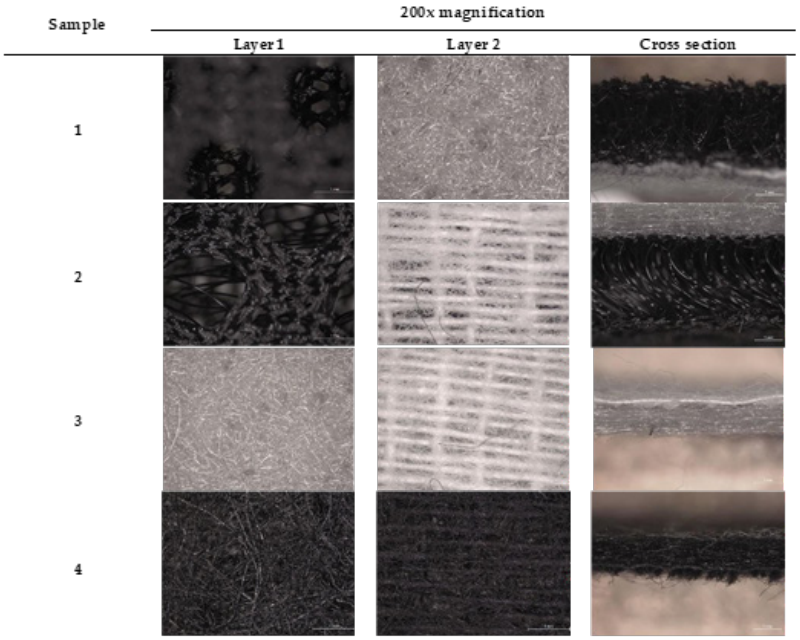


Figure 1: Samples at 200x magnification

1.2 Methods

The delamination force was determined according to DIN 54310 (Gruyter, D. 2023). The sample of laminate measuring 5 cm x 20 cm were produced. One layer of the laminate is first placed in the upper press and the lower press with other layer of the laminate is clamped on an Instron 5567 dynamometer. The speed of the upper press is 100 $mm \cdot min^{-1}$.

The breaking stress and deformation under compressive load with a ball was performed according to ASTM D3787 (Gruyter, D. 2023). The sample is compressed with a ball with a diameter of 4 cm until it breaks. The compressive force is expressed as a stress, taking into account the area of the 4.5 cm diameter opening. The deformation until breakage is also recorded.

2. RESULTS WITH DISCUSSION

The results of the delamination force are shown in Figure 2, while the results of the breaking stress under compressive load are shown in Figure 3.

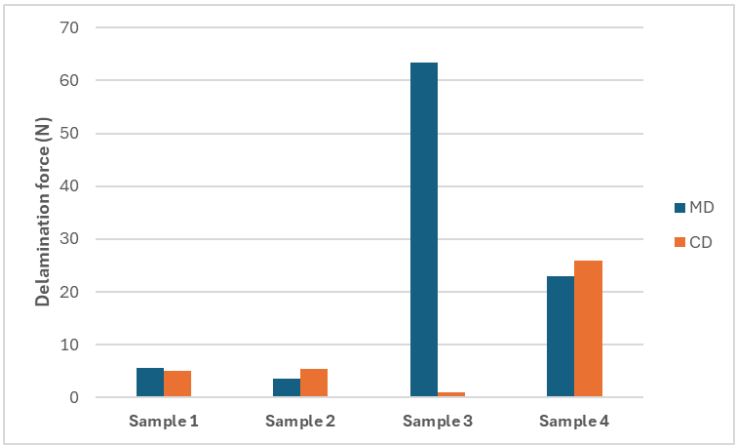


Figure 2: The results of the delamination force (MD-machine direction; CD-cross machine direction)

The results (Figure 2) show that sample 3 has the highest value for delamination force in the machine direction, while it has the lowest value in the cross-machine direction. Sample 4 exhibits the second highest delamination force in both directions. Both sample 3 and sample 4 consist of a multilayer nonwoven and woven fabric in which the binder is used in powder form. In sample 4, which also has the lowest mass, the binder is distributed more evenly during lamination, resulting in a similar value of delamination force in the machine and cross-machine directions. So exactly the opposite of sample 3, which has a higher mass, but the delamination force is much higher in the machine direction than in the cross-machine direction. The reason for this is due to the orientation of the fibres of the multilayered nonwoven, which is mainly longitudinal, for that it causes such a difference in the machine and cross-machine directions.

Sample 2 shows the lowest value of delamination force in the longitudinal direction. Sample 2 consists of a 3D knitted fabric and a woven fabric bonded with a powdery binder. Sample 1, which consists of a 3D knitted fabric and a nonwoven fabric and is reinforced with a thermoplastic mesh, exhibits the lowest delamination force in both the machine and cross-machine directions, just like sample 2. The reason for this is the smooth surface of the 3D knitted fabric, which affects the poorer bonding between the individual layers and the binder in the form of powder or thermoplastic mesh fabric that we used in the lamination of samples 1 and 2.

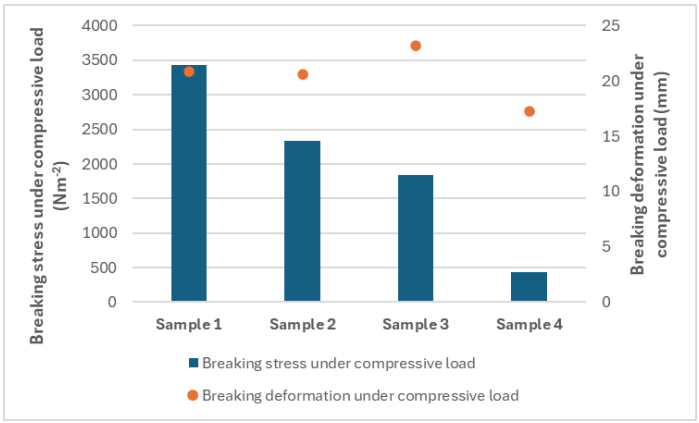


Figure 3: The results of the breaking stress under compressive load (MD-machine direction; CD-cross machine direction)

The results show that samples 1 and 2, which contain 3D knitted fabrics (Figure 3), have higher values of the breaking stress under compressive load than samples 3 and 4, which consist of multilayer nonwovens.

Sample 3 comes very close to the results of sample 2. The reason for this is the greater mass of sample 3 and the orientation of the fibres in the multilayer nonwoven. Sample 3 also shows the highest delamination force in the machine direction.

The deformation results for determining the breaking stress under compressive load show that only sample 3 exhibited a deformation of more than 20 mm. Sample 4 had the lowest deformation values (less than 5 mm). Sample 3, which has the highest deformation, is made of a multilayer nonwoven and woven fabric and has a higher mass than sample 4. Due to its higher mass, the breaking stress and deformation under compressive loading with a ball of sample 3 are comparable to samples 1 and 2, which are made of a 3D knitted fabric. Sample 4, on the other hand, also has the lowest breaking stress and deformation under compressive loading with a ball due to its lower mass.

3. CONCLUSIONS

Based on the study in which we investigated the influence of the structure of a single layer in two-layer laminates, in which we compared 3D knitted fabrics and multilayer nonwovens, we can conclude that laminates consisting of multilayer nonwovens have higher delamination force.

In this case, the delamination force also depends on the orientation of the fibers in the nonwoven fabric. Laminates consisting of 3D knitted fabrics have significantly lower delamination force. The reason for this is the smooth surface of the 3D knitted fabric and the resulting poorer contact between the thermoplastic mesh fabric and the second layer, as in our case the nonwoven and the woven fabric (samples 1 and 2). In both cases, the lowest force was measured during delamination.

In contrast, laminates with 3D knitted fabrics have a higher spherical compressive strength and deformation than those with multilayer nonwovens.

Laminates that contain multilayer nonwovens with a mass per unit area of more than 250 g/m^2 therefore also have a higher strength when subjected to a compressive load with a sphere and can replace laminates with 3D knitted fabrics.

4. REFERENCES:

Chang, C.W.; Chang, F.C. (2021) Fracture Characteristics and Energy Dissipation of Textile Bamboo Fiber Reinforced Polymer. Polymers, 13, pp. 634.

Gruyter, D. (2023) Smart and Functional Textiles. Oxfordshire: Taylor and Francis Group.

Yuping, C.; Liu, Y.; Hong, H. (2022) ‘Deformation behavior of auxetic laminated fabrics with rotating square geometry’. Textile Research Journal, 92, pp. 4652-4665.

Joshi, M., Butola, B.S. (2013) Application technologies for coating, lamination and finishing of technical textiles. London: Woodhead Publishing Series in Textiles, pp. 355-411.

Reis, B. et al. (2022) Functional Design of Tri-Laminated Wool Fabrics Improving Comfort Properties’. In Journal of Biomimetics. Biomaterials and Biomedical Engineering, 57, pp. 65–76.

Yuping, C.; Liu, Y.; Hong, H. (2022) ‘Deformation behavior of auxetic laminated fabrics with rotating square geometry’. Textile Research Journal, 92, pp. 4652-4665.

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POSTER PRESENTATION

BIBLIOMETRIC ANALYSIS OF TEXTILE WASTE RESEARCH

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Abstract: The topic of textile waste, both pre- and post-consumer, solid textile waste and wastewater from textile production, has been studied due to environmental concerns, mainly due to volume, resource consumption and/or toxicity. In our study, we use a bibliometric approach to investigate the thematic structure and current trends in textile waste research. The Scopus database was searched for the term *textile waste* and related terms over the last 12 years. The data was analysed with Bibliometrix/Biblioshiny and VOSviewer software. Documents, citations and keywords were examined. The results include annual production and citations, the most prolific/influential authors and sources, and the most frequent keywords. The co-occurrence keyword network revealed clusters on textile wastewater treatment, mainly related to dye removal/degradation, and a cluster on solid textile waste. While wastewater remains a prevalent topic, circular economy, sustainability and waste management have become more frequent keywords in recent years. Dye/salt separation is the latest trend among wastewater treatment methods.

Keywords: *textile waste, textile wastewater, bibliometric analysis, science mapping*

1. INTRODUCTION

Textile waste includes textile materials (fibres, yarns, fabrics and garments) that are no longer usable or valuable (Anjimoon et al., 2024). It is divided into pre-consumer waste, which is generated during textile production and post-consumer waste, which is generated after the product has been used. It is a cause for concern primarily because of its volume and resource consumption. Textile industry processes such as dyeing, printing and finishing also generate textile wastewater, which is characterised by its high volume and complex chemical composition (Kumar and Saravanan, 2017). Textile waste management and wastewater treatment are two highly researched topics. The aim of this study was to investigate the current structure and trends in the field of textile waste research using the bibliometric approach. So far, only a few bibliometric analyses have been conducted on the topic of textile waste (Kasavan et al., 2021), with some other works focusing on individual subtopics, e.g. textile wastewater treatment (Halepoto et al., 2022), circular economy (Hora et al., 2023) and green manufacturing (Sarker and Bartok, 2024).

2. EXPERIMENTAL

The bibliometric methodology described by Donthu et al. (2021) was applied in our study. The approach involves two types of analysis: 1) performance analysis, which uses the number of documents/citations to identify the most prolific/influential units (e.g., authors, sources, and documents), and 2) science mapping, which aims to shed light on the topic structure through co-occurrence networks. The dataset for the analysis was obtained by searching the Scopus database using the search expression TITLE-ABS-KEY ((“textile* waste*” OR “cloth* waste*” OR “garment* waste*” OR “apparel* waste*” OR “fabric* waste*”)). A filter was applied to the document types (journal articles, reviews and conference papers) and the publication years from 2013 to 2024. The filtered search results were exported and transferred to Microsoft Excel where they were pre-processed. Duplicates were removed and a thesaurus was created for the author keywords to merge similar terms such as synonyms, abbreviations and variants. The final dataset comprised 5,001 documents. Microsoft Excel, Bibliometrix/Biblioshiny (Aria and Cuccurullo, 2017)fragmented, and controversial research streams. Science mapping is complex and unwieldly because it is multi-step and frequently requires numerous and diverse software tools, which are not all necessarily freeware. Although automated workflows that integrate these software tools into an organized data flow are emerging, in this paper we propose a unique open-source tool, designed by the authors, called bibliometrix, for

performing comprehensive science mapping analysis. bibliometrix supports a recommended workflow to perform bibliometric analyses. As it is programmed in R, the proposed tool is flexible and can be rapidly upgraded and integrated with other statistical R-packages. It is therefore useful in a constantly changing science such as bibliometrics.","container-title":"Journal of Informetrics","ISSN":"1751-1577","issue":"4","journalAbbreviation":"Journal of Informetrics","page":"959-975","source":"ScienceDirect","title":"Bibliometrix: An R-tool for comprehensive science mapping analysis","title-short":"bibliometrix","volume":"11","author":[{"family":"Aria","given":"Massimo"},{"family":"Cuccurullo","given":"Corrado"}],"issued":{"date-parts":[["2017",11,1]]}}],"schema":"https://github.com/citation-style-language/schema/raw/master/csl-citation.json"} and VOSviewer (van Eck and Waltman, 2023) were used for data analysis and visualization of the results in the form of tables, charts and network diagrams.

3. RESULTS WITH DISCUSSION

In the final dataset, the majority of documents were original research articles published in journals (85%), followed by conference papers (9.3%) and review articles (5.7%).

3.1 Documents

The annual scientific production is shown in Figure 1, which also shows the number of total citations (TC) per document and year. The number of published documents showed an average annual growth rate of 16.3%, with the highest value reached in 2019 (39.4%). The average document was 4.7 years old and had 25.6 citations. Articles from 2020 had the highest average citation rate per document per year (7.7).

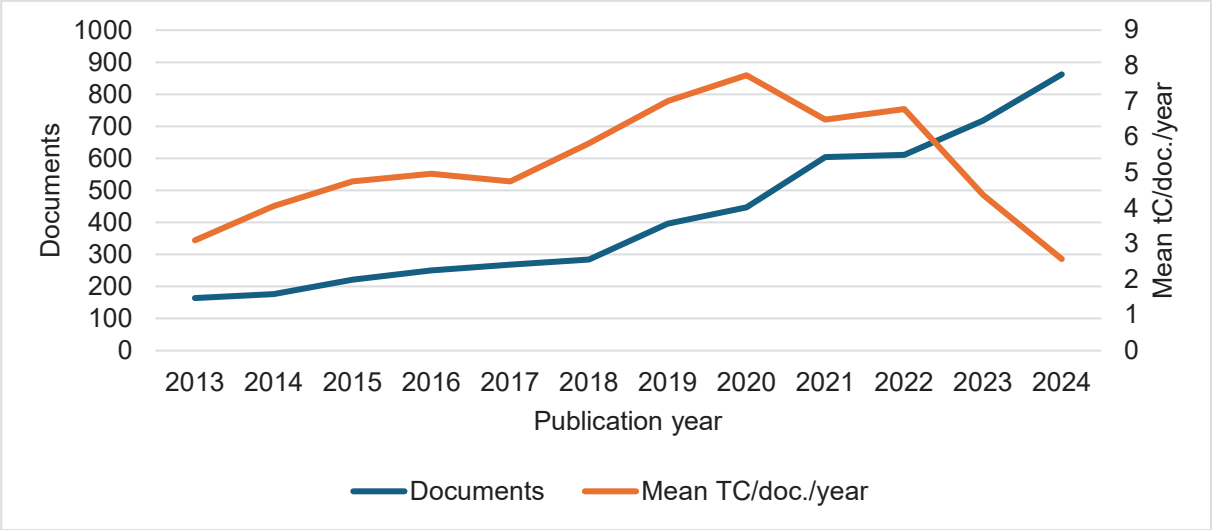


Figure 1: Production over time (number of documents), and mean of total citations (TC)

Four documents from our dataset were cited more than 1000 times each in Scopus. A further eight were cited over 500 times. Ten of these 12 documents are review articles, only two contain original research. Similarly, 11 of the most cited articles relate to the topic of textile wastewater treatment, while the remaining article focuses on the impact of fast fashion (Niinimäki et al., 2020)however, the industry continues to grow, in part due to the rise of fast fashion, which relies on cheap manufacturing, frequent consumption and short-lived garment use. In this Review, we identify the environmental impacts at critical points in the textile and fashion value chain, from production to consumption, focusing on water use, chemical pollution, CO2 emissions and textile waste. Impacts from the fashion industry include over 92 million tonnes of waste produced per year and 79 trillion litres of water consumed. On the basis of these environmental impacts, we outline the need for fundamental changes in the fashion business model, including a deceleration of manufacturing and the introduction of sustainable practices throughout the supply chain, as well a shift in consumer behaviour — namely, decreasing clothing purchases and increasing garment lifetimes. These changes stress the need for an urgent transition back to 'slow' fashion, minimizing and mitigating the detrimental environmental impacts, so as to improve the long-term sustainability of the fashion supply chain.","container-title":"Nature Reviews Earth & Environment","ISSN":"2662-138X","issue":"4","journal-

Abbreviation":"Nat Rev Earth Environ","language":"en","page":"189-200","source":"www.nature.com","title":"The environmental price of fast fashion","volume":"1","author":[{"family":"Niinimäki","given":"Kirsi"},{"family":"Peters","given":"Greg"},{"family":"Dahlbo","given":"Helena"},{"family":"Perry","given":"Patsy"},{"family":"Rissanen","given":"Timo"},{"family":"Gwilt","given":"Alison"}],"issued":{"date-parts":[["2020",4]]}}],"schema":"https://github.com/citation-style-language/schema/raw/master/csl-citation.json"} . The single most cited article (Holkar et al., 2016) provides an overview of textile wastewater treatment methods. The predominant topic is dye removal/degradation, which is covered in seven titles, e.g. (Al-Tohamy et al., 2022)the continuous discharge of wastewater from a large number of textile industries without prior treatment has significant negative consequences on the environment and human health. Textile dyes contaminate aquatic habitats and have the potential to be toxic to aquatic organisms, which may enter the food chain. This review will discuss the effects of textile dyes on water bodies, aquatic flora, and human health. Textile dyes degrade the esthetic quality of bodies of water by increasing biochemical and chemical oxygen demand, impairing photosynthesis, inhibiting plant growth, entering the food chain, providing recalcitrance and bioaccumulation, and potentially promoting toxicity, mutagenicity, and carcinogenicity. Therefore, dye-containing wastewater should be effectively treated using eco-friendly technologies to avoid negative effects on the environment, human health, and natural water resources. This review compares the most recent technologies which are commonly used to remove dye from textile wastewater, with a focus on the advantages and drawbacks of these various approaches. This review is expected to spark great interest among the research community who wish to combat the widespread risk of toxic organic pollutants generated by the textile industries.","container-title":"Ecotoxicology and Environmental Safety","ISSN":"0147-6513","journalAbbreviation":"Ecotoxicology and Environmental Safety","page":"113160","source":"ScienceDirect","title":"A critical review on the treatment of dye-containing wastewater: Ecotoxicological and health concerns of textile dyes and possible remediation approaches for environmental safety","title-short":"A critical review on the treatment of dye-containing wastewater","volume":"231","author":[{"family":"Al-Tohamy","given":"Rania"},{"family":"Ali","given":"Sameh S."},{"family":"Li","given":"Fanghua"},{"family":"Okasha","given":"Kamal M."},{"family":"Mahmoud","given":"Yehia A.-G."},{"family":"Elsamahy","given":"Tamer"},{"family":"Jiao","given":"Haixin"},{"family":"Fu","given":"Yinyi"},{"family":"Sun","given":"Jianzhong"}],"issued":{"date-parts":[["2022"]]}}],"schema":"https://github.com/citation-style-language/schema/raw/master/csl-citation.json"} .

3.2 Authors

There were 14899 contributing authors, with an average of 4.7 co-authors per paper, while 160 authors published 189 (3.8%) papers as single authors. Fifty-six authors published 10 or more documents. The publication timeline and influence of the 11 most productive authors (with 15 or more documents) was visualised using Biblioshiny (Figure 2). Sabir Hussain is in the lead with 24 documents, followed by Bart Van der Bruggen (22), Munawar Aqeel Iqbal (19) and Nadir Dizge (18 documents). One author started publishing in 2019. Based on the colour intensity of the dots representing the citations in Figure 2, we can see notable peaks in 2019 (three authors with documents with more than 100 citations per year) and in 2022 (one such author). The 11 authors mentioned above published a total of 157 documents. Thematically, more than half of the titles contain the term *wastewater*. The keyword *textile wastewater* was used by 9 authors, *photocatalysis* and *textile wastewater treatment* by 6, *decolorization* and *adsorption* by 5, *dye/salt separation* by 4, *azo dyes* and *biodegradation* by 2 authors. Thirty-five authors have more than 1,000 total citations each. Munawar Aqeel Iqbal and Bart Van der Bruggen, who are also among the most prolific authors, are the most cited authors with 2138 and 2005 total citations respectively. Iqbal published the most articles on absorption and biodegradation, while Van der Bruggen researched the dye/salt separation. 16 other authors have more than 1500 citations each, but with less than 15 documents per person (resulting in more than 100 citations per document).

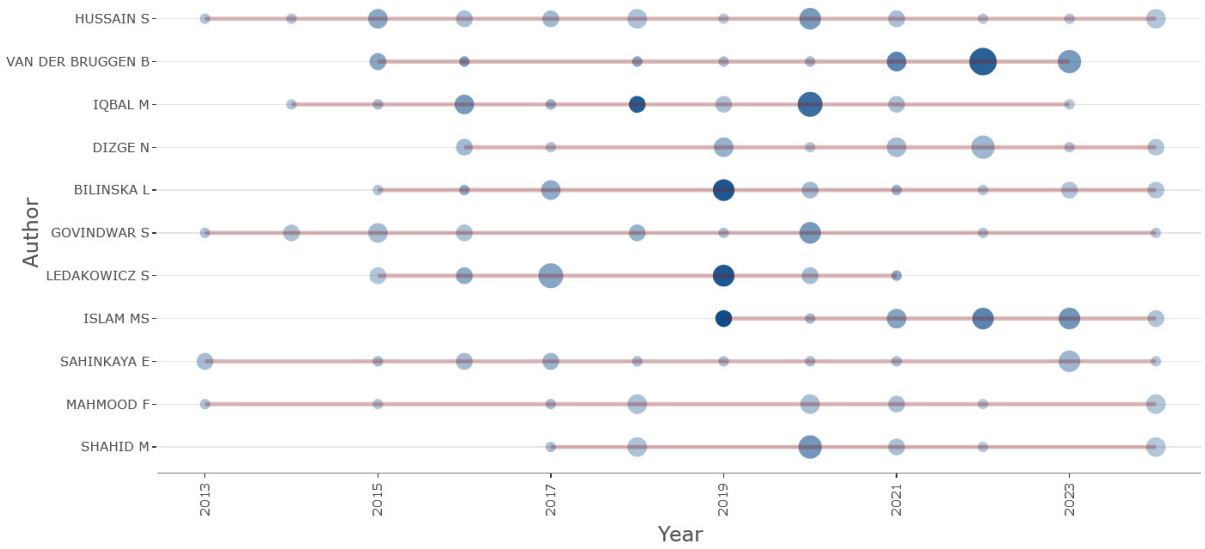


Figure 2: Publication timeline for the 11 most productive authors (dot size = number of documents, dot colour intensity = number of citations); visualisation: Biblioshiny

3.3 Sources

Ten of the top 11 sources with more than 61 published documents in our dataset are journals and the remaining source is a conference (Table 1). All sources except one publish in the Environmental Science Scopus subcategory.

Table 1: Ten most productive sources (TC = total citations)

Rank	Source	Scopus subcategories	Doc.	TC	TC/ Doc.
1	*Desalination and Water Treatment*	Env. Sci., Eng.	179	1912	10.7
2	*Environmental Science and Pollution Research*	Env. Sci.	118	3295	27.9
3	*Journal of Cleaner Production*	Env. Sci., Eng., Ener., Bus.	113	6286	55.6
4	*Journal of Environmental Chemical Engineering*	Env. Sci., Chem. Eng.	100	4866	48.7
5	*Journal of Water Process Engineering*	Env. Sci., Eng., Chem. Eng., Biochem.	93	2691	28.9
6	*Chemosphere*	Env. Sci., Chem., Med.	75	3760	50.1
7	*Chemical Engineering Journal*	Env. Sci., Eng., Chem. Eng., Chem.	72	6281	87.2
8	*Journal of Environmental Management*	Env. Sci., Bus., Econ.	68	5684	83.6
9	*Separation and Purification Technology*	Chem. Eng., Chem.	62	3131	50.5
10	*IOP Conference Series: Earth and Environmental Science*	Env. Sci., Earth & Plan. Sci.	62	267	4.3
11	*Water Science and Technology (20)*	Env. Sci.	62	1184	19.1

The journal *Desalination and Water Treatment* has by far the most documents (179). Nine sources are also in the top 10 by number of total citations, although the most productive source is only the 14th most cited. The *Journal of Cleaner Production* and the *Chemical Engineering Journal* are the leaders in terms of total citations (6286 and 6281 respectively). The latter also has the most total citations per article (87.2) while the *Earth and Environmental Science* conference is the least cited (4.3).

3.4 Topics

The author keywords were present in 91.06% of the documents, while the keywords added by Scopus were only present in 71.63%, therefore the former were taken into account in this study. The ten most frequent keywords are listed in Figure 3. *Textile wastewater* was by far the most frequent keyword. The oldest keyword in the top 10 was *decolorization* (APY – avg. publication year 2018.7) and the most recent was *circular economy* (2022.1). Eight out of 10 keywords relate to liquid waste from textile processing, while the remaining two mainly relate to solid textile waste.

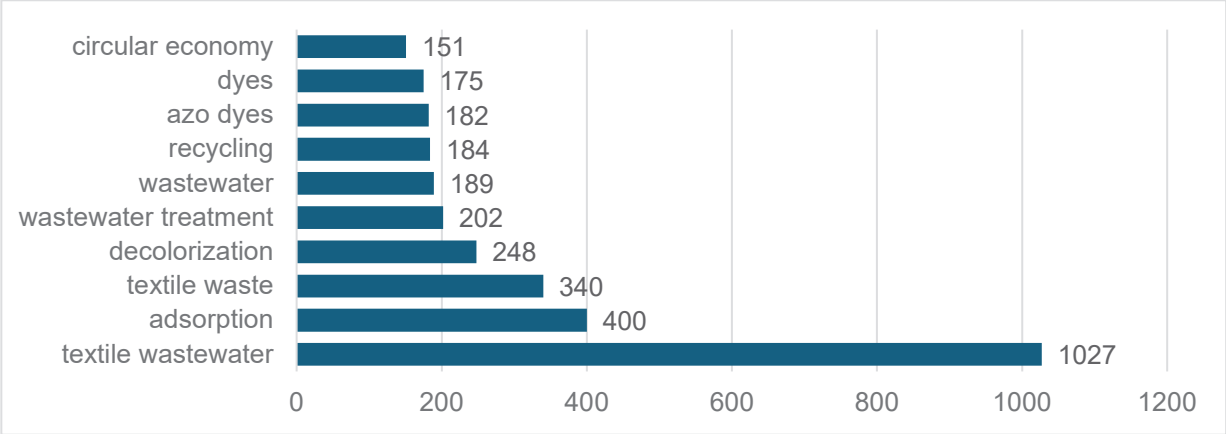


Figure 3: Ten most frequent author keywords

Next, we analysed the first 30 keywords (frequency higher than 71) and grouped them by topic (the terms are listed in decreasing frequency): 1) **wastewater treatment methods** (8 keywords: *adsorption, electrocoagulation, advanced oxidation, photocatalysis, activated carbon, biodegradation, photodegradation, bioremediation*), 2) **dyes/ decolorization** (7 keywords: *decolorization, azo dyes, dyes, methylene blue, dye removal, color removal, textile dyes*), 3) **wastewater** (5 keywords: *textile wastewater, wastewater treatment, wastewater, textile effluent, textile wastewater treatment*), 4) **solid waste** (4 keywords: *textile waste, recycling, circular economy, sustainability*). The remaining 6 keywords were either general (textiles, textile industry) or related to wastewater treatment methods (response surface methodology, kinetics, COD, isotherms). Among the last 20 keywords, *sustainability* was the newest (APY 2021.6) and *color removal* the oldest (APY 2018.5).

To investigate the thematic structure, VOSviewer was used to create a co-occurrence network for the 161 most frequent author keywords with a frequency of 15 or more (Figure 4). The six keyword clusters obtained are identified by different colors, with the dot size corresponding to the keyword frequency. For each cluster, the most frequent word and the most prominent keywords are listed grouped by topic, focusing on methods and processes: 1) **textile wastewater** (red cluster, 38 keywords): *electrocoagulation, advanced oxidation, electrochemical treatment, electrochemical oxidation* (methods); *dye degradation, color removal, reactive black 5* (dyes/removal); *COD – chemical oxygen demand* (parameters); 2) **adsorption** (green cluster; 32 keywords): *photocatalysis, activated carbon, photodegradation, electrospinning* (methods/processes); *congo red, methylene blue, methyl orange* (dyes); 3) **textile waste** (blue cluster, 31 keywords): *recycling, reuse* (methods), *circular economy, sustainability (practices), waste management*, environment (general); 4) **decolorization** (yellow cluster, 27 keywords): *biodegradation, bioremediation, biosorption, phytoremediation* (methods); *azo dyes, dyes, textile dyes* (dyes); *wastewater* (general); 5) **wastewater treatment** (purple cluster, 21 keywords): *nanofiltration, dye/salt separation,*

desalination (methods); *dye removal, dye/salt separation* (dyes/removal); *textile wastewater treatment, textile industry* (general); 6) **reactive dyes** (light blue, 12 keywords): *coagulation, dye adsorption; flocculation* (methods); *chitosan* (material)*; industrial wastewaters* (general).

The slightly offset blue cluster mainly contains terms that refer to solid waste, while the other five clusters are strongly related to textile wastewater and its treatment methods. Another common group of words found in these clusters are specific dyes and/or processes related to dye removal. Keywords at the edges of the network visualisation diagram (e.g. from the purple cluster) indicate niche topics that are less related to other concepts, while the main topics remain in the middle of the diagram (green, red and yellow clusters). The last cluster (coloured light blue) overlaps strongly with other clusters.

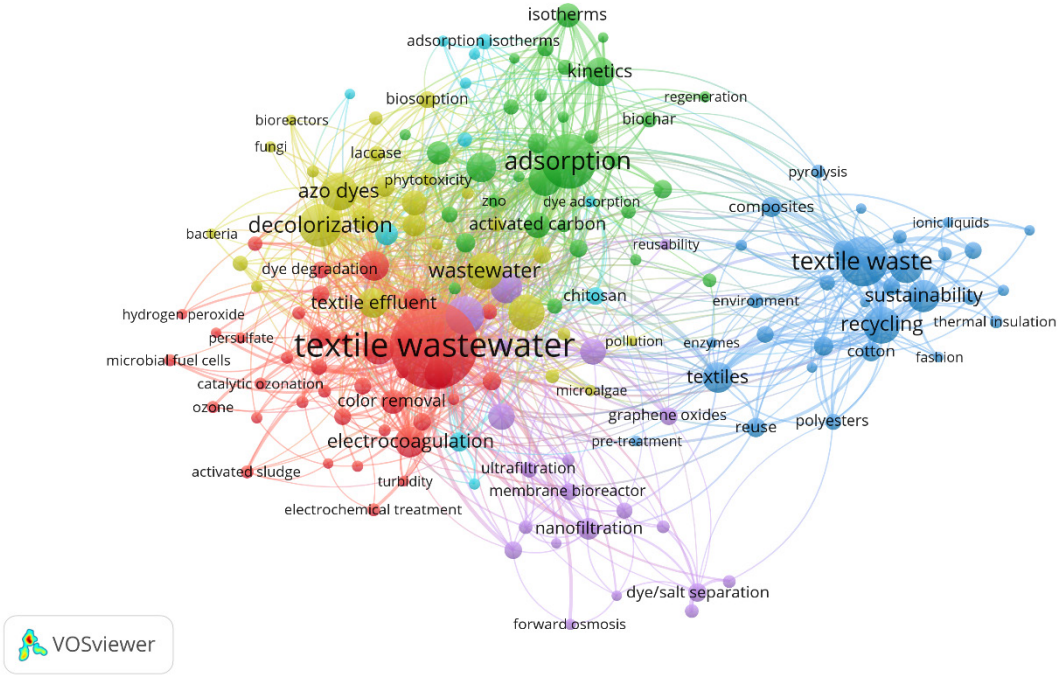


Figure 4: Main research topics by keyword network; visualisation: VOSviewer

Another type of topic visualization, a thematic map, was created with Biblioshiny, based on centrality and density calculations (Figure 5). The centrality of a cluster/topic is related to the number of connections with other clusters and reflects the cluster's relevance, while the density reflects the interconnectedness within the topic itself and indicates the degree of development. In our analysis, 161 keywords with a minimum frequency of 15 were considered.

Next, we draw parallels between the two representations. The two largest clusters (circles) in Figure 4 represent two of three motor (relevant and well-developed) themes and both relate to dye removal/degradation methods in textile wastewater. Cluster 1 (leading keyword *textile wastewater*) comprises 64 keywords, including treatment methods such as *electrocoagulation*, *coagulation*, *advanced oxidation*, *biodegradation* and *bioremediation*, corresponding to the combined red, yellow and most of the light blue clusters in Figure 3. Cluster 2 (adsorption, 49 keywords), which deals with *adsorption* and *photocatalysis* processes, is largely associated with the green cluster in Figure 3. The third motor theme, characterised by cluster 3 (textile waste, 17 keywords), focuses on solid waste and includes terms such as *recycling*, *circular economy* and *waste management*. These are part of the blue cluster in Figure 3. In the same blue cluster we find the keywords from cluster 4 (textiles, 14 keywords) of the thematic map, which also deals with solid waste and contains keywords about *reuse* and *pyrolysis*, as well as materials such as *cotton*, *cellulose* and *composites*. Clusters 5–7 (textile wastewater treatment – 11 keywords, dye/salt separation – 3 keywords, antifouling – 2 keywords) shown on the left-hand side of the map in Figure 3 (indicating

low connectivity with other topics) all relate to filtration of wastewater (ultra/nanofiltration/loose nanofiltration, desalination, dye/salt separation), which corresponds well to the purple cluster in Figure 4. The only term in cluster 8 (mechanical properties) is found in the blue cluster in Figure 4 together with other solid waste.

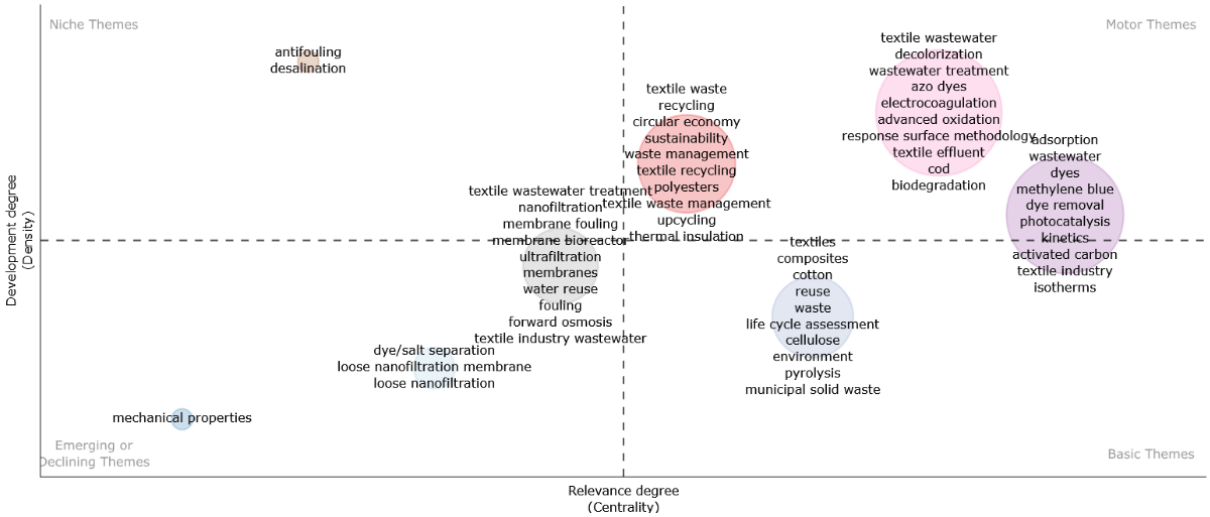


Figure 5: Thematic map of main research topics by author keywords; visualisation: Biblioshiny

To identify trends and emerging research topics, we looked for the keywords whose relative frequency has increased over the last four years (2021–2024). During this period, 56% of the documents in our dataset were published. Using the chi-square test, we identified the following top 10 keywords with a total frequency of at least 30: dye/salt separation (96% instead of the expected 56% in the last four years), circular economy (81%), cellulose (81%), graphene oxides (79%), waste management (78%), polyesters (77%), sustainability (76%), life cycle assessment (72%), textile waste (68%) and recycling (66%). It can be seen that the terms are related to solid waste, reducing resource consumption (circular economy, sustainability), smart textiles (graphene oxides) and filtration (dye/salt separation). Conversely, some keywords appeared less frequently than expected in the last 4 years. These were related to certain dye removal methods such as coagulation and biosorption as well as keywords related to chemical oxygen demand. Despite this trend, documents on wastewater treatment continue to outnumber articles dealing with solid waste.

Thematically, the most influential documents related to single wastewater treatments methods deal with photocatalysis (Ajmal et al., 2014), advanced oxidation (Asghar et al., 2015), and adsorption (Kausar et al., 2018), while the most cited article on solid waste concerns fast fashion (Niinimäki et al., 2020)however, the industry continues to grow, in part due to the rise of fast fashion, which relies on cheap manufacturing, frequent consumption and short-lived garment use. In this Review, we identify the environmental impacts at critical points in the textile and fashion value chain, from production to consumption, focusing on water use, chemical pollution, CO2 emissions and textile waste. Impacts from the fashion industry include over 92 million tonnes of waste produced per year and 79 trillion litres of water consumed. On the basis of these environmental impacts, we outline the need for fundamental changes in the fashion business model, including a deceleration of manufacturing and the introduction of sustainable practices throughout the supply chain, as well a shift in consumer behaviour — namely, decreasing clothing purchases and increasing garment lifetimes. These changes stress the need for an urgent transition back to ‘slow’ fashion, minimizing and mitigating the detrimental environmental impacts, so as to improve the long-term sustainability of the fashion supply chain.”,”container-title”:”Nature Reviews Earth & Environment”,”ISSN”:”2662-138X”,”issue”:”4”,”journalAbbreviation”:”Nat Rev Earth Environ”,”language”:”en”,”page”:”189-200”,”source”:”www.nature.com”,”title”:”The environmental price of fast fashion”,”volume”:”1”,”author”:[{“family”:”Niinimäki”,”given”:”Kirsi”},{“family”:”Peters”,”given”:”Greg”},{“family”:”Dahlbo”,”given”:”Helena”},{“family”:”Perry”,”given”:”Patsy”},{“family”:”Rissanen”,”given”:”Timo”},{“family”:”Gwilt”,”given”:”Alison”}],”issued”:{“date-parts”:[[“2020”,4]]}}}],”schema”:”https://github.com/citation-style-language/schema/raw/master/csl-citation.json”} . All of the above examples have over 700 citations. Outside of the predominant wastewater topic, another article on circular fashion/economy

(Shirvanimoghaddam et al., 2020) stands out with 333 citations. A paper on dye/salt separation (Tavangar et al., 2020)while contact angle measurements confirmed improved membrane hydrophilicity. The performances of the membranes were tested by aqueous dye solutions viz., Direct Red 23, Congo Red, and Direct Red 243 as well as real textile wastewater. Low rejection rates were observed for different aqueous salt solutions following the sequence: MgSO4 (4.1% was also cited nearly 300 times. Examples of more recent influential research (26 articles with 40–110 citations) include 5 review articles on wastewater treatment related to dye removal, e.g. (Valli Nachiyar et al., 2023)2023, an article on cotton waste recycling and an article on plastic waste management. Eight out of 19 titles of original research mention adsorption, three of which refer to activated carbon developed from plants, e.g. (Fito et al., 2023). Nine documents are related to the use of nanotechnology in wastewater treatment (4 related to adsorption, 3 to filtration and 2 to (photo)degradation). One such example concerns graphene oxide used in nanocomposite membranes (Jafarian et al., 2023). The most frequently cited work in the last two years deals with the use of textile waste materials in supercapacitors (Fan et al., 2023).

4. CONCLUSIONS

The study examined the textile waste research field using two methodological approaches: performance analysis and science mapping. Data from the Scopus database for the period from 1913 to 2024 were analysed and visualised using Microsoft Excel, Bibliometrix/Biblioshiny and VOSviewer. The number of articles, conference papers and review articles showed an increasing trend in new documents, and four documents from our dataset received more than 1000 citations each. Thematically, the most influential documents related to unique wastewater treatment methods deal with photocatalysis, advanced oxidation and adsorption, while the most cited article on solid waste concerns fast fashion. The most productive author was Sabir Hussain with 24 documents, while Munawar Aqeel Iqbal and Bart Van der Bruggen were the most cited with over 2000 citations. The most (179) papers were published in the journal *Desalination and Water Treatment,* while the *Journal of Cleaner Production* and the *Chemical Engineering Journal* lead in total citations (over 6000). The co-occurrence network of author keywords revealed six clusters of related concepts, one containing keywords related to solid waste, while the remaining five clusters deal with textile wastewater and its treatment methods. To identify trends and emerging research topics, we searched for the keywords that have increased in relative frequency over the last four years (2021–2024). These keywords relate to resource consumption (sustainability, circular economy), smart textiles (graphene oxides) and filtration (dye/salt separation). The latest articles deal with the use of nanotechnology in wastewater treatment.

5. REFERENCES

Ajmal, A., Majeed, I., Naseem Malik, R., Idriss, H., and Amtiaz Nadeem, M. 2014. 'Principles and Mechanisms of Photocatalytic Dye Degradation on TiO2 Based Photocatalysts: A Comparative Overview'. RSC Advances 4 (70): 37003–26.

Al-Tohamy, R., Ali, S.S., Li, F., Okasha, K.M., Mahmoud, Y.A.-G., Elsamahy, T., Jiao, H., Fu, Y., and Sun, J. 2022. 'A Critical Review on the Treatment of Dye-Containing Wastewater: Ecotoxicological and Health Concerns of Textile Dyes and Possible Remediation Approaches for Environmental Safety'. Ecotoxicology and Environmental Safety 231:113160.

Anjimoon, S., V, A., Gurnani, J., Khan, I., Paul, S., and Al-Jawahry, H.M. 2024. 'Innovations and Opportunities in Sustainable Textile Recycling'. E3S Web of Conferences 507:01065.

Aria, M., and Cuccurullo, C. 2017. 'Bibliometrix: An R-Tool for Comprehensive Science Mapping Analysis'. Journal of Informetrics 11 (4): 959–75.

Asghar, A., Abdul Raman, A.A., and Wan Daud, W.M.A. 2015. 'Advanced Oxidation Processes for in-Situ Production of Hydrogen Peroxide/ Hydroxyl Radical for Textile Wastewater Treatment: A Review'. Journal of Cleaner Production 87:826–38.

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., and Lim, W.M. 2021. 'How to Conduct a Bibliometric Analysis: An Overview and Guidelines'. Journal of Business Research 133:285–96.

Eck, N.J. van, and Waltman, L. 2023. VOSviewer Manual: Manual for VOSviewer Version 1.6.19. Leiden, The Nederlands: Universiteit Leiden. https://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.20.pdf.

Fan, W., Wang, Q., Rong, K., Shi, Y., Peng, W., Li, H., Guo, Z., et al. 2023. 'MXene Enhanced 3D Needled Waste Denim Felt for High-Performance Flexible Supercapacitors'. Nano-Micro Letters 16 (1): 36.

Fito, J., Abewaa, M., Mengistu, A., Angassa, K., Ambaye, A.D., Moyo, W., and Nkambule, T. 2023. 'Adsorption of Methylene Blue from Textile Industrial Wastewater Using Activated Carbon Developed from Rumex Abyssinicus Plant'. Scientific Reports 13 (1): 5427.

Halepoto, H., Gong, T., and Memon, H. 2022. 'Current Status and Research Trends of Textile Wastewater Treatments—A Bibliometric-Based Study'. Frontiers in Environmental Science 10:1–18.
Holkar, C.R., Jadhav, A.J., Pinjari, D.V., Mahamuni, N.M., and Pandit, A.B. 2016. 'A Critical Review on Textile Wastewater Treatments: Possible Approaches'. Journal of Environmental Management 182:351–66.
Hora, S.T., Bungau, C., Negru, P.A., and Radu, A.-F. 2023. 'Implementing Circular Economy Elements in the Textile Industry: A Bibliometric Analysis'. Sustainability 15 (20): 15130.
Jafarian, H., Dadashi Firouzjaei, M., Aghapour Aktij, S., Aghaei, A., Pilevar Khomami, M., Elliott, M., Wujcik, E.K., Sadrzadeh, M., and Rahimpour, A. 2023. 'Synthesis of Heterogeneous Metal Organic Framework-Graphene Oxide Nanocomposite Membranes for Water Treatment'. Chemical Engineering Journal 455:140851.
Kasavan, S., Yusoff, S., Guan, N.C., Zaman, N.S.K., and Fakri, M.F.R. 2021. 'Global Trends of Textile Waste Research from 2005 to 2020 Using Bibliometric Analysis'. Environmental Science and Pollution Research 28 (33): 44780–94.
Kausar, A., Iqbal, M., Javed, A., Aftab, K., Nazli, Z.-H., Bhatti, H.N., and Nouren, S. 2018. 'Dyes Adsorption Using Clay and Modified Clay: A Review'. Journal of Molecular Liquids 256:395–407.
Kumar, P.S., and Saravanan, A. 2017. 'Sustainable Wastewater Treatments in Textile Sector'. In Sustainable Fibres and Textiles, edited by Subramanian Senthilkannan Muthu, 323–46. The Textile Institute Book Series. Woodhead Publishing.
Niinimäki, K., Peters, G., Dahlbo, H., Perry, P., Rissanen, T., and Gwilt, A. 2020. 'The Environmental Price of Fast Fashion'. Nature Reviews Earth & Environment 1 (4): 189–200.
Saravanan, R., Karthikeyan, S., Gupta, V.K., Sekaran, G., Narayanan, V., and Stephen, A. 2013. 'Enhanced Photocatalytic Activity of ZnO/CuO Nanocomposite for the Degradation of Textile Dye on Visible Light Illumination'. Materials Science and Engineering: C 33 (1): 91–98.
Sarker, Md.S.I., and Bartok, I. 2024. 'Global Trends of Green Manufacturing Research in the Textile Industry Using Bibliometric Analysis'. Case Studies in Chemical and Environmental Engineering 9:100578.
Shirvanimoghaddam, K., Motamed, B., Ramakrishna, S., and Naebe, M. 2020. 'Death by Waste: Fashion and Textile Circular Economy Case'. Science of The Total Environment 718:137317.
Tavangar, T., Karimi, M., Rezakazemi, M., Reddy, K.R., and Aminabhavi, T.M. 2020. 'Textile Waste, Dyes/Inorganic Salts Separation of Cerium Oxide-Loaded Loose Nanofiltration Polyethersulfone Membranes'. Chemical Engineering Journal 385:123787.
Valli Nachiyar, C., Rakshi, A.D., Sandhya, S., Britlin Deva Jebasta, N., and Nellore, J. 2023. 'Developments in Treatment Technologies of Dye-Containing Effluent: A Review'. Case Studies in Chemical and Environmental Engineering 7:100339.

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COMFORT AND QUALITY CONTROL OF TEXTILES

ORAL PRESENTATION

INFLUENCE OF THE WOVEN FABRICS SURFACE HAIRINESS ON THEIR ELECTRICAL RESISTANCE UNDER DIFFERENT ATMOSPHERIC CONDITIONS

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Abstract: *The high value of textile materials electrical resistance can lead to accumulation of electrostatic charge on its surface. There are many factors that influence the accumulation of electrostatic charge on textiles, such as: yarn type, fabric structure, thickness, moisture content, porosity or the addition of surface pretreatment, but the surface hairiness of textiles, caused by protruding fibers is usually overlooked property. Therefore, this study investigates the influence of height of materials surface hairiness layer to its electrical resistance at different atmospheric conditions, by calculating it residual electrical resistance. The height of materials surface hairiness layer was assessed on the image taken via camera of digital microscope (Dino-Lite), while the materials electrical resistance values were measured according to the European standard methods for surface resistivity (r) EN 1149-1 and vertical resistance (R) EN 1149-2.*

Keywords: *hairiness, surface resistivity, vertical resistance, relative humidity, woven fabrics*

1. INTRODUCTION

The accumulation of electrostatic charge on the surface of textiles is a widespread phenomenon that becomes more visible in winter when the air humidity is low, in a form of a spark. The greater the amount of electrostatic charge that can accumulate on materials surface the higher the probability of electrostatic discharge (ESD). In most situations it is harmless and can do no serious damage, but at gas stations or certain work environments it can cause fire, explosions or do serious damage to electronic devices (Abo-Basha 2024; Paasi 2005; 2002; Welker 2005; Nurmi 2007)in order to minimise the device failures due to electrostatic discharge (ESD. The accumulation of electrostatic charge in textile materials is usually caused by direct physical contact or friction between two surfaces, which occurs frequently in their everyday use. During contact or friction between two textile materials, the electron transfer occurs, from the surface of one material to the surface of the other material, especially if they are made from different type of fibers. Electron transfer causes the materials surfaces to become electrically unbalanced, and positively "+" or negatively "-"charged. The positively charged material is a material from which the electrons have been transferred, while the negatively charged material is a material to which they have been transferred. The direction of electron transfer between two materials depends on their type, more specific their triboelectric property. The textile materials triboelectric property is described in the *Triboelectric series*, where textile fibers are distributed between a positive "+", and a negative "-" end. The closer the fiber in Triboelectric series is to the positive end the more inclined is to releasement of electrons, while the fibers closer to negative end are more inclined to acceptance of electrons (Nurmi 2007; Kim 2021). Textile materials that are susceptible to the accumulation of electrostatic charge are usually made of less electro conductive, synthetic fibers, which generally absorb a small amount of moisture and have high electrical resistance (Hałgas 2024). The accumulation of electrostatic charge is not limited to the materials made from synthetic fibers or fibers with low moisture content, but it also can occur on materials made of different type of fibers in atmospheres with low air humidity (Zhu 2013; Varnaite-Žuravliova 2013; Salvado 2012)as well as their advantages and disadvantages. And the correlation study on different standards showed that testing results of different materials according to the same method had similar change trend, but no evidence proved a definite linear relationship of three test methods. © (2013. Therefore, when the material propensity to the accumulation of electrostatic charge is determined is often done by measuring it electrical resistance. In Europe, the electrical resistance of textile materials is determined by two EN 1149 stan-

dard test methods, first EN 1149-1 for surface resistivity (*r*) and second EN 1149-2 for vertical resistance (*R*). This European standards are meant for testing the electrostatic dissipative protective clothing or fabrics. The standards contain information on the test method, materials requirements, and the atmospheric conditions under which the specimen and the test method should be carried out, i.e. at a temperature of 23 ± 1 °C and a relative humidity of 25 ± 5 %. In reality, in addition to the atmospheric conditions that influence the accumulation of electrostatic charge on textiles, there are many other factors that have been researched over the years, such as the type of yarn, the fabric structure, surface roughness, the thickness, the moisture content, the porosity or the addition of any type of pretreatment (Hong 2020; Abo-Basha 2024; Sereda 1964; Nurmi 2007; Varnaite 2009; Asanovic 2022). The most overlooked factor when it comes to determining the textile materials tendency to accumulate electrostatic charges is their surface appearance, more precisely materials surface hairiness caused by protruding fibers. Therefore, this study investigates the influence of materials surface hairiness to its electrical resistance, by performing measurements of materials surface resistivity and vertical resistance under different atmospheric conditions. The study was performed on selected reference woven fabric made of cotton, viscose, polyamide 6.6 and polyester (PET) fibers, and the height of their surface hairiness layer was determined on the image obtained via camera of digital microscope (Dino-Lite).

2. EXPERIMENTAL

2.1 Materials

Samples of single fiber cotton, staple viscose, polyamide 6.6 and polyester (PET) colorless reference adjacent fabrics, in plain weave, which are used for color fastness testing (ISO 105-F series) of textile materials, were selected for this study. Selected fabrics do not contain chemically damaged fibers, residues of finishing agents, dyes or fluorescent brighteners. The values of fabrics mass per unit area (ISO 3801:1977) and thickness (EN ISO 5084:1996) were determined according to the standard methods. For the purpose of this study, three circular specimens with a diameter of 140 mm were cut from each fabric. During testing, values for mass, thickness and moisture content (ASTM D2654-22) were determined for each specimen and each atmospheric condition under which it was conditioned.

2.2 Fabric surface hairiness

The height of the surface hairiness of the fabric, expressed in millimeters, was determined for each prepared specimen using the digital image of the surface (Fig. 1c) taken with the camera of the digital microscope. The digital image of the specimen surface had to be converted to black and white image so that the average height of the surface hairiness could be determined (marked with a red line, Fig. 1d).

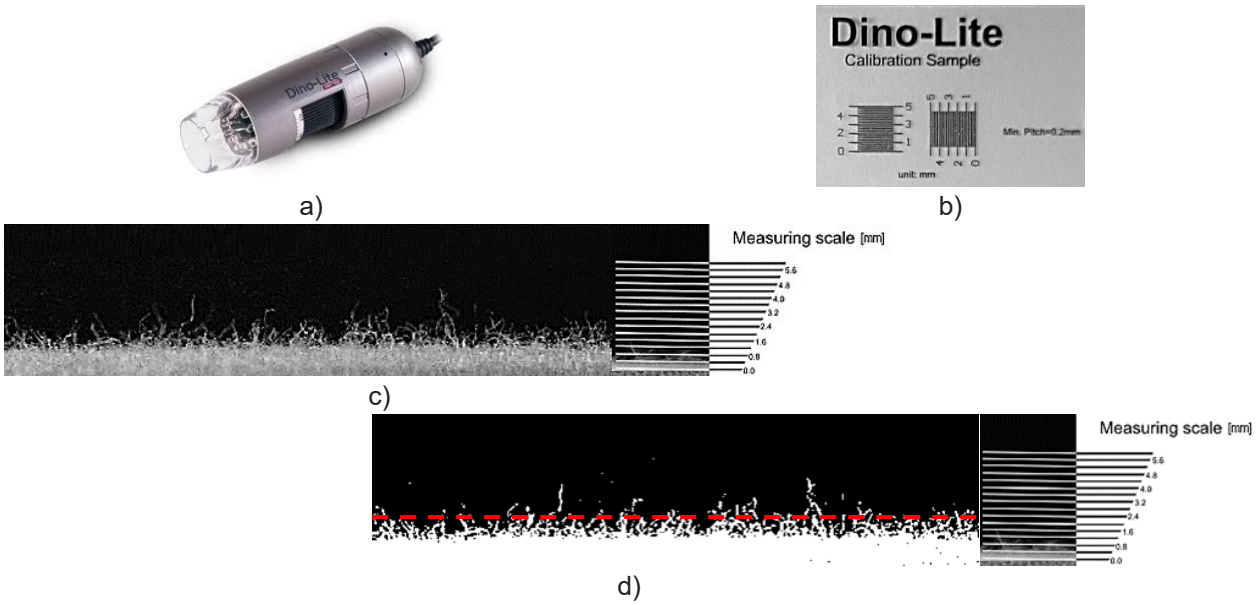


Figure 1: Dino-Lite AM - 4113ZT digital microscope a), Dino-Lite calibration measurement tool b), digital image of the cotton fabric surface (5.7x), with added measuring scale c), and it black and white image d)

During image acquisition, the specimen was placed on specimen holders used for modified Martindale method, and therefore they were supported by felt. The device used for image acquisition was the Dino-Lite AM - 4113ZT digital microscope (Fig. 1a), which was positioned at the height of the specimen surface at a distance of 26 cm from the edge of the specimen holder, with a magnification of 5.7x. During image acquisition, the specimens were placed in a darkened room and their surface was illuminated with a light source with artificial daylight D65 at an angle 15° to the plane of the specimen surface. The Dino-Lite calibration measuring tool (Fig. 1b) was used to create a measuring scale (Fig. 1c, d) to determine the average height of the surface hairiness. The mean value (H_{sl}) from the determined height of the surface hairiness layer of the three specimens for each fabric, was used as the result for the atmospheric condition under which they were conditioned.

2.3 Fabric electrical resistance

The measurement of surface resistivity (r) and vertical resistance (R) was carried out according to the European standard methods EN 1149-1 and -2 by using the conductivity tester, Static Lab 291B (Fig. 2), which is equipped with circular electrode, specimen holder and isolating plate. When the specimen is placed on the specimen holder with the insulating plate, the surface resistivity is measured and when the specimen is placed on the specimen holder without the insulating plate, the vertical resistance is measured.

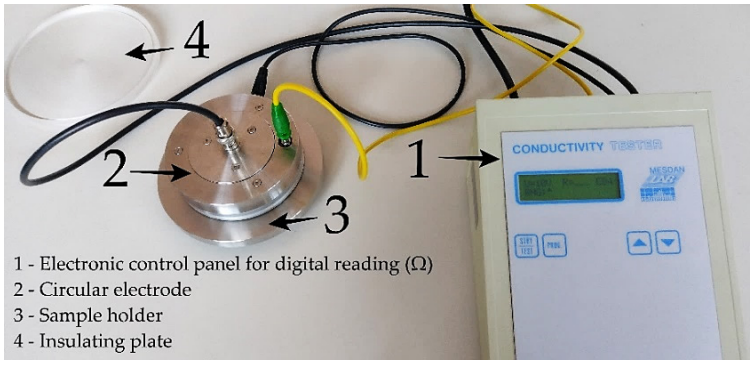


Figure 2: Conductivity tester - Static Lab 291B Mesdan S.p.A., Italy

According to the standard methods for the measurement of textile materials electrical resistance values, the tested specimens should be conditioned in an atmosphere with a temperature of 23 ± 1 °C and a relative humidity of 25 ± 5 % (AC1) before testing. However, since the aim of this study is to assess the influence of fabric surface hairiness on it electrical resistance, the measurements of the fabrics electrical resistances were performed on specimens conditioned under different atmospheric conditions. Three additional atmospheric conditions were selected and one of these corresponded to the standard atmosphere for conditioning and testing of textiles (EN ISO 139:2005/A1:2011), which is generally used for textile testing, with a temperature of 20 ± 2 °C and a relative humidity of 65 ± 4 % (AC3). The other two conditions were then interpolated around these values, with a temperature of 20 ± 2 °C, but in a lower and higher range of relative humidity of 40 ± 5 % (AC2) and 80 ± 5 % (AC4).

2.4 Fabric residual electrical resistance

The influence of surface hairiness on the electrical resistance of the fabric was investigated by analyzing the measured resistances, or more precisely fabrics residual electrical resistances and the determined height of the surface hairiness layer. The residual electrical resistance is an additional factor, expressed as a percentage, which represents the ratio between the resistances measured under atmospheric conditions with higher relative humidity (AC2, AC3 or AC4) and the one with the lowest relative humidity AC1.The residual electrical resistances are calculated separately according to equations 1 and 2 for measured values of surface resistivity ($R_{r40,65,80}$, Eq. 1) and vertical resistance ($R_{R40,65,80}$, Eq. 2).

$$R_{r40,65,80} = \frac{r_{AC2}, r_{AC3}, r_{AC4}}{r_{AC1}} \cdot 100 \quad , \quad R_{R40,65,80} = \frac{R_{AC2}, R_{AC3}, R_{AC4}}{R_{AC1}} \cdot 100 \qquad (1,2)$$

3. RESULTS WITH DISCUSSION

At the beginning of this study, the basic physical properties of the fabric were determined under a standard atmosphere for textile testing (AC2). The results (Tab. 1) show that the viscose fabrics has the highest value for mass per unit area, while the polyamide 6.6 fabric has the highest value for thickness.

Table 1: Fabrics physical properties determined under standard atmosphere for testing (AC2)

Fabric physical properties	Cotton	Viscose	Polyester	Polyamide 6.6
Mass per unit area [g/m^2]	114.4	141.6	134.2	131.4
Thickness [mm]	0.28	0.26	0.26	0.33

Table 2: Mean values of mass, moisture content, thickness and height of surface hairiness layer (H_{sl}) of the three specimens of the same fabric after conditioning under different atmospheric conditions (AC1-AC4)

Fabric		Mass of specimen [g]	Moisture content [%]	Thickness [mm]	H_{sl} [mm]
Cotton	AC1	1.648	1.978	0.28	1.22
	AC2	1.674	3.627	0.28	1.31
	AC3	1.717	6.282	0.28	1.42
	AC4	1.739	7.659	0.28	1.64
Viscose	AC1	1.961	3.468	0.26	1.93
	AC2	1.983	4.615	0.26	2.16
	AC3	2.103	10.940	0.26	2.30
	AC4	2.159	13.907	0.26	2.57
Polyester	AC1	2.007	0.117	0.26	0.23
	AC2	2.010	0.261	0.26	0.24
	AC3	2.012	0.359	0.26	0.24
	AC4	2.013	0.408	0.26	0.24
Polyamide 6.6	AC1	1.966	0.924	0.33	1.24
	AC2	1.983	1.800	0.33	1.30
	AC3	2.019	3.660	0.33	1.31
	AC4	2.040	4.715	0.33	1.35

As there are many factors that can influence the electrical resistance value of fabrics, the values for mass, moisture content, thickness and height of surface hairiness layer where determined for each specimen during the test. The average values of three specimens of the same fabrics for every atmospheric condition under they were conditioned are shown in Table 2. The mass of the specimen changed depending on the amount of moisture absorbed under different atmospheric conditions, while the value of the fabrics thickness has not changed. The height of the surface hairiness layer (H_{sl}) of the specimens increased slightly under atmospheric conditions with higher relative humidity.

Table 3: Results of surface resistivity (r) and vertical resistance (R) measured at different atmospheric conditions

Electrical resistance		Cotton	Viscose	Polyester	Polyamide 6.6
r [Ω]	AC1	57.800×10^{12}	49.667×10^{12}	81.200×10^{12}	43.00×10^{12}
	AC2	3.217×10^{12}	11.390×10^{12}	31.567×10^{12}	35.467×10^{12}
	AC3	0.028×10^{12}	0.042×10^{12}	28.000×10^{12}	16.260×10^{12}
	AC4	0.003×10^{12}	0.003×10^{12}	21.420×10^{12}	3.275×10^{12}
R [Ω]	AC1	29.640×10^{9}	475.200×10^{9}	227.400×10^{9}	497.400×10^{9}
	AC2	4.857×10^{9}	69.425×10^{9}	76.862×10^{9}	360.000×10^{9}
	AC3	0.084×10^{9}	0.166×10^{9}	2.747×10^{9}	18.100×10^{9}
	AC4	0.005×10^{9}	0.007×10^{9}	1.204×10^{9}	3.197×10^{9}

The measured values for surface resistivity and vertical resistance listed in Table 3 show a decrease in the values when the specimens were conditioned under atmospheric conditions with higher relative humidity. This decrease is more pronounced for cotton and viscose fabrics than for polyester and polyamide 6.6 fabrics.

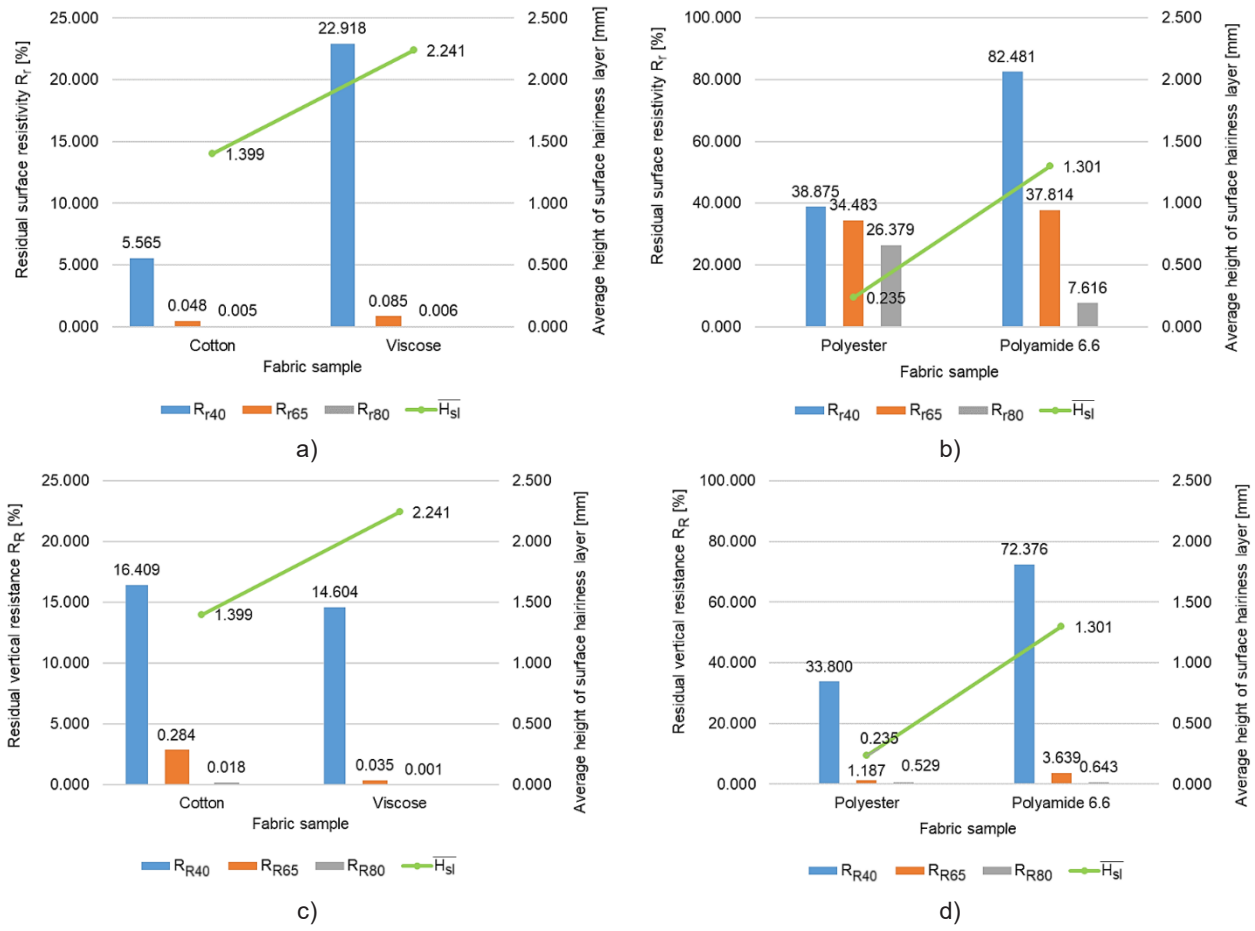


Figure 3: Graphical representation of height of surface hairiness layer and the calculated residual surface resistivity (a, b) and vertical resistance (c, d) values

When analyzing the results of the individual residual electrical resistances, fabrics are divided into two groups, one for the cotton and viscose fabric and the other for the polyester and polyamide 6.6 fabric, as there is a large difference between their values. The results of the calculated residual surface resistivity ($R_{r40,65,80}$) are shown in Figures 3 a and b, and the results of the calculated residual vertical resistance ($R_{R40,65,80}$) are shown in Figures 3 c and d. In all diagrams, these values are compared with the average height of surface hairiness layer (), which is calculated from the mean values determined under AC1-AC4 conditions (Tab. 2).

From this perspective, it can be seen that the values of the residual electrical resistances for each fabric sample decrease with the increase in the relative humidity of the atmospheric conditions under which they were conditioned. Furthermore, when analyzing the values of residual surface resistivity (Figs. 3a, b), it can be seen that they correlate with the average height of surface hairiness, which means that a lower height of surface hairiness layer leads to lower values of the fabric's residual surface resistivity. The values of residual vertical resistance for polyester and polyamide 6.6 fabrics (Fig. 3d) show the same correlation with the average height of the surface hairiness layer as the values of their surface resistivity. This is not the case for cotton and viscose fabrics. The reason for that can be assigned to fabric structure (Tab. 1) and the moisture content (Tab. 2), which has a major influence on the electrical resistance of the fabric (Tab. 3).

4. CONCLUSIONS

From the conducted research, it can be seen that the introduced residual electrical resistance value captures the influence of fabrics surface hairiness layer on its electrical resistance values. The influence can be seen in the residual surface resistivity values of the fabric, whereby the fabrics with a higher surface hairiness have a higher residual surface resistivity value. The electrical resistance values still depend strongly on the fiber composition and the atmospheric conditions (relative humidity) under which the fabric is conditioned. Therefore, the influence of the fabrics surface hairiness layer on its electrical resistance should not be conducted under atmospheric conditions with very high relative humidity (AC4).

5. REFERENCES

Abo-Basha, S.S., Nassar, K.M. and Mohamed, R.A. 2024. “Antistatic Textiles: Current Status and Future Outlook.” Journal of Art, Design and Music 3 (2): 236–50.
Asanovic, K.A., Cerovic, D.D., Kostic, M.M., Maletic, S.B. and Ivanovska, A.M. 2022. “Electro-Physical Properties of Woven Clothing Fabrics Before and After Abrasion.” Journal of Natural Fibers 19 (4): 1–12.
Hałgas, S., Wilbik-Hałgas, B. and Sidyk, P. 2024. “Modeling and Testing of ESD Protective Textiles.” Applied Sciences (Switzerland) 14 (16): 1–24.
Hong, H., Hu, J. and Yan X. 2020. “Effect of the Basic Surface Properties of Woven Lining Fabric on Printing Precision and Electrical Performance of Screen-Printed Conductive Lines.” Textile Research Journal 90 (11–12): 1212–23.
Kim, W. G., Kim, D. W., Tcho, Il-W., Kim, J.-K., Kim, M.-S. and Choi, Y.-K. 2021. “Triboelectric Nanogenerator: Structure, Mechanism, and Applications.” ACS Nano 15 (1): 258–87.
Nurmi, S., Hammi, T. and Demoulin B. 2007. “Protection Against Electrostatic and Electromagnetic Phenomena.” Springer Series in Materials Science 97: 63–83.
Paasi, J., Coletti, G., Fast, L., Lemaire, P. and Vogel, C. 2002. “ESD-Protective Clothing for Electronics Industry – A New European Research Project ESTAT-Garments.” Solutions 1 (8): 2–9.
Paasi, J., Fast, L., Kalliohaka, T., Smallwood, J., Börjesson, A., Haase, J., Vogel, C. et al. 2005. “Risks of Damage to Electronics with Reference to Charged Clothing.” Journal of Electrostatics 63 (6–10): 603–8.
Salvado, R., Loss, C., Gonçalves, R. and Pinho, P. 2012. “Textile Materials for the Design of Wearable Antennas: A Survey.” Sensors (Switzerland) 12 (11): 15841-15857.
Sereda, P.J. and Feldman R.F. 1964. “Electrostatic Charging on Fabrics at Various Humidities.” Journal of the Textile Institute Transactions 55 (5): T288–98.
Varnaite-Žuravliova, S., Stygiene, L., Čepliauskiene, R., Krauledas, S. and Sankauskaite, A. 2013. “The Influence of Three-Layer Knitted Fabrics’ Structure on Electrostatic and Comfort Properties.” Materials Science 19 (4): 415–19.
Varnaite, S., and Katunskis, J. 2009. “Influence of Washing on the Electric Charge Decay of Fabrics with Conductive Yarns.” Fibres and Textiles in Eastern Europe 76 (5): 69–75.
Welker, R.W., Nagarajan, R. and Newberg, C.E. 2005. “Fundamentals of ESD Control.” In Contamination and ESD Control in High Technology Manufacturing, 48–118. New Jersey: John Wiley & Sons, Inc., Hoboken.
Zhu, R., Zhang, P. and Nie, F. 2013. “Overview and Correlation Study on Electrostatic Property of Different Testing Standards.” In Advanced Materials Research 627:325–28.

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POSTER PRESENTATION

COMPARISON OF ABSORBENCY PROPPERTIES OF DISPOSABLE AND REUSABLE SANITARY PADSTITLE OF THE PAPER

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Abstract: *Sanitary pads are hygiene products that belong to the medical textiles, which are categorised as technical textiles. Both disposable and reusable sanitary pads can be found on the market, whereby disposable sanitary pads represent a large amount of poorly degradable waste, while reusable sanitary pads are more environmentally friendly. The study compared the absorption properties of disposable and reusable sanitary pads. Five different disposable sanitary pads, which are the most commonly used in Slovenia, and one type of reusable sanitary pads were used. In terms of comfort and absorption properties such as fluid absorption and retention, moisturising sensation and capillary rise, disposable sanitary pads have significantly better properties as they usually contain SAP and are comfortable for the user. Reusable sanitary pads are more environmentally friendly but less comfortable, as our study also confirms.*

Keywords: *reusable and disposable sanitary pads, absorption properties, absorption rate, wetting, moisturising sensation.*

1. INTRODUCTION

Sanitary pads are hygiene products that belong to the medical textiles, which are categorised as technical textiles. There are disposable sanitary towels and reusable sanitary pads. In both cases, the choice of materials is important in order to achieve the required mechanical, functional, comfortable, permeable and absorbent properties. At the same time, the materials must be safe for women's health and preferably biodegradable. Several studies have shown that people living near landfills, where sanitary pads are commonly disposed of, have a higher risk of becoming ill. An increased risk of bladder cancer and leukaemia in women has been demonstrated. Other studies have shown malformations of the nervous system and musculoskeletal system (Zins 2011). According to calculations based on market data and assumptions about census data, the amount of sanitary waste generated in the UK is around 28,114 tonnes per year. Sanitary towels are the most commonly used, accounting for around 21,049 tonnes of waste per year (Blair 2022).

Disposable sanitary pads are mainly made from synthetic materials, namely polyethylene for the top layer and superabsorbent polymers for the middle absorbent layer. The bottom layer usually consists of a liquid-tight film to prevent leakage and is usually made of polyethylene. Reusable pads also consist of a top layer, a middle absorbent core made of absorbent materials and a leak-proof layer of polyurethane laminate (PUL) at the bottom. The top layer is the absorbent layer and transports the liquid to the absorbent core underneath. The upper and absorbent middle layer consists of materials such as cotton, viscose, bamboo viscose or lyocell. The fabrics can be velour, fleece, jersey, terrycloth or flannel (Barman 2017).

Researchers have been looking for suitable biodegradable materials that could replace conventional synthetic materials in disposable sanitary pads. It was found that lyocell fibres could replace polypropylene fibres. Organic cotton fibres could be used for the top layer, bamboo, jute, banana, rice and flax fibres as well as cellulose hydrogel for the absorbent core and a bioplastic polymer PLA for the lower, impermeable layer (Barman 2017, Siddiqe 2019). It was found that most of the samples of the upper layer were made of polypropylene, which was composed of a nonwoven fabric using the spunbond technique with point bonding (Pohlmann 2016). Some researchers have also compared the properties of disposable and reusable sanitary pads. They investigated the skin irritation of

disposable and reusable sanitary pads when wet and dry. They found that the friction force of disposable sanitary pads is lower than that of reusable sanitary pads, while the wettability of disposable sanitary pads with a non-woven surface is lower than that with a perforated surface. They also found that reusable sanitary towels absorb more moisture directly on the skin than disposable sanitary pads under the same load (Tang 2020, Tang 2019).

2. EXPERIMENTAL

In order to compare the absorption properties of disposable and reusable sanitary pads, five disposable sanitary pads (samples 1 to 5) and one reusable sanitary pad (sample 6) were used. The most commonly used brands of sanitary pads in Slovenia were used. Disposable sanitary pads (sample 5) and reusable sanitary pads (sample 6) were produced by two different Slovenian manufacturers. All sanitary pads are used for medium to heavy bleeding. Table 1 shows the composition of the samples.

All sanitary pads were analysed with the SEM (JSM-6060LV (JEOL – Japan) at 100x magnification, the composition of the tested sanitary pads were determinated with the FT-IR Spectrum 3 (Perkin Elmer, Great Britain).

The following tests were performed to compare the absorption properties: absorption rate of the entire sanitary pad and individual layers, transferred liquid, which can give a sensation of moisture, drop test, wetting and capillary rise.

The absorption rate of the entire sanitary pad and the individual layers was tested using water with dispersed dye dripped onto the centre of the pad. The initial mass of the entire sanitary pad and the individual layers was measured. 15 ml of liquid was dripped onto the pad and was allowed to absorb. The process was repeated until the liquid began to spill over the edge. The pad was then weighed again. The absorption rate was calculated using equation 1. After testing the absorbency of the entire pad, the layers were separated and weighed again. The absorption rate of the entire sanitary pad and individual layers was calculated using equation 1.

$$absorption\ rate = \frac{absorbed\ liquid\ [ml]}{time\ [min]}\ (ml/\min\ ) \qquad (1)$$

The transferred liquid, which present a sensation of moisture feels moist, was tested with filter paper. 5 minutes after the last addition of liquid in the absorbency test, the previously weighed dry filter paper was placed on the sanitary pad and held there for 30 seconds. The filter paper was then removed and weighed immediately. If no liquid is transferred, the filter paper remains relatively dry.

The absorbency drop test was performed according to the AATCC test method 79 using a stamp and a dropper. First, the circles were stamped on each sanitary pad with a dot in the middle. A drop of coloured water was placed in the middle of the circle and the time taken for the drop to be completely absorbed by the material was measured.

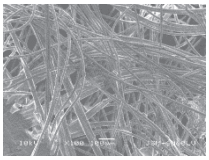
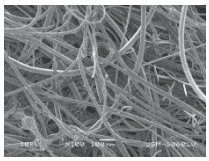
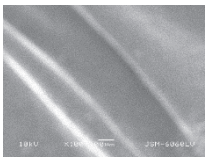
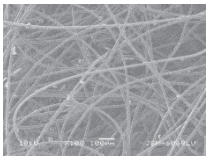
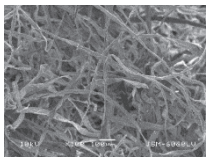
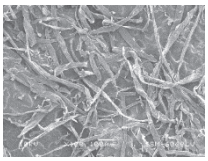
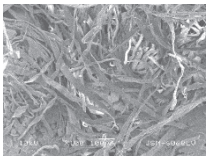
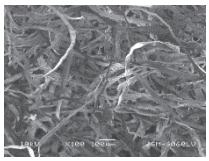
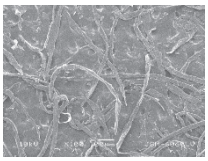
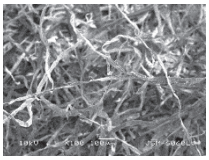
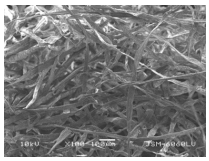
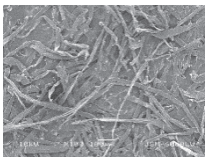
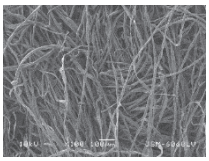
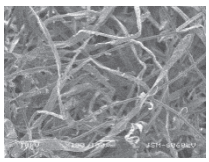
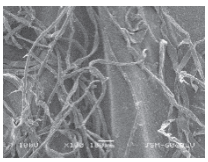
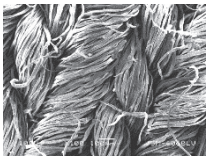
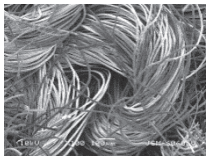
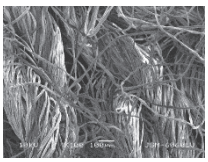
Wetting was evaluated using the sinking test method based on the standard method EN 14697:2005 - Textiles - Terry towels and terry towel fabrics - Specification and methods of test, Annex B - Determination of the time of absorption. The time required for a piece of fabric to sink completely out of the surface layer of water in a beaker was measured. For this purpose, a 3 × 3 cm piece was cut out of the fabric and placed on the surface layer of water in a 500 ml beaker. The wetting time was estimated with a stopwatch as the time interval between the moment of immersion and the moment when the sample had sunk below the water level. Each experiment was performed at least three times (Pavko Čuden, 2010, Saville, 1999)

Samples measuring 200 mm x 25 mm in the longitudinal direction were used to measure capillary rise. The sample was rotated vertically and immersed in a beaker containing distilled water and dye (1% Prussian blue). After a specified time (1 min, 2 min, 3 min, 4 min and 10 min), the height of the capillary rise of the water was read. The measurements were carried out in accordance with DIN 53924.

3. RESULTS WITH DISCUSSION

In Table 1 the composition of the studied samples with corresponding SEM images is presented.

Table 1: Compositions of the studied sanitary pads.

Sample	Upper (surface) layer	Middle layer	Bottom layer
1	polypropilen spunbonded nonwoven fabrics 	cellulose and SAP 	Polyethylene 
2	polypropilen spunbonded nonwoven fabrics 	cellulose and SAP 	Polyethylene 
3	polypropilen spunbonded nonwoven fabrics 	cellulose and SAP 	Polyethylene 
4	cotton spunbonded non-woven fabrics 	cellulose and SAP 	Polyethylene 
5	cotton spunbonded non-woven fabrics 	cellulose and SAP beads 	Polyethylene 
6	knitted single jearsy 95% cotton, 5% elastan 	knitted terry of 77 % bamboo viscose in 23 % polyester 	knitted terry fabrics of 70% cotton and 30% polyester with polyethylene film 

The absorption rate results (Figure 1) show that some disposable sanitary pads have a higher absorption rate than reusable sanitary pads, while others have a lower absorption rate, depending on the structure and materials used in the upper and middle layers. Disposable pads have a more absorbent middle layer, while the top and bottom layers absorb very little liquid. In reusable pads, the middle and top layers absorb almost the same amount of liquid. From the results in Figure 1, it can be concluded that samples 3, 4, 5 and 6 have almost the same absorption rate, although the composition of the sanitary pads is different. The middle layer has a major influence on the absorption rate. The most absorbent middle layer is found in disposable sanitary pads that have an absorbent core of cellulose fibres with added SAP beads (sample 5). The bamboo viscose terry, the middle layer in reusable pads (sample 6), does not absorb as much liquid, but the bottom layer of knitted cotton terry also absorbs as much liquid as the middle layer, except that it is protected by a film to prevent the pad from leaking. Together they absorb almost as much liquid as the most absorbent middle layer.

Figure 1 also shows that the top layer does not absorb much liquid in all the samples tested, as it serves as a collection container. It allows the liquid to pass through to the middle layer, which can absorb as much as possible to prevent leakage at the sides. The bottom layer only absorbs a minimal amount of liquid as it is made of hydrophobic, impermeable materials that primarily prevent the liquid from running over the cartridge, except for the reusable pads.

When measuring the moisture sensation (wet feeling) of the surface, it was found that reusable sanitary pads transfer almost twice the amount of liquid to the filter paper compared to disposable sanitary pads (Figure 2). The lowest transformation of liquid on the filtration paper was observed for samples 3 (0,03 ml), 1 (0,29 ml) and 5 (0,44 ml). The upper layer, which consists of polypropylene spunbond in samples 1 and 3 and cotton nonwoven in sample 5, has the greatest influence on the moisture perception. The absorption rate of the middle layer and the entire sanitary pad also had an influence on the moisture sensation, while these samples also absorbing the most liquid.

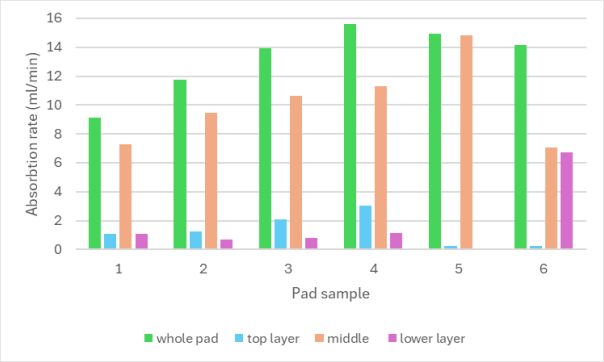


Figure 1: Absorbency of whole pad and individual layers.

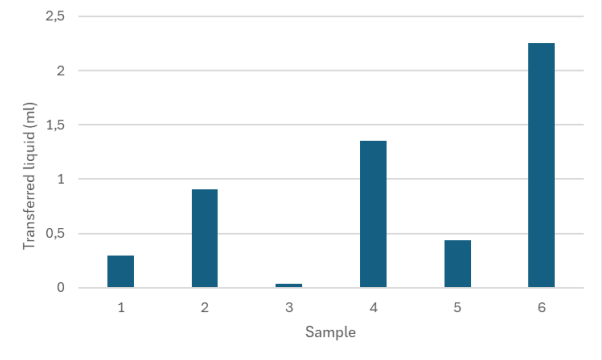


Figure 2: Transferred liquid from sanitary pads to filtration paper, represents a wet feeling.

The results of the drop test and the wetting test show that the liquid is absorbed fastest by the disposable sanitary pad sample 5 (with a cotton surface and a middle layer of cellulose mixed with SAP beads), while the result of the reusable sanitary pads was in the middle of the field. The cotton layer absorbs the liquid the fastest compared to the other upper layers. The liquid is absorbed most slowly by the disposable sanitary pad sample 1 (with a polypropylene surface and a middle layer of cellulose and SAP). The top layer of sample 1 does not allow rapid absorption.

Sample 5 was also the fastest to absorb the liquid completely in the wetting test (15.6 s), and the slowest sample 1 behaved in the same way as in the drop test. Sample 1 takes more than 2 hours to sink. The reason for this lies in the construction of the disposable sanitary pads. Sample 6, the reusable sanitary pad, takes almost a minute to completely absorb the liquid and sink. Cotton and bamboo viscose fabrics in reusable sanitary pads cannot absorb as much liquid as the middle layer of disposable sanitary pads with incorporated SAP.

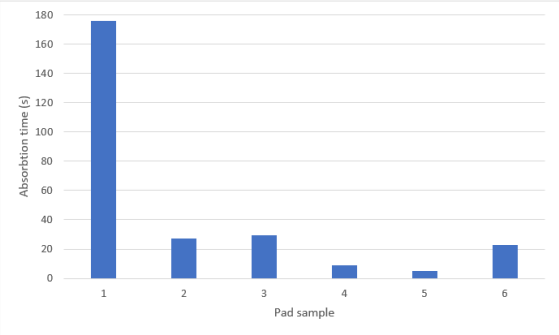


Figure 3: Absorbency time in drop test.

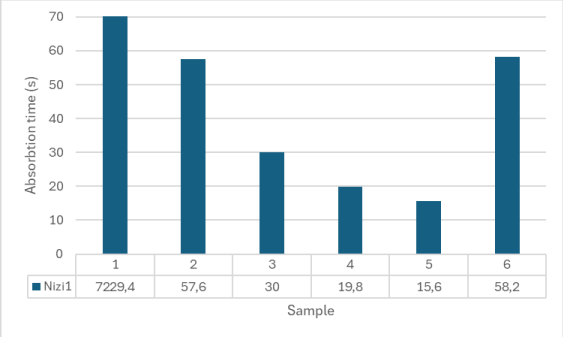


Figure 4: Time of total absorbency in wetting test.

The capillary rise test shows that disposable sanitary pads are vertically more absorbent than reusable sanitary pads, which achieve the worst result.

The capillarity test shows that after 10 minutes the best result is achieved with sample 2, which has absorbed the liquid along its length (18 cm). The second best absorption is observed with sample 5. As Figure 5 shows, there is no major difference in capillary rise between the disposable sanitary pads tested.

The lowest result in the capillary rise test was achieved by the reusable sanitary pads (sample 6), as can be seen in Figure 5. As with wetting, the speed of capillary rise is also influenced by the hydrophilicity of the fibres and the distance between them. The more hydrophilic the fibres are and the more space they have, the faster they become wet and swell.

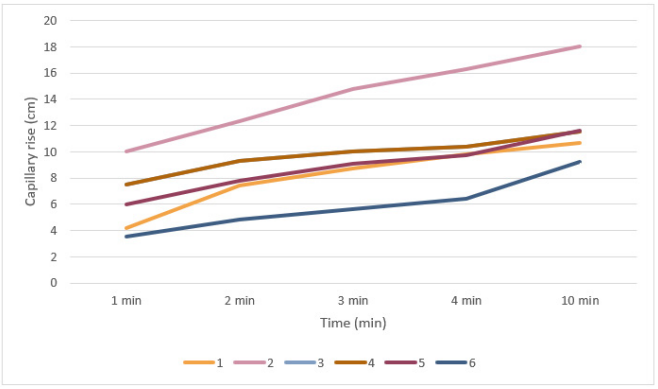


Figure 5: Capillary rise of a sanitary pad.

4. CONCLUSIONS

In terms of comfort and absorbency properties such as liquid absorption and retention, moisturising sensation and capillary rise, disposable sanitary pads have much better properties as they usually contain SAP.

The best properties are achieved by sanitary pads that contain a high proportion of natural materials in their composition and thus achieve good absorption properties. According to the research results, the best performance was observed in sample 5, adisposable sanitary pads from the Slovenian manufacturer. They are highly absorbent and have an excellent ability to retain a large amount of liquid. They provide a medium feeling of dryness. The disposable pads in samples 3 and 4 have good absorbency and good liquid retention capacity. The sanitary pads in sample 3 provide a dry feeling, while the pads in sample 4 provide a rather moist feeling on the surface during use. Disposable pads of sample 1 absorb liquid poorly, but give a fairly good feeling of dryness. Disposable pads of sample 2 are fairly absorbent and provide a medium feeling of dryness. The reusable sanitary pads tested are well absorbent but give a moisturizing feeling on the surface. Disposable pads are simply convenient and popular, as the reusable pads produced to date do not achieve the same comfort properties. The use of reusable pads could increase with improvements in the materials used and thus improved comfort properties.

5. REFERENCES

Barman, A., Katkar, P. M., Asageker, S. D. 2017. “Natural and Sustainable Raw Materials for Sanitary Napkin”. Journal of Textile Science & Engineering 7(4): 1–3.
Blair, L. A. G., Bajon–Fernandez, Y. and Villa, R. 2022. “An exploratory study of the impact and potential of menstrual hygiene management waste in the UK”. Cleaner Engineering and Technology 7: 1–7.
Pavko Čuden, A., Stanković Elesini, U. 2010. “Elastane Addition Impact on Structural and Transfer Properties of Viscose and Polyacrylonitrile Knits”. Acta Chimica Slovenica 57(4): 957–962.
Pohlmann, M. 2016. “Design and Materials Selection: analysis of similar sanitary pads for daily use”. International Journal of Engineering Research and Application 6(11): 74-79.
Saville, B.P. 1999. “Physical testing of textiles”. Cambridge: Woodhead publishing, p.235.
Siddiqe, R. 2019. “Sustainable alternatives for producing biodegradable Sanitary Napkins”. Bioresearch Communications 5(2): 737–743.
Tang, K. M., Li, C. H., Kan, C. W. 2019. “Measurement of Liquid Transport Properties of Sanitary Napkin with Modified Forced Flow Water Transport Tester”. Fibers and Polymers 20(12): 2646–2653.
Tang, K. M., Li, C. H., Kan, C. W. 2020. “Instrumentation for Measuring the Wet Frictional Property of Sanitary Pads”. Fibers and Polymers 21(1): 216–223.
Zins, H. M. 2011. “Reusable medical textiles”. In Handbook of medical textiles, edited by V. T. Bartels, 80–105. Philadelphia: Woodhead Publishing Limited.

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TEXTILE AND CLOTHING DESIGN

ORAL PRESENTATION

SUSTAINABLE PRACTICES IN SLOVENIAN FASHION LANDSCAPE

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Abstract: *The data collected in the research is related to sustainable practices in Slovenian fashion. The research included the mapping of the contemporary Slovene fashion brands as well as examples of Slovenian clothing industry that used some sustainable approaches. The activities included are zero-waste or less-waste design, recycling and up-cycling, the focus on the design and production of products that adapt and improve over the years, consumer participation in the design process, use of social media and the development of fashion communities by fashion brands themselves. The review also includes services with product life-long repairs, the data on technological or production innovations, data on the local and/or regional supply and production chain as well as technological or production innovations implemented. In the need to reduce the fashion loop size, we reviewed the situation regarding the existence of ideas that contribute to less production and dematerialization.*

Keywords: *Slovenian fashion, sustainable fashion, cultural diversity, handcraft tecniques.*

1. INTRODUCTION

The most emphasized segments in sustainable fashion design are the basic life cycle of the garment (production, use, and end of use) and the cultural and social aspects of fashion design (prevalence and nature of consumerism, participation of the user and the local environment, speed of the production and delivery). The involvement of the user or the community in the entire process is crucial and necessary; the fashion system transmits messages from the outside world to objects - clothes, while the user's rituals (ritual of sale, ritual of maintenance, ritual of possession) enable the transmission of meanings from the object to the user (McCracken, 1986). Throughout the entire life cycle of clothing, the elements of social responsibility, economic profitability and protection of the natural and cultural environment should be taken into account and must be clearly reflected in the visualization of the product as well as in the conveyed meaning.

Over the past fifty years, Slovenian fashion has demonstrated various approaches to sustainable fashion development, many times unplanned, but as positive reminders that the Slovenian fashion landscape instinctively perceived steps in the right direction of development, but was unable to capitalize them on the market. In the past, Slovenian clothing industry used some sustainable approaches, the realization of which was the result of economic reasons and social circumstances. In contemporary Slovenian fashion, there are several different examples of the implementation of sustainable processes, which in many cases are not highlighted enough by brands as such. The first step within the research included overview of the fashion practices in the past, brands in the Slovenian clothing industry which mostly no longer exist, but according to the data obtained, they included various sustainable practices in the past.

The next step within the research included the mapping of the contemporary Slovene fashion brands which includes the definition of fashion practices (scale and specialization) and the legal forms of businesses e.g. independent designers, private sector, NGO's, cooperatives and initiatives. The criteria according to which they were selected were that they have been operating for several years in a row, over years successively design regular collections and they are present online (websites, Instagram or Facebook). The activities we considered in the research analysis included zero-waste or less-waste design, recycling and up-cycling, the focus on the design and production of products that adapt and improve over the years, consumer participation in the design process, use of social media (as a tool to educate about sustainable fashion as well to share brand stories) and the develop-

ment of fashion communities by fashion brands themselves. The review also includes services with product life-long repairs as one of the options to slow the fashion consumption. In reducing the impact of the fashion industry on the environment, it is important to reduce energy and water consumption. Thus, in the further analysis of the selected mapped contemporary fashion brands, the data on technological or production innovations that require minimal energy and water consumption (e.g. clothes that require minimal cleaning, technical coatings to reduce washing, innovative and informative clothing labelling) were collected, where there were accessible. In addition, data on the local and/or regional supply and production chain were reviewed as well as technological or production innovations implemented. In the need to reduce the fashion loop size, we reviewed the situation regarding the existence of ideas that contribute to less production and dematerialization. This strategy introduces service concepts such as leasing, sharing and repair services that support the existing products. It is necessary to emphasize the importance of the use of digital media tools of communication, which enable all the interested users' traceability and transparency of the entire design and production process. In the context of sustainable fashion, we consider this as one of the key factors, as it also enables the democratization of information within fashion industry. With these communication channels, fashion can become better connected with its users, while at the same time using them as a tool to spread positive activist messages about the importance of sustainable fashion (Fletcher and Grose, 2011). Sustainable fashion design must also respect the cultural and historical specifics of ceratin geographical areas. Therefore, we include in the analysis the integration of handicraft techniques in fashion design as one of the central activities in the framework of sustainable and durable fashion, taking into account the meaning of preserving cultural heritage, as well as the promotion of do-it-yourself activities.

In the research, the descriptive method was used as well as numerical evaluation, where the data collected allows it.

2. EXPERIMENTAL (MATERIALS AND METHODS)

The research is focused on different sustainable solutions and practices implemented in Slovenian fashion landscape. Methodologies used were based on qualitative and quantitative analysis of the gathered data, collected through reviews of official statistics and data, archives, interviews, and questionnaires. According to the Statista.com survey for 2021 in terms of revenue in the fashion industry Slovenia is ranking 76th globally. In addition, it also does not have a high symbolic value in terms of fashion recognition. Therefore, in the research, we wanted to find out wheter Slovenian fashion has an opportunity to form a sustainable national identity, given the sustainable activities that have been and are still being carried out by Slovenian fashion brands.

In determining the criteria for research, the following fashion segments were included, which will have to be addressed in the future, namely (Fletcher and Grose, 2012):

- Products (materials, processes, distribution, maintenance of the products and their disposal);
- Fashion system (speed, costumer's needs, inclusion of customers, services of sharing/renting, local production and supply chain, life cycle optimization);
- Design practices (communicator/educator, facilitator, activist and entrepreneur).

The first step included the mapping of the fashion practices which includes the definition of fashion practices (scale, infrastructure and specialization e.g. sport wear, men wear, women wear, luxury) and the legal forms of businesses e.g. independent designers, private sector, investors, fashion recycling projects, NGO's, cooperatives and initiatives. In Slovenia, 45 brands were detected, most of them micro-scale businesses (more like one-man-b(r) and units). The criteria according to which they were selected were that they have been operating and designing for several years in a row, that they include fashion design process and successively design regular collections. The legal forms of businesses are very different: self-employed workers in culture, types of corporate structure or sole proprietors. They are geographically dispersed throughout the entire territory of Slovenia. Regarding the area of activity, fashion designers in Slovenia are mostly applying their skills in private sector, contrary to the requirements of sustainable fashion in which designers should be active across economic areas, e.g. public sector, non-profit sector and research (Fletcher and Grose: 156).

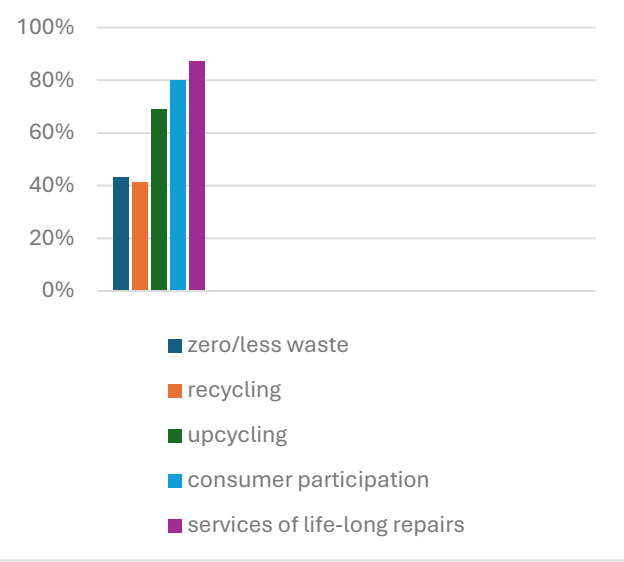
In the past, companies of Slovenian clothing industry were socially responsible, as today we would describe care for employees and the environment in which thay operated. In the period between 1945 and up to political and

social changes, the clothing industry was specific, as the production space also developed into a potential social space (Bole, 2020). Employees in companies were connected to factories where they work, private life and their jobs were intertwined. The Slovenian clothing industry supported sport clubs, managed holiday homes, financed the construction of cultural institutions and the operation of cultural activities, supported firefighting associations etc. Company *Industrija usnja Vrhnika* (Vrhnika leather industry) purchased and systematically collected works of Slovenian art over the years of its existence. They took care of creating an atmosphere of trust and respect for employees and their well-being. The example of the company *Modni salon Velenje* (Fashion salon Velenje) is well known, in which, in order to prevent injuries and disabilities of production employees, they provided a break for recreation during work and for female workers over 40 years of age, the norm was abolished in favor of quality.

3. RESULTS WITH DISCUSSION

The mapped business entities were then analyzed from the point of view of waste reduction, both in the production process and after the users discard it. The activities we considered in the analysis included zero-waste or less-waste tailoring, recycling and upcycling, the focus on the design and production of products that adapt and improve over the years (table 1), consumer participation in the design process, using social media (as a tool to educate about sustainable fashion as well to share brand stories) and the development of fashion communities by fashion brands themselves. The review also includes services with product life-long repairs as one of the options to slow the fashion consumption and overcome the current clothing metabolism (Fletcher and Grose, 2012: 89). Due to the micro scale size of the brands in Slovenia, most of them have a service with product life-long repairs (87%) as well as consumer participation (80%). In this context, Slovenia has an advantage due to the size of the businesses and should promote this as an important activity of sustainable fashion among users and as brand management. Slovenian fashion brands are less successful in including zero waste or less waste design (47%). In the field of recycling, this is mainly present in knitting-based brands (42%) and in some cases in using textiles made out of recycling material.

Table 1: Minimizing waste strategy



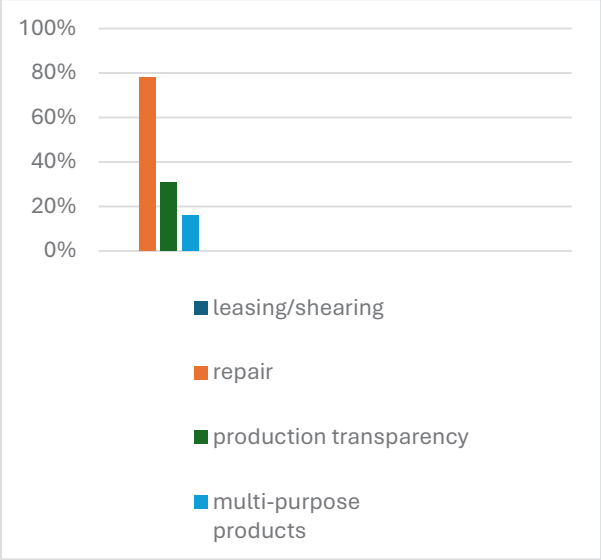
Thus, in the further analysis of the selected mapped fashion brands, the data on technological or production innovations that require minimal energy and water consumption (e.g. clothes that require minimal cleaning, technical coatings to reduce washing, innovative and informative clothing labelling) as well as localization and the use of natural energy systems were collected. In addition, data on the local and/or regional supply and production chain were reviewed. In Slovenia, most brands use textiles that are not locally produced (only 9% of them use locally produced textiles). Unlike clothing production, which is almost entirely local (96%). The need for self-sufficiency in the field of textile production was already discussed in the 1970s. At that time, Slovenia was completely dependent

on the import of textiles from abroad or purchases in other former Yugoslav republics of the common country. They were aware of the strategic importance of self-sufficiency in textiles, so the strategic plans envisaged covering the needs for textiles until 1980 with a 34% share from own production and a 66% share that would still be imported.

Technological or production innovations, which are key in reducing resources, are poorly represented in Slovenian fashion brands (only a third of them use some elements of technological or production innovations within the clothing production and even then, innovations are not tied to reducing the energy consumption due to clothing maintenance).

In the need to reduce the fashion loop size, we reviewed the situation regarding the existence of ideas that contribute to less production and dematerialization (table 2). This strategy introduces service concepts such as leasing, sharing and repair services that support the existing products. It also promotes multi-purpose products (modular clothing). In this context, a transparent supply and production chain is extremely important, as is the formation of local/regional or online communities within these chains. It is necessary to emphasize the importance of the use of digital media tools of communication, which enable all the interested users' traceability and transparency of the entire design and production process. In the context of sustainable fashion, we consider this as one of the key factors, as it also enables the democratization of information within fashion industry. With these communication channels, fashion can become better connected with its users, while at the same time using them as a tool to spread positive activist messages about the importance of sustainable fashion. In Slovenia various services concepts are not evenly developed. Forms of leasing or sharing are not developed enough (the resellers of wedding and formal dresses were not included in the analysis) in comparison to repairs which are implemented as their core activities in almost three quarters of brands in Slovenia. They rarely use publicly verifiable data in their supply and production chain, therefore production transparency is very poor (31%). Digital communication channels are very poorly developed, so the data cannot even be widely available.

Table 2: Design for dematerialization and development of systems and services



Sustainable fashion design must respect the cultural and historical specifics of individual geographical areas. There is the so-called *fashion colonialism*, within which the existence of local fashion specifics is not possible or allowed. Therefore, there is a 'universal' fashion that enforces the voluntary global uniformity of communities and individuals. *Decolonization of fashion* means not only the actual geographical elimination of the dominance of fashion centres and their superiority, but also a change in the acceptance of one's own fashion activity by the community in which fashion originates (Jansen, 2020). We should not associate decolonization of fashion exclusively with the exploitation of the natural environment and labour force, but also with the establishment of a democratic image of confident fashion, which arises from the specifics of a particular geographical space in which fashion originates and not only as copying universal fashion trends set by established fashion centres. In developing a more sustainable fashion industry, the integration of traditional handicraft techniques is crucial. The latter are upgraded

by designers with modern technological innovations. Creation of the products combines design and handicraft processes as a single indivisible whole. The importance of handicrafts is recognized as an important step in preserving the collective and individual cultural identity, while contributing to local production and waste reduction.

The main handicraft techniques used by Slovenian fashion brands are knitting (13%), handmade screen printing (13%) and less embroidery. When reviewing the fashion situation in Slovenia, we also took into account the analysis of the data related to labour rights and working conditions that are fair in case of Slovenian fashion.

A sustainable fashion approach also opens up different business forms and operations. Due to the nature of the evolution of the Slovenian fashion landscape, various approaches are known in modern times, which ensure a sustainable and responsible approach in the long term. The *shirting* platform, developed by Elena Fajt together with Lucija Jankovec in 2014, is a project of a new clothing metabolism of wardrobe sharing. The invited designers each designed one shirt for themselves, which different users could 'own' for a certain period of time. They then passed it on to others for further use. The multifaceted project is an example of conceptual approaches in Slovenian fashion, which raises questions about the relevance of well-known and established business models in fashion, as well as connecting designers and users. With its attitude, the *shirting* platform is a pioneer in the Slovenian space in the context of creating fashion communities. The brand *Things I Miss* by designer Tina Princ connects interdisciplinary sustainable fashion practices with architecture, sound, movement and installations. The designer is actively involved in various global platforms – Fashion Revolution, Fashion Changers, Ethical Fashion Platform and others. Her clothes are also based on a conceptual connection with other creators with the aim of designing on the principle of zero waste. *Vili Van Style* was the pilot project of Julie Kaja Horvat. It was a boutique pop-up mobile store that operated from 2021 to 2023 with minor stops in between. It was intended to create a fashion community, a decentralized sales offer of Slovenian fashion and to connect young creators. *Hishka* is a brand of an interdisciplinary group led by Nataša Peršuh. It is based on three pillars: Re_Made, Re_Touch and Re_Vived. *Sewist's Appetite* is Nastje Sagadin Grmek's brand, which aims to involve users in the making of clothes by sharing the knowledge of complex cuts and finishing touches, encouraging individual creativity in the process of handmade clothes.

4. CONCLUSIONS

The relationship between production and consumption plays a key role in the requirements for establishing elements of a circular or regenerative economy. Technologically innovative production processes, respect for the rights of producers throughout the supply and production chain, thoughtful use of resources, and the inclusion of cultural diversity in individual geographical areas can be key in establishing a successful sustainable fashion context. Slovenian fashion has several examples of good sustainable practices, both in the past and today, and they can be guides for a successful breakthrough of Slovenian fashion on the global decolonized fashion landscape in the future.

We believe that the data have shown that, due to many factors (especially economic and social), Slovenian fashion is able to formulate a sustainable fashion identity based on creativity and sophisticated fashion design, as a necessary foundation for modern long-term design solutions in the fashion landscape. Here, the advantage of Slovenian fashion lies in the fact that the majority of clothes are made with short production chains. Even more, most designers know the garment makers and are closely involved in the manufacturing process. The downside is that most of the manufacturing is outsourced. It is necessary to strengthen the local and regional supply and production chain. Given the micro-smallness of operating fashion brands, it is almost inevitable to connect in this area. Thus, Slovenian brands will have better production conditions, greater opportunities for presentations to other markets and, in general, greater recognition in the social environment in which they operate. Slovenia is very poorly developed in the production of natural fibers and textiles, which should be a priority in research and development. The opportunity lies in the establishment of a boutique made-to-order textile production. Due to their size, Slovenian fashion brands have the opportunity to enrich their communication activities with transparent information about production and supply chains and the introduction of open communication with users, all with the aim of forming fashion communities. Handcrafts are important but not widely implemented. In doing so, we can strengthen activities related to handcrafting, at the same time preserving the intangible cultural heritage with the aim of cultural diversity in the formation of a recognizable national fashion identity in the dominant fashion generic

image. It is necessary to follow and strengthen innovative modern business forms that are adapted to the tradition and level of development of the Slovenian fashion landscape, and as such contribute even more to sustainable business forms of fashion.

Cultural background defines the design of fashion products in order to get more diverse and sustainable fashion. We must proudly build a sustainable fashion future in Slovenian fashion landscape on the foundations that are already implemented, and strengthen the segments in which we are already lagging behind. So that it will not be necessary for some brands to hide their origins in order to succeed abroad, this is the way to jointly create results in the future within the framework of the sustainable fashion made in Slovenia brand.

5. REFERENCES

Bole, P. 2020. “Muzealizacija Almire”. In *Preteklost oblikuje sedanjost: Zbornik ob razstavi Alpska modna industrija Almira-Preteklost oblikuje sedanjost* edited by Tanja Devetak, 21-31. Radovljica: Muzeji radovljiške občine.

Carter, M. 2003. *Fashion Classics: From Carlyle to Barthes*. Oxford, New York: Berg.

Fletcher, K., Grose, L. 2012. *Fashion & Sustainability: design for change*. London: Laurence King Publishing.

Jansen, Angela 2020. Decolonizing Fashion: Defying the ‘White Man’s Gaze‘ http://vestoj.com/decolonialising-fashion/ (last accessed on 12. 11. 2020).

Ladika, N. 1975. “Problematika tekstilne industrije.” *Vezilo* 11(12): 2.

McCracken, G. 1986. “Culture and Consumption: a theoretical account of structure and movement of the cultural meaning of consumer goods.” *Journal of Consumer Research* 13(1):71-84.

https://www.statista.com/outlook/244/141/fashion/italy (last accessed on 28. 2. 2021).

The Fashion Praxis Collective 2014. *The Fashion condition*. New York, Gothenburg: The Fashion Praxis Collective/SelfPassage.

Veblen, T. 2020. *Teorija brezdelnega razreda: ekonomska študija institucij*. Ljubljana: Znanstvena založba Filozofske fakultete.

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ORAL PRESENTATION

FROM URBAN STREETS TO SANDY SHORES: EXPLORING THE "CITY TO BEACH" TREND IN FASHION

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Abstract: *The COVID-19 pandemic has significantly altered consumer behaviour, societal norms, and fashion industry strategies, emphasizing comfort, versatility, and sustainability. One emerging trend, "Bleisure," merges business and leisure, influencing fashion choices that seamlessly transition between professional and casual settings. Post-pandemic work-life changes, including remote work and flexible schedules, have further reinforced the demand for adaptable clothing. This study examines these shifts through Mavi's certain products, themed "City to Beach," which highlight multi-contextual designs. The product group integrates natural fibres like cotton and linen for durability and thermal comfort, while innovative fabric blends enhance flexibility and style. Sustainable materials, minimalist aesthetics, and user-centric designs address evolving consumer expectations shaped by social media and pandemic-related needs. Findings indicate that lifestyle changes continue to reshape fashion preferences, urging brands to innovate sustainably. Mavi's approach serves as a model for integrating style, functionality, and eco-consciousness, reflecting broader industry transformations in response to global challenges.*

Keywords: *Bleisure, sustainable fashion, versatile design, post-pandemic trends, consumer adaptation.*

1. INTRODUCTION

The apparel industry exhibits a marked sensitivity to a confluence of social, economic, political, and psychological factors, alongside the impact of global events such as wars, pandemics, and technological advancements. The COVID-19 pandemic, originating in 2019 and significantly impacting global society, directly influenced individual and collective lifestyles. The post-pandemic period has witnessed substantial lifestyle shifts, notably a heightened interest in sustainable fashion consumption. These evolving patterns are driven by the intricate interplay of consumer resilience mechanisms, life aspirations, and approaches to sustainable consumption (Hwang et al., 2024). Concurrent studies indicate a growing consumer prioritization of comfort over adherence to fleeting trends, coupled with an increasing preference for sustainable fashion choices. Such behavioral changes necessitate adaptable marketing strategies aligned with these dynamic consumer demands (Ilijana & Jossan, 2024). Su and Bae (2022) underscore that these transformations have also intensified the focus on inclusivity and diversity in both consumer preferences and business strategies. Significantly, the transition towards remote work and flexible workspaces has reshaped clothing requirements and expectations, compelling the textile industry to adapt rapidly. These lifestyle adjustments, persisting even in the post-pandemic era, continue to exert influence on consumer demands and industry strategies (Karaca & Kozbekçi Ayranpınar, 2021).w

Castells (2017) argues that spatial and societal transformations are mutually constitutive, emphasizing the reciprocal relationship between fashion design and evolving workplace dynamics. As workspaces become increasingly flexible, their influence on fashion design is inevitable. Social changes reshape physical spaces, and these spaces, in turn, influence the clothing preferences of the individuals inhabiting them.

The pandemic significantly altered perceptions of living and working spaces. During this period, there was a notable shift towards less densely populated, nature-integrated environments, with a corresponding decline in the appeal of traditional urban lifestyles (Tayanç, 2022). This trend coincided with a growing reliance on remote work models, adopted as a viable strategy for mitigating disease transmission risks (Dockery & Bawa, 2020).

Business tourism, historically defined by work-related activities such as meetings, traditionally lacked a leisure, cultural, or recreational component. However, contemporary trends, particularly the increased flexibility offered by employers regarding work hours and locations, have transformed business travel into a hybrid of work and leisure, commonly termed „Bleisure“ (Betül & Ayyıldız, 2020; Çetinsöz & Hazarhun, 2020; Sood & Juneja, 2024). Bleisure travel enables professionals to integrate their work and personal lives, fostering a lifestyle that accommodates both responsibilities and relaxation. While the pandemic significantly disrupted global tourism, leading to a substantial decline in tourism revenues, post-pandemic projections anticipate a recovery (Sood & Juneja, 2024). This evolving travel dynamic underscores the importance of addressing consumer expectations and needs across diverse industries.

As Bleisure travel increasingly becomes a lifestyle facilitated by flexible work arrangements, professionals can extend this blended work-leisure approach into their daily lives. Clothing that offers adaptability across various contexts, ease of styling, and comfort has emerged as a paramount expectation within this lifestyle. The „City to Beach“ theme, for instance, exemplifies this shift by emphasizing versatile, travel-friendly garments suitable for seamless transitions between urban and leisure environments (WGSN, 2024).



Figure 1. City to Beach Theme (WGSN, 2024)

The pandemic also heightened awareness of sustainability, encouraging individuals to re-evaluate their consumption habits and embrace sustainability as a core value. Sustainable consumption, which seeks to minimize negative environmental impacts while generating positive societal effects, aligns closely with this study‘s focus on reducing the need for separate work and vacation wardrobes and emphasizing garments with functional versatility and comfort (Halaçeli Metlioğlu & Yakın, 2021).

This study investigates the characteristics of products designed within the „City to Beach“ theme and the Bleisure concept, addressing user needs and expectations shaped by post-pandemic lifestyle changes. The research examines the fashion industry‘s transformation in response to evolving societal dynamics, specifically focusing on the integration of work and vacation lifestyles into consumer clothing preferences.

2. EXPERIMENTAL

The methodological approach employed is a qualitative case study, designed to provide an in-depth examination of a specific phenomenon within a real-world context. The primary aim of this case study is to offer a comprehensive analysis of the dynamics and interactions surrounding the phenomenon under investigation (Gerring, 2004). In this context, the case study serves not only as a research method but also as a strategic tool within the research process (Punch, 2005).

This study evaluates Mavi, a globally recognized lifestyle fashion brand originating in Turkey, specifically focusing on its 2024 summer women‘s „City to Beach“ woven and knit product lines. The analysis examines how Mavi has achieved competitive advantage in the global market and adapted its design processes through innovative approaches reflective of evolving societal dynamics. Furthermore, the research explores how these product groups have been shaped by global fashion trends and user demands, particularly concerning sustainability, comfort,

aesthetics, and functionality. The corresponding product groups are analysed not only from a design perspective but also to elucidate how the brand‘s consumer-focused strategies are integrated into its overall approach.

3. RESULTS WITH DISCUSSION

The findings of this study demonstrate how consumer expectations and needs within the apparel industry have evolved, particularly in the post-pandemic period. The pandemic profoundly transformed individuals‘ lifestyles, work habits, and social interactions, leading to a significant reshaping of clothing preferences. The concept of Bleisure travel, which merges work and leisure, has played a crucial role in addressing these shifting demands. The necessity for garments that offer flexibility, comfort, and adaptability across diverse settings has been further reinforced by the rise of new work models, increased remote working opportunities, and growing awareness of sustainability. Modern consumers are increasingly gravitating toward multi-functional, versatile clothing that seamlessly transitions between professional and casual environments. Key features such as stretchable fabrics, breathability, and materials that ensure long-lasting comfort have become paramount in meeting these emerging demands.

3.1 Design Features

Designs prioritizing versatile usage across different locations and contexts have gained prominence. These designs, emphasizing ease of styling, empower users to express their preferences across a wide range of applications while maintaining a sophisticated aesthetic without compromising comfort. Design elements inspired by coastal aesthetics introduce a refreshing and dynamic dimension to urban lifestyles, enhancing the overall user experience.

A defining stylistic characteristic across product groups is an emphasis on elegance. In knitwear, adaptations for diverse locations are achieved through innovative pattern interpretations. The underlying concept facilitates seamless transitions between daytime and evening wear and between urban and beach environments. This approach aligns with sustainability considerations in fashion. A notable innovation is the use of knit fabrics with a woven appearance, providing a lightweight yet elegant solution that also prioritizes thermal comfort.

For Mediterranean-themed product groups, the traditional evil eye talisman has been reinterpreted in terms of colour and form (Figure 2). The design process incorporates embroidery, printing, and accessory details to create distinctive products. For the „Warm Mediterranean“ theme, the conventional colour palette has been expanded with mint green for the base and pale yellow tones in patterns, reflecting a forward-looking approach that balances tradition and innovation.

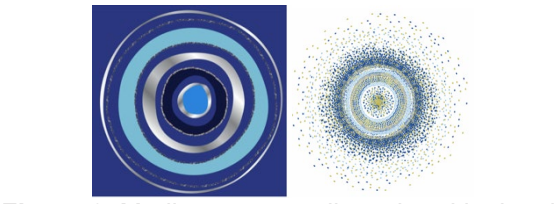


Figure 2. Mediterranean evil eye bead in the city

To reflect the cultural significance of the evil eye talisman, graphic patterns incorporating phrases such as „nazar değmesin“ (may you be protected from the evil eye) and „mavi boncuk“ (blue bead) were featured on select products. These elements serve as cultural references and establish a user-friendly communication style consistent with Mavi‘s brand identity (Figure 3). For the knitwear group, fabric research prioritized linen and linen-blend options. Cotton fabrics with a linen-like appearance were also considered to provide affordable alternatives while maintaining aesthetic appeal.



Figure 3. Evil eye themed slogans

In the woven product group, natural and breathable materials such as linen and cotton were used, emphasizing cool textures suitable for summer. Finishing processes included silicone and fabric softener treatments, combined with steam ironing, to enhance softness and achieve a natural look. The designs focused on unlined, minimalist garments adaptable to various locations and occasions. Key pieces included long, unstructured items designed for versatility and elegance (Figure 4).



Figure 4. Minimal Logo Design Details

3.2 Functional Features

The functional features of garments are defined by specific attributes that enhance user comfort, performance, and utility. These features are developed through advanced materials and processing techniques, enabling garments to meet specialized needs (Sela et al., 2020). Such developments are facilitated by various textile industry techniques and materials, ensuring versatility and suitability for specific applications. In the post-pandemic period, evolving consumer expectations have emphasized the importance of flexibility, sustainability, and functionality in clothing, positioning these attributes as key determinants of the industry‘s future (Zhang et al., 2023).

This study prioritizes ease of use in modern clothing designs, featuring wrinkle-free fabrics and ergonomic cuts. Designs promoting comfort and freedom of movement are further supported by the use of breathable materials. Sustainability goals are emphasized through the selection of durable fabrics that extend garment lifecycles. Stylish yet comfortable knit fabrics are prioritized for the +30 age group, while Mediterranean-inspired woven fabrics and patterns are prominent for the +20 age group.

Brands can effectively address post-pandemic consumer demands by developing designs tailored to age-specific preferences, fabric innovations, and cultural inspirations. Implementing such insight-driven design strategies ensures that garments meet aesthetic and functional requirements while contributing to a more sustainable and versatile wardrobe approach.

4. CONCLUSIONS

This study reveals the profound influence of large-scale events, such as pandemics, on societal lifestyles and their subsequent impact on the fashion and textile industries. Specifically, societal crises like the COVID-19 pandemic have demonstrably altered individual shopping habits, clothing preferences, and overall lifestyles, resulting in substantial transformations within the fashion sector.

These evolving consumer needs and expectations have permeated every facet of product design, from patterns and material composition to functionality and intricate details. During the pandemic, priorities shifted towards

physical health and personal comfort, compelling fashion brands to adapt their product lines accordingly. Factors such as comfort and practicality became paramount, leading to an increased emphasis on functionality and convenience in design.

Consequently, the fashion industry must transcend traditional aesthetic concerns and embrace functional approaches that align with contemporary consumer lifestyles and expectations. The previously distinct boundaries between traditional workwear and casual clothing have blurred, with hybrid, multifunctional textile products gaining prominence. This trend has further diminished the demarcation between sportswear and classic business attire, characterized by the emergence of flexible and comfortable cuts as defining features across both categories.

In conclusion, large-scale crises act as catalysts for industry-wide adaptation in response to evolving consumer expectations. The fashion industry, in particular, has evolved beyond purely aesthetic considerations to encompass broader societal and environmental impacts within its processes. This shift has propelled the adoption of more sustainable and conscious approaches to design and production. To address these changing demands, fashion brands are increasingly integrating environmentally friendly materials and enhancing production efficiency, reflecting a growing commitment to sustainability.

5. REFERENCES

Betül, A. L. P., Ayyıldız, A. Y. (2020) 'Turizm Pazarında Yeni Bir Fırsat: Bleisure (A New Opportunity in Tourism Market: Bleisure)', *Journal of Tourism & Gastronomy Studies*, 8(1), pp. 336-354.

Castells, M. (2017). *Kent Sınıf* İktidar. A. Türkün (Çev.), Ankara: Phoenix Yayınları

City to beach, *WGSN S/S 2024 Trend Report*.

Çetinsöz, B. C., Hazarhun, E. (2020) 'Turizm Endüstrisinde Yeni Bir Trend: Bleisure Seyahatler ve Motivasyon Unsurları ', *Journal of Recreation and Tourism Research*, 7(4), pp. 500–527.

Dockery, M., & Bawa, S. (2020). Working from home in the COVID-19 lockdown. *Bankwest Curtin Economics Centre Research Brief COVID-19*, 1-5.

Gerring, J. (2004) 'What is a case study and what is it good for?', *American Political Science Review*, 98(2), pp. 341–354.

Halaçeli Metlioğlu, H., Yakın, V. (2021) 'Tekstilde Sürdürülebilirlik: Hızlı Moda Markalarının Sürdürülebilirlik Stratejileri', *OPUS International Journal of Society Researches*, 18(Yönetim ve Organizasyon Özel Sayısı), pp.1883-1908.

Hwang, J., Sun, X., Zhao, L., & Youn, S. Y. (2024). Sustainable Fashion in New Era: Exploring Consumer Resilience and Goals in the Post-Pandemic. Sustainability, 16(8), 3140.

Ilijana, P., & Jossan, A. (2024). Sustainable fashion preferences among millennials during pandemic. Business Management and Strategy, 15(1), Article 21618. https://doi.org/10.5296/bms.v15i1.21618

Karaca, H., Kozbekçi Ayranpınar, S. (2021) 'Covid 19 Pandemi Sürecinde Değişen Moda Eğilimleri', *Socrates Journal of Interdisciplinary Social Studies* , 11(7), pp. 78-94.

Punch, K.F. (2005). *Sosyal araştırmalara giriş- Nicel ve nitel yaklaşımlar*. (Çev.: D. Bayrak, H. B. Arslan ve Z. Akyüz). Ankara: Siyasal Kitabevi.

Sela, S., Nayab-Ul-Hossain, A., Rakib, M., & Niloy, M. (2020). Improving the functionality of raw cotton: simultaneous strength increases and additional multi-functional properties. *Heliyon*, 6. https://doi.org/10.1016/j.heliyon.2020.e04607.

Sood, D., Juneja, M. (2004) 'The Rise of Flexible Work and Its Impact on Tourism', in *Amalgamation of Two Worlds: Bleisure Travel - A Contemporary Concept in the Travel and Tourism Industry*, ed. By Shilpi Gupta, Swati Sharma, Prashant K. Gautam, pp. 23-46. 4. IGI Global.

Su, Y., & Bae, B. (2022). Pandemic and post-pandemic fashion consumer and business trends. Visions in Leisure and Business, 24(2), Article 06. https://doi.org/10.25035/visions.24.02.06

Tayanç, M. (2022). 'Mekân ve Pandemi: Değişen Roller ve Dönüşen Evin Halleri', *Habitus Toplumbilim Dergisi*, 3(3), 71-96.

Zhang, Y., Xia, X., K., Xia, G., Wu, M., Cheung, Y., Yu, H., Zou, B., Zhang, X., Farha, O., & Xin, J. (2023). Functional Textiles with Smart Properties: Their Fabrications and Sustainable Applications. *Advanced Functional Materials*, 33. https://doi.org/10.1002/adfm.202301607.

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ORAL PRESENTATION

INNOVATING TOGETHER: DIGITAL FASHION LEARNING THROUGH COLLABORATION

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Abstract: *Digital fashion is reshaping the industry through 3D modeling, virtual prototyping, and extended reality (XR). As digital tools become essential, education must adapt by integrating collaborative and interdisciplinary learning. This study presents the Erasmus+ project ME-YOU-US and its study module "Futuring US through Virtual Touch", which engaged students, educators, and industry experts in digital fashion design. The project combined CLO3D, digital prototyping, and speculative design with hands-on material exploration to develop future fashion scenarios. Collaborative learning across disciplines enhanced technical skills, creativity, and teamwork. The results, including digital garments, virtual environments, and physical scale models, highlight the importance of balancing digital innovation with traditional craftsmanship. This approach prepares students for an evolving fashion industry by fostering both technological proficiency and material awareness, ensuring they contribute to a more sustainable and inclusive future.*

Keywords: *Digital fashion, 3D modeling, virtual prototyping, collaborative learning, extended reality (XR), sustainable design.*

1. INTRODUCTION

Digital fashion is the intersection of fashion design, technology and virtual environments, focusing on clothing and accessories that exist digitally rather than physically. Advances in 3D modelling, augmented reality (AR) and virtual reality (VR) have catapulted digital fashion into the mainstream and transformed the way designers create, present and market their work (Sayem, 2022). As the industry moves towards digitalization, fashion education needs to evolve to equip future designers with the necessary technical and conceptual skills.

Integrating digital tools into fashion education improves design, production and business processes while promoting sustainability. Virtual prototyping, digital materials and immersive technologies allow designers to explore new creative possibilities while reducing waste. However, mastering these tools requires interdisciplinary collaboration between designers, software developers and industry experts (Santos, 2020). Collaborative learning plays a key role in fostering innovation by encouraging students to engage in teamwork, problem solving and critical thinking. Studies have shown that collaboration increases student motivation, persistence and engagement while accelerating deeper understanding through meaningful social interactions (Scager, 2017). In digital fashion education, teamwork between students, faculty and industry professionals bridges the gap between theory and practice. By working together on real projects, students develop important digital skills and learn from different perspectives. Collaborative problem solving has been shown to strengthen critical thinking and adaptability, essential qualities for designers operating in a rapidly evolving industry (Xu, 2023).

This paper explores the importance of collaboration in digital fashion education, drawing on findings from the Erasmus+ project ME-YOU-US. Based on the development of a study module concentrating on future applications of virtual fashion, strategies for effective interdisciplinary learning are identified and the challenges and opportunities of integrating digital tools into fashion education are discussed.

2. EXPERIMENTAL

Since September 2022, the Chair of Textile and Clothing Design at the Faculty of Natural Sciences and Engineering (NTF) at University of Ljubljana has been part of the Erasmus+ project Me-You-Us. This initiative promotes digital 3D skills in textile and apparel design, focusing on diversity, inclusion and sustainability. Over a three-year period, the project brings together three institutions — Designskolen Kolding (Denmark), Willem de Kooning Academy (Netherlands) and the University of Ljubljana (Slovenia) — to develop nine open-access educational modules that use digital tools to promote education in textile and apparel design. The final module, Module 3, focused on the US, while the overarching title of the first module was ME and of the second YOU. Module 3 dealt with developments in virtual fashion and its future applications. The aim was to train educators and students alike in the new technologies and software applications and to create modules that explore future scenarios in fashion and virtual fashion.

2.1 Development of the Study Modul "Futuring US through virtual touch"

Module 3, conducted at NTF, focused on the communities we formed to create a collaborative teaching environment with different co-educators. First with the groups of students, then with the mentors, the teachers of the same department and then more broadly with the teachers and the students of the other department, guest lecturers and industry.

The project carried out in the study module aimed to design speculative concepts that present future scenarios for people's lives and their clothes. The design process included creating physical scale models of environments and textures and the use of CLO3D for the virtual production of clothing prototypes. The students then moved on to other digital tools such as 3D application Blender where they developed speculative virtual spaces with avatars and digital garments. Collaboration with students was a fundamental component of the planning phase for the module. During this phase, students were actively invited to participate in discussions and evaluations of previous modules and collaborative efforts, thereby creating an environment conducive to the generation of new proposals and ideas. The primary objective was to engage students in the planning process, enabling them not only to execute the project but also to contribute to its development. This inclusive approach fostered greater motivation and enthusiasm among students, as they felt empowered to tackle new challenges and influence the direction of the module. By involving students in the shaping of the project, we aimed to enhance their commitment and investment in the learning experience. The integration of five courses: Fashion design, Digital 3D design, Textile design, Art styles and Presentation techniques, required extensive coordination, but the block study format allowed students to focus on one project, which encouraged their engagement. The input of all educators in the form of lectures, tutorials and skills delivery played an important role in the development of the project.

Throughout the module, we organized two "US Days," dedicated to promoting connections between students and mentors, aligned with the overarching theme of the module.

The first "US Day," planned by the mentors, was scheduled at the outset of the module. This initial event provided an opportunity to present the final project plan and allowed students to gradually acclimate to the new challenges ahead. The day was intentionally held outside the traditional educational environment, encouraging participants to engage with one another and with nature.

In contrast, the second "US Day" was designed by the students themselves. They organized a roundtable focused on discussions surrounding digital and virtual fashion. This event featured invited speakers from both the institution and the industry, who addressed pertinent concerns and questions related to the topic. This student-led initiative not only facilitated meaningful dialogue but also empowered students to take an active role in shaping the discourse surrounding their field of study.

Collaboration in digital fashion education goes beyond traditional teamwork; it advances an ecosystem of knowledge sharing in which students and teachers jointly develop learning resources and technical solutions. In this context, students and teachers developed a platform for sharing information about technical challenges and answers related to working in a 3D digital environment. This collaborative approach enabled students to support each other in mastering complex digital tools and reinforced peer learning as a fundamental aspect of skills development. Peer learning, as described by Boud Et al. (Boud, 1999), increases student engagement, deepens understanding, and improves problem-solving skills. In a rapidly evolving field such as digital fashion, where

technological advances are constantly reshaping design processes, peer collaboration allows for the sharing of different perspectives and hands-on problem solving. Through collaboration, students develop adaptability, technical dexterity and the ability to critically evaluate digital design solutions. The integration of student problem solving and professional guidance creates a dynamic learning experience that prepares future designers for the challenges of the industry.

During the module, there was an interdisciplinary collaboration with students and tutors from two courses of the Graphic Arts programme. Students had the task of further developing the projects with the help of multimedia applications and integrating the work of the textile and fashion design students. They actively participated in the interim and final presentations, gaining an insight into the conceptual, creative and technical challenges faced by their fellow students. This engagement allowed them to critically evaluate and refine the integration of avatars and virtual environments created by the design student teams. The collaboration between textile, fashion and graphic arts students created a dynamic, interdisciplinary learning environment that strengthened technical skills, conceptual development and teamwork.

The most important advantages of collaborative work are

- Interdisciplinary exchange: Graphic arts students learned about materials, garment construction and digital fashion, while fashion and textile students explored digital visualisation, multimedia and storytelling.

- Technical progress: Fashion students improved 3D design and digital rendering, while graphics students enhanced their skills in animation, virtual spaces and multimedia presentation.

- Stronger storytelling: Both groups refined their ability to visually convey ideas through avatars, environments and fashion elements.

- Adaptability and problem-solving skills: Students navigated through various creative processes, adapting workflows and developing innovative solutions.

- Improved teamwork and communication: Joint presentations and discussions encouraged the exchange of ideas, feedback and collaboration.

By promoting peer learning, the module prepared students for the evolving digital fashion and multimedia industry.

3. RESULTS WITH DISCUSSION

The results of the project ranged from essays on future scenarios, reflections on guest lectures, digital clothing, handmade textures and scale models of spaces to virtual scenes of digital fashion, also shown with XR. The first part of the module included the creation of the concept, the development of textures, the development of the environment and the virtual prototyping of the garment in CLO3D. Figure 1 shows a dress created in the virtual prototyping software CLO3D and a handmade scale model of the environment. In the second part of the module, the students worked with Blender, where they upgraded the clothing, created the desired avatar and designed the environment. This was based on the concept developed and the results of the first part. Figure 2 shows one of the results, the avatar whose garment was created in CLO3D and then modified and completed in Blender.



Figure 1: Digital garment created in CLO3D (left) and the physical scale model of the environment (right). Authors: Lia Sara Likar and Taja Sejdić



Figure 2: Avatar modified and completed in Blender. Authors: Taša Blatnik and Brina Cotič

The avatars and digitised environments were ultimately the basis for the further work of the graphic arts students, who considered further visualisation of the avatars in virtual environments and other advanced visualisations of the avatars. Figure 3 shows the visualisations and illustrated designs developed by the graphic design students, and Figure 4 shows a virtual atmosphere created in the Unreal Engine from elements of the environment developed by the design students.

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Figure 3: Rendered and sketched ideas for creating a common space for all avatars by graphic design students. Authors: Judita Kociper, Lina Peharc, Rajović Milena

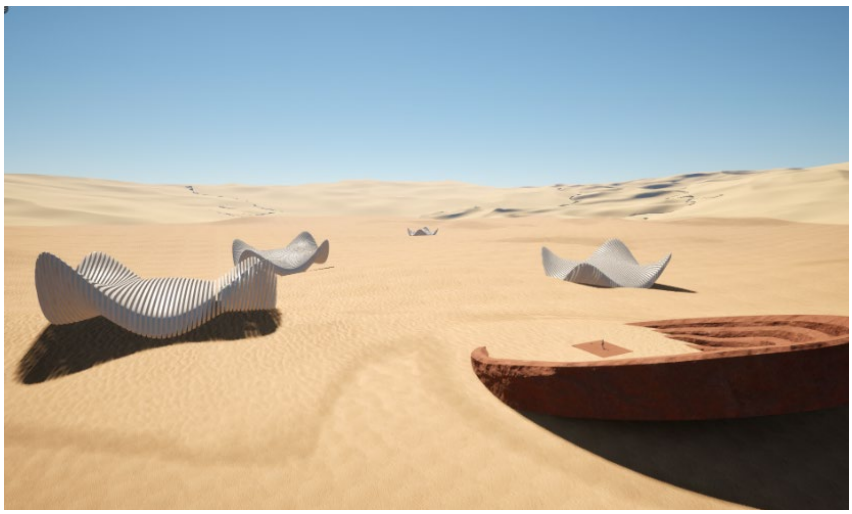


Figure 4: Virtual environment created in the Unreal Engine from elements of an environment developed by design students. Author: Marko Šiškovič

4. CONCLUSIONS

The evolving model of digital fashion education emphasizes the critical role of collaboration between students, educators and industry partners. This synergy fosters innovation, improves learning outcomes and bridges the gap between theory and practice. While digital tools and 3D technologies are transforming design, manual skills and hands-on experimentation remain essential to understanding materiality, craftsmanship and creativity. By combining collaborative learning with a balanced mix of digital and manual methods, education programs can prepare students to meet the diverse demands of the fashion industry. Graduates are not only technologically savvy, but also rooted in traditional design principles, enabling them to make a meaningful contribution to a sustainable and inclusive future for fashion.

The dynamic nature of digital fashion education emphasizes the importance of collaboration between students, faculty and industry partners. This synergy encourages innovation, improves learning outcomes and bridges the gap between theory and practice. Understanding materiality, craftsmanship and originality still requires manual skills and hands-on experimentation, even as digital tools and 3D technologies revolutionize design. Educational programs can equip students for the diverse demands of the fashion industry by integrating collaborative learning with a balanced combination of digital and manual approaches. Graduates can make an important contribution to a sustainable and inclusive fashion industry as they are not only technically adept but also have a sound knowledge of classic design concepts.

5. REFERENCES

Santos, L. R., Montagna, G., & Neto, M. J. P. (2020). The virtualization of the fashion product. V G. Di Bucchianico, C. S. Shin, S. Shim, S. Fukuda, G. Montagna, & C. Carvalho (Ur.), Advances in Industrial Design (Let. 1202, str. 820–830). Springer International Publishing.

Sayem, A. S. M. (2022). Digital fashion innovations for the real world and metaverse. International Journal of Fashion Design, Technology and Education, 15(2), 139–141.

Scager, K., Boonstra, J., Peeters, T., Vulperhorst, J., & Wiegant, F. (2016). Collaborative learning in higher education: Evoking positive interdependence. CBE—Life Sciences Education, 15(4), ar69.

Xu, E., Wang, W., & Wang, Q. (2023). The effectiveness of collaborative problem solving in promoting students' critical thinking: A meta-analysis based on empirical literature. Humanities and Social Sciences Communications, 10(1), 16.

Boud, D., Cohen, R., & Sampson, J. (1999). Peer learning and assessment. Assessment & Evaluation in Higher Education, 24(4), 413–426.

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SUSTAINABILITY AT KOTO

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Abstract: *The fashion industry is undergoing a transformative shift towards sustainability, requiring a comprehensive understanding of sustainable design principles and their importance in educational curricula. This paper explores the multifaceted nature of sustainability, which has evolved from a focus on social change to encompass environmental, social, and economic responsibilities. It emphasizes the importance of education in fostering a culture of sustainability among future designers, highlighting the need for practical applications that align with industry practices. The paper presents various sustainable design projects conducted at the Department of Textile and Clothing Design at the University of Ljubljana, which were jointly presented through multiple activities with the support of the HUD fund (Humanistic, Artistic, and Social Science Research) in a project called „Sustainability at KOTO.“ Ultimately, this paper advocates for a holistic approach to fashion education that empowers designers to navigate the complexities of sustainability and contribute to a more responsible and equitable industry.*

Keywords: *sustainability in fashion, responsible design, public awareness, fashion education*

1. INTRODUCTION

Sustainability in the fashion industry has gained significant attention over recent decades, evolving from a social concern into a mainstream imperative. The term „sustainable“ itself has become multifaceted and often misinterpreted, frequently conflated with concepts like recycling and environmentalism. Originally rooted in social change aimed at alleviating global poverty, the meaning of sustainability has diversified to encompass various dimensions, including environmental, social, and economic responsibilities (Gwilt and Rissanen, 2011). As the industry confronts the pressing challenges of climate change and resource depletion, understanding sustainable design principles and integrating them into educational curricula has become crucial. This paper delves into the sustainable design principles in fashion and textile design and highlights the importance of education in fostering sustainable practices within the industry.

2. SUSTAINABLE DESIGN PRACTICES IN FASHION

The concept of sustainable fashion transcends mere eco-friendly materials or ethical labor practices; it represents a holistic approach to design that considers the life cycle of garments from conception to disposal. The rise of ethical fashion in the late 1990s marked a pivotal shift, with consumers increasingly demanding transparency and accountability from the industry (Henninger et al., 2016). Yet, as the fashion sector grapples with over 70 definitions of sustainability, the ambiguity surrounding what constitutes sustainable fashion poses challenges for practitioners (The True Cost, 2015). The True Cost documentary emphasizes that sustainable fashion must address the social, environmental, and economic impacts of production, urging designers to rethink traditional processes and adopt innovative frameworks.

A growing body of designers recognizes their responsibility to implement sustainable practices, yet many express uncertainty in navigating these frameworks. To effectively integrate sustainable design principles, it is essential to critique conventional design processes and explore alternative methodologies that promote holistic engagement with sustainability (Gwilt and Rissanen, 2011). This shift towards a circular economy, characterized by principles such as traceability, transparency, and circularity, offers a pathway for the industry to mitigate its environmental footprint. The linear „cradle to grave“ model that dominates current production practices must evolve into a „cradle to cradle“ approach, where waste is minimized, and materials are continuously reintegrated into the production cycle (Rinaldi, 2019).

Furthermore, the fashion industry's significant contribution to pollution and resource depletion necessitates a collective response. The UN Sustainable Development Goals (SDGs) emphasize the need for enhanced awareness and education around sustainable practices, recognizing that informed consumers and designers are pivotal to driving change (Rinaldi, 2019). The circular economy paradigm not only promotes responsible consumption but also encourages innovation in materials, design concept, and production techniques, facilitating a transition towards sustainability.

It is important to mention also cultural sustainability, which is a response to society's shifting attitudes towards inclusivity, representation, and respect for others and their cultural heritage, as well as the awareness and preservation of cultural variety.(Loach et al., 2017)

The conservation and development of cultural practices, material culture, and craft to transmit culture entails understanding past biases and attempting to resolve them. Moreover, acknowledging and preserving cultural variety, inclusivity, representation, and respect for people and their cultural history are

responses to cultural sustainability. It encourages preserving cultural practices and material culture to maintain cultural diversity and identity. It also acknowledges the significance of craft as a form of cultural language. (Wang et al., 2025)

3. THE IMPORTANCE OF EDUCATION IN SUSTAINABLE FASHION

Education plays a critical role in implementing sustainable practices within the fashion industry. As fashion evolves, aligning educational curricula with sustainability principles is essential to prepare future designers and fashion professionals for the challenges ahead (Wang et al., 2025). Recent advancements in digital fashion and the adoption of technologies like 3D design tools present unique opportunities for hands-on learning, enabling students to develop essential skills in problem-solving and adaptive thinking (Särmäkari, 2023). However, the current educational frameworks often fall short, focusing predominantly on theoretical instruction rather than practical applications that reflect the realities of the industry.

The European Commission has recognized textiles as a priority category for the circular economy, highlighting the urgent need for educational initiatives that bridge the knowledge gap in sustainable textile design (Wang et al., 2025). Since up to 80% of a product‘s environmental impact is determined during the design phase, equipping aspiring designers with the tools to create durable and recyclable garments is cruucial (Wang et al., 2025). By fostering a culture of sustainability within educational institutions, we can cultivate a new generation of designers who are not only aware of their environmental responsibilities but also equipped to innovate and lead the industry towards a more sustainable future.

3.1 Sustainable practice at Department of Textile and Clothing Design

At the core of the main design courses at the Department of Textile and Clothing Design, we are focused on developing sustainable design projects. These topics are primarily approached in practical terms, with some rare projects being soley conceptual. We guide students to reflect on the issues and potential solutions that are currently applicable and to speculate and inovate new processes. We strive to use environmentally friendly methods and concepts, ecological processes, and reduce environmental impacts: we incorporate principles of recycling and upcycling, working with donated or discarded materials and products, dead stock materials, recycling pre-owned clothing, and using environmentally friendly materials and technologies. We employ digital printing techniques, laser cutting, and engraving, and introduce new digital programs for modeling and visualizations that reduce paper and textile material usage during the design and product development phase. We encourage students to design for long lifespan, including multifunctional garments. We also promote the preservation of local crafts and cultural heritage by teaching handcrafts and developing projects related to preserving Slovenian lace. In these projects, we collaborate with socially engaged non-governmental organizations and individuals. We focus on diverse target groups by promoting intergenerational knowledge transfer between the elderly and younger generations or, for example, cultural exchange between refugees and students. We encourage equality and social justice, emphasizing inclusivity, diversity and gender equality.

As a Higher Educational Institution, we recognize that our responsibilities extend beyond merely educating our students and guiding them toward sustainable outcomes. It is essential to disseminate our projects to a broader audience in order to enhance the visibility of the research and artistic endeavors produced by the Department of Textile and Clothing Design (KOTO). By doing so, we aim to raise awareness and stimulate self-reflection and critical thinking among consumers. This initiative seeks to foster a greater sense of responsibility and encourage a shift in shopping habits within the wider public.

Some of our sustainable projects have been presented to the wider public with the support of the HUD Fund, as we recognize that by raising awareness of problems and showcasing various topics related to sustainable fashion and socially engaged projects through textile media and cultural traditions, we can influence greater understanding of these issues, change attitudes toward them, and ultimately encourage social change.

3.2 »Sustainability at KOTO«

With the project »Sustainability at KOTO« we carried out various activities aimed at engaging and raising awareness among the wider public about the importance of sustainability in fashion and textile creation.
By presenting information on sustainable practices through our projects and highlighting the negative impacts of fast fashion, we raised awareness of environmental and societal effects, encouraged various target groups to reconsider shopping habits, support local cultural heritage, recognize the importance of local economies and brands, and educate on inclusivity in fashion and political and cultural correctness in contemporary design.

As part of the project, we carried out six activities that represented student projects, developed in academic year 2023-2024, and approached sustainability in textiles and fashion in different ways.

- The first activity, »Prinesi & Odnesi“ (eng. Bring&Take) took place in collaboration with the Rog Center and was a clothing exchange event as part of the „Fashion Revolution“ initiative and movement
- The second activity, „NTFsKRIM,“ (eng. NTFwithKRIM) was organized to celebrate the 40th anniversary of the Krim Handball Club. We presented a collection of recycled clothing made from sports jerseys at this event.
- In July, we held an embroidery workshop and presented the „Skupnostna Vezenina“ (eng. Community Embroidery). The workshop was aimed at intercultural collaboration and was carried out in partnership with the Terra Vera association, artist Tjaša Bavcon, refugees from Ukraine, Poland, Turkey, and Kazakhstan, and students.
- As part of the „Svobodni ljudje“ (eng. Free People) exhibition in Idrija, which explored the artistic placement of bobbin lace within the mining cultural heritage (cultural sustainability), we conducted guided tours.
- The exhibition of the „Niti&Kode“ (eng. Threads & Codes) project took place at the „Dobimo se pred Škucem“ event. This project explores the central theme „Human-AI,“ where we carry out projects related to sustainable processes, including digitalization and the use of artificial intelligence.
- The final activity in December was held as part of the „Modnovanje“ event, where we presented jewelry created in collaboration with the Rog Center. It was a combination of hand-crafted and digitally designed fashion accessories.

3.2.1 Activity 1: Clothing exchange „Prinesi & Odnesi“ as part of fashion revolution week. (Activity leader: full prof. Elena Fajt)

Year 2024 marks the 11th anniversary of the tragic event when the eight-story Rana Plaza factory in Bangladesh collapsed, burying more than 1,100 people. Following this tragic incident, the international organization Fashion Revolution was established, which every year organizes Fashion Revolution Week to commemorate and raise awareness of this event, highlighting the urgent need for change in the fashion and textile industrie. For the first time this year, KOTO, UL joined the event at our department, in collaboration with Center Rog, by organizing a clothing swap that also included an awareness campaign. With this event, we aimed to reintegrate clothing into a cycle of reuse. We invited Slovenian fashion designers to participate, as we wanted to highlight domestic brands, their quality, and the importance of ethical and local garment production. 29 Slovenian designers participated at the event.

With the clothing swap, we sought to support more sustainable approaches in fashion and consuming, as well as create space for raising awareness about the consumer culture, environmental impact and social injustice. The event was aimed at both professionals and the wider public.

3.2.2 Activity 2: Presentation of the »NTFsKRIM« project with a fashion show celebrating the 40th anniversary of the krim mercator handball club. (Mentors: full prof. Almira Sadar, full prof. Elena Fajt, prof. Nataša Peršuh, assist. Nataša Hrušič, assist. Sara Valenci, assist Alenka More, Nina Glavič, Mojca Košir)

The »NTFsKRIM« project was created in collaboration with the handball club Krim Mercator Ljubljana. The competition jerseys, which served as both the official wear for the handball players and a means of uniting fans with the club, became an unlimited source of inspiration and a tool for non-verbal communication between the players and students during the workshop. The jerseys were recycled and upcycled using various techniques to create unique garments that represent students‘ exploration. The design process included various solutions such as weaving, crocheting, laser-cutting of jerseys, tracksuits, balls, and nets. The collection featuring soft-separates, was completed with denim bottoms. The contemporary collection of women‘s clothing was presented by the club‘s handball players at a special event, which allowed us to share the project with a wider audience, one that our projects don‘t typically engage with.

3.2.3 Activity 3: Embroidery workshop and presentation of the „Skupnostna Vezenina“ project. (Mentor: associate prof. Katja Burger Kovič)

»Skupnostna Vezenina“ project, an initiative for the social activation of women from different cultural backgrounds, is based on the use of textile handicrafts and the appreciation of textile cultural heritage. Workshop participants from Ukraine, Turkey, Poland, and Kazakhstan presented their modern interpretations of traditional embroidery, created using machine embroidery techniques. Workshop aimed at the exchange and transfer of knowledge, as well as the establishment of connections between Slovenia’s embroidery cultural heritage and the aforementioned countries. The presentation was conveyed through the visual language of prototype-designed modern community embroidery. As part of this activity, art and textile creation were used as tools for the empowerment of women from vulnerable groups, going beyond the role of expressive means to serve as a foundation for establishing dialogue and mutual understanding between different cultures, thereby strengthening intercultural solidarity and promoting cultural diversity. The participants, which included women from vulnerable groups and a group of design students, were encouraged to develop their own and possibly joint projects, which allowed for the enrichment of their personal development and the enhancement of their professional potential. An important aspect of this activity was the final evaluation, conducted in the form of a guided dialogue. This phase allowed participants to delve into a reflection on their artistic works and analyze their inner creative processes.

3.2.4 Activity 4: Four guided tours of the „Svobodni ljudje“ exhibition. (Menthors: full prof. Marija Jenko, associate prof. Katja Burger Kovič, assist. Jana Mršnik, Nina Glavič, Marjeta Čuk, Mojca Košir, Maja Svetlik (ČŠI))

The project involved the artistic placement of bobbin lace within the mining cultural heritage—specifically the Jožef Shaft complex in Idrija. The project, with its approach as a contemporary cultural value, entered the local community, which preserves, develops, and spreads the art of bobbin lace among the youth. We used the bobbin lace in the context of contemporary creative practices and in relation to architectural heritage. This context was transformed into the functionality of the lace, where the craft technique is understood as a design factor in space. The exhibition was intended for a wider audience; the Idrija Lace Festival attracts thousands of visitors, especially young people who are entering various professions, possibly related to cultural heritage, tourism, technical culture, as well as craft and industrial design. Bobbin lace-making is practiced by a wide range of social groups, including both young and older individuals, particularly many women, for whom this activity provides not only additional income but also social empowerment. We organized several expert-led tours of the exhibition, to which we invited representatives from various fields, each emphasizing the meaning of the exhibition and its long-term cultural and economic significance from their own perspective.

3.2.5 Activity 5: Exhibition of the »Niti&Kode«. (Mentors: assist.prof. Arijana Gadžijev, assist. Nastja Sagadin Grmek)

The exhibition took place as part of the event „Dobimo se pred Škucem.“ The presented project explores the overarching theme „Human-AI,“ which inspired our projects related to sustainable processes, including digitalization and the use of artificial intelligence. The student works, including actual use of AI as well as conceptual thinking and reflecting was in both, material execution and virtual presentation. The project focuses on sustainable design of textiles and clothing using digital tools, virtual pattern models, and artificial intelligence applications, which also optimize their environmental impact. The main purpose of the event was to raise awareness about more sustainable design possibilities through the use of new tools. The event attracted various social and intergenerational groups from artistic and design circles, as well as the wider public. We opened the exhibition on one of the most visited days of the „Dobimo se pred Škucem“ event, which received significant media support and further contributed to its success.

3.2.6 Activity 6: Presentation of the handcrafted and digitally made jewelry „Nakit, nosi me“. (Mentors: prof. Nataša peršuh, assist. Nataša Hrupič, expert associate Peter Dragolič)

As part of the „Nakit, nosi me“ project, students explored the possibilities and work environment of the laboratories at the Rog Center. They researched various classical and innovative materials and techniques applicable in the processes of contemporary jewelry design. Innovative sustainable solutions in design, production, and application of body jewelry were realized by the students through various techniques and materials, primarily bronze and brass, which, as a new non-textile medium, represented an inexhaustible source of artistic articulation. The result was a diverse range of jewelry collections, with individual pieces combining traditional handcraft techniques in goldsmithing and textiles, as well as new technologies such as laser cutting and 3D printing. The project was presented as part of the „Modnovanje“ event, which is our largest cultural event in the second half of the calendar year. It has become a traditional presentation of student works in the form of exhibitions that are open to the professional public, wider audiences, students, and potential students over a long period of time.

4. CONCLUSION

In conclusion, integrating sustainable design principles into the fashion industry is essential for tackling the significant social and environmental challenges we face today. Education plays a crucial role as a catalyst for change, equipping future designers with the knowledge and skills needed to navigate the complexities of sustainable fashion. By adopting holistic, circular approaches and prioritizing sustainability in both practice and education, the fashion industry can move towards a more responsible and equitable future.
Through the activities carried out in „Sustainability at KOTO,“ we successfully showcased projects that each address a different yet equally important pillar of sustainability. These initiatives were made visible to a broader audience, an essential step in raising awareness and empowering consumer with the information.

5. REFERENCES:

Gwilt, A., Rissanen, T., 2011. Shaping Sustainable Fashion; changing the way we make and use clothes, First edition. ed. Earthscan, London, UK and Washington, DC.

Henninger, C.E., Alevizou, P.J., Oates, C.J., 2016. What is sustainable fashion? Journal of Fashion Marketing and Management 20, 400–416. https://doi.org/10.1108/JFMM-07-2015-0052

Loach, K., Rowley, J., Griffiths, J., 2017. Cultural sustainability as a strategy for the survival of museums and libraries. International Journal of Cultural Policy 23, 186–198. https://doi.org/10.1080/10286632.2016.1184657

Rinaldi, F.R., 2019. Fashion Industry 2030; Reshaping the Future Through Sustainability and Responsible Innovation, First edition. ed. Boconi University Press EGEA S.p.A., Milano.

Särmäkari, N., 2023. Digital 3D Fashion Designers: Cases of Atacac and The Fabricant. Fashion Theory - Journal of Dress Body and Culture 27, 85–114. https://doi.org/10.1080/1362704X.2021.1981657

Wang, M., Murphy, R., Christie, I., 2025. Bringing Sustainable Practices, Fashion Shows, and Sociological Insights Together to Reinvigorate Sustainable Fashion Education. Sustainability (Switzerland). https://doi.org/10.3390/su17020631

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POSTER PRESENTATION

DESIGN OF A MATERNITY COLLECTION WITH MULTIFUNCTIONAL PROPERTIES

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Abstract: *Maternity clothes are products specially designed for pregnant women. The aim of these products is to create designs that are most suitable for the changes that occur in women's bodies during this period and to provide them with a comfortable use. However, since women experience such as body swelling and skin sensitivity not only during pregnancy but also after birth, they prefer comfortable, flexible and soft-touch products. (Shamsaei, Kazemi, Enteshary-Najafabadi & Borujeni,2022) The aim of this study is to create a collection with clothes that women could use both during pregnancy and postpartum. The main features of the products in the collection are that they are compatible with a protruding belly, light, soft, comfortable and have functional uses added for both pregnancy and breastfeeding*.

Keywords: *sleepwear, loungewear, maternity, comfort, functionality*

1. INTRODUCTION

Comfort and clothing comfort are seen as the most important needs of women when considering both pregnancy and postpartum processes. In order to meet the prominent needs in this collection, designs were made by focusing on fabric and product details. Different quality fabrics were used in the products, and it was aimed to increase comfort and convenience by combining different quality fabrics with various product details. Women may have to spend most of their time at home during pregnancy and postpartum processes. For this reason, our products were planned for sleepwear and casual wear categories suitable for wearing at home. Products were designed for both upper and lower clothing. T-shirts, pants, dresses are the products designed for this collection.

2. EXPERIMENTAL

In this collection, which is specially designed for women's pregnancy and postpartum processes, we divided our products into two categories: sleepwear and lounge wear. Three different quality fabrics are used in products designed for sleepwear. These are siroviskon supreme, viscose camisole and cotton modal jersey. Modal blended jersey fabrics are preferred for lounge wear. The most requested features of products designed for pregnancy and postpartum are that they are soft and feel comfortable all day long. The reason for choosing modal and viscose fabrics in the collection is that they are both made of natural material which is cellulose and have a soft touch. In addition to the advantages of the fabric features of the products, the functionality of the products has been increased by adding different features such as adding snap buttons and using gathering that facilitate breastfeeding and are suitable for the protrusion of the abdomen during the design phase. As it is known, newborn babies need to be breastfed frequently during the day. It can be challenging for mothers to constantly take off their clothes and put them back on during these breastfeeding times. The healing process of surgical wounds and stitches, especially after cesarean delivery, is painful for mothers. At this stage, the sensitivity of surgical wounds and stitches can cause restrictions on mothers' movements. A solution to this problem was provided by adding different functions to the models we designed in the collection that will allow breastfeeding by taking the chest part out. In one product, it was designed by sewing two separate pieces of fabric in layers so that it would open under the chest area. In another t-shirt product, snap buttons were added to the area under both arms so that the breast could be taken out when the snaps were opened. In the tank top models, snap drops were added to the middle of the chest area to facilitate access to the chest area. In order to support the products, care was taken to select the accessories to be used in the product in a way that would contribute the most to the comfort of the product. Preferring snap

buttons instead of classic buttons can be given as an example of accessory choices that increase comfort. Due to the high elastane content in the fabrics, the products are flexible and when the snaps are opened, it is aimed to stretch the t-shirt or tank top and bring the breasts out. Product details such as collar detail and sleeve length selection in the models are preferred in a way that supports comfort in the design. For instance, the reason why a double-breasted collar is preferred in the design of the dress model in sleepwear is to provide the mother with the convenience of exposing her breast during breastfeeding. In addition to the functions added considering the breastfeeding period, technical features have also been added for the growing of the abdomen during pregnancy. In our sleepwear t-shirt product, two separate pieces of fabric are sewn diagonally from the middle of the growing area of the abdomen and folds, providing a wide area for the abdomen. Thus, women who can wear this product in the first months of their pregnancy will be able to continue to wear it in the following months as the abdomen grows, as the folded fabric stretches and opens. Since the products are flexible, they can quickly return to the same form after being stretched. In this way, mothers will be able to continue using the product after the belly has gone down after birth. In this way, both the wear comfort features of the product have been increased and it has contributed to sustainability by adapting to the physical changes of a consumer in different periods. Another feature that can adapt to the expansion in the abdominal area is the adjustable elastic added to the abdominal part of the dress model. This elastic can be stretched and expanded or pulled and narrowed according to the size of the abdomen. At the same time, two layers of fabric were used in the chest area of the dress and snaps were added to the shoulder strap. In this way, the fabric left in the outer area can be opened. The chest parts of the fabric in the lower layer are left empty and breastfeeding can be done without having to take off the dress during breastfeeding moments. The studies on improving comfort and providing technical features in top wear products have been adapted to suit the bottom wear products. In order for the bottoms not to squeeze the abdominal area, gathers have been added to the sides of the products from both sides of the waist, and with this addition, it is aimed to shape according to the size of the abdomen. In this way, it is aimed to be a sustainable product that can be worn by the user in different periods, by adapting to the changing size of the abdomen both during pregnancy and postpartum, and to be a sustainable product that can be used for a long time.



Figure 1: Sleepwear products



Figure 2: Loungewear products

3. RESULT AND DISCUSSION

The collection aims to increase the comfort of mothers during pregnancy and after birth by using different fabric types. In addition to increasing comfort with different fabric types in the products, it is aimed to increase user comfort by improving the functionality of the products with design differences. Clothing comfort is increased with details such as a double-breasted collar detail in the models. Thanks to the double-breasted collar product design, the product provides ease of breastfeeding without taking it off, which saves the mother from the problem of putting it on and taking it off. In addition, the fabrics in the abdominal area offer the possibility of stretching, so the product can also be used after pregnancy. In the bottom clothing products, gathers are used so that it does not squeeze the growing belly, and a functional feature is added to increase the clothing comfort of the product.

Table 1: Products and their composition

Product	Fabric	Composition
T-shirt	Jersey	95% Viscose %5 Elastane
T-shirt	Jersey	80% Modal 20% Polyester
Dress	Pique	80% Modal 20% Polyester
Bottom	Jersey	80% Modal 20% Polyester
Tank top	Jersey	80% Modal 20% Polyester
Nightdress	Jersey	50% Cotton 50% Modal
Nightdress	Camisole	95% Viscose %5 Elastane
Pyjamas set	Jersey	50% Cotton 50% Modal
Pyjamas set	Camisole	95% Viscose %5 Elastane

4. CONCLUSION

The main purpose of preparing this collection was to design products with increased functionality and comfort features by using fabrics and details that women can easily prefer during both pregnancy and postpartum periods and that will increase clothing comfort. Jersey fabric is soft and highly elastic, making it ideal for loungewear. Pique fabric has a denser and slightly textured structure, providing a more structured look. Camisole fabric, on the other hand, is thin and lightweight, commonly used in underwear. In terms of flexibility, viscose and elastane blends offer the highest stretchability. Modal and polyester blends provide both slight elasticity and durability. Cotton and modal blends stand out for their breathability but have more limited elasticity compared to other blends. Thanks to the different features added to the products, the chest area can be easily opened without having to completely remove the clothing during breastfeeding periods, and during pregnancy, the product can be stretched and narrowed according to the protrusion of the abdomen and take shape according to the size of the abdomen. The desired softness and flexibility in the product structure is due to the natural fiber materials of the different fabrics used in the products. These technical functions added to the products are provided with both fabric selections, product design and auxiliary accessories.



Figure 3: Final products

5. REFERENCES

Visconti, F., Quaresima, P., Rania, E., Palumbo, A. R., Micieli, M., Zullo, F., ... & Di Carlo, C. (2020). Difficult caesarean section: A literature review. European Journal of Obstetrics & Gynecology and Reproductive Biology, 246, 72-78.

Shamsaei, A., Kazemi, A., Enteshary-Najafabadi, H., & Borujeni, N. K. (2022). Essential criteria for designing healthy maternity wear: A narrative review. Iranian Journal of Nursing and Midwifery Research, 27(6), 492-495.

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POSTER PRESENTATION

DESIGN OF A SLEEPWEAR COLLECTION WITH COOLING EFFECT

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Abstract: *With increasing global temperatures and evolving consumer expectations, cooling textiles have gained significance, especially in sleepwear where thermal comfort is essential. This study aims to evaluate the performance of four knitted fabrics incorporating various fiber compositions and cooling finishes. The fabrics—based on modal and lyocell blends—underwent different finishing treatments, including collagen-based, silicone-based, and hydrocool technologies. Standardized testing (ISO 11092, ISO 9237, Alambeta, and ISO 13938-1) assessed thermal conductivity, thermal resistance, air permeability, moisture permeability, and bursting strength. Results showed that the silicone-treated fabric offered superior cooling but had low durability, while the hydrocool-treated fabric achieved a balanced performance, making it suitable for functional sleepwear applications.*

Keywords: *cooling effect, thermal resistance, moisture management, breathable textiles, functional finishing, eco-friendly fibers*

1. INTRODUCTION

With technological developments and evolving consumer expectations, textiles are no longer limited to providing basic protection but have evolved into smart and multifunctional materials. A major area of innovation in textile technology is thermal regulation, particularly for personal cooling applications because the increasing global temperatures and the discomfort caused by excessive heat have led to a rising demand for textiles that can efficiently dissipate heat, wick moisture, and provide a cooling effect (Jing, 2024).

There are different methods to obtain cooling-effect fabrics which are:

- Moisture-wicking technology: Fibers designed to absorb and quickly evaporate sweat.
- Phase Change Materials (PCMs): Microencapsulated compounds that absorb and release heat as they transition between solid and liquid states.
- Cooling finishes and additives: Specialized treatments, including hydrophilic coatings, collagen-based technology, and silicone-based „ice-feeling“ finishes, which create a cooling sensation upon skin contact (Tarai, 2024; Gulrajani, 2011).

In addition to these methods, cooling can be obtained with the fabric structure. Open-knit structures or specialized weaves that enhance airflow and heat dissipation.

Modal and lyocell fibers are widely used in cooling textiles due to their high moisture absorption, soft texture, and breathability. Modal has excellent moisture management and softness. However, lyocell is considered a more sustainable alternative with enhanced moisture-wicking and air permeability properties (Özdemir, 2017). This study investigates different finishing technologies applied to modal and lyocell-based fabrics to enhance cooling properties.

To evaluate the cooling performance, the selected fabrics were tested using standardized methods, including Permatest ISO 11092 (thermal resistance and moisture permeability), Alambeta (thermal conductivity and heat retention), ISO 9237 (air permeability) and bursting strength. According to the test results, the best fabric composition and finishing technique for cooling sleepwear applications are determined.

2. EXPERIMENTAL

In this study we have selected 4 different types of fabric. Each fabric that is used in this study has different composition and finishing techniques. The fabrics are tested to see which properties show better cooling properties. The fabric properties and compositions are listed below:

Table 1: Code, composition, knit structure and cooling technology of the fabrics.

Fabric Code	**Fabric Composition**	**Knit structure**	**Cooling Technology**
Fabric 1	50% Cotton - 50% Modal	Single Jersey	No cooling effect (control fabric)
Fabric 2	74% Modal - 26% Polyamide	Single Jersey	Collagen-based cooling technology
Fabric 3	94% Modal - 6% Elastane	Single Jersey	“Ice-feeling” silicone additive
Fabric 4	95% Lyocell - 5% Elastane	Single Jersey	Hydrocool finishing technology

Finishing Techniques:

1. **Collagen-Based Cooling Technology** (Fabric 2): Collagen-infused treatments enhance moisture retention and provide a cooling sensation by increasing surface hydration (Huang, 2018).
2. **Ice-Feeling Silicone Additive** (Fabric 3): A thermoregulating finish containing eco-friendly silicone oil, creating a long-lasting cooling effect upon skin contact (Silibase Silicone, 2025).
3. **Hydrocool Finishing Technology** (Fabric 4): A moisture-management treatment that enhances the capillary action of lyocell, ensuring rapid sweat evaporation and increased breathability (Rudolf, 2025).

Testing Methods and Standards:

- **Permatest (ISO 11092):** Measures water vapor resistance and moisture permeability.
- **Alambeta Test:** Evaluates fabric thermal conductivity and heat retention properties.
- **Air Permeability (ISO 9237):** Assesses the breathability of fabrics by measuring air passage through the material.
- **Bursting Strength (ISO 13938-1):** Measures the capacity of the fabric to pressure.

3. RESULTS

Table 2: Test results of the fabrics.

Fabric Code	**La(mW/m.K)**	**r(mK/W.m^2)**
Fabric 1	30.4	9.4
Fabric 2	33.9	19.8
Fabric 3	18.2	15.4
Fabric 4	38.1	10.2

Table 3: Air water vapor permeability test results of the fabrics.

Fabric Code	**Permeability(Pa.m^2.W^{-1})**
Fabric 1	2.5
Fabric 2	3
Fabric 3	3.5
Fabric 4	3.8

Table 4: Air permeability test results of the fabrics.

Fabric Code	**P(mm/s)**
Fabric 1	1065.9
Fabric 2	1653.4
Fabric 3	1818.5
Fabric 4	1504.5

Table 5: Bursting strength test results of the fabrics.

Fabric Code	**Bursting Strength(N)**
Fabric 1	127.89
Fabric 2	148.47
Fabric 3	93.59
Fabric 4	131.81

4. DISCUSSION

The cooling and durability properties of the four fabrics were analyzed using standardized test methods.

Fabric 1, the control sample without a cooling finish, showed baseline thermal resistance (9.4 mK/W·m²) and moderate conductivity (30.4 mW/m·K), along with the lowest moisture and air permeability. These values reflect its limited effectiveness in promoting thermal comfort.

Fabric 2, treated with a collagen-based finish, offered improved resistance (19.8 mK/W·m²) and the highest bursting strength (148.47 N), indicating excellent durability. However, its moderate air and moisture permeability slightly limited its cooling potential.

Fabric 3, incorporating an “ice-feeling” silicone additive, demonstrated the highest air permeability (1818.5 mm/s) and lowest conductivity (18.2 mW/m·K), indicating excellent cooling ability. However, its bursting strength (93.59 N) was the lowest, highlighting a trade-off between breathability and structural integrity.

Fabric 4, finished with Hydrocool technology, balanced strong performance across all parameters. With the highest water vapor permeability (3.8 Pa·m²/W), good air permeability (1504.5 mm/s), and moderate mechanical strength (131.81 N), it stands out as the most practical option for long-term, wearable applications.

5. CONCLUSIONS

The results underscore the importance of thermal resistance over conductivity when assessing fabric insulation. The study also emphasizes that fabric finishes significantly influence both comfort and durability—two often competing priorities in textile design.

6. REFERENCES

Gulrajani, M. L., Gupta, D. 2011. "*Emerging techniques for functional finishing of textiles."* Indian Journal of Fibre & Textile Research, 36(4), 388–397.
Huang, C.-L., Fu, J.-Y. and Cheng, K.-Y. 2018. "Development of Woven Fabrics with High-Count and Cooling Collagen." Trends in Textile & Fashion Design 3(2): 299–301.
Jing, Y., Du, M., Zhang, P., Liang, Z., Du, Y., Yao, L., Chen, H., Zhang, T. and Zhang, K. 2024. "Advanced Cooling Textile Technologies for Personal Thermoregulation." Materials Today Physics 41: 101334.
Özdemir, H. 2017. "Permeability and Wicking Properties of Modal and Lyocell Woven Fabrics Used for Clothing." Journal of Engineered Fibers and Fabrics 12(1): 12–21.
Rudolf. 2025. Sustainable Solutions for Moisture Management. URL: https://www.textiletechnology.net/news/news/rudolf-sustainable-solutions-for-moisture-management-35271 (last accessed on 30. 01. 2025).
Silibase Silicone. n.d. Universal Ice Feeling Silicone Oil: Textile Softener Auxiliaries for Textiles. URL: https://www.silibasesilicone.com/silicone-softener-auxiliaries-for-textiles/ice-feeling-silicone-oil/universal-ice-feeling-silicone-oil.html (last accessed on 23. 04. 2025).
Tarai, M., Yadav, S. 2024. "Advances in textile finishing." International Journal for Research Trends and Innovation 9(4): 26–32.
Vivcharyuk, O. 2023. "Cooling Garment Design for Women: From Fibre to Fit." PhD diss., Toronto Metropolitan University.

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POSTER PRESENTATION

USE OF JAPANESE KNOTWEED IN WOVEN TEXTILES

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Abstract: *The project titled Use of Japanese knotweed in woven textiles explores the utilization of an invasive plant in textile applications in connection with the idea of regenerative design. The issue of invasive plant proliferation and the lack of constructive approaches to limit their excessive growth are highlighted. Solutions are sought in regenerative design, which goes beyond sustainable approaches by repairing negative consequences and taking a holistic view of the problem. The experimental part begins with the presentation of making paper yarn from locally sourced Japanese knotweed paper. It then discusses the use of dye and explores textile weaving techniques and post-processing of the resulting fabrics. The result is the presentation of a collection of fabrics that not only includes paper made from Japanese knotweed, but also dye derived from its roots and wood obtained from its stems.*

Keywords: *weaving, paper yarn, Japanese knotweed, regenerative design*

1. INTRODUCTION

Non-native plant species, unlike native ones, have been intentionally or unintentionally introduced into the environment by humans (GOV.SI, 2009). They typically establish themselves in degraded areas such as lands depleted by intensive agriculture, abandoned construction sites, and waste disposal areas (Paradiž, 2012). Through rapid spreading and consequent occupation of space, they can negatively affect the growth of native plants and disrupt the ecosystem in which they are found (Vrabič-Brodnjak & Možina, 2022). One of the most prevalent invasive non-native plants in our region is Japanese knotweed. Its rapid growth and spread are most often controlled through removal, which generates large quantities of biodegradable waste that must be handled carefully to prevent further spread (Frajman, 2008).

At the same time, we live in an era where the search for new, environmentally friendly material sources is increasingly important, enabling sustainable and circular economies. The waste from removed invasive plants could provide a solution, as it represents an abundant natural resource that can be repurposed for various uses.

The textile industry is one of the largest global polluters and resource consumers. Sustainable design practices are one approach to reducing the negative impact of the textile industry on the natural and social environment. However, this approach does not address the damage already done. Regenerative design takes this concept further, offering a promising method to introduce new materials, such as invasive plants, into existing design processes. The regenerative approach takes a step further than sustainability; whereas sustainability focuses on preserving a certain state with minimal or no impact, the regenerative approach strives to enhance and improve the current condition (Tate + Co, 2023).

One way to use invasive plants in textiles is through paper, which has a long history as a textile material, particularly in Eastern civilizations (Leitner, 2005). This study presents the use of paper to create yarn, which is then woven into a collection of handwoven pieces.

2. EXPERIMENTAL

Material Research

I began the project by researching Japanese knotweed and exploring which parts of the plant could be utilized, from paper made from its cellulose to its wood and rhizomes. My aim was to incorporate as much of the plant as possible into my textiles.

I harvested the plant parts in close proximity to my home, on the edge of the forest beneath Rožnik hill in Ljubljana. As with the collection of any invasive plant, I had to be careful to avoid unintentionally spreading the plant to new locations through careless harvesting or handling of its rhizomes.

Preparation of Paper Yarn

To make the paper yarn, I used Notweed paper made from Japanese knotweed, created by the Trajna collective. I worked with paper from two different series. The first, from 2021, was darker in colour and consisted of 50% knotweed cellulose and 50% wood cellulose. The second series, from 2023, was lighter in colour and made of 50% knotweed cellulose, 45% wood cellulose, and 5% waste paper.

I began making the yarn by cutting the paper into strips of different widths. I ultimately chose a strip width of 5 millimeters, as it provided the best results; the yarn wound smoothly and did not tear excessively. I cut the paper using a laser cutter, ensuring not to cut it all the way to the edge, leaving a 1-centimeter margin. Then, using scissors, I cut through to the edge on every other strip, creating a continuous strip. The paper was moistened with water using a spray bottle, as the spinning process is much easier when the strips are damp. I then twisted the strips into yarn using a hand spindle (Figure 1). The yarn was left to dry and then I wound it into a skein using a yarn winder.



Figure 1: Paper yarn spinning (foto: Tjaša Bavcon).

Dye

Dye can be extracted from various parts of the Japanese knotweed plant. Since I started the project during the colder part of the year, I only had access to its rhizomes. I experimented with how the dye changes when the pH level is altered. The dye extract, obtained by boiling dried knotweed rhizomes in distilled water, was divided into two containers. To one, I added white vinegar, and to the other, washing soda.

Paper absorbs dye without requiring special pre-treatments or post-treatments necessary for dyeing textile fibers. This allowed me to experiment with different methods of applying dye to the paper yarn. During testing, I applied the dye to both the warp and the weft, evaluating which method was more suitable. Ultimately, I decided on a dyeing process that involved directly applying the dye to the wound yarn spool, resulting in a gradient-colored

fabric (Figure 2). Along with dyeing the weft yarns, I also experimented with dyeing the warp yarns. This created vertical color stripes to complement the horizontal ones produced by the dyed weft yarns.



Figure 2: Dyeing a skein of paper yarn (photo: Tjaša Bavcon).

Wood

While exploring all the possibilities for using Japanese knotweed in textiles, I also experimented with the use of its woody parts. The woody stems were first soaked in water, then split lengthwise and spread apart, resulting in a thin, veneer-like material. During the research, several small woven pieces made from knotweed wood were created, and in the final collection, it was used as an element for hanging the fabrics.

Weaving

Before setting up the loom, I created a plan and prepared a complete pattern (Figure 3):

- Warp: paper yarn – Nm 1.65 / tex 625 (Lankava thin paper yarn)
- Weft: handmade paper yarn – Nm 1.4 / tex 713
- Threading: straight draw in 8 shafts
- Thread density in the reed: 1 thread/cm
- Warp width: 50 cm
- Warp length: 6 threads/cm

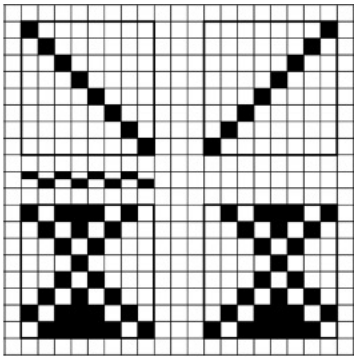


Figure 3: weaving draft for waffle weave.

After completing the process of setting up the loom, I began weaving samples. To make the weaving process easier, I sprayed water onto the yarn, which also increased the thread density and resulted in a denser fabric. The fabric in the left photograph was woven with a dry warp and dry weft, while the fabric in the right photograph was woven with both the warp and weft moistened with water (Figure 4).

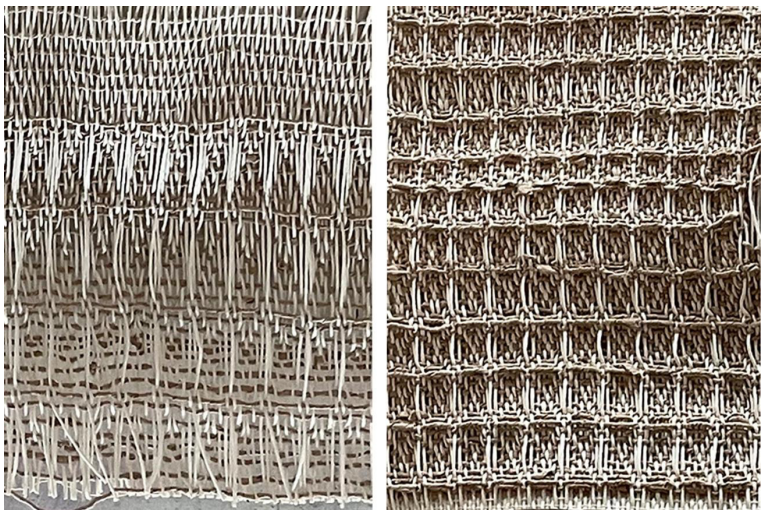


Figure 4: Comparison of fabric in waffle weave; in the left image, the warp and weft threads were not moistened during weaving, unlike the threads in the fabric on the right.

I was able to shape the paper fabric while it was wet, and it retained that shape after drying. In this way, I attempted to model three-dimensional forms from the woven surface. I also worked to create spatial shapes by weaving double fabrics, which were later modeled while wet.

Development of the fabric collection

Inspired by the trials I had previously woven, I created a collection of woven textile pieces. (Figure 5). I tried to incorporate different technicques, use of color and shaping of the fabrics to get a diverse collection.

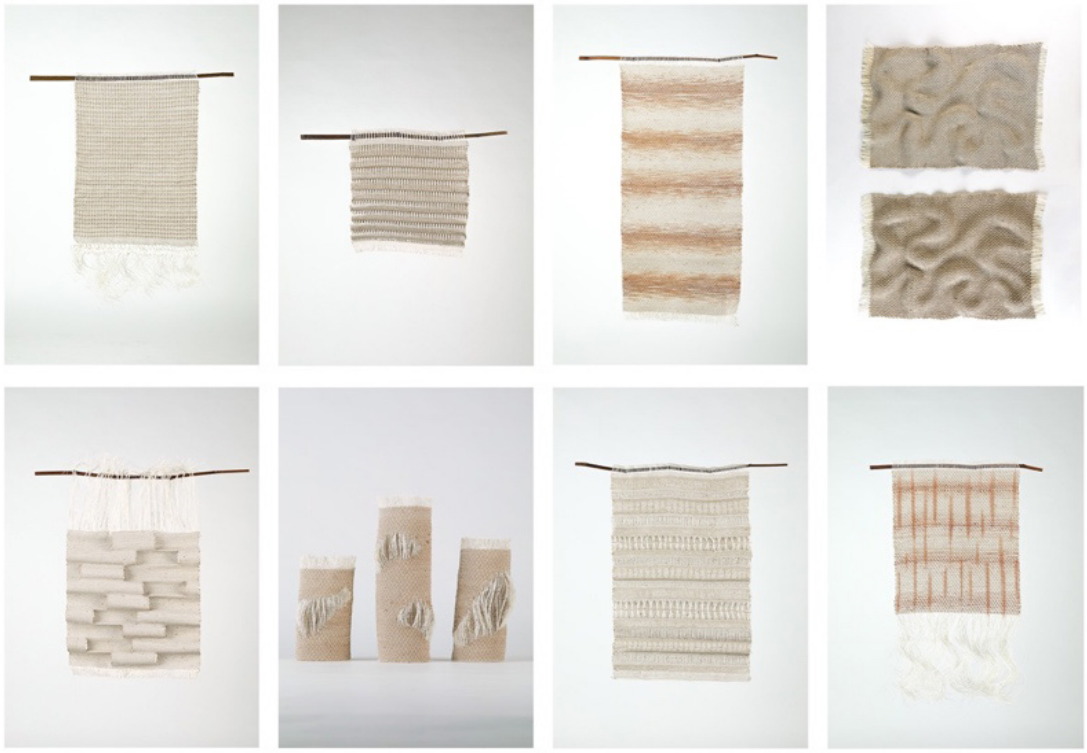


Figure 5: collection of paper yarn weavings (foto: Kristjan Jarni).

3. RESULTS

Inspired by the trials I had previously woven, I created a collection of woven textile pieces. Some pieces are part of diptychs or triptychs. All share the same warp and weft material, with some featuring added colour, while others emphasize the shaping of the woven material into forms. The result is a collection of fabrics made from handmade yarn produced from Japanese knotweed paper. Alongside the cellulose-based paper from this widespread invasive plant, a dye derived from its rhizomes was also used. Some smaller experiments were carried out using wood from the stems, but in the final collection, these were included solely as supports for hanging the textiles. The fabrics showcase various possibilities of weaving with paper yarn and incorporating the dye, each of them capable of serving as a standalone decorative piece or in combination with other textiles from the collection.

4. DISCUSSION

Japanese knotweed is among the most invasive species in the world. With its rapid spread and consequent occupation of space, it can negatively impact the growth of native plants and affect the ecosystem in which it is found. This project demonstrates the use of locally produced paper from Japanese knotweed to create yarn, which is then woven into a collection of textile pieces. The choice of paper as the sole material used in the fabrics follows the principle of monomateriality. My aim was to create an environmentally friendly collection that not only addresses sustainability but tries to actively engage in ecological regeneration. Due to the characteristics of the handmade yarn, which is relatively fragile, the range of applications is somewhat limited, particularly for products exposed to daily contact with other surfaces or the body. On the other hand, the use of paper allows for the creation of fabrics that transcend the two-dimensionality of more conventional textile materials, giving them a stronger spatial presence. For this reason, the fabrics could be integrated into interiors as architectural elements, such as partition walls, directly referencing the historical use of paper in house construction and spatial division. A unique feature of paper fabrics is their ability to be shaped while wet into a chosen form, which they retain once dried. Fabrics arranged in triptychs with cylindrical shapes could, for instance, be transformed into lighting elements by adding light components.

5. CONCLUSION

The project explores various possibilities for utilizing Japanese knotweed for textile purposes. The aim of the project was to address the problem of biodiversity decline and the spread of invasive species while searching for alternative material sources for textile making. By demonstrating how invasive species can be repurposed into sustainable textiles, this project highlights the potential for design to contribute to ecological regeneration and inspire new approaches to sustainable material sourcing.

6. REFERENCES

Frajman, B. Japonski dresnik Fallopia japonica, Informativni list 1. (2008). In: Tujerodne vrste. Available from: https://www.tujerodne-vrste.info/wp-content/uploads/2018/05/INF1-japonski-dresnik.pdf [6. February 2024].

GOV.SI. Invazivne tujerodne vrste rastlin in živali. Available from: https://www.gov.si/teme/invazivne-tujerodne-vrste-rastlin-in-zivali/ [17. January 2024].

Leitner, C. (2005). Papier Textilien : Geschichte, Materialien, Experimente. 1. edition. Bern: Haupt Verlag, pp. 35.

Paradiž, J. (2012) Tujerodne rastlinske vrste in ugotavljanje območja njihove razširjenosti v krajinskem parku ljubljansko barje : Končno poročilo o rezultatih preiskovanja invazivne kanadske zlate rozge, japonskega dresnika in žlezave nedotike v vzhodnem delu Krajinskega parka Ljubljansko barje. Available from: https://www.ljubljanskobarje.si/wp-content/uploads/2021/06/koncno-porocilo_Paradiz_KP-2012.pdf [4. February 2024].

Tate + Co. (2023) What is regenerative design? Available from: https://tateandco.com/answers/what-is-regenerative-design/ [29. February 2024].

Vrabič-Brodnjak, U. & Možina, K. (2022) Invasive alien plant species for use in paper and packaging materials. Fibers, vol. 10, no. 11, str. 2.

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POSTER PRESENTATION

BAUHUS INSPIRED HOME TEXTILES AND CARDBOARD MODULAR FURNITURE FOR CHILDREN

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Abstract: *The paper explores the development of surface patterns and modular cardboard furniture for children, encouraging free and creative play. The theoretical part presents key principles of children's design, the importance of modularity, and the role of colours, shapes, and patterns in children's perception and development. It also examines the influence of Bauhaus, particularly its learning-through-play approach and the "Vorkurs" foundation course. The experimental part introduces the development of illustrated characters inspired by Oskar Schlemmer's costumes, transformed into graphic patterns and textile or cardboard objects for children's interiors. Additionally, it presents the development of modular cardboard furniture, exploring various assembly methods and the integration of textile elements to create contrasting surfaces with added tactile and aesthetic value.*

Keywords: *surface pattern design, home textiles, modular design, cardboard furniture, children's interior.*

1. INTRODUCTION

Toys and objects surrounding a child play a crucial role in their development, particularly through play, which encourages their cognitive, emotional, social, and motor growth. In contemporary design for children's products the emphasis is on innovation, sustainable materials, and aesthetic appeal. Parents are increasingly interested in thoughtfully designed products that encourage child's creativity and provide long-term usability (Appleton 2018; Birks 2018).

Designing for children has evolved alongside changes in society, technology, and pedagogy. At the end of the 19th and the beginning of the 20th century, educational theories highlighted the importance of open-ended play and child-friendly learning environments, influencing the development of products tailored to children's needs. Modernism introduced lightweight and practical materials into design, simplifying use, cleaning, and maintenance of the products. Between the 1950s and 1970s, plastic became the dominant material due to its durability and low production costs. Today, designers prioritize sustainable materials such as cardboard, wood, and EPP foam. These materials enable the creation of functional, safe, and modular products that grow with the child while encouraging free play and exploration. Throughout history, cardboard has proven to be an exceptionally popular material because it is lightweight, recyclable, easy to shape, and sustainable. These qualities make it ideal for creating furniture and toys that stimulate children's creativity (Appleton 2018; Birks 2018).

Modularity is one of the key concepts in children's design, providing flexibility, sustainability, and multifunctionality. Construction toys based on modularity allow children to engage in unlimited creation while developing spatial understanding, motor skills, and imagination. Additionally, the visual appeal of a product – its shape, colours, textures, and patterns – plays a pivotal role in establishing interaction between the child and the object (Bilham 2022; Reynolds 2023).

The Bauhaus artistic movement (1919–1933) had a significant influence on design for children, blending art, technology, and craftsmanship. The movement championed simplicity, functionality, the use of authentic materials, and encouraged experimentation through play. A leading designer in children's products during this period

was Alma Siedhoff-Buscher, who created iconic Bauhaus toys and modular furniture that encouraged children's creativity and exploration (Droste 2023; Kinchin and O'Connor, 2012).

The research focuses on the field of design for children and its principles, the importance of modularity in children's products and the role of colours, shapes and patterns in children's perception of the world and their holistic development. The aim of the research was the development of surface pattern designs and modular cardboard furniture for children that invite them to explore their environment and encourage free and creative play.

2. EXPERIMENTAL

The focus of the experimental part of the research was on the Bauhaus theories of learning and creating through play, following the exercises of the so-called "Vorkurs", or preliminary course that was taught at the school. This section presents the development of playful, illustrated characters inspired by Oskar Schlemmer's costumes for the "Triadic Ballet", embodying the Bauhaus preference for primary colours and geometric shapes. By assembling forms from basic shapes such as circles, squares, triangles, squiggles, zigzags, spirals, a chequerboard pattern, etc., a group of playful graphic figures was created. The colour palette consists of a minimal number of contrasting colours, which was maintained throughout the collection.

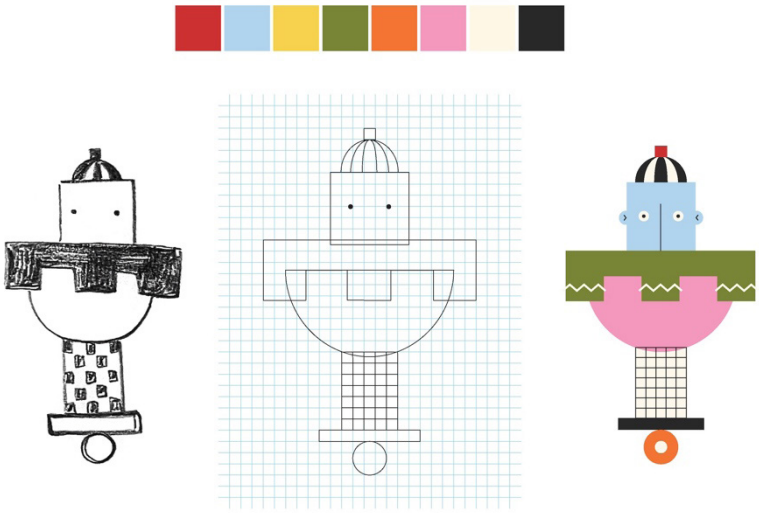


Figure 1: Colour palette and character design (from sketch to final digital illustration) (Source: the author)

The characters were then grouped into all-over patterns. Due to their simplicity, the characters were also easily transformed from flat digital illustration into new spatial forms. Digital printing was used to transfer the patterns onto different types of textiles. Certain products were also embellished with hand embroidery, while products made of cardboard were produced using laser cutting technology and digital printing on cardboard.

The second part of the experimental research presents the development of modular cardboard furniture. It shows methods of assembling modules into abstract and functional forms and integrating other materials into spatial constructions in the form of improvised or textile modules. Cardboard was chosen as the main material, as its properties make it a very suitable material for making products for children. It is light, strong and 100% recyclable and, above all, safe for children to use. The plain cardboard also attracts and allows children to freely explore and personalise their creations.

Through spontaneous experimentation of assembling different forms of modular constructions, flat modules that can be joined together with notches proved to have the greatest potential. This type of module production is much simpler and faster, and the material consumption is also much lower. It was also studied where the notches should best be placed to have as many possibilities as possible to create different forms, both functional and completely abstract.

The basic structure that led to the design of the remaining modules was a child's chair that can be connected to other structures or transformed into other forms of shelters, toys and furniture. Based on the grid, the final shapes of the geometrically simple and refined modules were designed, all with rounded corners for children's safety. The final form of the construction set prototype in a scale of 1:1 was created in collaboration with the Pulp and Paper Institute (ICP) in Ljubljana.

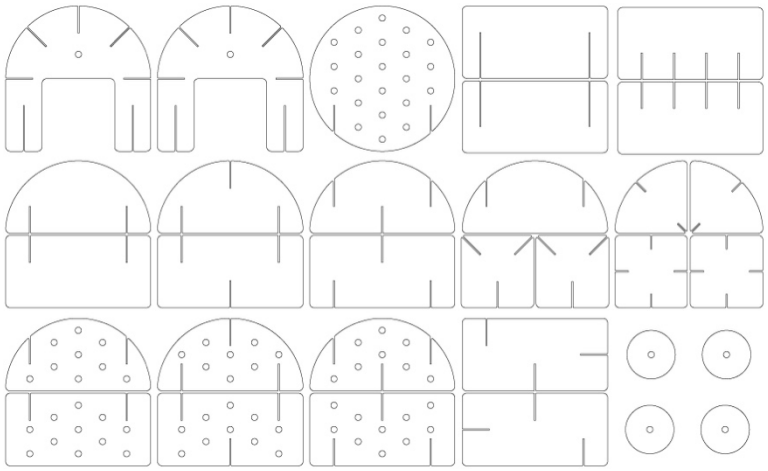


Figure 2: Modular construction set in vector form (Source: the author)

The study of contrasts and materials based on Itten's Vorkurs led to researching the relationship between textiles and cardboard. To this end, some modules were given perforated surfaces to serve as embroidery walls, with the aim of encouraging the development of children's motor and manual skills as well as providing additional uplifting and softening of the hard cardboard.

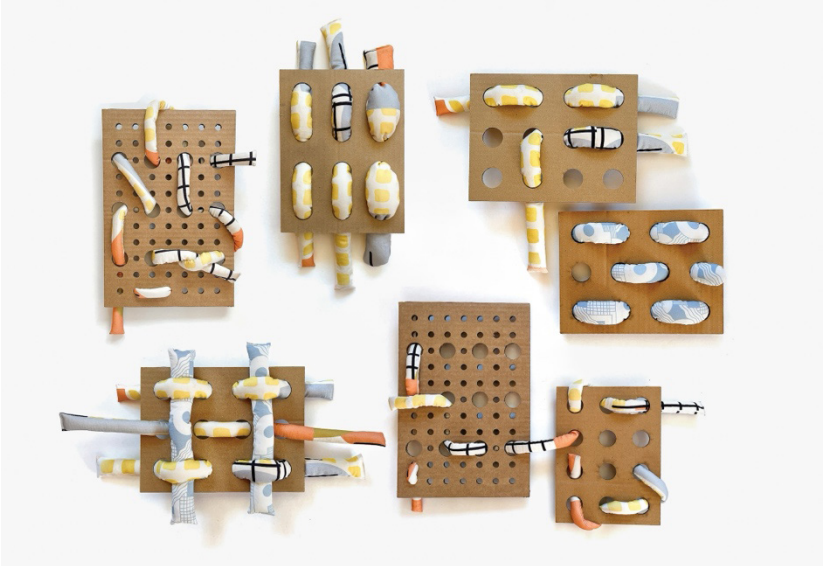


Figure 3: The study of contrasts between soft and hard modules (Source: the author)

3. RESULTS WITH DISCUSSION

The final products include a collection of playful illustrated characters assembled into all-over patterns for print or transformed into other forms of textile and cardboard objects for children's interiors, such as cardboard lamps and toys, patterned pillows and hand embroidered dolls. Moreover, a cardboard modular system was developed. Due to its composability and interactivity, the modules can be easily transformed into various furniture or playing constructions. Textile worms made from scrap fabric can be inserted and woven into the perforated mesh of the cardboard modules, creating new contrasting surfaces with additional tactile and aesthetic values. Cardboard surfaces can also be scribbled on, painted and covered with stickers.

The work focuses on designing simple and accessible products for children that encourage play, creativity, and holistic development. It is important to recognize that designing for children is a complex process, as it requires adhering to numerous principles and quality standards that determine when a product can enter the market. The products presented in this work are prototypes, offering significant potential for further development.

A collection of products was created that can adapt to various children's needs, avoiding focusing on any specific age group. Textile products, due to their softness and sensory qualities, are suitable even for the youngest children. Meanwhile, the construction set is more appropriate for children aged 4 and above, as it aligns with their more advanced motor skills and ability to tackle various challenges. The construction set is also well-suited for groups of children, as it promotes group collaboration and collective problem-solving.





Figure 4: Textile and cardboard products for children's interior (Source: the author)

Figure 5: Cardboard modular construction with textile worms (Source: the author)

4. CONCLUSIONS

In designing for children, it is essential to incorporate not only functional and aesthetic principles but also sustainable and advanced solutions, focusing on integrating concepts of circular design. Emphasizing the principles of modularity and multifunctionality is equally important, as they are key to creating flexible and long-lasting products that can adapt to the diverse needs of children and their environment. Through research and experimentation different products have been created. They are appealing to children and encourage them to play, while also resonate with adults who value colour, playfulness, and joy in their homes. By studying children's culture and developing modular and textile products, I have laid the groundwork for further exploration in the fields of children's design, illustration, and textile creation.

5. REFERENCES

Appleton, L. 2018. "Design for children matters". In Design for children: play, ride, learn, eat, create, sit, sleep, edited by Kimberlie Birks, 4–6. New York: Phaidon Press.

Birks, K. 2018. Design for children: play, ride, learn, eat, create, sit, sleep. New York: Phaidon Press.

Bilham, Jasmine. 8 things to consider when designing for children. URL: https://raw.studio/blog/designing-for-children (last accessed: 30. 1. 2025).

Droste, M. 2023. Bauhaus: 1919–1933. Köln: Taschen.

Kinchin, J., O'Connor, A. 2012. Century of the child: growing by design 1900–2000. New York: Museum of Modern Art.

Reynolds, Oliver. Building Blocks: The Importance of Construction Toys for Child Development. URL: https://reynoldsoliver.medium.com/building-blocks-the-importance-of-construction-toys-for-child-evelopment-38f96eadabfd (last accessed: 30. 1. 2025).

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TEXTILE EDUCATION

ORAL PRESENTATION

SERVICE LEARNING IN TEXTILE, CLOTHING AND FASHION EDUCATION

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Abstract: *Service learning is an educational approach that combines academic learning with community service. It expands students' knowledge by engaging them in real-world projects that address community needs. Unlike volunteering, charity work, community service, internships or field education, service learning integrates structured reflection and coursework so that both sides, students and communities, benefit. It is used in a variety of settings, including education, healthcare and business, and promotes civic engagement, critical thinking and social responsibility. In the textiles and fashion industry, service learning can include sustainable clothing projects, community-based textile recycling or working with marginalised artisans. Students gain hands-on experience while addressing the environmental and ethical challenges of the industry. The paper provides a comprehensive overview of the foundations, the development of the service learning concept and its potential in the fields of textiles, clothing and fashion as well as the associated challenges.*

Keywords: *service learning, community service, textiles, clothing, fashion, sustainability.*

1. INTRODUCTION: SERVICE CONCEPTS

Service learning is an educational concept that is often associated or even (mis)interpreted with terms such as volunteering, charity, community service, internship or field education, as it contains elements of all these activities. **Volunteering** is the engagement of students in activities where the focus is on the service provided and the primary beneficiary is clearly the recipient of the service. Volunteers are people who perform a service or good deed of their own free will and without payment. **Charity** is the voluntary giving of help, typically in the form of money, goods or services, to those in need. It is driven by compassion and aims to improve the well-being of individuals or communities in need. Charitable actions can be carried out by individuals, organisations or institutions and often involve humanitarian aid, social services and philanthropic initiatives. **Community service** is the engagement of students in activities that focus primarily on the service provided and the benefit of the activities to the recipients. Students benefit by learning more about how their service makes a difference in the lives of service recipients. **Internship** programmes engage students in service primarily for the purpose of providing them with practical experience that enhances their learning or understanding of topics relevant to a particular field of study. **Field education** programmes provide students with extracurricular service opportunities that are connected to, but not fully integrated with, their formal academic studies. Students perform service as part of a programme that is primarily designed to enhance students' understanding of a particular field of study, although the service performed also plays an important role (Furco, 1996; Oxford English Dictionary, n.d.).

Service learning is an innovative educational approach that combines academic teaching with social engagement. By emphasising the application of knowledge in the real-world, it enhances both the learning experience and the impact on society. Unlike a field education programme, where service is performed in addition to students' coursework, a service learning programme integrates service into the course(s).

2. THEORETICAL FRAMEWORK

2.1 Experiential learning

Learning methods are evolving alongside the need to improve the quality and effectiveness of the teaching and learning process, with three components interlinked in learning activities: teachers, students and the learning environment (Rahmi, 2024). One approach that is receiving more and more attention is experiential learning (EL). This method was first introduced by David A. Kolb in 1984 and has since become one of the most influential learning models in contemporary education. The theory of experiential learning is based on the idea that knowledge is acquired through experience. Kolb introduces the experiential learning cycle, which consists of four phases (Figure 1):

- concrete experience (CE) – engaging in a new experience or situation,
- reflective observation (RO) – observing and reflecting on the experience,
- abstract conceptualization (AC) – developing theories or concepts from reflection,
- active experimentation (AE) – applying learned concepts to test ideas in practice.

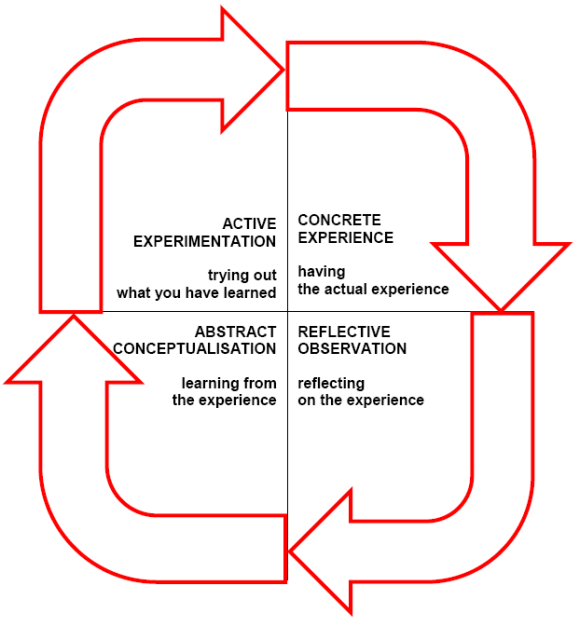


Figure 1: Kolb's learning cycle (adapted from Kolb, 1984)

The approach aims to combine theory with practise so that students not only understand the concepts theoretically, but can also apply them in real-life situations. Each of these phases is interlinked and forms a continuous learning cycle. Kolb's model emphasises the importance of personal involvement in learning rather than passive absorption of information and highlights how experiential learning impacts education, professional development and lifelong learning. Kolb also argues that learning is a continuous process that is shaped by individual experiences and environments and influences personal growth and skill development (Kolb, 1984).

2.2 Service learning

Service learning is an experiential learning pedagogy that empowers students beyond the classroom to actively engage in their learning and develop civic knowledge and skills. Through service learning, students have the opportunity to apply the knowledge and skills they have gained in the classroom to real-world community needs. This hands-on, experiential learning not only reinforces academic concepts, but also promotes the development of the whole person.

The concept of service learning (SL) has evolved over the years and can be traced back to the broader principles of experiential education. Originally, SL in the broadest sense of the word focused primarily on volunteering and community service, emphasising the service component over academic learning. This approach often manifested itself in an informal setting, such as campus organisations or community clubs, where students engaged in service activities without structured educational goals (Furco, 1996). Nonetheless, the historical development of SL in education reflects broader societal changes and evolving pedagogical theories. While early service learning efforts were often associated with moral and civic engagement, contemporary models increasingly focus on knowledge of community needs, critical thinking, problem solving, self-awareness, and communication skills as central educational goals (Kennedy, 2023). The emphasis on these skills is particularly relevant in the context of textiles, clothing and fashion education, where the need for innovative, sustainable practises to address global challenges is paramount.

Service learning programs are distinguished from other approaches to experiential education by their intention to equally benefit the provider and the recipient of the service as well as to ensure equal focus on both the service being provided and the learning that is occurring.

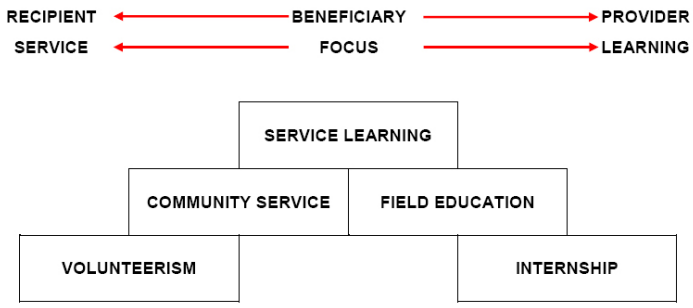


Figure 2: Distinction among service concepts/programs (adapted from Jacoby,1996)

Therefore, service learning is a form of education in which students participate in organised activities designed to meet human and community needs, along with structured opportunities for reflection aimed at achieving desired learning outcomes, including a better understanding of course content, a broader appreciation of the discipline, and a stronger sense of civic responsibility (Jacoby, 1996; Bringle, 1996). Service learning aims to balance student learning with community outcomes. Rather than charity, service-learning emphasises reciprocity (Furco, 1996).

2.3 Service learning potential in textile, clothing and fashion education

Service learning offers significant potential in the textile, clothing and fashion industry by bridging academic knowledge with real-world applications. Through hands-on projects that address social and environmental challenges, students gain practical experience while contributing to meaningful change:

- Sustainability and ethical fashion – Service learning can include projects such as textile recycling initiatives, upcycling programmes and sustainable fashion campaigns. Students can collaborate with local communities to reduce textile waste and promote ethical consumption, organise clothing swaps and sustainable fashion shows, etc.

- Community engagement and empowerment – Working with non-profit organisations, marginalised artisans, underprivileged communities or local cooperatives allows students to apply design, production and business skills while supporting traditional craftsmanship and fair labour practises.

- Industry collaboration and innovation – Service learning can foster partnerships between universities, textile, clothing and fashion brands and non-profit organisations and support innovative problem solving in areas such as waste management, circular fashion, smart textiles and sustainable material sourcing.

- Education and awareness – Students can participate in awareness-raising campaigns about ethical fashion choices, responsible consumer behaviour and environmental impact, strengthening their role as future industry leaders with a strong attitude towards social responsibility.

By integrating service learning into textile and fashion education, students not only refine their technical and creative skills, but also develop a deeper understanding of ethical and sustainable practises, preparing them for socially responsible careers (Black, 2012; Kolb, 1984; Fletcher, 2016).

2.4 Service learning challenges in higer education

Integrating the concept of service learning into the curriculum can pose significant challenges that can stand in the way of effective implementation in educational institutions. One major obstacle is often a lack of time. Teachers are often busy with curricula, leaving little opportunity to incorporate service learning activities that require additional planning and commitment. When these time constraints are coupled with traditional assessment schedules, they can lead to superficial engagement rather than deep learning experiences. Teachers often find it difficult to incorporate aspects of reflection and community interaction into their lesson plans.

Another major challenge is the limited resources. Implementing service learning requires access to community partners, funding for projects, and training for teachers and their assistants to facilitate these experiences. Educational institutions often face budget constraints that limit funding for projects, training and materials needed for effective implementation. Without sufficient funding, teachers may struggle to develop meaningful service learning opportunities. In addition, building collaborations with local organisations requires time and effort, both of which can be in short supply for busy teachers. This reliance on external partners can lead to inconsistent project delivery and lower student engagement. In addition to financial and partnership challenges, resources can also be limited by a lack of staff. The lack of trained staff can affect the quality of service learning experiences, ultimately impacting student outcomes and the development of their social responsibility.

To effectively overcome these resource constraints, institutions must prioritise strategic partnerships and seek alternative funding opportunities. Establishing clear goals is fundamental to effective integration of service learning. Involving students in defining these goals encourages student ownership and engagement.

In addition, alignment with academic standards can present difficulties. Educators must ensure that service learning projects complement existing curriculum requirements while meeting educational goals. This balancing act is important to maintain academic rigour while providing experiential learning opportunities.

3. SERVICE LEARNING IN SLOVENIA

3.1 Publications and projects

The fundamental problem in exploring the areas of service learning in Slovenia is the inconsistency of Slovenian terminology, as various more or less appropriate translations are used to describe the concept of service learning, which also include the broader area of socially beneficial learning, community learning, learning through community service, etc.

The concept of service learning has been incorporated into projects such as the Erasmus+ project „Change Your Role“, which aimed to bring together different ways of working with young people in the environmental field to lead them towards active citizenship (Borovinová, 2021). Another Erasmus+ project „Trainee“ focussed on developing effective approaches in the field of community learning (i.e. service learning) in the context of training professionals working in the field of youth employment support (Trainee Project, n.d.; Ferlin, 2022).
Several papers related to service learning have been published, e.g. the report on the approach that combines environmental education, citizen science and community learning to develop green skills (Robinson, 2024), or the paper that provides important insights into the theoretical and methodological challenges of measuring adult participation in lifelong learning (Mikulec, 2023). The role of education for sustainable development (ESD) was explored, emphasising how education for sustainability impacts on wider societal understandings of public interest

and adult learning (Bogataj, 2021). Community service learning in primary and secondary schools has also been analysed. The literature also addresses the concept of academic service learning in a variety of ways, from its definition as a teaching method to definitions that view academic service learning as a movement for social change. It was noted that academic service learning is becoming increasingly important and promoted at European level (Grandić, 2019). The current state of education for sustainable development in Slovenia was also analysed in a paper presenting the situation on the Slovenian education market with a focus on adult education and lifelong learning (Rozman, 2020).

3.2 TexUnite Erasmus+ project

The TexUnite project (Erasmus+) promotes the key competences needed to achieve sustainability goals by introducing service learning in textile, clothing and fashion education through project-based seminars. The project develops an online educational seminar for higher education with digitally enhanced teaching and learning arrangements for the implementation of sustainability-oriented service learning project seminars with external partners. The virtual exchange method will be used to create an intercultural exchange between the six European partner universities. The project brings digitalisation and sustainability together.

The integration of service learning into a curriculum trains democratic values and awareness and leads university teachers, students and external partners to critical thinking, reflection on textile production and fashion consumption, cooperation and social competence as well as international exchange (TexUnite, n.d.).

The partners of the TexUnite project are: University of Education Freiburg, Germany (lead), University of Applied Sciences Albstadt-Sigmaringen, Germany, Gheorghe Asachi Technical University of Iaşi, Romania. Trakia University Stara Zagora, Bulgaria, University of Ljubljana, Slovenia and Ege University, Izmir, Turkey.

TexUnite

Figure 3: TexUnite logo and QR

4. COCLUSIONS

So far, no work has been found that deals with the method of service learning specifically for sustainability in the textile, clothing and fashion industry. Therefore, the method of service learning has great potential for implementation in higher education curricula in the field of sustainability in the textile and fashion industry in Slovenia and abroad. In this field, the contribution of the TexUnite project will undoubtedly be significant.

Integrating the concept of service learning into the curricula of textiles, clothing and fashion higher education can pose significant challenges due to time constraints, limited financial and human resources and partnership issues. To effectively overcome these constraints, higher education institutions need to set clear goals and involve teachers, students and the learning environment in defining these goals. Service learning projects must also harmonise curriculum requirements and educational goals.

Overall, integrating service learning into higher education not only enhances students' academic experiences, but also prepares them to be responsible citizens. By actively engaging with the community and society, students develop a sense of social responsibility that extends beyond their academic pursuits.

The project TexUnite is co-funded by the European Union. Co-funded by the European Union

5. REFERENCES

Black, Sandy. 2012. *The Sustainable Fashion Handbook.* London: Thames & Hudson.
Bogataj, Nevenka. 2021. „Vzgoja in izobraževanje za trajnostni razvoj širita razumevanje javnega interesa v izobraževanju odraslih.“ *Andragoška Spoznanja* 27 (1): 121–138. https://doi.org/10.4312/as/9747.
Borovinová, Katarína, Martina Dobiášová, Lea Marovt, Gregor Cerar, Mária Butyka, Laura Bondiuc, and Mihai Prisacariu. 2021. *Spremeni svojo vlogo: Priročnik za učitelje za izobraževanje o trajnostnem razvoju v skupnosti.* https://ekosola.si/wp-content/uploads/2021/07/Spremeni-svojo-vlogo_priro%C4%8Dnik_2021.pdf.
Bringle, Robert G., and Julie A. Hatcher. 1996. „Implementing Service Learning in Higher Education.“ *Journal of Higher Education* 67 (2): 221–239. https://doi.org/10.1080/00221546.1996.11780257.
Ferlin, Štefan. 2022. „Projekt TRAINEE skozi skupnostno učenje za večjo zaposljivost mladih.“ *Urad RS Za Mladino - mlad.si*, December 9, 2022. https://www.mlad.si/projekt-trainee-skozi-skupnostno-ucenje-za-vecjo-zaposljivost-mladih/.
Fletcher, Kate. 2016. *Craft of Use: Post-Growth Fashion.* London: Routledge.
Furco, Andrew. 1996. “Service-Learning: A Balanced Approach to Experiential Education.” In *Expanding Boundaries: Service and Learning*, 1–9. Washington, DC: Corporation for National and Community Service.
Grandić, Romana, and Maja Bosanac. 2019. „Predstavitev in analiza modela družbeno koristnega učenja.“ *DIDACTICA SLOVENICA. Pedagoška Obzorja.* https://www.dspo.si/index.php/dspo/article/view/137.
Jacoby, Barbara, ed. 1996. *Service-Learning in Higher Education: Concepts and Practices.* San Francisco, CA: Jossey-Bass.
Kennedy, Laura. 2023. „The Teacher’s Guide to Service Learning [+ 5 Examples].“ *Prodigygame.com*, July 6, 2023. https://www.prodigygame.com/main-en/blog/service-learning/.
Kolb, David A. 1984. *Experiential Learning: Experience as the Source of Learning and Development.* Englewood Cliffs, NJ: Prentice Hall.
Mikulec, Branka. 2023. „Teoretična in metodološka vprašanja pri merjenju in spodbujanju vključenosti odraslih v vseživljenjsko učenje.“ In *Trenutki sprememb: Izobraževanje odraslih v času epidemije covida-19*, edited by Jelena Mirčeva, 33–20. Ljubljana: Andragoški center Slovenije. https://www.acs.si/digitalna-bralnica/trenutki-sprememb/.
Oxford English Dictionary. n.d. „Charity.“ *Oxford English Dictionary.* Retrieved from www.oed.com.
Rahmi, Wahyuni. 2024. „Analytical Study of Experiential Learning: Experiential Learning Theory in Learning Activities.“ *EDUKASIA: Jurnal Pendidikan Dan Pembelajaran* 5 (2): 115–126. https://doi.org/10.62775/edukasia.v5i2.1113.
Robinson, J. A., Alenka Gradišek, Damjana Bevk, and Nataša Bogataj. 2024. „Skupnostno učenje odraslih kot ogrodje za občansko znanost.“ In *Pedagoški inštitut eBooks*, 183–195. https://doi.org/10.32320/978-961-270-357-8.183-195.
Rozman, Tomaž, and Maja Frangež Rozman. 2020. „Education for Sustainability: Learning Methods and the Current State in Slovenia (a Preliminary Study).“ *International Journal of Smart Education and Urban Society (IJSEUS)* 11 (1): 41–63. https://doi.org/10.4018/IJSEUS.2020010104.
TexUnite. n.d. Project Summary. URL: https://texunite.eu/ (last accessed on 01. 02. 2025).
Trainee Project. n.d. “Trainee Project – TRAINEE: Training and Raising Awareness through In-service Networks for Employment and Entrepreneurship.” https://traineeproject.eu/.

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POSTER PRESENTATION

TEXUNITE – ERASMUS+ PROJECT ON SERVICE LEARNING IN THE FIELD OF SUSTAINABILITY IN TEXTILE AND FASHION EDUCATION

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Abstract: *The EU textile and fashion sector is required to transform into a sustainable system. All stakeholders need to adapt to EU regulations and engage at local and global level. The TexUnite project promotes the key competences needed to achieve the sustainability goals by introducing Service Learning (SL) in textile and fashion education through project-based seminars. Lecturers are enabled to carry out SL projects through active participation in the Sustainable Textile Lab training module. The project develops an online further education seminar for higher education with digitally enhanced teaching and learning arrangements for the implementation of sustainability-oriented service-learning project seminars with sustainability-oriented and socially committed external partners. In order to establish an intercultural exchange between the projects at six European partner universities, the method of Virtual Exchange is used. The project brings together digitalisation and sustainability. The results will be made available as Open Educational Resources. The integration of SL into a curriculum trains democratic values and awareness and leads university teachers, students and external partners to critical thinking, reflection on textile production and fashion consumption, cooperation and social competence.*

Keywords: *TexUnite, textiles, fashion, sustainability, Service Learning, Virtual Exchange, Open Educational Resources.*

1. INTRODUCTION

The textile and fashion sector in the European Union (EU) is currently undergoing a profound transformation aimed at creating a sustainable system in response to pressing environmental and social challenges. In the past, the industry has struggled with problems such as pollution, excessive waste and labour exploitation, mainly driven by the fast fashion model, which relies on rapid production and low costs (Velimirović, 2023; Corso, 2024; Van Keulen, 2024)

In 2022, the EU launched the Green Deal and the Strategy for Sustainable and Circular Textiles, which set ambitious targets for eco-design, waste reduction, and sustainable production practises. These initiatives reflect the growing recognition of the importance of environmental awareness in the textile industry. However, the transition is not without its challenges, including the shortage of skilled labour, the need to overhaul the supply chain and balancing consumer demand for fast fashion with sustainable practises (Tappr, 2023; Dubey, 2025; Van Iterson, 2022). On 6 June 2023, the European Commission published a transition pathway for the textile ecosystem, co-created with industry stakeholders. This pathway describes specific actions to improve sustainability and digitalisation in the industry, with around 50 actions across eight building blocks. These actions promote circular and sustainable practises while supporting SMEs to innovate and grow in international markets. In addition, the pathway emphasises the importance of upskilling and reskilling the workforce through access to lifelong learning opportunities (European Commission, 2023).

The regulatory framework continues to evolve to support this transformation, with key policies such as the Ecodesign Sustainable Products Regulation (ESPR) and the ban on products made using forced labour. These regulations aim to promote the circular economy, accountability and transparency within the industry, while encouraging companies to adopt sustainable practises throughout their supply chain. Despite these efforts, the industry is struggling with the complex dynamics of consumer expectations and the economic impact of switching to sustainable models, particularly for small and medium-sized enterprises (Hussain, 2023; Burkhardt, 2023; EISMEA, 2021).

Prominent controversies include debates about greenwashing, the effectiveness of regulations and the commercial viability of sustainable practises for brands traditionally reliant on fast fashion. The EU textile and fashion sector continues its transition towards sustainability and remains a focal point for discussions on environmental responsibility, ethical labour practises and the future of consumer behaviour in an increasingly environmentally conscious market. All stakeholders need to adapt to EU regulations and engage on a local and global scale. (Campbell, 2024; European Commission, 2023).

2. TEXUNITE PROJECT

2.1 Project core

The international project TexUnite aims to improve the key competences required to achieve sustainability goals through the integration of Service Learning and Virtual Exchange in textile and fashion education. The project is the first international study programme with Service Learning components in the textile and fashion sector in Europe. By implementing Service Learning in project-based seminars with partner organisations such as NGOs, communities or sustainability-oriented companies, the initiative promotes environmental and social commitment in higher education. The aim is to give students the opportunity to get involved in social and sustainable activities as part of their academic learning and to see what they can contribute. As a pedagogical strategy, Service Learning enables students to cultivate sustainability-oriented knowledge and attitudes while serving the community and providing them with an active learning experience. All activities are in line with European approaches to sustainability in the textile and fashion industry (TexUnite, 2024).

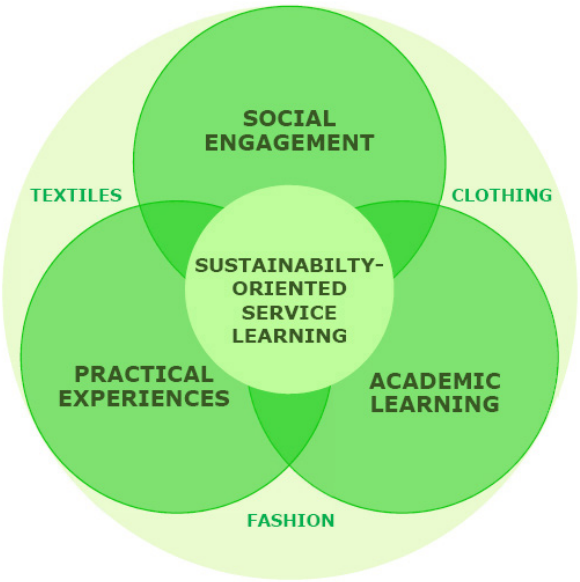


Figure 1: Service Learning as a basic teaching method

As part of TexUnite, the University of Education Freiburg in Germany is cooperating with the Albstadt-Sigmaringen University in Germany and universities from four different countries: the George Asachi Technical University of Iaşi in Romania, the University of Ljubljana in Slovenia, the Trakia University of Stara Zagora in Bulgaria and Ege University in Izmir, Turkey. The 3-year project, which will end in August 2027, is co-funded by the European

Union‘s Erasmus+ programme, one of the most successful initiatives in Europe, which is also of great importance for higher education programmes (TexUnite, 2024).

The project TexUnite is co-funded by the European Union. Co-funded by the European Union

2.2 Project objectives

The general objective of the Erasmus+ TexUnite project is to promote the key competences needed to achieve sustainability goals by introducing the concept of Service Learning in textile and fashion education. The TexUnite project has three main specific main objectives:

- **Sustainable Textile Lab**: Development and implementation of an online further education seminar with digitally enhanced teaching and learning arrangements to conduct sustainability-oriented Service Learning project seminars with students and to enter into an intercultural exchange using the Virtual Exchange method.

- **Service Learning projects**: Development, implementation and evaluation of Service Learning projects at each partner university. On the basis of the SusTexLab, partners for the Service Learning projects are found, e.g. NGOs, communities or sustainability-oriented companies, and integrated into international tandems via Virtual Exchange.

- **Open Educational Resources**: Creation of OER, consisting of the teaching and learning materials of the SusTexLab and the content of the SL projects on the open access repository ZOERR and the project presentation on the European platform EPALE (TexUnite, 2024).

The project focuses on economic models of sustainability in the textile and fashion sector as well as on an analysis of EU regulations on sustainable textile industry and their relevance for partner countries and is linked to the priority environment, green skills and the fight against climate change.

2.3 Research steps

The TexUnite project develops in six steps:



Figure 2: 6-phase TexUnite project plan

3. IMPLEMENTATION AND RESULTS

The introduction of sustainability-oriented SL projects in textile, clothing and fashion education offers students the opportunity to actively engage with real-world challenges. Such projects can educate students about the environmental and social issues facing the textile and fashion industry, thus increasing their sense of responsibility and awareness. Students are challenged to develop sustainable solutions and encourage creativity and innovation in the design of environmentally friendly processes or products. SL projects involve collaboration with industry

stakeholders, local communities and experts, fostering a sense of collective responsibility. They provide students with hands-on experience in implementing sustainable practises and prepare them for future careers focused on environmental protection. In addition, SL projects can have a positive impact on local communities by promoting sustainable practises and improving community well-being. Addressing the environmental and climate impacts of the textile and fashion industry through sustainability-focused Service Learning is critical to creating a more responsible and resilient industry while educating and empowering the next generation of professionals and leaders. Students will develop critical thinking and empathy as well as problem-solving skills to address climate change and environmental issues and find solutions for transforming the textile and fashion sector into a circular system (TexUnite, 2024).

4. CONCLUSION

Addressing sustainability issues in the fashion and textiles is in line with the concept of global citizenship education. Students who participate in real-world projects gain a broader perspective on global challenges and develop a sense of responsibility for creating a more sustainable and just world.

The TexUnite project promotes the key competences required to achieve sustainability goals by introducing Service Learning into textile and fashion education through project-based seminars. The integration of Service Learning concept into a curriculum fosters democratic values and awareness and leads university teachers, students and external partners to critical thinking, reflection on textile production and fashion consumption, cooperation and social competence as well as international exchange.

To summarise, the TexUnite project has the potential to create synergies between different sectors, impact education and training, engage young people and contribute to wider societal and environmental goals. It is in line with the principles of experiential learning, interdisciplinary collaboration and the promotion of sustainable practises. By building a bridge between the academic and non-academic communities and using their knowledge to help solve environmental, social and economic challenges, universities fulfil their third mission of social engagement.

5. REFERENCES

Burkhardt, Delara. “REPORT on an EU Strategy for Sustainable and Circular Textiles | A9-0176/2023 | European Parliament.” © European Union, 2023 - Source: European Parliament, May 9, 2023. Accessed December 21, 2024. https://www.europarl.europa.eu/doceo/document/A-9-2023-0176_EN.html.

Campbell, Niamh. “Driving the Apparel Sector Just Transition.” Innovation forum. Innovation Forum, November 7, 2024. Accessed January 30, 2025. https://www.innovationforum.co.uk/articles/driving-the-apparel-sector-just-transition.

Corso, Tommaso & Paolucci, Federica. 2024. “EU Strategy for Sustainable and Circular Textiles: Key Actions at a Glance | Econyl Blog.” Econyl, October 31, 2024. https://econyl.aquafil.com/eco-design-magazine/eu-strategy-for-sustainable-and-circular-textiles-key-actions-at-a-glance/.

Dubey, Manoj. “European Textile Industry’s Response to Stricter Rules.” Global Textile Times, February 25, 2025. https://www.globaltextiletimes.com/apparel/european-textile-industry-s-response-to-stricter-rules/.

European Commission. “Commission and Industry Players Commit to Make the Textile Sector Greener, More Digital and Competitive,” June 6, 2023. Accessed February 10, 2025. https://single-market-economy.ec.europa.eu/news/commission-and-industry-players-commit-make-textile-sector-greener-more-digital-and-competitive-2023-06-06_en.

European Innovation Council and SMEs Executive Agency (EISMEA). “Towards a More Sustainable & Circular Fashion Sector: Four COSME Projects Making It Happen,” n.d. https://eismea.ec.europa.eu/news/towards-more-sustainable-circular-fashion-sector-four-cosme-projects-making-it-happen-2021-06_en.

Hussain, Tanveer. “Ultimate Guide to EU Strategy on Sustainable and Circular Textiles.” The Textile Think Tank, July 26, 2023. https://thetextilethinktank.org/ultimate-guide-to-eu-strategy-on-sustainable-and-circular-textiles/.
Tappr. “The EU Strategy for a Sustainable & Circular Textile Sector,” December 6, 2023. Accessed February 1, 2025. https://www.usetappr.com/blog/eu-strategy-sustainable-and-circular-textiles.
TexUnite. “About.” Accessed February 10, 2025. https://texunite.eu/index.php/about/.
Van Iterson, Rannveig. “EU Sustainable Textiles Strategy: Everything You Need to Know.” Ohana Consultancy, October 22, 2024. https://www.ohanapublicaffairs.eu/2022/07/28/eu-strategy-sustainable-circular-textiles/.
Van Keulen, Roos. “EU Strategy for Sustainable Textiles: 5 Takeaways | Earth.Org.” Earth.Org, January 5, 2024. https://earth.org/5-takeaways-from-the-new-eu-circular-fashion-strategy/.
Velimirovic, Milica. “Threads of Progress: Reviewing the History and Building a Sustainable Future for the EU’s Textile Industry - BioLUSH.” BioLUSH - (blog), December 11, 2023. https://biolush.eu/threads-of-progress-reviewing-the-history-and-building-a-sustainable-future-for-the-eus-textile-industry/.

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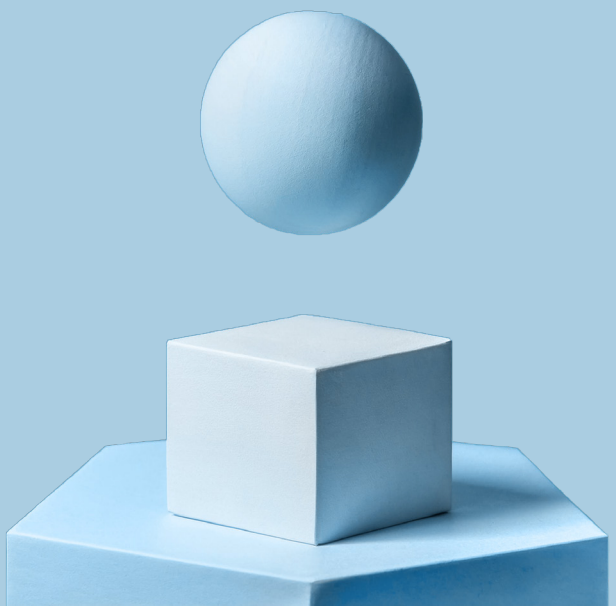
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CROSSING BOUNDARIES

10th Conference on Information and Graphic Arts Technology



INVITED LECTURES

SESSION-INVITED LECTURE

ORAL PRESENTATION

IMPLEMENTATION OF THE EU PACKAGING AND PACKAGING WASTE REGULATION (PPWR) FOR SLOVENIA AND EUROPE: CHALLENGES AND OPPORTUNITIES

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Abstract: *On December 16, 2024, the Council of the European Union officially adopted the EU Packaging and Packaging Waste Regulation (PPWR), making it legally binding across all EU member states. The regulation entered into force at the beginning of 2025, with its provisions becoming applicable after a general transition period of 18 months. The regulation is considered one of the most significant legal frameworks in the field of packaging, with major implications for all EU member states, including Slovenia. This paper provides an overview of the key elements of the PPWR, its implications for stakeholders, and explores sustainable approaches and innovative solutions within the packaging sector to meet the new standards and promote a circular economy.*

Keywords: *EU Packaging and Packaging Waste Regulation, Sustainable packaging, Recycling, Circular economy.*

1. INTRODUCTION

The European Union recently adopted the long-anticipated PPWR, a pivotal step towards improving the sustainability of packaging across the union. Initially proposed by the European Commission in 2022, the regulation introduces a broad set of binding requirements and ambitious targets aimed at reducing packaging waste and promoting recycling, reuse, and circularity. As the most prolonged regulatory process in the EU's history, the PPWR has been at the centre of intense lobbying efforts. According to the Food Packaging Forum, concerns have been raised that the final version has been significantly diluted by the influence of profit-driven interest groups (Food Packaging Forum, 2025).

2. OVERVIEW OF THE PPWR

The PPWR introduces several stringent measures aimed at reducing packaging waste and enhancing recycling and reuse rates across the EU. Among its provisions, the regulation mandates a significant reduction in the use of non-recycled raw materials in packaging, setting minimum recycled content requirements for various packaging types, such as a minimum of 25% recycled content for plastic bottles by 2025. The regulation also bans materials that are not easily recyclable and limits the use of single-use packaging in food and beverage services. Another crucial provision is the phased elimination of PFAS in food-contact materials (European Commission, 2025).

Despite these advancements, the success of the regulation will depend heavily on the establishment of unified systems for the collection, sorting, and recycling of different materials across EU member states. In Slovenia, for example, different municipalities still employ varying systems for waste collection and separation, creating confusion and inefficiencies. Some regions use a colour-coded bin system (e.g. blue for paper, yellow for packaging etc.) (Javni holding Ljubljana, 2021), while others separate waste into "dry" and "wet" categories (Javno podjetje Komunala Slovenj Gradec, 2016). This lack of harmonisation—on such a small national territory—is unacceptable and undermines the efficiency of the overall waste management system.

3. CHALLENGES AND OPPORTUNITIES IN IMPLEMENTATION

The regulation places significant emphasis on recycling and reusing packaging products and materials in all areas where this is possible. The main reason for updating the regulation is the fact that, despite various past efforts, packaging is still considered one of the key global environmental challenges. The packaging industry also remains one of the main consumers of virgin (non-recycled) raw materials. Estimates suggest that as much as 40% of all freshly produced plastic and 50% of all paper and cardboard production is used for packaging purposes. Moreover, packaging is responsible for approximately 36% of all municipal solid waste. The high consumption of packaging materials, coupled with low levels of reuse and recycling, significantly hampers the development of a low-carbon society and a circular economy (European Commission, 2025).

Data from Eurostat and various market reports, monitored and utilized by the European Parliament, also highlight an increasing share of packaging products whose properties can obstruct recycling processes. Packaging is deemed “non-recyclable” if it cannot be separately collected or presents challenges for the most advanced sorting and recycling processes within the European Union. Between 2012 and 2020, the share of technically non-recyclable packaging increased significantly. Moreover, even packaging with favourable properties for recycling is often not recycled because the necessary systems for collection, sorting, and processing are not available, regionally accessible, or cost-efficient. Recycled raw materials or recycled products are frequently of insufficient quality to meet market and secondary raw material user demands (European Commission, 2025).

Notably, even if there were a hypothetical breakthrough in the research and development of new and advanced packaging materials and these materials were introduced into the market within a few years, this would not necessarily result in a significant improvement. The current pace of testing and approval of new materials, especially those coming into direct contact with food, is exceptionally slow. For the vast majority of these materials, there are also (at least likely) no suitable large-scale recycling processes in place, further complicating their effective integration into the circular economy. It is worth noting that refill and reuse concepts still represent a significant opportunity for improvements in the packaging sector, particularly in Slovenia. However, this is achievable only if the systems supporting these concepts are well-organized and safe for both products and consumers (Lavrič, 2023).

The regulation also does not clearly define how the clear environmental benefit of packaging or packaging materials will be demonstrated. However, it is almost certain that such packaging will need to be made from circular and alternative raw material sources. The demanding challenge in Slovenia is also broader and more balanced implementation and realization of various concepts for the multiple use of packaging (refill and reuse concepts), which should be enabled by retail stores or chains with a more extensive offer of bulk products. Of course, each time the issue arises about the safety of packaging, which, with appropriate guidelines and directions, is entirely manageable.

As already mentioned, the regulation places great emphasis on the reuse and recycling of packaging or packaging materials. For paper and cardboard, which, along with various types of plastic, are the most commonly used packaging materials in the world, recycling does not pose significant challenges. According to CEPI data, 71.4% of paper and cardboard were recycled in the European Union in 2021 (CEPI, 2022). This is 2% less than in 2020 but more than 40% higher than the percentage for plastic materials. According to Eurostat, the recycling rate for plastic materials in 2020 was 38% (Eurostat, 2023).

This ratio in favour of paper certainly partly stems from the fact that recycling processes for plastic materials are more complex and challenging than those for paper. Despite the variety of papers, cardboards, and corrugated boards, their primary raw material is almost always the same—cellulose fibre, which can be recycled up to 25 times with adapted processes, according to the latest data (Packaging Europe, 2023). Given these facts and the other properties of paper and plastic, we can conclude or predict that, in the future, concepts will likely be more developed where plastic materials will be used for various packaging products intended primarily for reuse (refill and reuse), while paper will be used where plastic is not reasonable or justified based on various evaluation parameters, such as barrier properties, weight-to-strength ratio, cost-effectiveness, and environmental impact assessments. Such concepts are already emerging in practice, particularly abroad. One recently prominent example, comes from the global fast-food chain McDonald’s. In France, at the end of 2022, the corporation replaced its primarily paper fry packaging with reusable plastic for the first time in its history (Abboud, 2023).

Especially for warm or hot and greasy foods—such as French fries—there is an easy transfer of certain (potentially harmful) components from the packaging to the food through the medium (hot oil). Therefore, the use of papers or cardboard made almost entirely from virgin cellulose fibres is recommended or prescribed. After use, this type of packaging also poses challenges for recycling. These papers and cardboards often contain films or coatings to improve their barrier properties, which can be problematic for conventional recycling processes. Additionally, once paper and cardboard come into direct contact with food, they are no longer suitable for recycling into similar-quality materials, even if their raw composition would allow it, mainly for hygienic reasons. In practice, this means that high-quality papers and cardboards, made almost entirely from virgin cellulose fibres, are, after just a few minutes of use, downgraded to much lower-quality papers and cardboards that are no longer suitable for food packaging.

The market also offers numerous applications in medicine, pharmaceuticals, and food, where the use of recycled materials for packaging is not suitable or even prohibited. Therefore, it is crucial that we continue developing diverse packaging applications from alternative raw material sources.

One of the main challenges in using various alternative raw materials for the production of packaging materials and applications will undoubtedly be ensuring their purity, which will enable the safe packaging of various types of products. Even when this is indisputable, it does not necessarily mean that the newly developed material can be used for food packaging. The material or newly developed substance must first be approved by the relevant authority. In the European Union, this responsibility lies with the European Food Safety Authority (EFSA). Different countries also refer to and apply different, often uncoordinated national regulations and guidelines. The current pace of development of new materials and applications is not well matched by the relevant authorities. Waiting times for material approval are very long, and the procedures are expensive and rigid. Certain institutions hold a monopoly over these procedures and, due to various interests, do not allow the expansion of research to other institutions, which would certainly accelerate the evaluation. This results in a highly rigid, slow, and non-competitive system that collapses under the burden of thousands of new materials, substances, and compounds waiting to be evaluated and approved.

If this area becomes better regulated in the future—particularly regarding the approval processes for new materials—some of the most suitable candidates will likely be materials based on various forms of (nano)cellulose, as they can be easily integrated into existing recycling streams and, in some cases, even enhance the functional properties of paper-based packaging (Lavrič, 2018).This is a significant advantage in the context of recycling new bio-based materials, as recycling processes for other materials, such as chitosan or alginate, do not currently exist. They are currently classified as biodegradable or compostable, which is acceptable when these materials enrich the soil or compost during their degradation. However, almost every such breakdown releases CO_2 into the environment as a by-product, which, under the current aspirations for a CO_2-neutral society, can present a major challenge in certain frameworks.

Given the current recycling capacity of the European Union, the draft regulation still allows biodegradable materials to undergo biodegradation as the only end-of-life scenario if they are demonstrably beneficial to the environment and made from biodegradable and compostable polymers. Member States will have to decide, based on their own waste collection schemes and infrastructure, whether to mandate the use of compostable plastics, particularly for lightweight plastic bags. If a country lacks the capacity to recycle these bags, it is better to mandate the use of compostable ones and accept some of the disadvantages this step entails. This is also important to avoid consumer confusion regarding proper sorting and disposal. All other plastic packaging must still undergo material recycling, and it is crucial that biodegradable bags are not mixed in with recyclable plastics, as this could disrupt the recycling process.

4. CHALLENGES AND OPPORTUNITIES IN IMPLEMENTATION

These facts further confirm the need for developing new materials, despite the lack of fully developed recycling processes for them. It is also true that such exceptions are mainly possible due to poor infrastructure and processes that are problematic even for well-established plastic materials in Slovenia.

However, poor infrastructure and the lack of suitable recycling processes are not the only reasons why non-recyclable materials will remain present in the market in the coming years. For some applications, it is more practical for the material to decompose or accelerate the degradation of certain waste rather than be recycled. Such sce-

narios include different types of waste collection bags, where their purpose and nature make degradation a more practical solution than recycling, which would be challenging and largely impractical due to contamination.

5. REFERENCES:

Abboud, Leila. Macron Versus McDonald's: How France Ditched Disposable Food Packaging. Financial Times. URL: https://www.ft.com/content/baa23798-7c6b-45be-b6a1-00b446976331 (last accessed on 13 February 2025).
CEPI. 2022. Key Statistics 2021 – European Pulp and Paper Industry. Brussels: Confederation of European Paper Industries. URL: https://www.cepi.org/wp-content/uploads/2022/07/Key-Statistics-2021-Final.pdf (last accessed on 14 April 2025).
European Commission. Packaging Waste. URL: https://environment.ec.europa.eu/topics/waste-and-recycling/packaging-waste_en (last accessed on 13 February 2025).
Eurostat. 2023. Packaging Waste Statistics. Brussels: European Commission. URL: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Packaging_waste_statistics (last accessed on 14 April 2025).
Food Packaging Forum. European Council Adopts Final Provisions of PPWR. URL: https://foodpackagingforum.org/news/european-council-adopts-final-provisions-of-ppwr (last accessed on 13 February 2025).
Javni holding Ljubljana. Plakat za četrtne skupnosti – Ravnanje z odpadki. Ljubljana: Voka Snaga. URL: https://www.vokasnaga.si/sites/www.jhl.si/files/dokumenti/plakat_za_cetrtne_skupnosti_1.6.2021_0.pdf (last accessed on 14 April 2025).
Komunala Slovenj Gradec. 2016. Priročnik za ravnanje z odpadki. Slovenj Gradec: Javno podjetje Komunala Slovenj Gradec d.o.o., Pameče 177a. URL: https://www.komusg.si/Portals/0/Dejavnosti/Ravnanje-z-odpadki/prirocnik-za-ravnanje-z-odpadki-2016.pdf (last accessed on 14 April 2025).
Lavrič, Gregor. 2018. The Influence of Nanofibrillated Cellulose on Mechanical and Printing Properties of Packaging Paper. Master's thesis, University of Ljubljana. URL: https://repozitorij.uni-lj.si/IzpisGradiva.php?id=103024&lang=eng (last accessed on 14 April 2025).
Lavrič, Gregor. 2023. Development of Advanced Packaging Materials from Bio-Based Sources. PhD diss., University of Ljubljana. URL: https://repozitorij.uni-lj.si/IzpisGradiva.php?id=147526&lang=slv (last accessed on 13 February 2025).
Packaging Europe. New Study Suggests Cartonboard Can Be Recycled 25 Times Without Loss of Integrity. URL: https://packagingeurope.com/news/new-study-suggests-cartonboard-can-be-recycled-25-times-without-loss-of-integrity/7752.article (last accessed on 13 February 2025).

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SESSION-INVITED LECTURE

ORAL PRESENTATION

EXPLORING SCULPTURAL REALISM THROUGH WAX MODELING AND 3D PRINTING: A PERSONAL ARTISTIC EVOLUTION

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Austria

Abstract: *From the outset of this artistic trajectory, the central objective has been the faithful materialization of sculptural forms as vividly envisioned in the mind's eye—highly detailed, three-dimensional internal images arising through dreams, meditation, or moments of contemplative focus. The initial challenge involved selecting a material capable of accurately capturing these internal visions. Natural materials such as stone or wood rarely conformed to the desired base forms, and manual carving proved limiting. Furthermore, tactile engagement in the creation process was deemed essential, offering not only creative fulfillment but also therapeutic value through sensory interaction and stimulation of acupuncture points in the hands. While clay presented an initial alternative, it proved unsuitable due to its fragility, cracking during drying, and sensitivity to breaks in the working process. The discovery of wax modelling resolved these issues, offering unparalleled sculpting freedom, enabling the production of delicate structures, and allowing for long-term iterative work. To complete the wax sculptures, bronze casting was employed. Although bronze is a durable and aesthetically rich material, the process introduced several constraints: reliance on external foundries, long-distance travel, unwanted alterations during casting and finishing, high costs, and loss of control over artistic integrity. A critical turning point occurred when several raw wax models were melted down without consent, prompting a search for alternative methods. This led to the adoption of 3D scanning and printing technologies, initiating a new phase of experimentation and skill acquisition. The process involved learning to scan wax models, refine digital files, and identify suitable materials for post-processing and long-term outdoor durability. An additional artistic imperative was to avoid the appearance of mass production and synthetic plasticity. As a solution, each sculpture is produced in a unique size, undergoes individual surface reworking through manual modelling, and is distinctively finished through hand-painting. Through this hybrid process of traditional modelling and digital fabrication, significant creative freedom has been achieved. Large-scale sculptures and installations can now be realized, and spatial possibilities previously unattainable in bronze—such as floating forms, suspended compositions, and internally illuminated transparent prints—have become viable. Despite the shift in medium, each sculpture remains a unique work and retains its value within the art market.*

Key-words: *sculptures, wax modelling, 3D printing, forms of human body, artistic expression*

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USER INTERFACE AND USER EXPERIENCE

ORAL PRESENTATION

USE OF GENERATIVE ARTIFICIAL INTELLIGENCE TOOLS IN TRANSFORMING DESIGN PROCESS

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Abstract: *This paper explores the integration of generative artificial intelligence (AI) tools into design processes and evaluates their impact on creativity, efficiency and collaboration between human designers and AI. Through theoretical and practical research, the study identifies the opportunities and challenges that generative AI offers in redesigning creative workflows. Interviews with representatives from Slovenian and Belgian design agencies provided insights into real-world applications, leading to the development of a digital communication campaign and a supporting physical brochure. Findings emphasize that while generative AI enhances efficiency and innovation, its ethical use requires careful consideration. The research concludes that generative AI should be seen as a complementary tool, augmenting rather than replacing human creativity.*

Keywords: *generative artificial intelligence, design process, creativity, digital campaign, optimization.*

1. INTRODUCTION

In recent years, technological advances have reshaped the landscape of creative industries, with generative artificial intelligence (AI) tools proving to be transformative instruments. These tools, which use machine learning algorithms to generate new and innovative content, offer designers unprecedented possibilities for efficiency and creativity. Generative AI can produce visual, textual and audio outputs, redefining the traditional design process by automating repetitive tasks and enabling rapid ideation (NVIDIA, 2024; Majumder, 2024).

The theoretical foundation of this study highlights the particular capabilities of generative AI, e.g. its ability to recognise patterns in large data sets and generate outputs based on these patterns (Feuerriegel et al., 2023). Tools such as ChatGPT, DALL-E, MidJourney and Adobe Firefly exemplify this potential by facilitating content creation, from drafting initial concepts to finalising high-quality designs. In addition, Khroma.ai's ability to personalise colour palettes and the seamless integration of Adobe Firefly into design workflows underline the practical benefits of these tools (Majumder, 2024).

Although the benefits of generative AI are undeniable, challenges remain, particularly concerning ethical and practical considerations. Issues such as copyright infringement, data privacy and bias in AI-generated content require critical evaluation by designers (Lawton, 2024). Furthermore, generative AI lacks the intuitive creativity, emotional intelligence and nuanced decision-making inherent to human designers, emphasising the need for its role as a complementary rather than a replacement tool (Pogla, 2024).

By examining current trends and conducting interviews with industry professionals, the study aims to provide actionable insights into the integration of these tools into creative workflows. It also emphasises the importance of continuous education and skill development for designers to adapt to the rapidly evolving technological landscape.

2. EXPERIMENTAL

2.1 Materials and Methods

The research was conducted in a combination of theoretical analysis and practical experimentation. Interviews were conducted with representatives of Slovenian marketing agencies (Luna/TBWA, DROM Agency and Pristop) and the Belgian design studio WillemsPeeters. These interviews provided insights into the real-world application of generative AI in creative processes. A digital communication campaign for Laški akademski klub was developed, supported by a brochure, to illustrate the effective use of generative AI tools such as Transkriptor, ChatGPT, Adobe Firefly and Khroma AI.

2.2 Development of campaign

The digital communication campaign on presenting facts and tips on how to use generative AI for individuals or companies was self-initiated and we did not have a client for it. This meant that we had a free hand in the design, as there were no specific requirements from the client. Our wish was for the campaign to be launched through the social networks of Laški akademski klub. The working methods follow the creative process, but are adapted to the specifics of this project. First, with the help of ChatGPT, we created a creative brief that formed the basis for the creation of a digital campaign and presented it to the president of Laški akademski klub. We then researched the area we wanted to present and, based on the creative brief and research, defined the design area, which we then developed further. In the process of developing the idea, we defined the colours and typography, and with the help of Adobe Firefly AI, we generated avatars that would be the central characters of our campaign and would enrich the creative. This was followed by the design of graphics for the Instagram/Facebook posts, graphics for the Google Display Network which would make people aware of our campaign and a brochure containing all the content presented on the digital channels. We held a meeting with the president of Laški akademski klub, who approved the designs. After that, the project was finalised and the materials were delivered in the agreed formats.

Generative AI tools played a crucial role in multiple stages of the design process (Figure 1), streamlining specific tasks and improving overall efficiency.

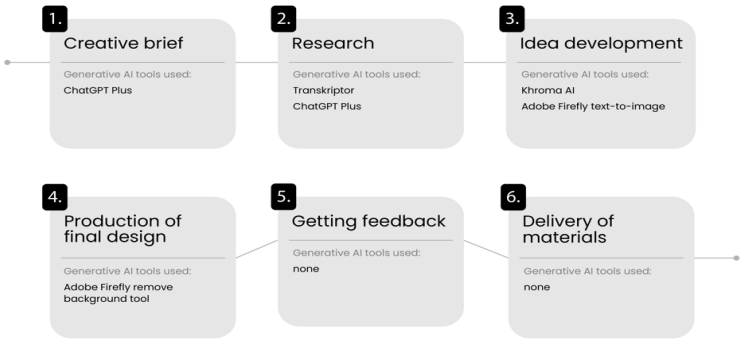


Figure 1: Stages of the design process and generative AI integrations

3. RESULTS AND DISCUSSION

The result of the research is a digital campaign for social media and a brochure, the aim of which is to introduce generative artificial intelligence to individuals and companies, give them tips on how to use it in creative processes and show them the most popular generative AI tools currently available.

3.1 Creative brief and research

The creative brief was developed with the assistance of ChatGPT, which provided suggestions for the title and structure of the campaign. Interviews with design professionals revealed that generative AI is integrated into the creative processes of the agencies and studios interviewed, from the early stages of campaign planning through to day-to-day work. They mainly use tools such as ChatGPT for conceptual designs, Dall-E, Adobe Firefly and MidJourney for rapid visual content creation. Some agencies are still in the research phase on how to best utilise this technology without losing their own creativity. Although AI enables the automation of certain tasks, such as the rapid creation of storyboards or the easy manipulation of spoken language in videos, they emphasise that AI is not self-sufficient, but is a tool that requires human guidance and critical judgement. They encounter ethical and legal considerations that require careful use. The experience of some shows that despite its effectiveness and cost reduction, caution is required when introducing AI, particularly when it comes to how the technology will be received by target audiences. Agencies see technology primarily as an assistant that can speed up and improve creative processes, but emphasise the importance of maintaining the human touch and critical thinking in creative work.

3.2 dea development and final design

Generative AI tools were used to create visual elements for the campaign, including avatars and colour palettes. Adobe Firefly was used to generate illustrations (Figure 2), while Khroma AI helped select the colour scheme.

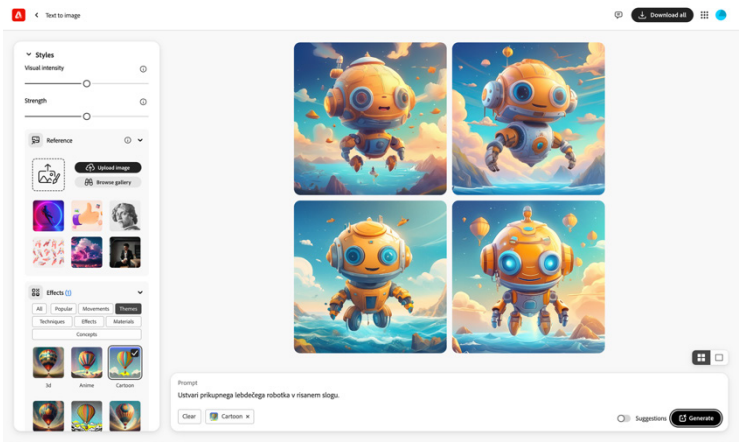


Figure 2: Adobe Firefly tool and first generations of avatars

After six iterations, the result was satisfactory. We removed backgrounds using the Adobe background removal tool built into Photoshop 2024. The result was 10 avatars that could be used for the final design (Figure 3).



Figure 3: The final set of avatars with the background removed

The text content was extracted from the interview transcripts using ChatGPT and adjusted to avoid mistakes and misinformation. The final designs included posts for social media (Figure 4), adverts for the Google Display Network and a brochure (Figure 5). The campaign successfully demonstrated how generative AI can enhance creativity and efficiency in the design process. For example, the use of Adobe Firefly enabled rapid iteration of illustrations, which would had to be sketched and drawn each time in a time-consuming process. Transkriptor significantly reduced the transcription time of the interviews, which would have been the longest task in this design process. Extracting useful tips and tricks from the transcriptions with ChatGPT was useful to a certain extent, however proofreading and our additions to the final text were very necessary.



Figure 4: Three sets of creatives for social media posts



Figure 5: Front side and back side of tri-fold brochure

3.3 Feedback and completion

The final designs were presented to the president of Laški akademski klub, who approved the campaign. The materials were delivered in the requested formats and the project was successfully completed. The client‘s feedback emphasised the effectiveness of generative AI in creating high-quality visual content in a short timeframe.

3.4 Influence of using generative AI tools on the design process

During the ideation phase, ChatGPT was used to generate potential titles for the campaign. While none of the generated titles were directly usable, they provided inspiration and a creative spark that led to the final name of the campaign name. In addition, ChatGPT helped source technical specifications for Google Display Network advertisements, which proved to be accurate and helpful.

The research phase benefited from an AI-powered transcription tool. The speech-to-text AI software Transkriptor was used to transcribe interviews with professionals from various agencies. Although the tool significantly accelerated the transcription process, certain limitations were noted, especially when transcribing Slovenian interviews that contained English terminology. In addition, the extraction of information gathered in the interviews with ChatGPT was very useful. Although the information was accurate, some generations lacked structure and manual corrections had to be made. Despite these minor shortcomings, the generative AI tools helped to reduce the time required for manual transcription, structuring interview responses and extracting information from long transcripts.

Generative AI also played a role in the visual development process. The AI tool Khroma was used to generate colour palettes based on selected preferences. This tool provided innovative combinations that would not have been easily imaginable in our minds. Similarly, Adobe Firefly Image 3 was used to create avatars, allowing for rapid prototyping and iterations. The AI-generated avatars were then refined using Photoshop’s „Remove Background“ tool. This shows how AI can help designers without specialised artistic skills, such as digital illustration, to create professional visuals.

Although generative AI provided solid benefits in accelerating the design process, critical human oversight was necessary to refine the results and ensure consistency with the creative objectives.
The experience with generative AI reaffirmed its potential as a supplementary tool rather than a replacement for human creativity. While it accelerated production, certain limitations, such as inconsistencies in text-based outputs and the need for iterative refinements, emphasized the crucial role of human judgement in the creative process. AI-powered tools provided efficiency and convenience, but require strategic human intervention to maximise their effectiveness.

3.5 Ethical and practical considerations

This study emphasises the importance of the ethical use of AI, particularly regarding copyright, data privacy and transparency. Designers need to critically evaluate AI-generated content to avoid issues such as misinformation or unintended bias (Majumder, 2024). Establishing guidelines for responsible AI integration is essential for maintaining trust and creativity in design processes (Lawton, 2024).

4. CONCLUSIONS

The study concludes that generative AI tools significantly improve the efficiency and creative potential of design processes. However, their integration requires careful management of ethical and practical considerations. Generative AI should be seen as a complementary tool that enhances, rather than replaces, human creativity. The study contributes to a deeper understanding of how generative AI can be effectively and ethically implemented into creative workflows, advancing the design industry without diminishing the role of human designers. Furthere research should focus on developing frameworks for the ethical use of AI and exploring its long-term impact on the creative industry.

5. REFERENCES

Feuerriegel, S., Hartmann, J., Janiesch, C. in Zschech, P. Title: Generative AI.
URL: https://link.springer.com/article/10.1007/s12599-023-00834-7 (Last accessed on 24. 4. 2024).
Lawton, G. Title: Generative AI ethics: 8 biggest concerns and risks.
URL: https://www.techtarget.com/searchenterpriseai/tip/Generative-AI-ethics-8-biggest-concerns
(Last accessed on 4. 6. 2024).
Majumder, S. Title: Top generative AI industry applications: an in-depth look.
URL: https://www.turing.com/resources/generative-aiapplications#understanding-generative-ai
(Last accessed on 23. 4. 2024).
NVIDIA. Title: Generative AI. URL: https://www.nvidia.com/en-us/glossary/generative-ai/
(Last accessed on 20. 4. 2024).
Pogla, M. Title: Artificial intelligence vs human intelligence.
URL: https://autogpt.net/artificial-intelligence-vs-human-intelligence/
(Last accessed on 4. 6. 2024).

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ORAL PRESENTATION

ENGAGING THE SENSES: A STUDY OF SYNESTHETIC DESIGN IN MOTION GRAPHICS

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Abstract:

This empirical investigation examines synesthetic design principles in motion graphics, exploring how sensory and emotional dimensions interact to create cohesive visual communication. Through an experimental design involving 37 participants, the study analyzed five animated sequences depicting fluid movements in red and blue color variations, utilizing an online survey methodology to assess multimodal perceptual responses. The research employed quantitative analysis to investigate how color, motion, and sound collectively influence viewers' perceptions of temperature, emotional tone, speed, and strength associations. Statistical findings revealed significant correlations between chromatic variations and perceptual interpretations, demonstrating that specific animation elements can strategically modulate sensory experiences. Color demonstrated substantial impact on thermal and emotional perception, while movement dynamics substantially influenced interpretations of velocity and energetic potential. By providing empirical evidence of cross-modal sensory interactions, this study contributes insights to perceptual psychology and motion graphic design, offering an understanding how designers can more effectively engage multiple sensory channels to enhance visual communication and emotional resonance.

Keywords: *synesthetic design, motion graphics, senses, animations.*

1. INTRODUCTION

Synesthesia, an uncommon neurological condition, is characterized by the involuntary elicitation of an additional perception—such as color—triggered by a primary stimulus characteristic, such as shape. This phenomenon serves as a foundational concept for understanding synesthetic design.

Synesthetic design represents an approach that explores and integrates the interconnectedness of multiple senses throughout the design process. This methodology aims to unify matter, shape, and content in a manner that appeals to diverse sensory modalities, thereby providing users with a multi-sensory experience (Hubbard, 2007). The focus extends beyond merely creating multisensory experiences; it encompasses a comprehensive understanding and harmonization of the relationships among different sensory attributes of a product or artifact (Van Campen, 2010.). This involves examining how various sensory qualities—such as sight, sound, touch, taste, and smell—can interact and complement one another to create a cohesive experience. Designers function as manipulators of the senses, working with various stimuli to achieve mutual harmony among them and evoke the human experience of reality. As articulated by Haverkamp, these intuitive strategies are grounded in cross-modal analogy, association, and symbolism that facilitate connections between the senses and enhance interpretability for users (Haverkamp, 2013).

A critical indicator of successful synesthetic design in motion graphics is its imperceptibility to the observer. The essence of this design lies in the harmonious synergy of sound, color, and movement, wherein none of these elements should dominate or distract from the primary message (Anceschi, 2000). Design, by its nature, appeals to our senses, which makes any kind of interaction and experience with a product unique and subject to further interpretation (Merter, 2017). Therefore, in developing high-quality synesthetic design, adherence to fundamen-

tal principles established through various scholarly studies is imperative. These principles include the judicious use of colors to elicit desired emotional responses, the harmonious integration of visual and auditory stimuli, and well-researched connections between colors and tastes (Spence, 2010). The importance of the product experience resulting from the interplay of senses demands for the development of new qualitative and quantitative research methods. The objective of this paper is to ascertain whether it is feasible to define a set of principles that accurately encapsulates formal elements, synesthetic possibilities, and animation techniques.

2. EXPERIMENTAL

To understand the interplay between sound, color, motion, and sensory attributes we made a breakdown of the key parameters and considerations for analysis:

- Colors: Red and blue were chosen as the two liquids. These colors are often associated with specific psychological and cultural meanings.
- Animation: The movement of the liquids illustrated five distinct fluid movements—stillness, rain, pouring, dripping, and splattering
- Sound: how well the sound matches the graphics in animations, as well as their descriptions of the pitch of the sound. Among the eighteen animations shown to participants, ten featured identical soundscapes while eight were differentiated by four higher tones and four lower tones.

2.1 Materials

To investigate this relationship, five animations depicting different fluid movements were created to assess their impact on subjects' multimodal perception (Table 1.). Each of five types of animations was designed in two colors: blue (B) and red (R). Then, different type of sound was added, suggesting the natural sound of flow. The pitch of sound was varied for still water and spraying.

Table 1: Stimuli (Animated Liquids): H- higher pitch of sound, L- lower pitch of sound

Animation type/sound		Link to animation
1. Still liquid/ Sound beneath the sea surface	B1	https://youtu.be/nb_UdkfmFCM
	R1	https://youtu.be/jDeJ-e3kpu4
	B1-H	https://youtu.be/K43dqfkEkAs
	B1-L	https://youtu.be/Ks-X6Cb2COg
	R1-H	https://youtu.be/GZwoE7oUA4M
	R1-L	https://youtu.be/-Lmxe1c5tQI
2. Rain/ The sound of rain	B2	https://youtu.be/JNS3e1fquSQ
	R2	https://youtu.be/v7wQOqaFTsM
3. Poring liquid/ Pouring sound	B3	https://youtu.be/-UDKqniKEec
	R3	https://youtu.be/aTNVCMaJS3I
4. Dripping/ Dripping sound	B4	https://youtu.be/jCwDDfNBH60
	R4	https://youtu.be/VmkXa5mFCE4
5. Spraying/ Liquid splash	B5	https://youtu.be/WOk7JbhGU28
	R5	https://youtu.be/y6S8M10TzvE
	B5-H	https://youtu.be/Ke5Ab4AglA0
	B5-L	https://youtu.be/ABxaqb5VLgo
	R5-H	https://youtu.be/2In0Q4uryiA
	R5-L	https://youtu.be/Bzz_kcgsJ1k

2.2 Methods

The study examined the interconnections among hearing and sight, within the context of motion graphics experiences. The subjects comprised a randomly selected group representing diverse ages, educational backgrounds, and cultural contexts. The experiment included a total of 37 participants: 22 from Croatia and 15 from other countries. Of the participants, 64.8 % (24) were bachelor and graduate students, 10.8 % (4) were postgraduate students, and 23.3 % (9) were employees. The total sample was comprised of 21,6 % male and 78.4 % female participants. Conducted via an online survey divided into two sections, the study aimed to determine how specific aspects of animation influenced viewer's experience. The first section's aim was to determine experience of sound related to the color and animation type, the second section's aim was related to the emotional perception and liquid's characteristic perception. The order of animation presentation was randomized for each respondent. The study combined forced-choice tasks (for perceived speed, strength, relaxation, and attractiveness) with scaled-response tasks (for sound, hardness, and warmth).

3. RESULTS WITH DISCUSSION

3.1 The sound matches the graphics of the animation

The first part of the research focused on participants' perceptions of how well the sound matches the graphics in animations (Table 2.), as well as their descriptions of the pitch of the sound (Table 3.). The data is divided into two sections:

1. Participants rated how well the sound matched the graphics using a Likert scale (1 = completely agree, 5 = completely disagree).

Table 2: Sound-Graphics Match.

Animation	Higher pitch of sound	AS	SD	Lower pitch of sound	AS	SD
still liquid	B1-H	2,03	0,87	B1-L	2,16	1,12
	R1-H	2,89	1,17	R1-L	2,46	1,04
spraying	B5-H	2,08	1,23	B5-L	2,00	1,31
	R5-H	2,14	2,14	R5-L	1,97	1,26

Participants perceived the match between sound and graphics differently depending on the color of the liquid and the pitch of the sound. Blue liquids were generally perceived as a better match for higher-pitched sounds in still liquid animations, while red liquids were perceived as a better match for lower-pitched sounds across all animations.

2. Participants described the pitch of the sound in the animations (1 = low, 5 = high).

Table 3: Pitch Description.

	Blue liquids	AS	SD	Red liquids	AS	SD
still liquid	B1	1,49	0,73	R1	1,54	0,73
rain	B2	3,38	0,89	R2	3,57	0,80
poring liquid	B3	3,57	0,77	R3	3,49	0,96
dripping	B4	3,46	1,22	R4	3,46	1,12
spraying	B5	3,65	0,79	R5	3,51	0,90
sum		15,55			15,57	

Still liquid animations were associated with low-pitched sounds, while dynamic animations (rain, pouring, dripping, spraying) were associated with moderately high-pitched sounds. Slight variations in pitch ratings were observed based on the color of the liquid.

3.2 Type of animation and color associations

The second part of research compared participants' perceptions of two animated liquids: red and blue. The attributes were: perceived speed (Table 4.), strength (Table 5.), relaxation (Table 6.), and attractiveness (Table 7.). The participants had to choose which one was perceived as quicker, stronger, more relaxed, and more attractive.

Table 4. Perceived speed

Animation	Blue liquids	points	Red liquids	points	I don't see the difference.
rain	B2	12	R2	7	18
poring liquid	B3	11	R3	6	20
dripping	B4	3	R4	8	26
spraying	B5	14	R5	13	20
sum		30		34	84

Table 5. Perceived strength

Animation	Blue liquids	points	Red liquids	points	I don't see the difference.
still liquid	B1	9	R1	13	15
rain	B2	10	R2	10	17
poring liquid	B3	15	R3	7	15
dripping	B4	6	R4	9	22
spraying	B5	13	R5	6	18
sum		29		47	72

Table 6. Perceived relaxation

Animation	Blue liquids	points	Red liquids	points	I don't see the difference.
still liquid	B1	25	R1	6	6
rain	B2	20	R2	8	9
poring liquid	B3	20	R3	7	10
dripping	B4	13	R4	8	16
spraying	B5	24	R5	6	7
sum		89		27	32

Table 7. Perceived attractiveness

Animation	Blue liquids	points	Red liquids	points	I don‘t see the difference.
still liquid	B1	19	R1	11	7
rain	B2	23	R2	8	6
poring liquid	B3	24	R3	6	7
dripping	B4	25	R4	6	6
spraying	B5	20	R5	11	6
sum		86		36	26

To determine if the preferences for red vs. blue are statistically significant for each attribute, we used chi-square test**.** The chi-square test revealed statistically significant differences in participants' preferences for red vs. blue liquids across all attributes. Blue is strongly associated with calmness and attractiveness, while red is slightly preferred for perceived speed and strength. The "I don't see the difference" option was frequently chosen, indicating that some participants did not perceive a clear distinction between the two colors for certain attributes (Table 8.).

Table 8. Preferences for red vs. blue liquids across all attributes

Attribute	**Blue Liquids**	**Red Liquids**	**I Don't see the Difference**	**Total**	**Chi-Square**
Perceived Speed	30	34	84	148	$\chi 2=36.71$, $p<0.05$
Perceived Strength	29	47	72	148	$\chi 2=18.84$, $p<0.05$
Calmness	89	27	32	148	$\chi 2=48.60$, $p<0.05$
Attractiveness	86	36	26	148	$\chi 2=42.07$, $p<0.05$

Additionally, the participants performed scaled-response tasks. They rated the hardness (1=soft, 5=hard) (Table 9.) and warmth (1=warm, 5=cold) (Table 10.) of the same animated liquids.

Table 9. Hardness ratings

Animation	blue	AS	SD	red	AS	SD
still liquid	B1	2,11	1,05	R1	2,22	1,00
rain	B2	2,43	1,14	R2	3,24	1,30
poring liquid	B3	2,11	1,13	R3	2,08	0,98
dripping	B4	2,05	1,18	R4	2,59	1,19
spraying	B5	3,14	1,27	R5	2,05	1,20
sum		11,84			12,18	

Table 10. Temperature ratings

Animation	blue	AS	SD	red	AS	SD
still liquid	B1	4,16	1,17	R1	2,19	1,35
rain	B2	4,22	1,11	R2	2,59	0,93
poring liquid	B3	3,81	1,20	R3	2,57	1,07
dripping	B4	3,59	0,98	R4	2,41	1,01
spraying	B5	3,89	0,77	R5	2,49	1,19
sum		19,67			12,25	

To analyze the data provided in the Likert-scale responses for hardness and warmth, we performed paired t-tests (if the data meets the assumptions of normality). We also calculated effect sizes using Cohen's d to assess the magnitude of the differences between red and blue liquids.

- Hardness: Red liquids are perceived as harder in some conditions (rain, dripping), while blue liquids are perceived as harder in others (spraying).
- Warmth: Blue liquids are consistently perceived as colder than red liquids across all conditions, with large effect sizes.

By performing these analyses, we can conclude that there are significant differences in how participants perceive the hardness and warmth of red and blue liquids, with warmth showing a stronger and more consistent effect.

To find out more whether participants' preferences for red or blue liquids are correlated with their ratings of hardness and temperature we performed a correlational analysis and a subgroup analysis of the data obtained by forced choice and Likert scale methods. The results suggested that color preferences influence participants' perceptions of hardness and temperature, but the relationships are relatively weak. Hardness perceptions are significantly influenced by color preferences. Participants who prefer a particular color tend to perceive liquids of that color as harder. The regression analysis reveals that temperature perceptions may be less strongly influenced by color preferences compared to hardness perceptions. These findings suggest that color preferences play a stronger role in shaping perceptions of hardness compared to temperature. Further research with a larger sample size and additional variables could provide more robust insights.

4. CONCLUSIONS

Our research unveils the intricate relationships between sound, color, and liquid animation dynamics, challenging simplistic perceptual mapping theories. The study demonstrates that color-sound associations are profoundly context-dependent, with blue liquids consistently linked to calmness and higher-pitched sounds in still animations, while red liquids correlate with warmth, strength, and lower-pitched sounds. Movement type significantly modulates these perceptual interpretations, revealing that slower animations emphasize hardness and controlled characteristics, whereas faster, more chaotic movements blur traditional color-attribute associations. Notably, spraying animations represent a perceptual "neutral zone" that challenges established categorizations. The results suggested that color preferences influence participants' perceptions of hardness and temperature, but the relationships are relatively weak.

These findings contribute to our understanding of cross-modal perception of animated liquids, suggesting that sensory experiences are more fluid and interconnected than previously understood. By illuminating how sound pitch, color, and animation dynamics interact, the research provides valuable insights for design, user experience, and cognitive psychology, highlighting the sophisticated, non-linear ways in which humans interpret sensory information. While providing significant insights, the study acknowledges the need for further investigation into: cultural variations in color-sound perception, neurological mechanisms underlying these cross-modal associations and potential.

5. REFERENCES

Anceschi G., Riccò D. (2000.) Research of Communication Design: a synesthetic approach, URL: https://www.researchgate.net/profile/Dina-Ricco/publication/265655354_Research_of_Communication_Design_a_synesthetic_approach/links/5444da470cf2e6f0c0fbd0ea/Research-of-Communication-Design-a-synesthetic-approach.pdf (last accessed on 28. 11. 2024)
Haverkamp M. (2013.) Synesthetic design; Handbook for a multisensory approach, Birkhäuser, Basel.
Hubbard E. M. (2007.) Current Psychiatry Reports; Neurophysiology of synesthesia, vol. 9., no. 3., 193 – 199., URL: https://doi.org/10.1007/s11920-007-0018-6 (last accessed on 28. 11. 2024)
Merter S. (2017.) Synesthetic approach in the design process for enhanced creativity and multisensory experiences, URL: https://www.tandfonline.com/doi/pdf/10.1080/14606925.2017.1352948 (last accessed on 22.05.2024.)
Spence C. (2019.) On the relationship(s) between color and taste/flavor, URL: https://econtent.hogrefe.com/doi/full/10.1027/1618-3169/a000439 (last accessed on 28. 11. 2024)
Van Campen C. (2010.) The hidden sense: Synesthesia in art and science, The MIT Press, London.

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ORAL PRESENTATION

EXPLORING AI-DRIVEN PERSONALISATION FOR EMOTIONAL DESIGN: THE IMPACT OF CUSTOM CONTENT ON EMOTIONAL CONNECTION

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Abstract: *The paper investigates how three personalisation strategies influence user emotional response, satisfaction, and privacy concerns. We experimented with three conditions: (A) Minimal personalisation, (B) Relevant preference-based personalisation, and (C) Extended personalisation with a feedback option. In a within-subjects design, 28 participants interacted with tailored suggestions. The SAM (Self-Assessment Manikin) and post-treatment questionnaires were used to measure the emotional responses. Findings suggest that Version C led to the most satisfaction and engagement whilst reducing discomfort compared to Version B, although extended personalisation also amplified privacy concerns. The study also highlights the critical role of digital literacy and AI experience, showing that users with greater familiarity with AI tools are more open to sharing data and reporting better overall experiences. These findings underscore the importance of balancing personalisation with user control and algorithm transparency to optimise AI-driven systems while addressing risks such as filter bubbles and privacy-related anxiety.*

Keywords: *mass personalisation, emotion design, AI-driven design, user experience*

1. INTRODUCTION

Emotional design, one of the fundamental concepts underlying user experience, has been explored through the psychological and emotional aspects of user interaction with the interface. Norman (2004) defines emotional design as a tool that evokes positive emotional states, while Hassenzahl and Tractinsky (2011) highlight its ability to enhance users‘ perceptions of a system‘s usefulness. Desmet and Hekkert (2007) offer a framework for analysing product experience, considering three dimensions: affective, cognitive, and behavioural. These studies indicate a shift from the previous emphasis on functionality toward a more holistic approach that integrates users‘ emotional and mental needs.

In the context of mass personalisation, Tseng and Jiao (2001) define mass customisation as constrained combinations of predetermined choices, whereas Kumar (2007) emphasises that generative AI has enabled real-time, data-driven individualisation. Zhou, Ji, and Jiao (2013) further develop this concept by stressing the importance of emotional patterns in designing personalised interfaces. Real-world examples include Spotify, which leverages AI to generate customised playlists, and Netflix, whose algorithms recommend content based on viewing history, showcasing the practical application of these ideas.

The ethical concerns of mass personalisation have been widely studied. The privacy–personalisation paradox, explored by Awad and Krishnan (2006), reveals that users simultaneously seek personalisation while fearing data exploitation. Acquisti, Brandimarte, and Loewenstein (2015) further suggest that increased privacy awareness can heighten resistance to personalisation, even when it enhances user experience. Additional phenomena, such as algorithm aversion (Dietvorst et al., 2015) and overtrust (Buçinca et al., 2021), highlight the complex relationship between users and AI, while the risks of filter bubbles and echo chambers (Flaxman et al., 2016) point to the dangers of limited information diversity. Ribeiro, Singh, and Guestrin (2016) examine the trade-offs between explainability and algorithmic accuracy, emphasising the need for transparency in personalised recommendations.
Although extensive research exists on emotional design and AI-driven personalisation, a notable gap exists in

exploring their synergy, particularly from an ethical perspective. For example, the impact of different personalisation modalities on affective connection and the long-term implications of intrusive data collection are still unclear. These gaps highlight the need for an interdisciplinary approach integrating design, ethics, and technological advancements.

The main objective of this study is to examine the effect of personalisation level on user satisfaction, level of engagement, and subjective discomfort. The study also investigates the impact of greater control over recommendations on the general level of user experience.

From this, the following fundamental questions emerge:
RQ1: How does the emotional reaction of users change while moving from minimal to intensive personalisation?
RQ2: How does the perceived discomfort result from increased personalisation level?
RQ3: How does the ability to change recommendation types or request alternative content affect user satisfaction and potentially mitigate the filter bubble effect?
RQ4: How do digital literacy and prior experience with AI tools influence users‘ openness to sharing personal data, their engagement with recommendation systems, and their overall user experience?

These questions relate to the privacy–personalisation paradox and related phenomena under emotional design, including algorithm aversion and overtrust in AI systems. The study also examines whether greater transparency, showing users recommendations beyond their usual preferences, and introducing a feedback mechanism can reverse the risks of creating „bubbles“ (filter bubble/echo chamber). The answers to these questions are expected to indicate the optimal balance between personalisation level and adequate user control over recommendations while easing users‘ discomfort and ensuring content variety.

2. METHOD

2.1 Participants

The experiment involved 28 participants (17 women and 11 men), all university graduates aged between 24 and 41. They reported extensive use of web and mobile applications, which aligned with a high average self-assessment of digital literacy (M = 4.57 on a 1–5 scale). However, their experience with AI tools such as ChatGPT and Gemini was comparatively lower (M = 3.6 on a 1–5 scale). Participants were informed about data usage and privacy measures and could withdraw from the study anytime.

2.2 Test environment

A specialised Custom GPT was developed using a paid ChatGPT Plus subscription, featuring:

- custom instructions governing the experimental flow and data handling, ensuring that all data would be erased after the study,
- an internal knowledge base designed to generate brief personalised messages and recommendations for each experiment version and
- privacy safeguards to ensure that personalised content was stored only during the experiment and permanently deleted afterwards.

The Custom GPT was instructed to address users by name, maintaining a casual and friendly tone, with optional emojis or icons (see Figure 1).

The study explores three levels of personalisation—Version A, B, and C—to assess how varying degrees of customisation and user control impact emotional responses, satisfaction, and perceptions of fairness.
Version A offers minimal personalisation, addressing users by name but providing only generic recommendations based on demographic data. This approach tests whether basic personalisation cues, like name recognition, can generate positive emotional responses without deeper customisation.
Version B introduces a more relevant personalisation level by incorporating demographic and preference data. Recommendations are explicitly linked to user history (e.g., „Because you watched X, we think you would enjoy Y“), which helps reduce the „black box“ effect, enhancing both trust and relevance.
Version C builds upon Version B by integrating feedback mechanisms and allowing users to explore alternative

recommendation categories (e.g., sports events, concerts). Users receive prompts like, „Would you like more of these or completely different suggestions?“ This version emphasises transparency and user control to address privacy concerns and reduce discomfort associated with excessive personalisation.

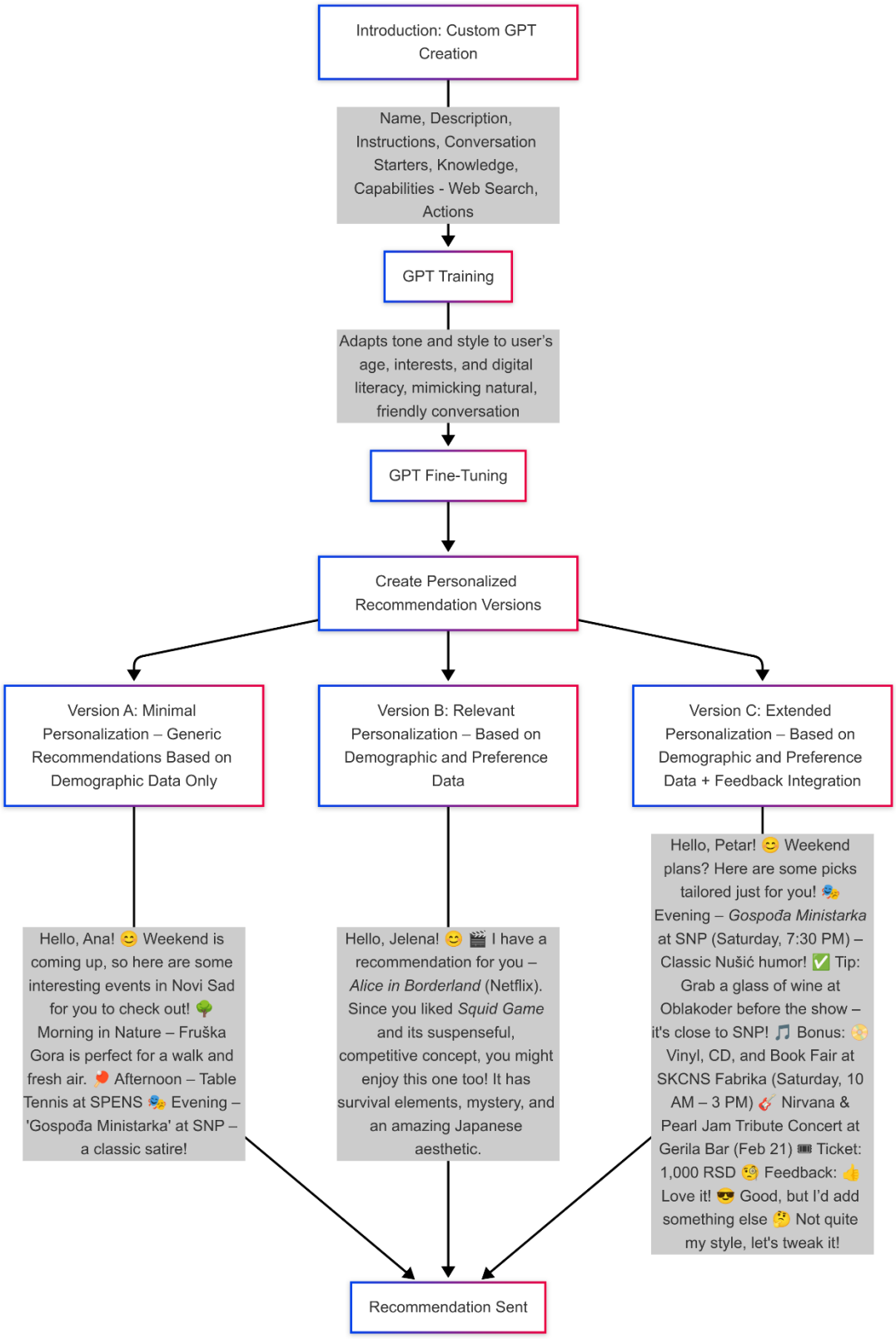


Figure 1: The Custom GPT training flow

2.3 Experiment Design

The experiment‘s flow, presented in Figure 2, had the following steps:

1. Pre-Survey

After reading and accepting the consent form, participants completed a pre-survey to provide demographic information, including their ID, age (24–42), frequency of using personalised apps (**TehUsage**, 1–5 scale), and self-assessed AI knowledge (**AISkill**, 1–5 scale). Following this, GPT collected detailed user preferences, such as weekend activities, leisure routines, entertainment habits, favourite movies, directors, actors, musicians, podcasts, and news sources.

2. Presentation of Each Version (A, B, C)

For each level of personalisation (A, B, and C), participants were presented with three recommended items across different categories, including music/podcasts, films/books, and weekend events. They spent approximately 2–3 minutes reviewing each set of recommendations.

3. Post-Treatment (Per Version) Survey

After viewing each version‘s recommendations, participants completed a short post-treatment questionnaire, which included:

- **The Self-Assessment Manikin (SAM)** (Bradley & Lang, 1994) to measure:
  - **Valence** (1 = very unpleasant, 5 = very pleasant)
  - **Arousal** (1 = calm, 5 = excited)
- **Satisfaction Measure (1–5 Likert Scale)**:
  - *“I am satisfied with the recommendations I just received.”*
- **Discomfort Measure (1–5 Likert Scale)**:
  - *“I felt uneasy during these recommendations.”*

The order of personalisation levels (A, B, and C) was randomised to prevent sequence bias.

4. Final (Post-Experiment) Questionnaire

The final questionnaire was divided into three sections:

- **User Experience Questionnaire (UEQ-S)**: A short version with eight items, each rated on a 1–7 scale using pairs of opposite adjectives:
  - Unclear (1) – Clear (7)
  - Clumsy (1) – Graceful (7)
  - Unreliable (1) – Reliable (7)
  - Conventional (1) – Innovative (7)
  - Boring (1) – Exciting (7)
  - Unattractive (1) – Attractive (7)
  - Not entertaining (1) – Entertaining (7)
  - Demotivating (1) – Motivating (7)

- **Privacy & Data Sharing Items (1–5 Likert Scale)**, adapted from **IUIPC** (Malhotra, Kim & Agarwal, 2004) and the **privacy-personalisation paradox** (Awad & Krishnan, 2006), including statements such as:
  - *“I believe using my data for this type of personalisation is justified.”*
  - *“I am willing to share my data in the future for better recommendations.”*
  - *“I would like more control over which data is used for generating recommendations.”*

- **Open-Ended Questions:**
  - *“Which level of personalisation did you find most pleasant and why?”*
  - *“Which one irritated or bothered you the most?”*

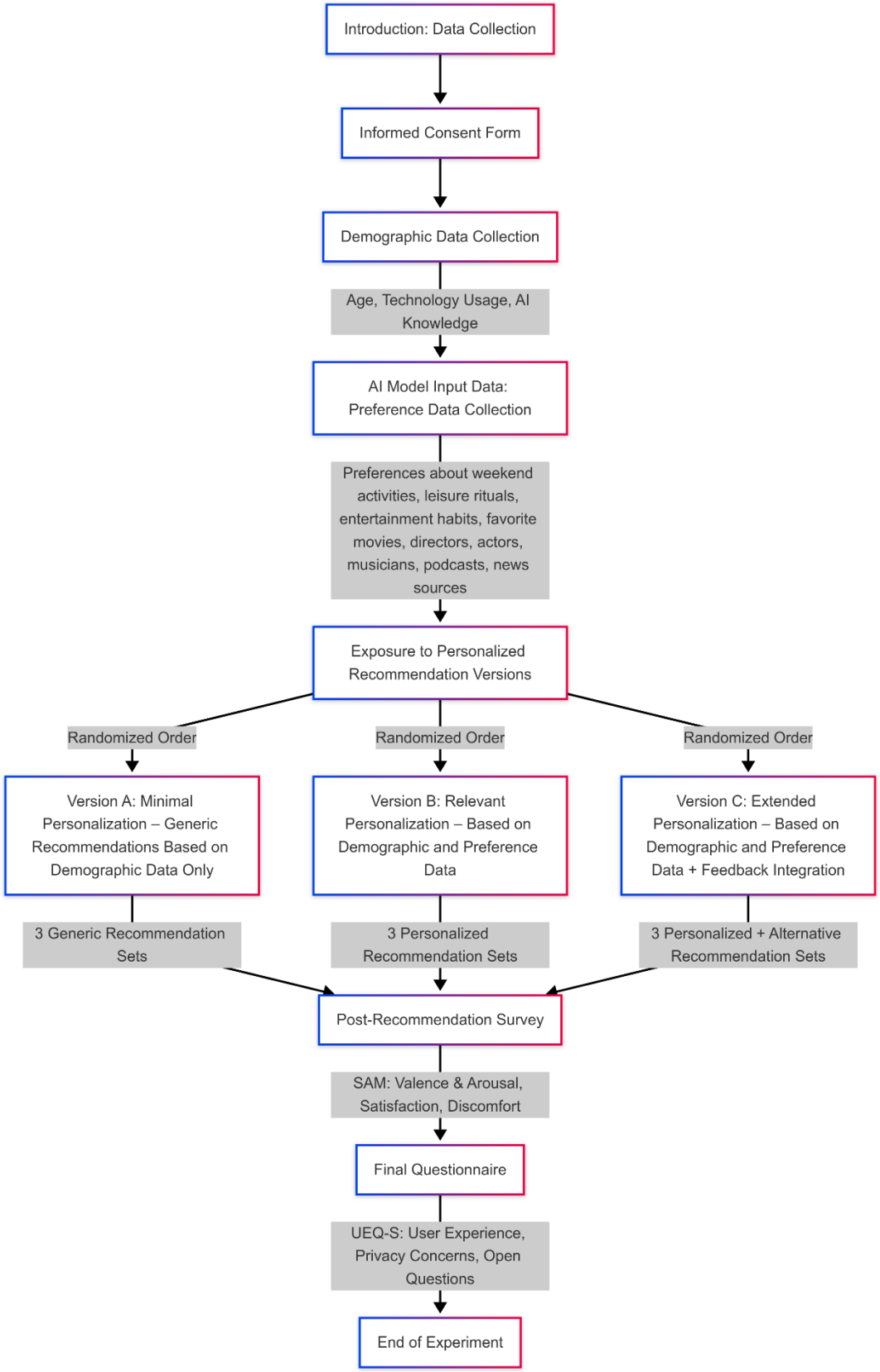


Figure 2: The experiment design

3. RESULTS AND DISCUSSION

The collected data was organised into a CSV file with the following columns:

- Demographic & pre-study data:
  - **TehUsage** – Frequency of using personalised applications (1–5 scale)
  - **AISkill** – Self-assessed AI knowledge (1–5 scale)
- Post-treatment data (Per Version A, B, C):
  - **A_Val, A_Aro, A_Sat, A_Dis** – Valence, Arousal, Satisfaction, and Discomfort scores for Version A
  - **B_Val, B_Aro, B_Sat, B_Dis** – Corresponding scores for Version B
  - **C_Val, C_Aro, C_Sat, C_Dis** – Corresponding scores for Version C
- User Experience Questionnaire (UEQ-S) items:
  - **UEQ1 – UEQ8** – Responses to the 8-item short version of the UEQ
- Privacy Concerns Responses:
  - **PC1, PC2, PC3** – Likert scale responses to privacy and data-sharing statements
- Open-Ended Responses:
  - **Open1, Open2** – Responses to the two open-ended questions

A repeated-measures ANOVA was conducted to analyse the effects of the three versions (A, B, and C) on four dependent variables: valence, arousal, satisfaction, and discomfort. All measures were averaged across three scenarios to provide reliable estimates of version effects.

Valence Ratings
A significant main effect of version was found: $F(2, 54) = 9.61$, $p < .001$, $\eta^2_\gamma = .089$. Post-hoc comparisons using Bonferroni correction revealed:
Version C ($M = 4.81$, $SD = 0.21$) elicited significantly higher valence ratings than Version A ($M = 4.54$, $SD = 0.46$, $p = .002$) and Version B ($M = 4.68$, $SD = 0.38$, $p = .040$). Practically, Version C is shifting users from a neutral-pleasant to a pleasant experience on the 5-point scale.

Arousal Ratings
Mauchly's test indicated a violation of sphericity ($W = 0.76$, $p = .028$), so Greenhouse-Geisser corrections were applied ($\varepsilon = 0.81$).
The analysis revealed a significant main effect of version: $F(2, 54) = 30.87$, $p < .001$, $\eta^2_\gamma = .183$.
Post-hoc comparisons showed that:
Version C ($M = 4.40$, $SD = 0.42$) and Version B ($M = 4.26$, $SD = 0.43$) both induced significantly higher arousal than Version A ($M = 3.90$, $SD = 0.50$, $p < .001$ for both). Version C also aroused substantially higher arousal than Version B ($p = .034$). This significant effect shows that the richer, interactive feed in Version C grabs attention far more effectively.

Satisfaction Ratings
A significant main effect of the version was observed: $F(2, 54) = 25.06$, $p < .001$, $\eta^2_\gamma = .150$.
Post-hoc analyses revealed:
Version C ($M = 4.82$, $SD = 0.31$) and Version B ($M = 4.69$, $SD = 0.42$) resulted in significantly higher satisfaction than Version A ($M = 4.42$, $SD = 0.49$, both $p < .001$).
The difference between Version B and Version C was close to but did not reach statistical significance ($p = .056$). A 0.40point jump (1–5 scale) from A to C is practically the difference between "mostly satisfied" and "very satisfied."

Discomfort Ratings
A significant main effect of the version was found: $F(2, 54) = 5.48$, $p = .007$, $\eta^2_\gamma = .041$.
Post-hoc comparisons showed:
Version B ($M = 1.88$, $SD = 0.32$) induced significantly higher discomfort than Version C ($M = 1.70$, $SD = 0.41$, $p = .010$). Although significant, the absolute gap (≤0.18/5) is small; Version C's transparency almost erases the discomfort spike in Version B. With η^2=.041, the absolute effect is mild, so designers should monitor discomfort qualitatively, not rely solely on mean scores.
Version A ($M = 1.74$, $SD = 0.41$) did not significantly differ from either B or C (all $p > .093$).

Correlation Analysis
All correlations were statistically significant at $p < 0.001$, showing robust positive linear relationships between participants' pre-survey scores and post-experiment evaluations (Figure 3).

For DIG_LIT (Digital Literacy Score), the strongest correlations were with UEQ1 ($r = 0.805$) and UEQ4 ($r = 0.731$). For AI_EXP (AI Experience Score), even stronger correlations were found (e.g., UEQ4: $r = 0.913$, UEQ1: $r = 0.904$). Practically, each extra point of digital literacy directly boosts perceived UX quality.

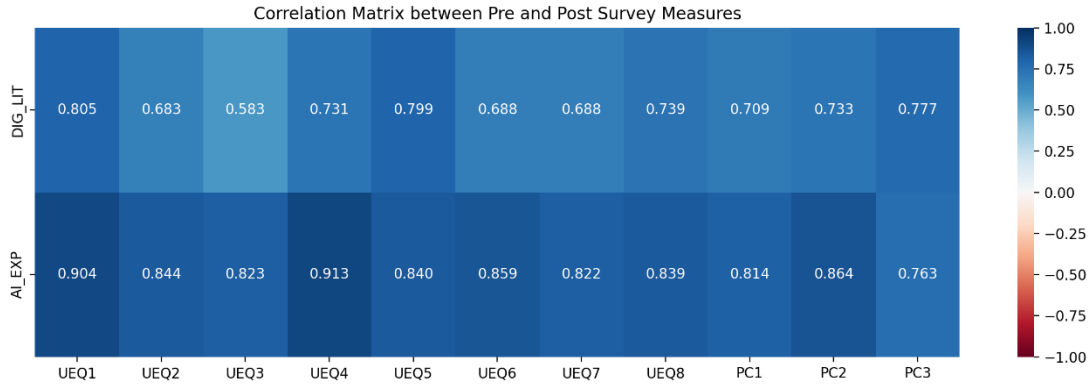


Figure 3: Correlation matrix between pre-survey and post-survey measures

RQ1: How does the emotional reaction of users change while moving from minimal to intensive personalisation?
Version C (extended personalisation with feedback) received the highest ratings for satisfaction and engagement without significantly increasing discomfort. This suggests that richer personalisation enhances user experience. However, some users reported increased discomfort when they realised the system „knew more" about them (Versions B and C). In practice, even modest feedback integration (Version C) upgrades the experience from "useful" to "desirable" without a parallel rise in discomfort.

RQ2: How does the perceived discomfort result from increased personalisation level?
Greater personalisation and data access increased discomfort, especially in Versions B and C. This aligns with the privacy–personalisation paradox, where users appreciate relevant recommendations but feel uneasy about how their data is used (Awad & Krishnan, 2006). Notably, Version C caused less discomfort than Version B, implying that transparency and feedback mechanisms help reduce user anxiety (Ribeiro, Singh & Guestrin, 2016).

RQ3: How does the ability to change recommendation types or request alternative content affect user satisfaction and potentially mitigate the filter bubble effect?
When it comes to user control over recommendations (RQ3), participants responded positively to features such as „show something else" and „I do not like this recommendation." These findings align with research on algorithm aversion (Dietvorst et al., 2015), highlighting that giving users the ability to influence content selection and correct AI-generated suggestions enhances perceptions of fairness and engagement (Buçinca et al., 2021).
Additionally, introducing alternative recommendations in Version C—offering content outside users' typical preferences—appears promising in mitigating the filter bubble effect. By exposing users to a more diverse range of content, Version C not only enhances satisfaction but also reduces the likelihood of users being trapped in narrow informational „bubbles."
The discomfort values were very low (between 1.70 and 1.88 on a scale of 1 to 5), which can be explained by the fact that the participants knew that the algorithm used only the data that they had previously entered voluntarily in the pre-survey experiment part.

RQ4: How do digital literacy and prior experience with AI tools influence users' openness to sharing personal data, their engagement with recommendation systems, and their overall user experience?
Users with higher digital literacy and AI experience rated personalised systems more positively in clarity, reliability, and satisfaction. These users were also more open to sharing personal data, agreeing with statements like „Using my data for personalisation is justified" and „I am willing to share data for better recommendations." This suggests that familiarity with AI fosters trust in data-driven personalisation.

However, even among these users, there was a strong preference for control over data usage, reinforcing concerns about the privacy–personalisation paradox. The statement „I would like more control over which data is used for recommendations“ received strong agreement, emphasising the need for transparent and user-controlled personalisation systems.

The within-subjects design allowed participants to experience all three levels of personalisation, strengthening statistical power and clarifying the privacy–personalisation paradox in emotional design. However, the small sample size (28 participants) and short-term exposure limit the robustness of findings. Future studies should expand demographic diversity and increase interaction time with AI systems to assess long-term effects like habituation and shifts in privacy attitudes. Furthermore, considering the spotted connection between algorithm transparency and level of discomfort, future studies should consider the scenarios where participants do not know what data was used for training the AI model.

4. CONCLUSION

The study results emphasise balancing personalisation depth with user control and transparency. As observed in Version C, which offered the most expansive personalisation and feedback mechanisms, users expressed higher satisfaction and engagement when given more control over the system. However, these benefits come with an increased need to address privacy concerns and discomfort, suggesting an optimal mix of personalisation levels and transparency to enhance the overall experience. Furthermore, the research highlights the importance of digital literacy and AI experience in determining user openness to sharing information and interacting with the recommendation system. These insights contribute to a deeper understanding of how AI-driven personalisation can be optimised to create positive user experiences while alleviating risks such as filter bubbles and privacy-related anxiety.

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6. REFERENCES

Acquisti, A., Brandimarte, L. and Loewenstein, G. 2015. „Privacy and Human Behavior in the Age of Information.“ *Science* 347(6221): 509–514. https://doi.org/10.1126/science.aaa1465

Awad, N. F. and Krishnan, M. S. 2006. „The Personalization Privacy Paradox: An Empirical Evaluation of Information Transparency and the Willingness to Be Profiled Online for Personalization.“ *MIS Quarterly* 30(1): 13–28. https://doi.org/10.2307/25148715

Bradley, M. M., & Lang, P. J. (1994). „Measuring Emotion: The Self-Assessment Manikin and the Semantic Differential,“ *Journal of Behavior Therapy and Experimental Psychiatry*, 25(1), pp. 49–59. https://doi.org/10.1016/0005-7916(94)90063-9

Buçinca, Z., Malaya, M. B. and Gajos, K. Z. 2021. „To Trust or to Think: Cognitive Forcing Functions Can Reduce Overreliance on AI in AI-Assisted Decision-Making.“ *Proceedings of the ACM on Human-Computer Interaction* 5(CSCW1): 1–21. https://doi.org/10.1145/3449287

Desmet, P. M. A. and Hekkert, P. 2007. „Framework of Product Experience.“ *International Journal of Design* 1(1): 57–66. https://www.ijdesign.org/index.php/IJDesign/article/view/66

Dietvorst, B. J., Simmons, J. P. and Massey, C. 2015. „Algorithm Aversion: People Erroneously Avoid Algorithms After Seeing Them Err.“ *Journal of Experimental Psychology: General* 144(1): 114–126. https://doi.org/10.1037/xge0000033

Flaxman, S., Goel, S. and Rao, J. M. 2016. „Filter Bubbles, Echo Chambers, and Online News Consumption.“ *Public Opinion Quarterly* 80(S1): 298–320. https://doi.org/10.1093/poq/nfw006

Hassenzahl, M. and Tractinsky, N. 2011. „User Experience — A Research Agenda.“ *Behaviour & Information Technology* 25(2): 91–97. https://doi.org/10.1080/01449290500330331

Kumar, A. From mass customisation to mass personalisation: a strategic transformation. *Int J Flex Manuf Syst* **19**, 533–547 (2007). https://doi.org/10.1007/s10696-008-9048-6

Malhotra, Naresh & Kim, Sung & Agarwal, James. (2004). Internet Users‘ Information Privacy Concerns (IUIPC): The Construct, the Scale, and a Causal Model. Information Systems Research. 15. 336-355. https://doi.org/10.1287/isre.1040.0032

Norman, D. A. 2004. *Emotional Design: Why We Love (or Hate) Everyday Things*. New York: Basic Books.

Tseng, M. M. and Jiao, J. 2001. „Mass Customization.“ In *Handbook of Industrial Engineering: Technology and Operations Management*, edited by G. Salvendy, 684–709. New York: Wiley.

Ribeiro, M. T., Singh, S. and Guestrin, C. 2016. „Why Should I Trust You?: Explaining the Predictions of Any Classifier.“ *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, 1135–1144. https://doi.org/10.1145/2939672.2939778

Zhou, F., Ji, Y. and Jiao, R. J. 2013. „Affective and Cognitive Design for Mass Personalization: Status and Prospect.“ *Journal of Intelligent Manufacturing* 24(5): 1047–1069. https://doi.org/10.1007/s10845-012-0673-2

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POSTER PRESENTATION

ANALYSIS OF THE RELEVANCE AND APPEAL OF THE VISUAL PRESENTATION OF MEAT PRODUCTS GENERATED USING ARTIFICIAL INTELLIGENCE

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Abstract: *Meat and meat products play a crucial role in a balanced diet, with consumers relying heavily on visual appeal. This study examines the accuracy of generative AI in the visualisation of meat products, hypothesising that AI-generated images cannot yet replace real photographs. Images of various meat products were created using Adobe Firefly 3 and evaluated by food technology professionals. The survey results show that AI-generated images of commonly advertised products such as burgers (82% approval) and prosciutto (67% approval) were relatively accurate, while complex products such as mortadella (9% approval) and beef tartare (19% approval) were considered unrealistic in terms of colour, texture and composition. The most common problems included inaccurate colour representations, cross-section details and plate arrangement. The results highlight the limitations of artificial intelligence in professional food photography and emphasise the need for skilled photographers. While AI can create visually appealing images, its lack of accuracy makes it unsuitable for demanding applications in the food industry. Future advancements may enhance AI's reliability, but until then, professional photography remains essential for precise representation of meat products.*

Keywords: *artificial intelligence, meat products, food industry, food photography, visual presentation*

1. INTRODUCTION

Meat and meat products are essential for a balanced diet (NIJZ). As consumers rely heavily on visual appeal when buying, sensory perception plays an important role.

Generative AI, which is increasingly being integrated into everyday life, enables users to create images, videos and code based on text prompts. Research focuses primarily on the distinction between AI-generated images and conventional photographs (Misal, 2024). As sensory perception influences food choices, consumers often rely on appearance, especially when they are unfamiliar with a product (Mugge, 2018).

This research explores how well generative AI represents meat products. The hypothesis is that AI cannot yet fully replace real images of meat products. The objectives include generating AI images of meat products and assessing their accuracy by surveying food professionals.

1.1. Artificial intelligence

The first AI definition dates back to 1955 (John McCarthy), but Elaine Rich later provided a more precise one: "*Artificial intelligence is the study of how to make computers do things at which, at the moment, people are better.*" (Ertel, 2024) Early AI systems were rule-based and supported decision-making through expert systems and knowledge bases. AI encompasses various computer algorithms that replicate human intelligence, including pattern recognition, language processing, decision making and learning. (Banh, 2023)

Machine learning, a central subfield of AI, enables systems to learn from data and improve their performance over time. (Janiesch, 2021) It includes unsupervised learning (finding patterns in unlabelled data), supervised learning (training on labelled data for predictions) and reinforcement learning (learning by interacting with the environment). (Banh, 2023)

Deep learning, a branch of machine learning inspired by the human brain, uses artificial neural networks to process one-dimensional data such as text, but also high-dimensional data such as images and videos. (Angelova, 2024; Banh, 2023)

1.2. Generative AI

Unlike earlier AI, which focused on recognition, generative AI creates new content — text, images, video, sound and code—mimicking human creativity. Its rapid rise since 2022 with ChatGPT-3 has opened up new possibilities, but also raised various concerns about job displacement, etc. (Wessel, 2024)

Generative tools such as DALL-E, Stable Diffusion and Adobe Firefly allow users to generate images without much design skills, with Firefly 2 standing out for its realism (Banh, 2023; Angelova, 2024). Adobe Firefly allows users to create images, illustrations and videos by inserting a prompt in over 100 languages and adjusting various settings. It sources data from Adobe Stock, ensuring licensed use (Adobe, 2024).

However, despite constant progress, AI still struggles with complex multi-object compositions (Frolov, 2021). Research on AI-generated images focuses more on appeal than accuracy. Studies show that people prefer AI images until they learn their origin, which causes scepticism, especially among older generations (Califano, 2024; Zeleny, 2024).

AI also raises ethical concerns, from job loss to data sourcing. Human oversight methods like crowdsourcing and expert-in-the-loop approaches aim to align AI with ethical standards (Kirova, 2023). In graphics, deepfakes pose major risks, violating human rights and spreading misinformation, prompting UNESCO and the EU to establish ethical guidelines (Kirova, 2023).

1.3. Meat as a sales item

The role of meat in human nutrition makes the choice of quality crucial (Šubic, 2022). Vision plays a decisive role in the perception of food and influences the first impression through colour, contrast and symmetry (Jelinčić, 2023). The association of colours with objects begins early in our cognitive development. Colour is the most important sensory attribute of food and is often directly related to the perceived quality of a product. (Clydesdale, 1991) Consumers often judge product quality when shopping based on sensory attributes such as smell and appearance. (Šubic, 2022)

Colour psychology plays an important role in the food industry. A study from the 1970s found that blue steaks and green fries caused nausea in participants under normal lighting, indicating an instinctive aversion to unnatural food colours (Jahnke, 2018). The appearance of food products is crucial. Certain additives can significantly enhance their appearance. (Šubic, 2022)

Due to various attractiveness factors, photos of meat dishes and products must show appealing, typical and expected shades and colours to attract buyers.

1.4. Food Photography

In food photography, composition, lighting and colour are taken into account, with the lighting enhancing the appeal. In commercial photography, the photographer also edits the image after it has been taken, paying particular attention to the colours to make them more attractive to buyers. Post-processing requires high-quality photos, so photographers need to know the lighting characteristics when taking the images. (Štampfl, 2024).

The integration of AI is increasing in the food industry, e.g. in creating recipes and understanding customer preferences. However, despite successful integration, the images generated by AI in this area are still considered unreliable. This is partly due to the high visual standards set by advertising agencies when promoting food. These representations are often heavily edited, creating a gap between reality and expectations. (Ong, 2024)

When photographing meat products, in addition to general requirements such as the right lighting, composition and angle, special attention must be given to colour and texture. The meat product should be easily recognisable and meet all quality standards. Evaluating the correct appearance of meat products is a complex process. (Šubic, 2022)

2. EXPERIMENTAL

To evaluate the accuracy of AI-generated images of meat products, we implemented a two-stage experimental approach: Image generation and expert evaluation. The aim of the study was to determine whether generative AI can accurately represent various meat products.

First, a selection of meat products with distinct sensory properties was made to ensure a diverse evaluation. Adobe Firefly 3 was then used to generate images, which were then evaluated in a survey of the industry professionals based on criteria such as colour, shape, texture and overall presentation.

2.1. Generating images

The AI-generated images were generated with Adobe Firefly 3. The prompts were inserted in English with appropriate wording for various meat products. To achieve optimal results, the images were generated 3-5 times and the prompts for each product were corrected where necessary.

2.2. Survey

The survey was conducted on the website 1ka to examine the accuracy of AI-generated images of meat products. We focused on the colour, shape, texture and arrangement of the products on the plate. Our target group were food technology professionals with good eyesight or corrective aids.

During the survey, the food technology professionals evaluated the sensory properties of AI-generated images of meat products. Twenty-two suitable people took part in the survey, while four people were excluded due to incorrect profession or poor eyesight without visual aids.

Firstly, respondents determined whether each image was professionally accurate or not. If they considered it unsuitable, they specified the reason why, choosing from colour, shape, cross-section composition, appearance of the plate or a comment of their own.

3. RESULTS WITH DISCUSSION

Figs. 1–10 show images of meat products, created with Adobe Firefly 3, that were part of the survey for food industry professionals.



Figure 1: AI-generated image of burger



Figure 2: AI-generated image of prosciutto



Figure 3: AI-generated image of chicken skewers

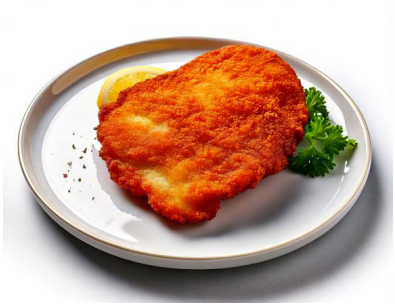


Figure 4: AI-generated image of Wiener Schnitzel



Figure 5: AI-generated image of steak



Figure 6: AI-generated image of Carniolan sausage



Figure 7: AI-generated image of dry salami



Figure 8: AI-generated image of hot dog



Figure 9: AI-generated image of beef tartare



Figure 10: AI-generated image of mortadella

Table 1 shows the results of the survey. It includes the percentages of people who rated the images as appropriate or inappropriate, as well as the main issues they found.

Table 1: Appropriateness of AI-generated images of meat products

Figure number	Meat product	**Appropriate image**	**Inappropriate image**	**Main issues**
1	Burger	82%	18%	- Colour, - shape.
2	Prosciutto	67%	33%	- Colour, - plate appearance, - cross-section.
3	Chicken skewers	59%	41%	- Colour, - shape, - plate appearance (too perfect).
4	Wiener schnitzel	57%	43%	- Colour, - plate appearance.
5	Steak	50%	50%	- Colour, - shape, - cross-section, - plate appearance.
6	Carniolan sausage	36%	64%	- Colour, - shape, - missing skewer.
7	Dry salami	29%	71%	- Colour, - shape, - cross-section, - too thick slices.
8	Hot dog	29%	71%	- Colour, - plate appearance, - artificial casing.
9	Beef tartare	19%	81%	- Colour, - texture, - shape, - unrealistic appearance.
10	Mortadella	9%	91%	- Colour, - cross-section, - missing fat particles.

In Fig. 1, 87% of participants found the burger's presentation accurate, but 18% criticized the meat patty's colour and shape.

Fig. 2 shows prosciutto, which 33% deemed unsuitable for professional use, citing issues with colour, plate appearance, and cross-section composition.

In Fig. 3, 41% found the chicken skewers inaccurate, mainly because of their colour, shape, and plate appearance. Some commented that they looked "too perfect" and that the colour made them appear as a lower-quality product.

Fig. 4 shows a Wiener Schnitzel or breaded veal slice. 57% of experts approved of its presentation, while 43% found the colour and plate appearance unsuitable.

Half of the participants considered the steak in Fig. 5 inaccurate, mainly because of its colour and cross-section composition. Additional comments described the image as too perfect and said that slices appeared to be different from the same piece of meat.

Fig. 6 depicts Carniolan sausage, which 64% of experts found unsuitable, mentioning colour and shape. Furthermore, additional comments mentioned an incorrect look, specifically the absence of the characteristic skewer and a resemblance to grilled sausage.

In Fig. 7 and Fig. 8, 71% found the presentations of dry salami and a hot dog unfit for professional use. Dry-cured sausage slices were considered too thick, while the hot dog's colour and plate appearance were criticized. Although the shape of the sausage inside the hot dog was considered correct, some participants found the sausage more appealing when presented in a natural rather than artificial casing.

Fig. 9 shows tartare, which 81% deemed inappropriate due to unnatural colour, texture, and an overly smooth, unnatural appearance.

Finally, in Fig. 10, 91% found the mortadella inaccurate due to its cross-section composition and colour. Additional comments noted that the lack of characteristic fat particles made it look unnatural. Only 9% considered the image suitable.

Bottom of Form

4. CONCLUSION

The results of this study highlight the current limitations of generative AI in accurately representing meat products for professional use. While AI-generated images of certain products such as burgers (82% approval) and prosciutto (67% approval) were considered relatively suitable, more complicated products such as mortadella (9% approval) and beef tartare (19% approval) were considered inappropriate due to unrealistic colour, texture and composition. The least appropriate images were of meat products that are not as heavily advertised, probably lacking the information about such products.

Colour was the most frequently cited issue for several images, especially for products where slight deviations in hue can signal differences in freshness, quality or even edibility. In addition, inaccuracies in the composition of the cross-section and appearance of the plate were frequently noted, emphasising that AI struggles to reproduce the complex structural details of processed and raw meat. The ability to generate visually appealing images does not necessarily translate into accuracy - a crucial aspect in the food industry, where confidence in product presentation is a key factor in purchasing decisions.

These findings emphasise the indispensable role of professional photographers. Unlike AI, photographers use their expertise in lighting, composition and post-processing to ensure that meat products are presented in an aesthetically pleasing and realistic way. Photographers are also able to make subtle but crucial adjustments to meet customer needs and industry standards, something AI is currently unable to do. Studies suggest that while AI tools are promising, they cannot yet replace professionally created photographs, but are a cheap solution with slightly lower quality.

In addition, AI is not able to produce consistently accurate textures, cross-sections and natural-looking compositions, further emphasising the need for human supervision in image creation. As AI continues to evolve, collaboration between AI technology and skilled photographers could increase efficiency without compromising authenticity to provide consumers with a reliable and trustworthy visual representation of food.

5. REFERENCES

Adobe Firefly – Free generative intelligence for creators.
URL: https://www.adobe.com/products/firefly.html (last accessed on 16. 1. 2025)
Angelova N. 2024. "The capabilities of the art-oriented artificial intelligence Adobe Firefly and its visual advantages and disadvantages." *Fundamental Sciences and Applications* 30(1):1–10.
Banh L, Strobel G. 2023. "Generative artificial intelligence". *Electron Markets* 33(1):63.
Califano G, Spence C. 2024. "Assessing the visual appeal of real/AI-generated food images." *Food Quality and Preference*. 116:105149.
Clydesdale FM. 1991. "Color Perception and Food Quality." *Journal of Food Quality* 4(1):61–74.
Ertel W. 2018. *Introduction to Artificial Intelligence*. Cham (Switzerland): Springer.
Frolov S, Hinz T, Raue F, Hees J, Dengel A. 2021. "Adversarial text-to-image synthesis: A review." *Neural Networks*. 144:187–209.
Janiesch C, Zschech P, Heinrich K. 2021. "Machine learning and deep learning." *Electron Markets*. 31(3):685–95.
Jelinčić DA. 2023. "Što utječe na doživljaj okusa?" In *Znanost i umjetnost doživljaja hrane*, 76–85. Zagreb: Jesenski i Turk.
Kirova VD, Ku CS, Laracy JR, Marlowe TJ. 2023. "The Ethics of Artificial Intelligence in the Era of Generative AI." *JSCI* 21(4):42–50.
Misal T, Satyam K, Ronit B, Rohit A, Prof. Shreya B. 2024. "Detection of AI-Generated Images." *International Journal of Trend in Scientific Research and Development* 8(5):805–10.
Mugge R, Dahl DW, Schoormans JPL. 2018. "What You See, Is What You Get?" Guidelines for Influencing Consumers' Perceptions of Consumer Durables through Product Appearance." *Journal of Product Innovation Management* 35(3):309–29.
NIJZ – Priporočila glede uživanja rdečega mesa in mesnih izdelkov.
URL: https://nijz.si/zivljenjski-slog/prehrana/prehranske-smernice/priporocila-glede-uzivanja-rdecega-mesa-in-mesnih-izdelkov/ (last accessed on 14. 1. 2025)
Ong SH, Ni SX, Vern HL. 2024. "Dimensions Affecting Consumer Acceptance towards Artificial Intelligence (AI) Service in the Food and Beverage Industry in Klang Valley." *Semarak International Journal of Machine Learning* 1(1):20–30.
Štampfl V, Ahtik J. 2024. "Quality of Colour Rendering in Photographic Scenes Illuminated by Light Sources with Light-Shaping Attachments." *Applied Sciences* 14(5):1814.
Šubic T. 2022. "Senzorične lastnosti klobas za kuhanje kot pomemben dejavnik pri odločitvi za nakup." In *Med vizijo in resničnostjo novih obzorij*, edited by Tina Košir, Andrej Pogorelec, 309−322. Strahinj: Biotehniški center Naklo.
Šubic T, Mavrin D, Leskovar Mesarič P. 2022. *Meso in mesni izdelki*. Podsmreka: Pipinova knjiga d.o.o.
Morgan J. 2018. "The Influence of Color on Taste Perception". *Interesting Thing of the Day*. URL: https://itotd.com/articles/3508/the-influence-of-color-on-taste-perception/ (last accessed on 18. 1. 2025)
Wessel M, Adam M, Benlian A, Majchrzak A, Thies F. 2024. "Generative AI and its Transformative Value for Digital Platforms." *Journal of Management Information Systems*. URL: https://www.jmis-web.org/cfps/JMIS_SI_CfP_Generative_AI.pdf (last accessed on 17. 1. 2025)
Zelený J, Ulrichová A, Fišer V, Husák J, Svobodová D. 2024. "Gastronomic Consumers' Attitudes Toward AI-Generated Food Images: Exploring Different Perceptions Based on Generational Segmentation." In *Marketing and Smart Technologies*, edited by Reis JL, Zelený J, Gavurová B, Santos JPM dos, 105−119. Singapore: Springer Nature.

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POSTER PRESENTATION

INCLUSIVITY AS A VALUE IN INFORMAL AND FORMAL PRIMARY SCHOOL EDUCATION - EXAMPLE OF VISUALIZING CHILDREN'S USER PATHWAYS

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Abstract: *The contribution presents student-centred didactic-research activities based on the Eutopia learning unit Urban Education. This research aligns with prior studies conducted in Belgium and France, addressing the central question: Does the future belong to cities? It explores inclusivity through a multidimensional approach, focusing on primary school pupils. At the Chair of Information and Graphic Arts Technology, we initiated the development of a virtual educational city journey. This interactive environment allows teachers, parents, and guardians to follow pupils' virtual paths and challenges in a „super-diverse" urban context. Through web research we analysed inclusivity in Slovenian primary schools. We defined categories of inclusivity for Slovenian primary schools and mapped daily pupil routes, identifying key learning opportunities within the city. The final prototype is a digital interactive game, placed as an interactive board along pupils' routes. Featuring five challenges based on different diversity categories, the game fosters collaboration, empathy, and understanding among pupils by encouraging them to engage with diverse perspectives.*

Keywords: *inclusivity, user-centred design, primary education, user paths, city, urban education.*

1. INTRODUCTION

Inclusivity ensures that all individuals, regardless of background, identity, or abilities, feel welcomed, valued, and respected. It goes beyond tolerance, actively embracing diversity in race, gender, age, disability, sexual orientation, and socioeconomic status (Thatcher, 2006). An inclusive society fosters equal opportunities, enabling people to contribute and thrive without fear of discrimination (Figure 1). In workplaces, schools, and communities, diversity drives innovation, creativity, and growth. True inclusivity requires intentional efforts –equitable policies, addressing biases, and ensuring accessibility (Gilbert, 2019). Small actions, like inclusive language or accessible spaces, make a difference. By embracing inclusivity, we create a society where everyone can reach their full potential (Microsoft, 2025).



Figure 1: The quote of Vernā Myers (AppNexus, 2025)

The research project work focused on the goals of Good Health and Well-being, Quality Education, Gender Equality, Reduced Inequalities, and Sustainable Cities and Communities. The research activities carried out within the Eutopia Urban Education (Eutopia, 2025) learning unit were designed to promote an interdisciplinary approach to addressing key social issues related to the inclusion of primary school children in Slovenia. The focus of the research project work was to design and prototype a virtual educational city journey. The aim was to integrate urban spaces with educational content for primary school pupils, to allow teachers, parents, and guardians to follow pupils' paths through the city and better understand the challenges they face in a "super-diverse" educational context (United Nations Publications, 2022).

2. METHODOLOGIES

The research was based on three key methodologies: a targeted analysis of the websites of Slovenian primary schools and the definition of inclusivity categories, user-centred design focused on primary school pupils as the main target group and the prototyping of the educational interactive pupil's city path. The project steps were:

- **Analysis of inclusivity in primary schools**: We reviewed existing inclusion practices in Slovenia (through the web publications) and analysed pupils' routes from home to school, focusing on their challenges and opportunities for informal learning.
- **Documenting diversity categories**: We identified key diversity categories encountered in Slovenian urban primary schools and defined representative users.
- **Mapping home-to-school routes**: We examined typical pupil routes for different groups and identified key "stopping points" in the urban environment where formal and informal learning content could be integrated.
- **Developing a virtual environment prototype**: We designed a **virtual city journey**, tailored to different diversity categories, embedding educational content to promote inclusivity.

3. RESULTS AND DISCUSSION

Categorisation of the diversity that was defined from the analysis of the documents available on web of primary schools in Slovenia is presented in Figure 2.

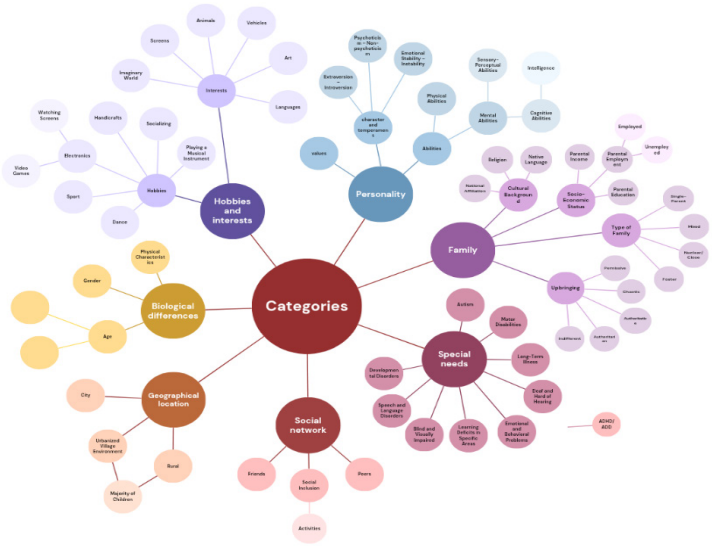


Figure 2: Categorisation of the diversity of the primary schools in Slovenia.

3.1 Summary of the Analysis of Primary School Websites on Inclusive Practices

An analysis of primary school websites in Slovenia reveals differences in how inclusive practices are presented. Some schools highlight specific projects supporting pupils with special needs and immigrant children, while others provide limited information. Preventive workshops, conflict resolution programs, and language support for immigrants are mentioned in some cases. However, not all schools detail their inclusion efforts online, and website quality varies. Oral sources confirm that certain schools offer Serbian language and culture classes for immigrant children, indicating that some inclusive practices may exist but are not always publicly documented.

3.2 Multiculturalism in Schools and Ethnic Discrimination

In Slovenia, most immigrants come from Bosnia and Herzegovina, Kosovo, Serbia, Croatia, North Macedonia, and Ukraine. This diversity is reflected in primary schools, but there are no unified guidelines on how to address pupils of different ethnic backgrounds. Practices vary significantly—some schools ignore multicultural challenges, while others isolate immigrant pupils. Roma children face low teacher and peer expectations, often assumed to perform poorly, affecting their motivation. Many enter special education programs due to low grades or unfinished schooling. Social isolation further hinders their integration.

Language barriers pose an additional challenge, as many pupils start school with little or no knowledge of Slovenian, affecting comprehension and progress. Other ethnic minority pupils experience similar difficulties, including exclusion due to cultural differences. Schools lack systematic support for immigrant pupils' native languages, leading to language loss and cultural identity erosion. Slovenian language instruction is available but often insufficiently tailored to individual needs.

3.3 Inclusion of Children with Special Needs

The inclusion of children with special needs in mainstream schools is a key aspect of educational policy, emphasizing social support to reduce stress and enhance belonging and self-confidence. Historically, children with developmental disabilities were considered unfit for schooling, but this changed with the establishment of specialized programs. From 1920 to 1960, segregation dominated, followed by integration between 1960 and 2000. True inclusive education only gained prominence after 2000.
Slovenia intensified efforts in this field after the *White Paper on Education* (1995), leading to legislative changes, including the *Placement of Children with Special Needs Act* (2000). Since then, 28 specialized schools have been established, enrolling 11,077 pupils by 2017/2018. Modern education emphasizes inclusion as a core value, requiring adjustments in the learning environment, expert support, and funding to ensure equal opportunities for all children. Inclusive education adapts systems for all children, moving beyond segregation and integration to create accessible learning environments.

3.4 Target Groups and Personas

According to the categorisation of the diversity the target groups were defined as follows:

Children of Immigrant Parents – These children do not speak Slovenian as their native language, limiting their proficiency. However, they are socially active with diverse friendships. Their families typically have an average income, with both parents employed. They participate in extracurricular activities and hobbies, highlighting their engagement. Ensuring access to language and social resources is crucial for their successful integration.

Children with ADHD/ADD or Autism – Often from low-income families, with one parent providing financial support while the other cares for the child. Some come from high-income families where their condition is overlooked. They struggle with social inclusion, often feeling isolated and misunderstood. Limited access to school programs, therapy, and technology further hinders their development.

Children with Physical Disabilities – Typically from extended families with authoritative parenting. They have a small but stable social network but face exclusion due to mobility limitations. Despite living in urban areas with better accessibility, they encounter challenges in full societal integration.

Average Slovenian Child – From small families with authoritative upbringing and average income. Well-integrated socially, they actively participate in various activities. They often live in rural areas and rely on public transport for school and extracurriculars, fostering strong peer support.

Children with Behavioural and Emotional Disorders – Frequently from unstable family environments, with divorced parents. They have limited social networks and lack interest in school. Living in urban areas, they have access to resources but often fail to utilize them. Special support is essential to improve their socialization and emotional well-being.

Personas were designed based on target groups. Fatima, age 15 – Recently moved from Bosnia, struggles with Slovenian, feeling excluded and frustrated. Finds school challenging due to fast-paced lessons and concentration difficulties. Commutes 45 minutes by bus, waking up early. Uses technology for chatting and reading comics but feels lonely due to limited social integration. Blaž, age 13 – Struggles with attention issues affecting academic performance. Has a strained relationship with his absent father. Enjoys outdoor activities and video games but feels different from peers. Walks or bikes to school in 15 minutes. Uses technology but has a basic phone due to financial limitations. Jakob, age 13 – Uses a wheelchair due to a spinal injury. Faces accessibility challenges in school despite supportive friends. His father drives him to school, causing stress due to inadequate facilities. Enjoys social media and video games, using technology extensively. Mojca, age 13 – Active in extracurriculars but struggles with peer relationships, impacting her confidence. Has a strong bond with her mother but feels misunderstood by her father. Walks 15 minutes to school, enjoys outdoor activities, and frequently uses Instagram and Messenger. Bor, age 15 – Lives with his emotionally distant mother, feeling isolated. Unmotivated in school, lacking friends, and associating with a negative peer group. Frequently late, disengaged, and struggling academically. Lives in the city center, heavily reliant on technology but lacking strong family connections.

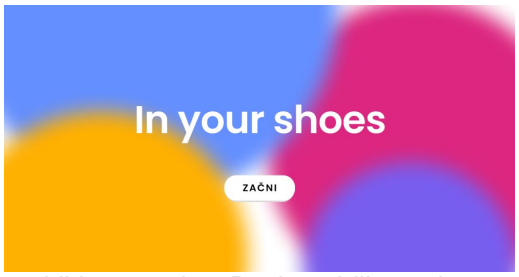
3.5 Development of a Digital Prototype

The prototype for the game *"In Your Shoes"* was designed to foster inclusivity and empathy among primary school pupils. The game allows players to experience different life situations faced by children with various needs, such as ADHD, physical disabilities, or immigrant backgrounds. This interactive experience helps children understand and empathize with the daily challenges of their peers. The prototype was developed in Figma for structuring the game and interactive challenges, while Canva was used for animations. The game features multiple interactive challenges accessible through interactive panels placed at key locations in the city, such as parks, libraries, and bus stops along pupils' daily routes to school. These panels provide engaging tasks that encourage children to reflect on the challenges faced by marginalized groups. Players can engage with the challenges individually or in groups, even connecting panels from different locations for a shared experience. Access is secured through school credentials to ensure safety. In the prototype, the following challenges were included:

- **Word Association:** Designed for children from immigrant backgrounds (e.g., Fatima), this challenge presents an interactive story where players make choices that shape the narrative, fostering empathy for immigrant experiences. At the end, the character becomes a digital companion who answers players' questions about their life.
- **Find the Object:** Simulating the struggles of children with ADHD/ADD or autism (e.g., Blaž), this challenge requires players to find an object within a set time while distractions appear on the screen. This simulates the attention difficulties these children face.
- **Jump Challenge:** Representing mobility-impaired children (e.g., Jakob), two players must complete a task while experiencing physical limitations (e.g., one with closed eyes, the other on one leg). This helps players understand the difficulties faced by children with physical disabilities.
- **Stand Against Bullying:** Addressing the experiences of the average Slovenian child (e.g., Mojca), this challenge presents scenarios where players must decide whether to participate in or stop bullying, encouraging awareness and proactive behavior.

- **My Garden:** Highlighting the struggles of children with behavioral and emotional difficulties (e.g., Bor), players care for a virtual garden. When a helper (gardener) stops assisting, the game becomes significantly harder, illustrating the impact of losing support. Players can collaborate, promoting discussions about real-life support systems.

Figure 3 present the interface of the prototype. The in-city placed interactive game serves multiple purposes. Each challenge educates children on the experiences of vulnerable groups while making learning accessible in public spaces. By situating the game outside traditional school settings—parks, libraries, and bus stops—it encourages engagement in urban environments. The game supports both individual and group learning, enhancing a sense of belonging and cooperation in problem-solving.

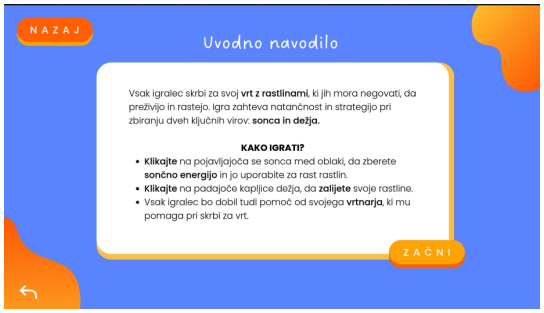



An interactive whiteboard in the park of city, inviting children to play. Designed illustrations on the interface pages.



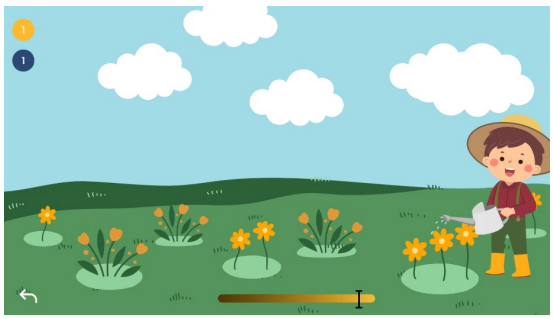


Prototype memory tasks.





Prototype thinking tasks.





Designed illustrations with the interaction elements on the interface pages.

Figure 3: User interface's pages with interaction and content design.

4. CONCLUSIONS

This research underscores the vital role of inclusivity in education, ensuring all pupils, regardless of background or ability, feel valued and supported. By analyzing Slovenian primary school inclusivity practices and mapping children experiences, the study identifies barriers faced by immigrant children, pupils with disabilities, and those with behavioral or emotional challenges. The development of a virtual city learning journey offers an innovative approach to fostering inclusivity, integrating educational content into urban environments. The interactive prototype, *In Your Shoes*, enhances empathy by allowing pupils to experience diverse challenges through gamification. Schools vary in their implementation of inclusive policies, with language barriers and social exclusion remaining significant obstacles. The study highlights the need for systematic support, tailored educational programs, and community engagement to create accessible learning environments. Through interdisciplinary collaboration and digital innovation, this research contributes to sustainable, inclusive education, ensuring equal opportunities for all pupils to thrive in a diverse society.

Acknowledgement: We sincerely thank the Eutopia network for enabling the results of this research and enriching the activities of the *Urban Education* learning unit through the student project.

5. REFERENCES

Eutopia, Urban Education, URL: https://eutopia-university.eu/english-version/education/eutopia-learning-communites/urban-education (last accessed on 27.2. 2025).

Gilbert, R. M. 2019. Inclusive Design for a Digital World: Designing with Accessibility in Mind (Design Thinking), Apress.

Microsoft, Inclusive Microsoft Design. URL: https://download.microsoft.com/download/b/0/d/b0d4bf87-09ce-4417-8f28-d60703d672ed/inclusive_toolkit_manual_final.pdf (last accessed on 27.2.2025)

Thatcher, J., Urban, M., Lawson, B., Burks, M. R., Rutter, R. Kirkpatrick, A., Heilmann, C., Lawton, S., Regan, H. R. and Waddell, C., D. 2006. Web Accessibility: Web Standards and Regulatory Compliance, 1st ed. Edition, Apress.

United Nations Publications. 2022. “Approaches to Measuring Social Exclusion.” Statistical standards and studies - Conference of European Statisticians, Ed. United Nations Publications.

Vernā Myers, AppNexus, URL: https://www.youtube.com/watch?v=9gS2VPUkB3M&ab_channel=AppNexus (last accessed 27.2. 2025).

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DESIGN AND TYPOGRAPHY

ORAL PRESENTATION

A BIBLIOMETRIC ANALYSIS OF TYPOGRAPHY RESEARCH

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Abstract: *Typography has long been an important part of communication, encompassing the design of typefaces, the study of print quality and legibility on paper or in digital media, but also including computer graphics, marketing and psychology. In this paper, a bibliometric approach was used to examine the content structure and trends in typography research. Scopus and Web of Science databases were queried for typography-related terms. The results were subjected to pre-processing, followed by analysis using Bibliometrix/Biblioshiny (performance analysis – document and citation counts) and VOSviewer software (science mapping – network visualisations). The results present the most cited documents, the most prolific and influential authors, the most prolific sources and the most frequent keywords. The keyword network reveals five main topic clusters, such as graphic design and printing, legibility/readability, reading comprehension/memory, perception/impact of design, character recognition and font generation. Trend topics are related to font generation by AI and font perception.*

Keywords: *typography, bibliometric analysis, performance analysis, science mapping*

1. INTRODUCTION

Since the invention of movable type and the printing process by Johannes Gutenberg, typography has become an essential aspect of communication (Možina, 2003). Initially, the focus was mainly on the design of the typeface and the quality of the printed typeface (Tracy, 2003). Many decades later, the legibility of a typeface has become very important (Reynolds, 1998; Tinker, 1963). First on paper, then on screens with different resolutions (Dyson and Haselgrove, 2001; Reynolds, 1998; Tinker, 1963)there is an urgent need to increase our knowledge of factors influencing reading from screen. We investigate the effects of two reading speeds (normal and fast. Eye-tracking technology has been developed to measure reading time and legibility, allowing researchers to study the impact of typeface design on reading fluency and memorisation (Beier et al., 2017; Franken et al., 2015; Medved et al., 2023). There is also interest in how different typefaces influence marketing and business (Davis et al., 2019). Nowadays, studies are even investigating the role of typography in computer graphics (Jordan et al., 2017).
The aim of this study was to examine the content structure and trends in the field of typography research to help scholars identify potential opportunities for new research from the perspective of topics, journals and references.

2. EXPERIMENTAL

The present study follows the methodology for bibliometric analyses described by Donthu et al. (2021). We used two methodological approaches: (a) performance analysis to examine the annual scientific production and citations and to identify the most prolific/cited authors, the most prolific sources, and the most cited documents, and (b) science mapping to identify and visualise the topic structure of the field and to identify trending topics based on the co-occurrence of keywords.
The search strategy included typography-related keywords (typograph*, legibility/readability and text/font*/typeface/type, font/typeface design, typesetting and font/fonts, reading and font weight/color/size/type/characteristics, eye movement/track* and font/fonts/typeface*, typeface, but excluded typographical errors, typographi/typographus beetles or linguistics) in the title and keyword search fields. Separate searches were carried out in the Scopus and Web of Science (WoS) databases, with results filtered by document type to include only journal articles, reviews, and conference papers. The search results were exported, combined (yielding 5579 documents) and imported into software programmes (Microsoft Excel, Bibliometrix/Biblioshiny and VOSviewer) to clean the original raw data, perform basic statistical analyses, create and visualise bibliometric networks and analyse the results.
To improve the quality of the original raw dataset for further analyses, the pre-processing phase was essential.

Duplicates were identified and removed from the combined set. The mean value of the total citations (TC) for WoS and Scopus was also calculated in this process. A thesaurus was created and used to merge key terms such as singular/plural, synonyms, different variants, different spellings, abbreviated and full terms. During the manual review, the titles and abstracts of the documents were checked to exclude “false positives”. The final data set comprised 3244 documents.

3. RESULTS WITH DISCUSSION

3.1 Documents

First, we examined the document types. Two thirds of the documents are journal articles, the rest are conference papers. Next, we looked at the number of documents and the number of total citations over time. Figure 1 shows that annual production has been steadily increasing since 1975, with a sharp increase in 2011. The means of total citations shown in red take into account both the number of documents and the age of the documents. The documents from 2006 were cited most frequently.

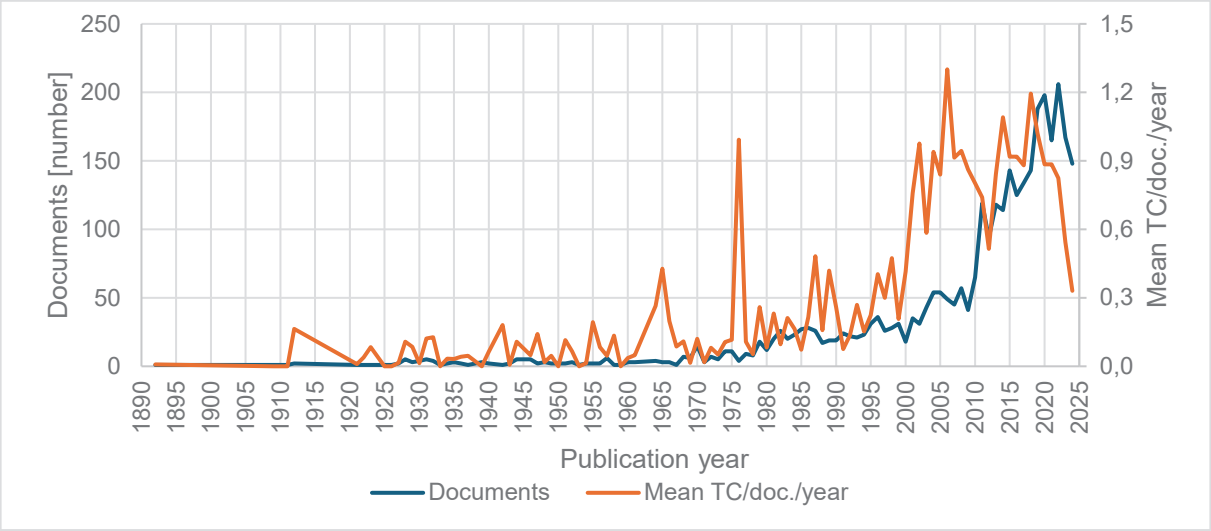


Figure 1: Production over time (number of documents), and mean of total citations (TC)

The documents were then ranked according to the total number of citations to determine the most influential documents. The ten most cited documents globally have at least 174 citations, with the paper by Rayner et al. (2006) half of the sentences were printed in a font that was easy to read (Times New Roman topping the list with 285 citations. The average year of publication is also 2006. Thematically, the ten most cited papers deal with legibility/readability/reading, e.g. the influence of type size and typeface (Henderson et al., 2004), in the context of vision (Mansfield et al., 1996; Rayner et al., 2006)the authors measured the influence of font in reading with normal and low vision. METHODS: Reading acuity, maximum reading speed, and critical print size (the smallest print that can be read with maximum speed, learning and memory (Lorch, 1989; Ozcelik et al., 2010)including: titles, headings, previews, overviews, summaries, typographical cues, recall sentences, number signals, importance indicators, and summary indicators. Most investigations have examined how the presence of signals in a text affects subsequent memory for the text. Virtually all types of signals produce better memory for information they cue in a text, whereas memory for unsignaled information often is unaffected. Less attention has been directed to signaling effects on other cognitive processes, such as attention, basic reading processes, and comprehension. It is argued that an understanding of how signals influence these processes will contribute to the application of signaling research to reading and writing instruction and to our general understanding of reading.”,”container-title”:”Educational Psychology Review”,”ISSN”:”1573-336X”,”issue”:”3”,”journalAbbreviation”:”Educ Psychol Rev”,”language”:”en”,”page”:”209-234”,”source”:”Springer Link”,”title”:”Text-signaling devices and their effects on

reading and memory processes",”volume”:”1”,”author”:[{“family”:”Lorch”,”given”:”Robert F.”}],”issued”:{“date-parts”:[[“1989”,9,1]]}}},{“id”:2604,”uris”:[“http://zotero.org/users/4575080/items/VCUXZFUT”],”uri”:[“http://zotero.org/users/4575080/items/VCUXZFUT”],”itemData”:{“id”:2604,”type”:”article-journal”,”abstract”:”Previous studies have suggested that signaling enhances multimedia learning. However, there is not enough evidence showing why signaling leads to better performance. The goal of this study was to examine the effects of signaling on learning outcomes and to reveal the underlying reasons for this effect by using eye movement measures. The participants were 40 undergraduate students who were presented with either signaled or nonsignaled multimedia materials. Labels in the illustration were signaled by temporarily changing the color of the items. The results suggest that the signaled group outperformed the nonsignaled group on transfer and matching tests. Eye movement data shows that signaling guided attention to relevant information and improved the efficiency and effectiveness of finding necessary information.”,”container-title”:”Computers in Human Behavior”,”ISSN”:”0747-5632”,”issue”:”1”,”journalAbbreviation”:”Computers in Human Behavior”,”language”:”en”,”note”:”p”,”page”:”110-117”,”source”:”ScienceDirect”,”title”:”Why does signaling enhance multimedia learning? Evidence from eye movements”,”title-short”:”Why does signaling enhance multimedia learning?”,”volume”:”26”,”author”:[{“family”:”Ozcelik”,”given”:”Erol”},{“family”:”Arslan-Ari”,”given”:”Ismahan”},{“family”:”Cagiltay”,”given”:”Kursat”}],”issued”:{“date-parts”:[[“2010”,1,1]]}}}],”schema”:”https://github.com/citation-style-language/schema/raw/master/csl-citation.json”} , or the influence of typography in marketing (Hall and Hanna, 2004), logos (Foroudi et al., 2014; Hagtvedt, 2011) or products (Henderson et al., 2004). One document (Leeuwen, 2006) refers to the fundamentals of typography. The latest document (Azadi et al., 2018) deals with typeface style transfer using neural networks.

3.2 Authors

A total of 5775 authors contributed to our dataset. Ten authors published 14 or more documents each (Table 1). Tinker is the only author with more than 30 publications, followed by Možina with 23. Six of the top ten authors deal with legibility and three with automatic typeface recognition and/or generation. The remaining author deals with design layout. Lian has the most citations overall and the most citations per document in the group.

Aside from the most prolific authors, we looked at the most influential authors – those with the highest number of citations regardless of the number of documents. In this list, Van Leeuwen is in first place with 404 citations for just three documents, closely followed by the aforementioned Lian with 403 for 20 documents. The next three most influential authors are Legge, Baird and Velasco with more than 370 citations each. Of the most prolific authors, Tinker ranks 9th on this list of most cited authors.

Table 1: Ten most productive authors with total citations (TC) and research topics.

Rank	Author	Doc.	TC	TC/ Doc.	Year started	Research topics / key-words
1	Tinker M. A.	31	300.5	9.7	1927	Reading, legibility, type, speed, blinking
2	Možina K.	23	157.5	6.8	2007	Typography, legibility, text, type, print
3	Paterson D. G.	22	264.0	12.0	1928	Reading, legibility, type, speed
4	Hartley J.	21	211.5	10.1	1973	Typography, layout, in-structional design
5	Uchida S.	21	96.0	4.6	2013	Font recognition, font gen-eration, neural networks, style transfer
6	Lian Z.	20	403.0	20.2	2015	Font recognition, font gen-eration, neural networks, Chinese fonts, style trans-fer
7	Beier S.	18	154.0	8.6	2010	Fonts, legibility, reading, typography, letter recog-nition
8	Dobres J.	15	240.0	16.0	2014	Typography, legibility, typeface design, reading, size
9	Choi J.	14	48.0	3.4	2017	Font generation, neural networks, Chinese fonts, style transfer
10	Reimer B.	14	213.0	15.2	2012	Typography, legibility, typeface design, automo-tive, displays

3.3 Sources

Among the ten most productive sources that published 19 or more documents, we find five journals and five conferences (Figure 2). *Visible Language* is the most productive journal with 49 documents. 48 documents were published in the proceedings of the *ACM Conference on Human Factors in Computing Systems*. The remaining titles deal with computer graphics and interactivity (*Displays*, conferences SIGGRAPH and HCII), psychology (*Journal of Applied Psychology*), design (*Information Design Journal*), communication (*Visual Communication*), ergonomics (*Applied Ergonomics*) and pattern recognition (conference ICDAR).

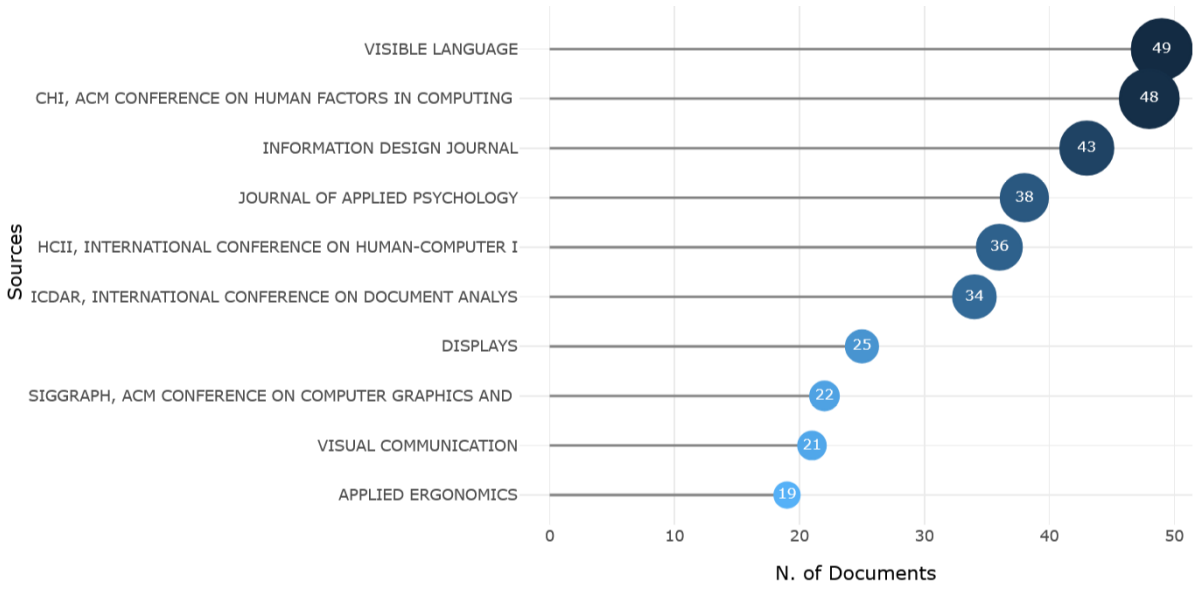


Figure 2: Ten most productive sources; visualisation: Biblioshiny

3.4 Topics

Combined authors- and Scopus-indexed keywords were first analysed for frequency (top 20 in Table 2). Typography was by far the most frequent keyword, followed by legibility and fonts. The keywords could be grouped by topic: 1) **fonts**, typefaces, typeface design, font design, typesetting; 2) **design**, graphic design, font design, typeface design; 3) **recognition**, OCR; 4) **legibility**, readability, reading, texts; 5) **properties**: font size, color, size; 8) **study**: perceptions, performance.

Table 2: Twenty most frequent keywords with frequencies of occurrence.

Rank	Words	Occurr.	Rank	Words	Occurr.
1	typography	571	11	recognition	94
2	legibility	232	12	color	92
3	fonts	216	13	graphic design	92
4	design	162	14	typeface design	85
5	typefaces	141	15	perceptions	78
6	readability	131	16	eye movement	76
7	texts	130	17	OCR	71
8	font size	119	18	size	67
9	reading	110	19	font design	66
10	typesetting	107	20	performance	66

To visualise the thematic structure of the field, VOSviewer was used to create a co-occurrence network for the 234 most frequent keywords (frequency at least ten, Figure 3). Typography was used as a stop word and therefore removed. Characteristics of the five keyword clusters, ordered by cluster size:

1) red (73 words, average year 2010) – classic graphic **design** topics, typesetting, printing, computer graphics, visualization and kinetic typography;
2) green (62, 2014) – **legibility**, readability, psychophysics of reading, font size, reading speed;
3) blue (36, 2017) – **memory**, reading fluency, dyslexia;
4) yellow (32, 2016) – **perception**, impact and emotions, associated with the use of fonts/typefaces;
5) purple (31, 2016) – font **recognition** and generation using neural networks.

The yellow (design) cluster appears at the center of the visualization, indicating its connectedness to other topics. Some of words are close to the border between two clusters (e.g. ergonomics (between red and green clusters) or eye movements (between blue and green clusters).

To identify new and emerging topics, in addition to the average age of clusters, the overlay version of the keyword network visualization in VOSviewer was chosen, where colour represents the average age of the words (Figure 4). It can be seen that most of the oldest terms (coloured blue) can be found in the first cluster (e.g. typesetting, computer graphics and printing). Examples of common middle-aged terms (in green) are legibility, readability/reading, fonts, design and recognition. The newest terms are coloured in yellow. These mainly include words from cluster 5 that relate to the use of neural networks (e.g. font generation, style transfer, deep learning), from cluster 3 (e.g. fluency, beliefs and dyslexia) and 4 (e.g. perceptions and impact). In cluster 2, the new term is helmet mounted displays. These are predominantly specific/niche terms found on the outer edge of network visualization.

The five most cited papers in the last four years (between 28 and 56 citations) deal with the text readability in social media (Gkikas et al., 2022), typographic enhancement in language learning (Majuddin et al., 2021), automatic typeface generation (Xie et al., 2021), typeface perception in relation to food (Motoki and Velasco, 2021)round shapes are associated with sweet taste, while angular shapes are associated with sour and bitter tastes. Previous studies have focused on one-to-one taste-shape associations, where either geometrical shapes or shapes on a product's packaging have been presented in isolation and evaluated separately. However, in real-life product displays, products are typically surrounded by other products. We examined whether shape contexts can influence the taste expectations associated with target products across five experiments (n = 1087 and icon legibility on displays (Shen et al., 2021).

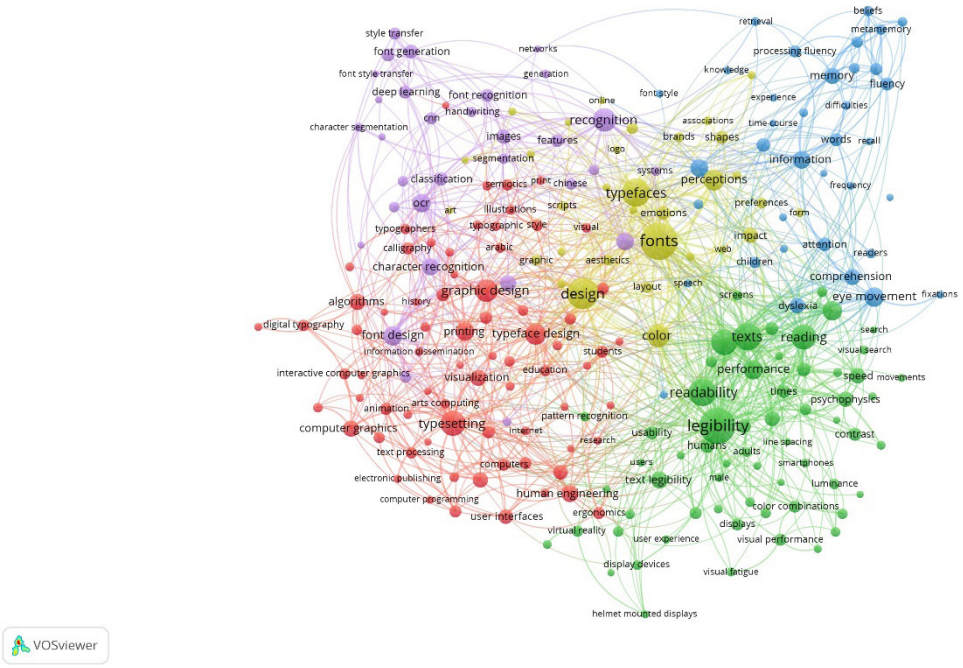


Figure 3: Main research topics by keyword network; visualisation: VOSviewer

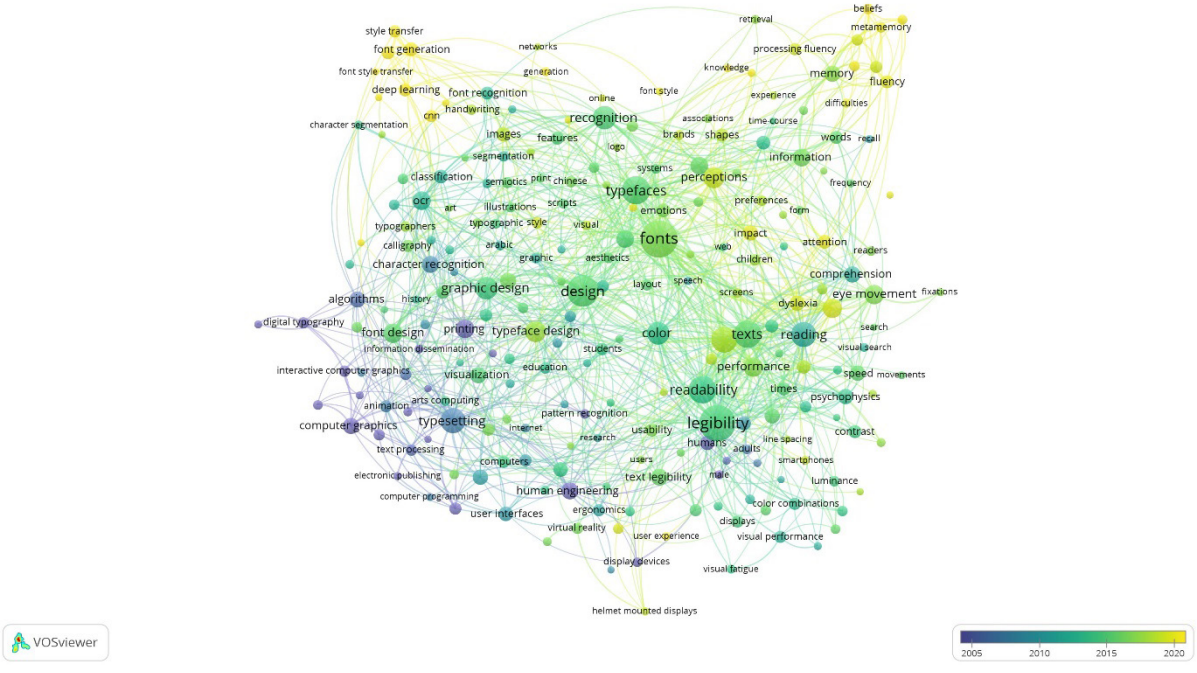


Figure 4: Keyword network by publication years; visualisation: VOSviewer

4. CONCLUSIONS

Our study provides an overview of the development of the research field of typography, drawing on two methodological approaches: performance analysis and science mapping. The oldest documents indexed in the WoS and Scopus bibliographic databases on typography research date from 1892, but the number of documents began to increase after 1975, with a sharp increase in 2011. The documents with the most citations deal with a range of topics, including the influence of typefaces on reading and perception, characteristics of letterforms, the influence of text colour and text signalling. Miles A. Tinker, who published his work before 1970, and Klementina Možina, after 2007, are the most prolific authors, while Theo Jacob van Leeuwen and Zhouhui Lian are the most frequently cited. Most papers were published in the journal Visible language and at the ACM Conference on human factors and computing. Apart from typography, the most common keywords are fonts, legibility and design. The topics identified through the scientific mapping deal with graphic design and printing, legibility/readability, reading comprehension/memory, perception/impact of design, character recognition and font generation. Type size is the most studied property. Recent topics include font generation using neural networks, user experience in XR, dyslexia research related to reading, and the impact/perception of design.

There are some limitations of the present study that should be mentioned. We could use co-word analysis in combination with co-citation analysis or bibliographic coupling to enrich the understanding and interpretation of the thematic clusters, to gain additional insights into the dynamics of the field and to predict future developments. In addition, the set of keywords, databases and database search fields could be extended to include more documents in the analyses.

5. REFERENCES

Azadi, S., Fisher, M., Kim, V.G., Wang, Z., Shechtman, E., and Darrell, T. 2018. 'Multi-Content GAN for Few-Shot Font Style Transfer'. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, 7564–73. IEEE.

Beier, S., Sand, K., and Starrfelt, R. 2017. 'Legibility Implications of Embellished Display Typefaces'. *Visible Language* 51 (1): 113–33.

Davis, S.W., Horváth, C., Gretry, A., and Belei, N. 2019. 'Say What? How the Interplay of Tweet Readability and Brand Hedonism Affects Consumer Engagement'. *Journal of Business Research* 100:150–64.

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., and Lim, W.M. 2021. 'How to Conduct a Bibliometric Analysis: An Overview and Guidelines'. *Journal of Business Research* 133:285–96.

Dyson, M.C., and Haselgrove, M. 2001. 'The Influence of Reading Speed and Line Length on the Effectiveness of Reading from Screen'. *International Journal of Human-Computer Studies* 54 (4): 585–612.

Foroudi, P., Melewar, T.C., and Gupta, S. 2014. 'Linking Corporate Logo, Corporate Image, and Reputation: An Examination of Consumer Perceptions in the Financial Setting'. *Journal of Business Research* 67 (11): 2269–81.

Franken, G., Podlesek, A., and Možina, K. 2015. 'Eye-Tracking Study of Reading Speed from LCD Displays: Influence of Type Style and Type Size'. *Journal of Eye Movement Research* 8 (1): 1–8.

Gkikas, D.C., Tzafilkou, K., Theodoridis, P.K., Garmpis, A., and Gkikas, M.C. 2022. 'How Do Text Characteristics Impact User Engagement in Social Media Posts: Modeling Content Readability, Length, and Hashtags Number in Facebook'. *International Journal of Information Management Data Insights* 2 (1): 100067.

Hagtvedt, H. 2011. 'The Impact of Incomplete Typeface Logos on Perceptions of the Firm'. *Journal of Marketing* 75 (4): 86–93.

Hall, R.H., and Hanna, P. 2004. 'The Impact of Web Page Text-Background Colour Combinations on Readability, Retention, Aesthetics and Behavioural Intention'. *Behaviour & Information Technology* 23 (3): 183–95.

Henderson, P.W., Giese, J.L., and Cote, J.A. 2004. 'Impression Management Using Typeface Design'. *Journal of Marketing* 68 (4): 60–72.

Jordan, T.R., Al Shamsi, A.S., Yekani, H.A., Al Jassmi, M., Al Dosari, N., Hermena, E.W., and Sheen, M. 2017. 'What's in a Typeface? Evidence of the Existence of Print Personalities in Arabic'. *Frontiers in Psychology* 8:1–8.

Leeuwen, T. van. 2006. 'Towards a Semiotics of Typography'. *Information Design Journal* 14 (2): 139–55.

Lorch, R.F. 1989. 'Text-Signaling Devices and Their Effects on Reading and Memory Processes'. *Educational Psychology Review* 1 (3): 209–34.

Majuddin, E., Siyanova-Chanturia, A., and Boers, F. 2021. 'Incidental Acquisition of Multiword Expressions through Audiovisual Materials: The Role of Repetition and Typographic Enhancement'. *Studies in Second Language Acquisition* 43 (5): 985–1008.

Mansfield, J.S., Legge, G.E., and Bane, M.C. 1996. 'Psychophysics of Reading. XV: Font Effects in Normal and Low Vision.' *Investigative Ophthalmology & Visual Science* 37 (8): 1492–1501.

Medved, T., Podlesek, A., and Možina, K. 2023. 'Influence of Letter Shape on Readers' Emotional Experience, Reading Fluency, and Text Comprehension and Memorisation'. *Frontiers in Psychology* 14:1–11.

Motoki, K., and Velasco, C. 2021. 'Taste-Shape Correspondences in Context'. *Food Quality and Preference* 88:104082.

Možina, K. 2003. *Knjižna Tipografija*. Ljubljana: Univerza v Ljubljani; Filozofska fakulteta and Naravoslovnotehniška fakulteta.
Ozcelik, E., Arslan-Ari, I., and Cagiltay, K. 2010. 'Why Does Signaling Enhance Multimedia Learning? Evidence from Eye Movements'. *Computers in Human Behavior* 26 (1): 110–17.
Rayner, K., Reichle, E.D., Stroud, M.J., Williams, C.C., and Pollatsek, A. 2006. 'The Effect of Word Frequency, Word Predictability, and Font Difficulty on the Eye Movements of Young and Older Readers'. *Psychology and Aging* 21 (3): 448–65.
Reynolds, L. 1998. 'Legibility of Type'. *Baseline: International Typographic Journal* 10:26–29.
Shen, Z., Zhang, L., Li, R., Hou, J., Liu, C., and Hu, W. 2021. 'The Effects of Color Combinations, Luminance Contrast, and Area Ratio on Icon Visual Search Performance'. *Displays* 67:101999.
Tinker, M.A. 1963. *Legibility of Print*. Ames: Iowa State University Press.
Tracy, W. 2003. *Letters of Credit: A View of Type Design*. Boston: David R. Godine.
Xie, Y., Chen, X., Sun, L., and Lu, Y. 2021. 'DG-Font: Deformable Generative Networks for Unsupervised Font Generation'. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, 5130–40. IEEE.

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ORAL PRESENTATION

TYPOGRAPHY STUDY PRACTICES (LETTERS AND SHAPES: COLLECTION OF TYPOGRAPHIC EXERCISES)

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Abstract: *Typography offers endless and ever-changing possibilities for graphic design. The success of a designer's career in setting and pushing the intellectual and physical boundaries of typography depends largely on the skills acquired in the earliest stages of a visual communication design degree.*

This paper is the result of a decade's development of practical study processes in typography and type design collected in an online publication titled Letters and Shapes. It includes a wide range of content based on typographic traditions, 20th-century modernist principles, simple artistic experimentation and current technological possibilities.
Assignments are always carried out in a "design, consult and evaluate" cycle. They combine analogue techniques with the use of digital tools. This encourages students to develop their design skills in later years when they are faced with more complex tasks. Teachers, however, are challenged to ask themselves contemporary questions that we can explore in the typographic medium.

Keywords: *Typography, graphic design, study, assignments, exercises.*

1. INTRODUCTION

The field of typography presents a vast array of possibilities for graphic design, offering a wealth of opportunities for exploration and innovation. The success of a designer‘s career in pushing the intellectual and physical boundaries of typography is contingent, to a considerable extent, on the competencies acquired during the initial stages of visual communication design studies. The challenge for students and teachers alike is to apply today the knowledge of typography accumulated over the last 500 years.

1.1 Literature and sources in the field

The publication of literature in the field of graphic design and typography in the English language is an ongoing process, with both professional and non-professional works being published. These books primarily address current production practices from the perspective of the author‘s or editor‘s position and the policies of publishing houses. Monographs offer insights into the work and output of the authors in question.

Textbooks such as *Inside Paragraphs* (Highsmith, 2012), *How to Design Typefaces* (Henestrosa et. al. 2017), *Detail in Typography* (Hochuli, 2008), *Stop Stealing Sheep & Find Out How Type Works* (Spiekermann, Ginger, 2003) are authored by educators and provide students with a solid foundation in the fundamental principles of the discipline, while concurrently directing them towards an appreciation of the distinctive particulars that are imperative for professional accomplishment in the domain of typography.

However, there is a paucity of translated literature on typography in the Slovenian language. Among the few translated works is Emil Ruder‘s pioneering work *Typography* (Ruder, 1977). A prolific author of original Slovenian professional literature is Prof. Dr. Klementina Možina, who wrote a comprehensive textbook, *Tipografska Kunšt* (Možina, 2023), in 2023.

The majority of literature on this subject focuses on achieving professional standards, with comparatively little attention devoted to the pedagogy of typography and student artworks. A notable exception is *Thinking with Type*

(Lupton, 2010), a textbook that offers practical applications and links theory to student projects. This book has served as a valuable source for the exercises included in this text, which have been further refined over time.

1.2 The primary objective

The primary objective of this publication (Collection of exercises and assignments *Letters and Shapes: Collection of typographic exercises*) is to offer a comprehensive array of content, drawing upon the traditions of calligraphy and letterpress, 20th-century modernist principles, simple artistic experimentation and current technological possibilities

2. EXPERIMENTAL (MATERIALS AND METHODS)

2.1 Conception of the collection

The Letters and Shapes collection of exercises is the result of a decade of development in the study of typography and type design in regular and elective courses. The archiving of student work was conducted in either analogue or digital format. A comprehensive array of literature and online sources has been consulted for the design of the exercises in this collection, with the author having attended international typography conferences and sharing teaching experiences with colleagues.

The texts and delivery incorporate the order and discipline that I typically aim to instil in the classroom environment. The importance of typographic discipline for the autonomous and consistent completion of exercises is emphasised in lectures, which are supported by theoretical foundations, historical contexts, and references from design practice.

2.2 Chapters in the collection

The exercises and assignments have been organised into seven chapters, which cover a broad range of topics. These include basic typographic vocabulary and grammar, typographic applications, the relationship between function and form, control of complex layouts, type as image, and the fundamentals of typeface design with an emphasis on analogue approaches and digital implementations. The final chapter provides a synopsis of the practical study undertaken by small groups of students, which fosters communication during the execution and presentation of the results of the task.

2.3 Structure of the instructions

Exercise and task instructions consist of three elements. Firstly, a guiding thought that contextualises the problem and the resulting task. Secondly, a guide for implementation. And thirdly, a tip. The learning outcomes at the end of the texts serve as an orientation for evaluating the results of the study with multiple solutions.

2.4 Criteria for the selection of student works

The selection of student work for publication is predicated on two fundamental criteria: the innovation of the solution and the quality of the execution. Concurrently, the pursuit of diversity in the results of the study has been undertaken to emphasise the extensive possibilities for students to confront the challenges of design.

2.5 Publication design

The design concept is pragmatic, and as this is the inaugural version of an open-access electronic publication, the format chosen is 16:9 for spread and 8:9 for a single page. The selected images of student works are diverse in terms of format, colour, scale, technique and media, while the written task instructions are uniform in structure and predominantly balanced in word count.

The text of the exercises is consistently positioned on the leftmost edge of the spread and aligned to the left, while the internal hierarchical division enables readers to engage with the task instructions to varying degrees of depth. The images are distributed freely over the subsequent one or two spreads, with each spread forming a new pictorial composition. The layout was realised using Adobe InDesign, and the typeface family used was Degular Mono. The export file is an interactive PDF of medium JPG quality.

3. RESULTS WITH DISCUSSION

The initial version of the publication is exclusively available in digital PDF format, accessible via the UL Publishing House website and the UL ALUO website. The publication's design incorporates an Adobe InDesign master file, which facilitates the subsequent preparation of files for printing.

3.1 Chapters

The publication comprises seven chapters, encompassing 63 exercises with accompanying example solutions. The total content encompasses 626 units of visual material across 210 pages, with the chapters meticulously structured to align with the sequence of the exercises by year. Each chapter functions as an independent entity, yet is interconnected with the others: Letter, word, line and paragraph; Function and form; Position control, Letter in drawing; Glyph, letter and font; Typeface design, School typography workshops

3.2 Chapter contents

Letter, word, line and paragraph (Fig.1)

In the initial year of the programme, the study of typography is founded upon an exposition of the fundamental typographic vocabulary and grammar. Thematic units address the letter, word, line and paragraph in the visual relationships of the printed and unprinted surface. Guided exercises initiate the development of a palette of typographic resources, which the individual implements in a comprehensive design pursuit as the course progresses.

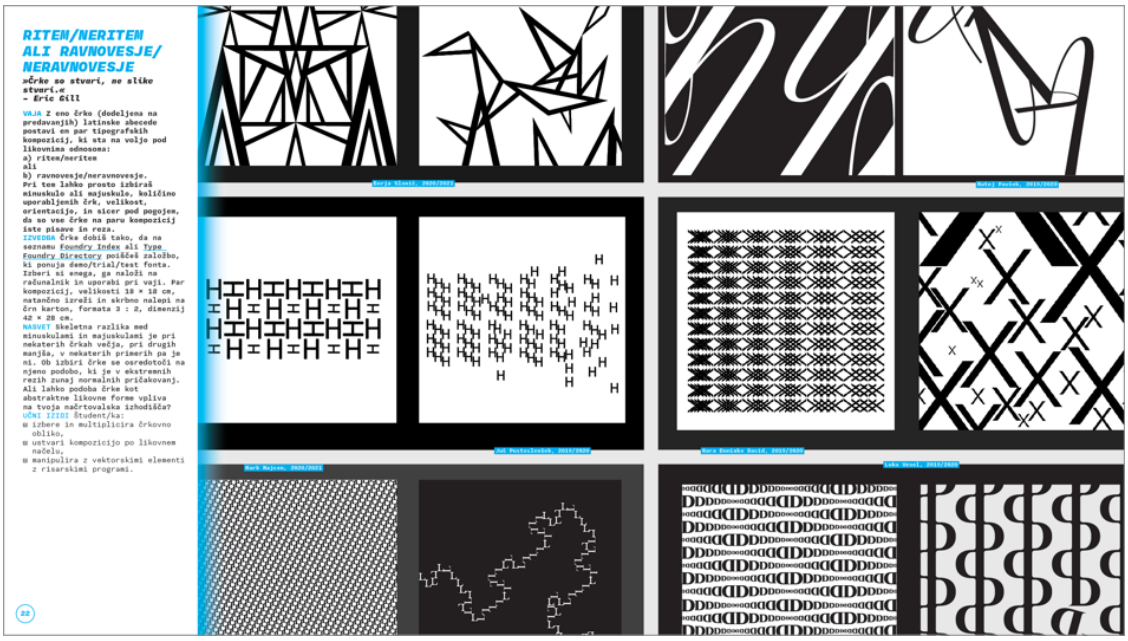


Figure 1: Spread from the chapter *Letter, word, line and paragraph*

Function and form (Fig. 2)

In the subsequent year, the study of typography is oriented towards applied typography. The course teaches students to understand the criteria for selecting typefaces, plan and design complex problems, respond critically to typographic essays and develop a visual language through the interpretation of a quotation. Students are taught to think of typography as a vehicle for a verbal message and an element of visual identity.

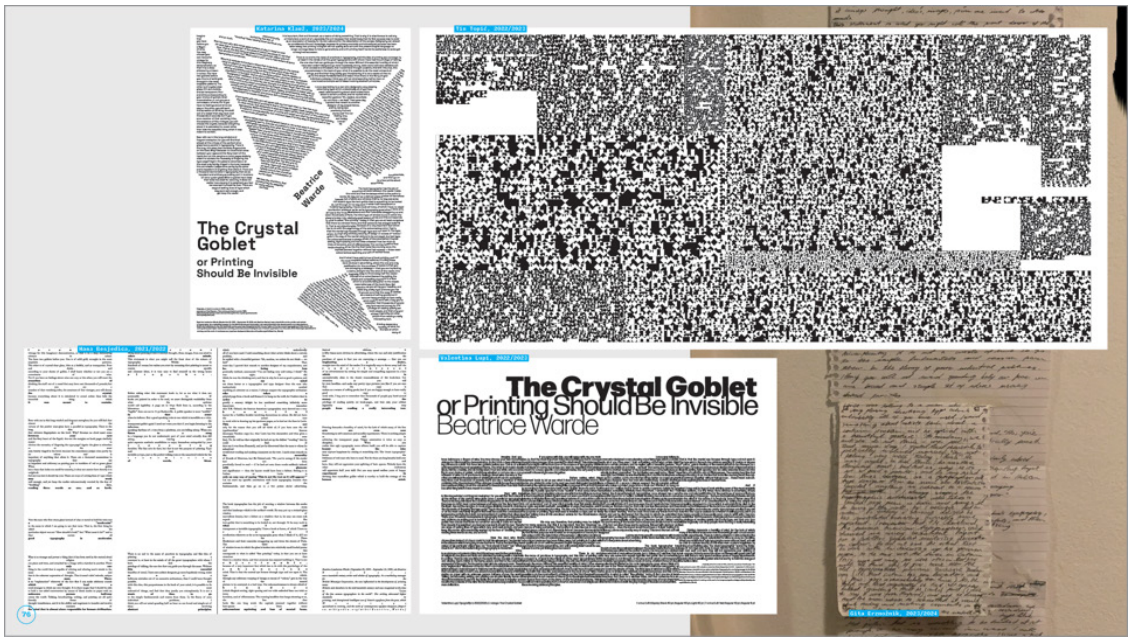


Figure 2: Spread from the chapter *Function and form*

Position control (Fig. 3)

The habitat of typography is flat. Typesetting is done horizontally and vertically while reading the Latin alphabet is done only from left to right and from top to bottom. The ability to manipulate the coordinate system in which we operate is a pivotal skill for typographers.

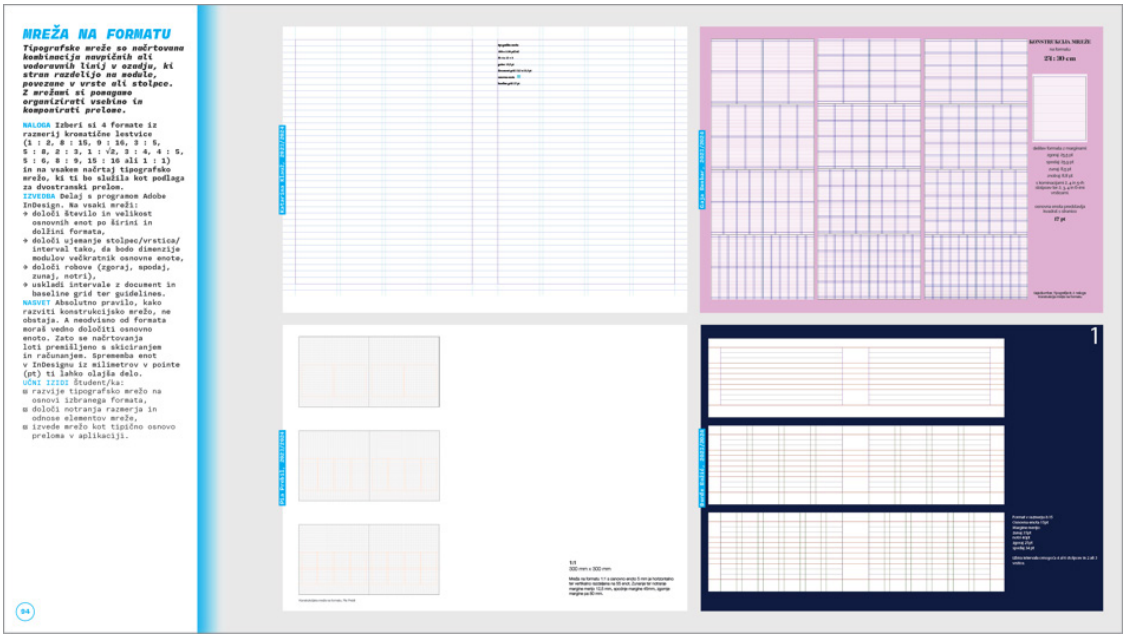


Figure 3: Spread from the chapter *Position control*

Letter in drawing (Fig. 4)

Despite the expanding array of typefaces available, it is often challenging to select or define the optimal typeface for a given task. In such instances, it is advisable to employ a custom approach. Rather than relying on typefaces that inadequately replicate handwriting, it is preferable to utilise one's handwriting.

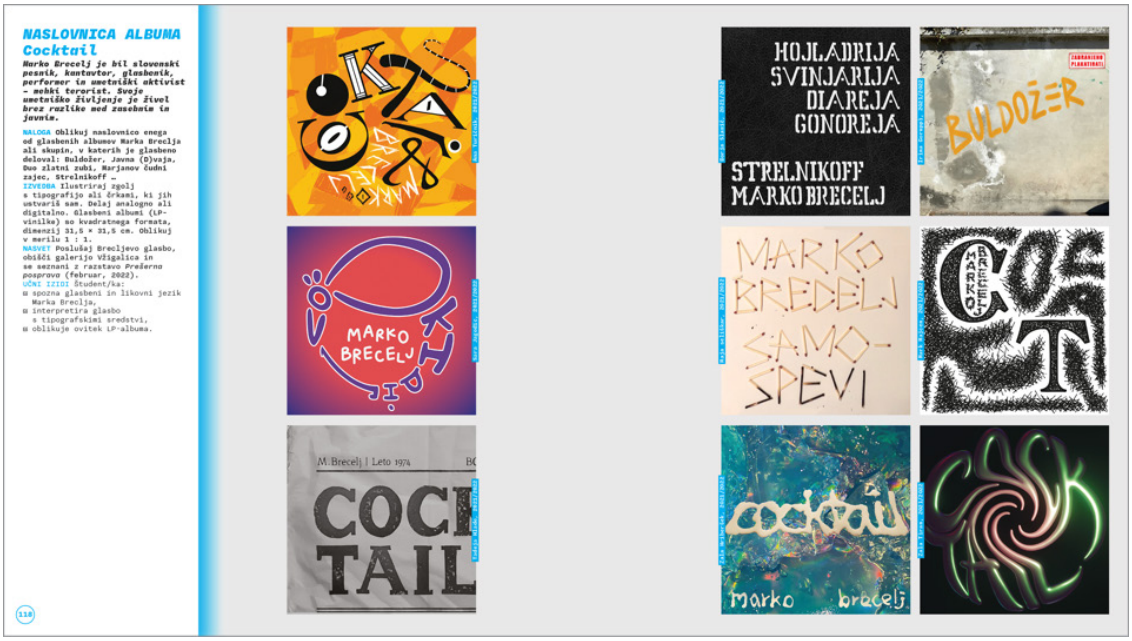


Figure 4: Spread from the chapter *Letter in drawing*

Glyph, letter and font (Fig. 5)

A plethora of approaches to type design have been shown to broaden typographic horizons and strengthen drawing skills. Although each assignment highlights one of the approaches, together they form a setting for understanding system design by integrating different design methods. Each of these methods shapes the designer and their authorial expression in its own way.

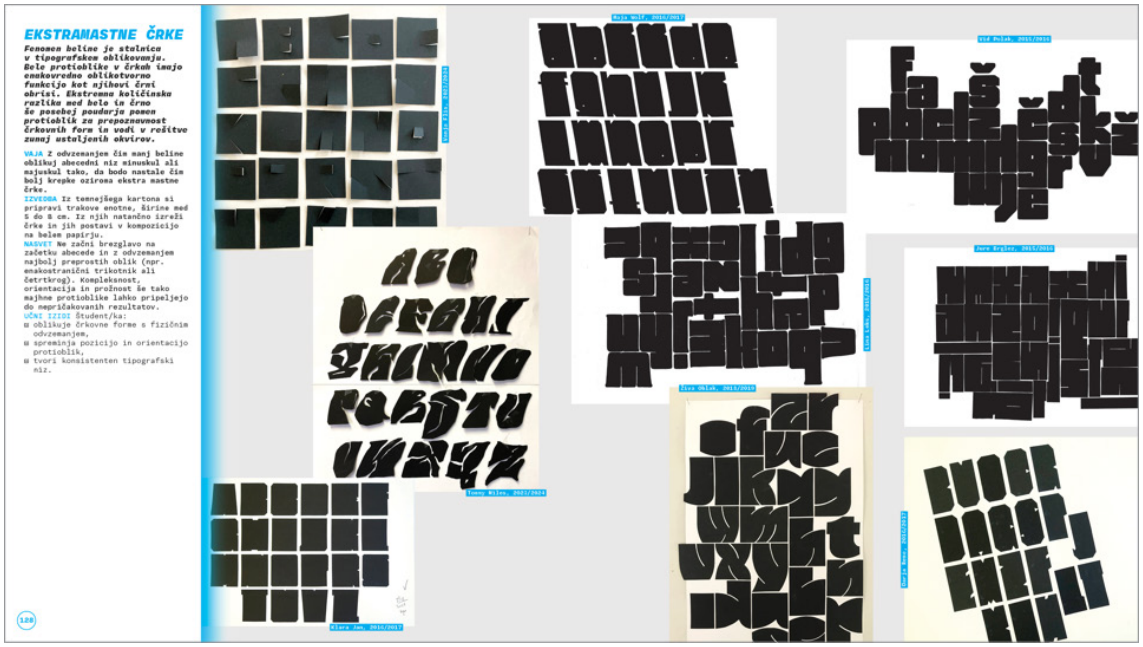


Figure 5: Spread from the chapter *Glyph, letter and font*

Typeface design (Fig. 6)

The impetus for embarking upon the pursuit of typeface design can vary, with the predominant motivation being the student's inherent fascination with typography. The undertaking of tasks may stem from a personal inclination, a research endeavour, or the necessity for a specific project if the typeface is developed concomitantly with the project to which it is affiliated. In our approach, we commence the delineation of characters from a conceptual and functional foundation, cognizant of the inherent interconnectedness among letterforms. The efficacy of a typeface is contingent upon its practical application; consequently, type designers must adopt dual roles: that of the user of the typeface (the graphic designer) and that of the user of the message (the reader).



Figure 6: Spread from the chapter *Typeface design*

School typography workshops (Fig. 7)

School workshops constitute a complementary element to lectures, serving as an introduction to independent study. Students engage in collaborative work in small groups to discuss topics and identify solutions to problems, undertaking this task manually without the use of any intermediary tools. The primary medium employed is paper, with collage techniques serving as the principal method of representation. The act of transferring the cut-out pieces onto the paper facilitates a connection among group members, and the outcomes of their collaborative efforts are made immediately apparent and can be objectively evaluated. After each workshop, a presentation of all the solutions is conducted, followed by a collective discussion among all participants.

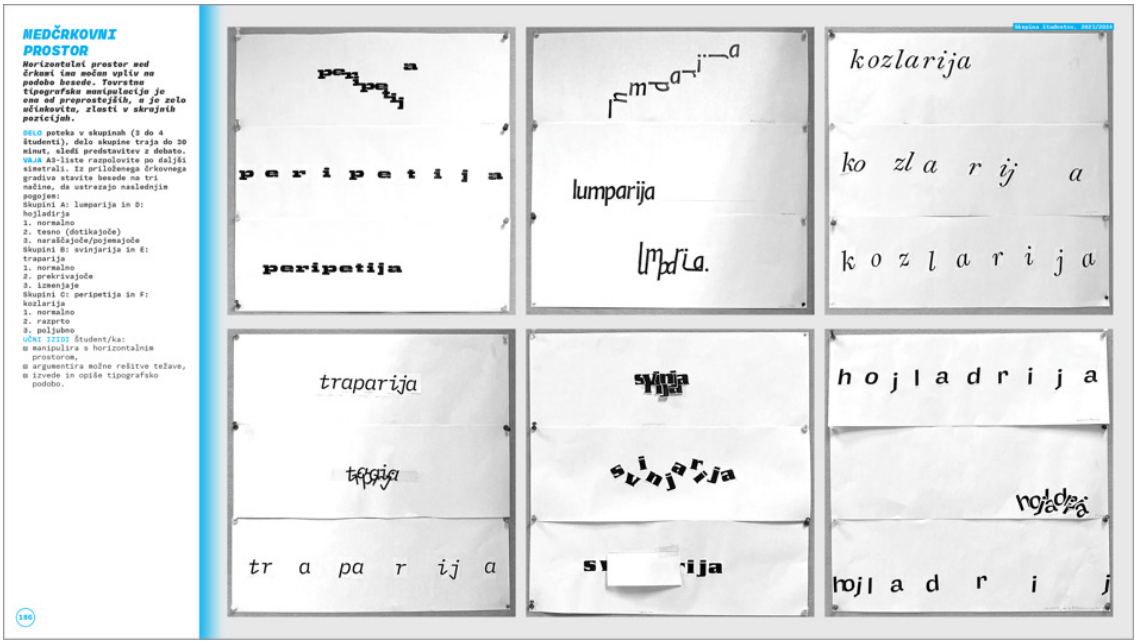


Figure 7: Spread from the chapter *School typography workshops*

4. CONCLUSIONS

The publication provides a synopsis of the pedagogical praxis employed in the Typography courses within the Visual Communication Design programme. The exercises and assignments are meticulously structured according to a well-established sequence, facilitating the acquisition of competencies about layering. The exercises and assignments are systematically executed within a recurrent cycle encompassing 'design, consultation and evaluation'. The duration of these exercises and assignments varies depending on the level of study and the complexity of the assignments. They can be completed within a few class periods, spanning a single lecture, or they may extend over a whole semester. A common feature of all assignments is the integration of analogue techniques and digital tools, fostering the development of design skills, even in the later years of study as the assignments become more challenging and complex.

The *Letters and Shapes collection* can be regarded as a cross-section of my pedagogical engagement over the past decade, offering a framework for a critical assessment of the quality, relevance and, ultimately, the actuality of the study of typography in the given circumstances. Although the publication is a complete whole, it is not a finished product; rather, it is a starting point for refinement, iteration and constant adaptation.

I plan changes in approaches, methods and delivery of content. It is beneficial to deviate from established routines, to omit or substitute exercises, to restructure them, or even to redesign them entirely. This approach is instrumental in maintaining a questioning mindset and utilising typographic methodologies to identify potential solutions.

5. REFERENCES

Books
Highsmith, Cyrus, *Inside paragraphs: typographic fundamentals*. Boston: Font Bureau, 2012.
Henestrosa, Christóbal, Laura Meseguer, in José Scaglione, *How to create typefaces: from sketch to screen*. Madrid: Tipo e, 2017.
Hochuli, Jost, *Detail in typography: letters, letterspacing, words, wordspacing, lines, linespacing, columns*. New ed. London: Hyphen Press, 2008.
Lupton, Ellen, *Thinking with type: a critical guide for designers, writers, editors, & students*. 2nd rev. and Expanded ed. New York: Princeton Architectural Press, 2010.
Možina, Klementina, *Tipografska kunšt: upodobitev informacij*. 1. izd. Ljubljana: Naravoslovnotehniška fakulteta, 2023.
Ruder, Emil, *Tipografija: priročnik tipografskega oblikovanja = Tipografija = Typographie*. Ljubljana: Partizanska knjiga; Znanstveni tisk, 1977.
Spiekermann, Erik, in E. M. Ginger, *Stop stealing sheep & find out how type works*. 2nd ed. Berkeley, Calif.: Adobe Press, 2003.

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POSTER PRESENTATION

ADAPTING BOOK COVER DESIGN BASED ON ITS TARGET GROUP

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Abstract: *Understanding the target group is essential when wanting to design a visually effective product, especially in the case of books. The appearance of a book reveals the story and message of the book, and leaves a lasting impression on the reader. Therefore, it is important to understand the psychology of colour and recognise the message expressed by the chosen typefaces and their shapes. The aim of this study was to identify the adjustments needed in the cover design of three different novels depending on their target group. Using the established guidelines, we designed a fantasy adventure novel for children, a contemporary novel for young adults and a contemporary romance novel for women. We were inspired by the current trends in the design of fiction books on the market. The design process leading up to the final product, including the colours and typefaces, was slightly different for each novel.*

Keywords: *target group, graphic design trends, fiction, book cover, book design.*

1. INTRODUCTION

Understanding the target group is essential when wanting to design a visually effective product, especially in the case of books. The appearance of a book reveals the story and message of the book, and leaves a lasting impression on the reader. Each element used in the book design can influence the reader in its own way. Therefore, it is important to understand the psychology of colour and recognise the message expressed by the chosen typefaces and their shapes. In order for the book to reach its target group, it is not only important to understand the psychology and follow established design guidelines, but we must also consider current design trends. By researching the market and paying attention to current trends, we can design a book that reveals its genre (Storyboard That, 2024), target gender and age of its readers by its appearance alone.

In this study, we designed three different novels to visually appeal to a corresponding target group. When analysing the current state, we found that the plot of the book is not only revealed by the genre (Storyboard That, 2024), but also by the cover design, chosen colours (Anderson Feisner, 2014), typefaces (Možina, 2023), graphic elements (Guide to Book Layout, 2024; Hendel, 1998; O'Connell, 2024) etc. We investigated the associations we have with certain colours and the importance of understanding the psychology of colour in conveying the message of the book (Anderson Feisner, 2014). We analysed the characteristics of typefaces and defined their components. We realised that the book cover plays a decisive role in the marketing of the book (Davies, 2024). It represents the reader's first contact with the book and can amuse, captivate, annoy or even repel them. The book cover expresses the tone and message of the text, which can indicate the book's genre and target group. While the cover piques the reader's interest, the interior design must maintain that interest (McCullough, 2024; The Psychology Behind Good Book Cover Design, 2024). We researched the market and trends in the design of young adult books and found that their covers often feature an illustration of a character or scene from the story with eye-catching illustrations appropriate to the genre of the book (How to Design a Young Adult Book Cover, 2024; Roberts, 2024; Young Adult Book Covers, 2024). We also investigated the trends in the design of books for adult women and concluded that these books are perceived as inferior due to their typical appearance (Bender, 2024; Darstaru, 2024; Roberts, 2024).

The aim of this study was to identify the adjustments needed in the cover design of three different novels depending on their target group.

2. EXPERIMENTAL

We designed the book's cover for three different novels. We designed a fantasy adventure novel for young adults, a contemporary novel for young adults and a contemporary romance novel for women. We were inspired by the current trends in the design of fiction books on the market.

For the Slovenian fantasy adventure novel *Varuhi življenja* for children (from nine to 14 years old), we created several designs (Figure 1). The contemporary novel *Moj brat lovi dinozavre* for young adults (from 11 to 18 years old) is a translation from Italian. First, we made two different designs (Figure 2), where we had to take some inspiration from the original design. Therefore, we designed four more versions of the book's cover (Figure 3). Based on the feedback from the original Italian publisher and their request to change the colour palette, we kept the original colour hierarchy idea, only altering it to shades of green (Figure 3, right). The contemporary romance novel *Sedem sester* for women was translated from English. For the design, we initially took the inspiration from the original design (Figure 4, left); however, we soon changed the style (Figure 5). All of the pink or yellow elements were planned to be printed using foil stamping with gold foil. The original publisher requested to add an armillary sphere to the cover; hence, we decided to replace it with the element of Rio at the bottom (Figure 5).



Figure 1: First two drafts of cover for *Varuhi življenja*



Figure 2: First two drafts of cover for *Moj brat lovi dinozavre*



Figure 3: Third, fifth, sixth and seventh draft of cover for *Moj brat lovi dinozavre*



Figure 4: Original cover (left) and first draft (right) of cover for *Sedem sester*



Figure 5: Second, third, sixth and eight draft of cover for *Sedem sester*

3. RESULTS WITH DISCUSSION

3.1 Book cover for novel *Varuhi življenja*

The book conveys its message through a fantasy story. Since dragons play an important role in it, we decided to use them as the main inspiration for the cover (Figure 6). Any colour in the original colour palette seemed too prosaic for a majestic and magical creature like a dragon. The colour purple is *inter alia* associated with spirituality, magic and fantasy. Therefore, we decided to build a new colour palette around purple. We chose a combination of purple, dark green, dark blue and pink instead of different darker or lighter shades of purple for the cover not to look too monotonous.

For the title *Varuhi življenja*, we chose the handwritten typeface P22 Stanyan in bold. We chose this typeface since we could imagine that it was the handwriting of one of the children's characters in the book. It does not look too serious and elegant; however, it conveys playfulness and youthfulness. We set the title in a size of 73 pt. Above the title, we added the authors' names in the sans-serif typeface Termina in a size of 11 pt. We set both the title and the authors' names in white, creating a contrast between the text and the background.

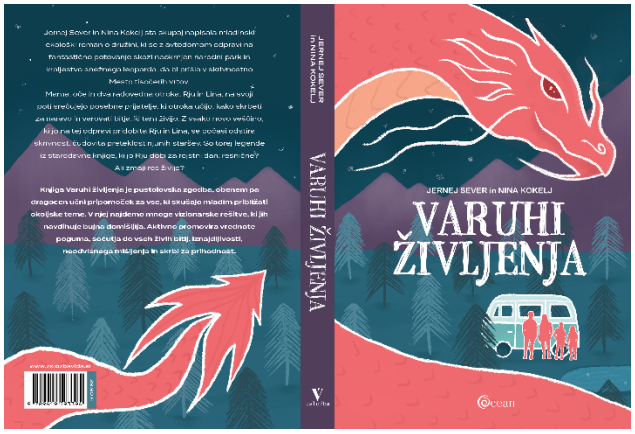


Figure 6: Final cover jacket for *Varuhi življenja*

3.2 Book cover for novel *Moj brat lovi dinozavre*

We created eight different designs for the book cover, the last of which was used for the final product (Figure 7). After designing the light green cover, we decided to combine the darkness of the blue version with the new green, resulting in a dark green cover. The title on the front and the synopsis of the book on the back were kept in soft yellow, while the short summary and the author's name on the front and the publisher's logo and website link on the back were kept in soft green. We coloured the silhouette of the boy in darker orange. The outlines of the plants were coloured in dark shades of green, while the outlines of the dinosaurs and the boy were coloured in the same yellow as the title. The same colour was also used for the stars and the elements on the spine.

For the title, we chose the decorative typeface BD Supper in 49.7 pt, which has the characteristics of a sans-serif graphic typeface. Below the title, we added the author's name in the same typeface in 23.4 pt. For the text on the back cover, we chose the transitional typeface Baskerville URW in 11.6 pt.

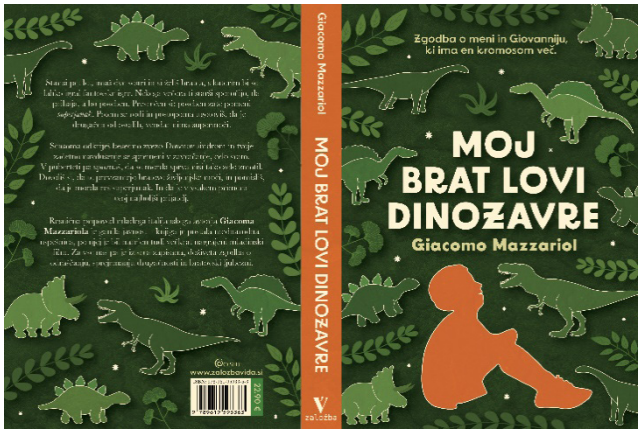


Figure 7: Final cover jacket for *Moj brat lovi dinozavre*

3.3 Book cover for novel *Sedem sester*

The tenth version of the book cover design was selected for the final product (Figure 8). For the women's novel, we chose a design that was not part of the typical design trends for women's novels and thus challenged gender-risation. For the design not to appear too complex, we chose a simple and plain colour palette. We focused on cooler colours for the background to create a better contrast between the background and the gold foil. We opted for blue, taking into account research on the preferred colours of our target audience, i.e. middle-aged women. Due to the risk of designing an atypical cover for a women's novel, we were reliant on the typefaces chosen to appeal to the target audience; thus, it was important that they had a more feminine feel.

For the title on the front cover, we chose the decorative typeface Rosalia in 40 pt, with its mix of soft and sharp strokes to match the overall design of the cover. The geometric sans-serif font Century Gothic in 26 pt. was used for the author's name. To achieve balance, the title was set in uppercase while the author's name was written in lowercase. For the short summary at the top of the back cover, the bold version of Century Gothic was used in 10 pt type size. For the longer summary of the book, we chose the transitional typeface Baskerville Display in 10.5 pt.

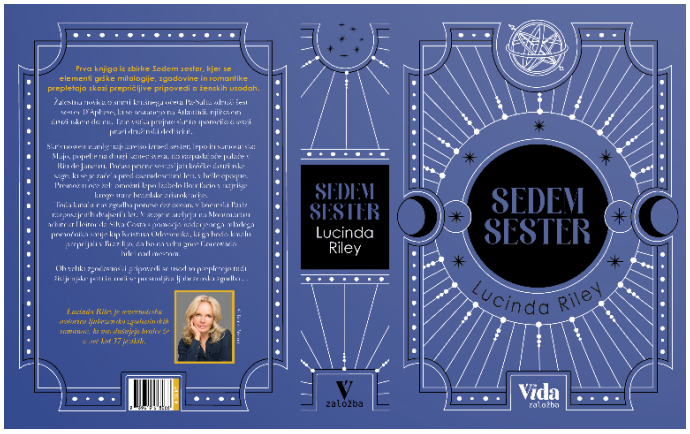


Figure 8: Final cover jacket for *Sedem sester*

In the final analysis of the design and production of the novels, we analysed the success and quality of the design. We identified errors that occurred during the process. These errors were noted to avoid their repetition in the future.

4. CONCLUSION

The study identifies the adjustments needed in the cover design of three different novels depending on their target group. We were inspired by the current trends in the design of fiction books on the market. The design process leading up to the final product, including the colours and typefaces, was slightly different for each novel. For the Slovenian fantasy adventure novel for children, we created several designs. The third one was selected for the final product. The contemporary novel for young adults is a translation from Italian. We had to take some inspiration from the original design. We created eight different designs for the book cover, the last one being used for the final product. The contemporary romance novel for women was translated from English. For the design, we initially took inspiration from the original design; however, we soon changed the style. The tenth version was selected for the final product. For the women's novel, we chose a design that was not part of the typical design trends for women's novels and thus challenged genderisation.

In the final analysis of the design and production of the novels, we analysed the success and quality of the design. We identified errors that occurred during the process. These errors were noted to avoid their repetition in the future.

5. REFERENCES

Anderson Feisner, E. and Reed, R. 2014. Color studies. New York: Fairchild Books, pp. 184–188.
Bender, J. YA Cover Art: Changes and Social Impact in the Last Twenty-Five Years. URL: https://scholarsarchive.byu.edu/cgi/viewcontent.cgi?article=1065&context=english_symposium (last accessed on 27. 2. 2024).
Darstaru, A. Design stereotypes: What Defines Feminine Design or Masculine Design? URL: https://www.creatopy.com/blog/masculine-design-feminine-design/ (last accessed on 27. 2. 2024).
Davies, P. The Psychology of Aesthetics and Style: How We are Attracted to These Notions. URL: https://play3r.net/news/the-psychology-of-aesthetics-and
-style-how-we-are-attracted-to-these-notions/ (last accessed on 27. 2. 2024).
Guide to Book Layout: What Makes a Book More Readable? URL: https://blog.reedsy.com/book-layout/ (last accessed on 27. 2. 2024).
Hendel, R. 1998. On Book design. London: Yale University Press, pp. 4, 35.
How to Design a Young Adult Book Cover: A Step-by-Step Guide. URL: https://www.publishingpush.com/blogs/how-to-design-a-young-adult-book-cover-a
-step-by-step-guide (last accessed on 19. 3. 2024).
McCullough, M. A. Young Adult Book Cover Design and Its Impact on Reader Interest. URL: https://firescholars.seu.edu/cgi/viewcontent.cgi?article=1148&context=honors (last accessed on 27. 2. 2024).
Možina, K. 2023. Tipografska kunšt. Ljubljana: Naravoslovnotehniška fakulteta, pp. 48–65, 71–76, 83–86, 207–211.
O'Connell, K. C. Young Adult Book Cover. URL: https://dl.uncw.edu/Etd/2010-1/oconnellk/kathleenoconnell.pdf (last accessed on 23. 2. 2024).
Roberts, R. Seeking Attention: What Covers Attract Readers. URL: https://editingresearch.byu.edu/2022/06/09/seeking-attention-what-covers-attract-readers/ (last accessed on 27. 2. 2024).
Storyboard That. URL: https://www.storyboardthat.com/sl/articles/e/literarno-zvrsti (last accessed on 8. 3. 2024).
The Psychology Behind Good Book Cover Design. URL: https://writerunboxed.com/2017/09/17/the-psychology-behind-good-book-cover-design/ (last accessed on 27. 2. 2024).
Young Adult Book Covers. URL: https://coverkitchen.com/young
-adult#:~:text=The%20trends%20in%20YA%20book,digital%20thumbnails%20and%20
physical%20books (last accessed on 19. 3. 2024).

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POSTER PRESENTATION

HOW COMPREHENSIBILITY OF PACKAGING SYMBOLS DEPENDS ON THE LEVEL OF ENVIRONMENTAL AWARENESS OF CONSUMERS

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Abstract: *The solution to packaging recycling is found by using symbols for proper waste disposal and increasing consumer environmental awareness. Previous research has shown the influence of demographic characteristics on the understanding of symbols on packaging. The aim of this paper is to examine the influence of age and level of education on the understanding of symbols and consumer environmental awareness. The research was conducted using an online survey in which 126 respondents participated. Respondents were asked to explain the meaning of 9 standardized symbols: International Symbol for Recyclable Packaging, Green Dot, Don't Pollute / Let's Save Nature!, Eu Eco Label, WWF World Wildlife Fund, Numbering System and Abbreviations for Packaging Labeling, Separate Waste Collection, FSC (Forest Stewardship Council), Compostable. The results showed the influence of age and environmental awareness on the understanding of environmental symbols, while the level of education did not affect the understanding of symbols.*

Keywords: *packaging, recycling symbols, understandability of symbols, environmental awareness*

1. INTRODUCTION

Environmental awareness refers to the recognition of the interconnection between human actions, sustainability, and responsibility, based on the understanding that humans and ecosystems coexist in a shared environment. Eco-labeling of products influences consumer awareness by signaling that the product's manufacturing process meets ecological standards, i.e., that it has the least possible environmental impact. However, an excessive number of eco-labels can lead to information overload, which may reduce their effectiveness in guiding purchasing decisions. This confusion may arise from the ambiguity of terms used in eco-labels, which may not align with consumer knowledge (Mitchell, 2005). A practical example is that consumers often do not understand environmental protection information on labels such as "CFC-free," "eco," and "green," especially the differences between them.

A study by Moon et al. (2016) shows that too much information on eco-labels reduces understanding. The ability to understand ecological symbols on packaging depends on numerous factors. Age has been identified as a significant determinant of attitudes toward the environment, as well as the studies conducted on this topic. The nature of these relationships is influenced by social, societal, and economic factors (Ogunbode, 2012). Previous research suggests that younger individuals are more aware of environmental issues (Arcury, 1990; Inglehart, 1995; Whitehead, 2006). Recent studies confirm an increase in environmental awareness among younger consumers, evident in their purchasing choices and pro-environmental behaviors (Wierzbiński, 2021), especially among millennials, who are actively involved in promoting sustainability (Carrión-Bósquez, 2024). Research by Abdul-Wahab (2010) showed that people with higher levels of education are more knowledgeable about ecology and environmental conservation, while Ogunbode (2012) found no differences among respondents with different educational backgrounds. Pam Scholder's research (1994) examined the recognition of symbols on packaging. The results indicated less objective and perceived knowledge among older individuals and those with only a high school education. Labeling on packaging and products can be ambiguous, which leads to difficulties in sorting waste into the appropriate recycling and collection systems (Jóźwik-Pruska, 2022). Eco-labels should be designed to be easily understood, visually appealing, and highly visible to facilitate product evaluation (Donato, 2022; Magnier, 2015). Symbols on packaging encourage pro-environmental behavior, making their understanding crucial. Previous studies have shown that individuals who have encountered ecological symbols are more likely to recognize and understand these symbols on packaging (Ma, 2018). Therefore, the aim of this paper is to examine

the impact of age and educational level on the understanding of symbols on packaging and overall environmental awareness among product users.
Four hypotheses are proposed:
H1: Younger individuals are more environmentally aware than older individuals – this aims to explore environmental awareness across three age groups of respondents.
H2: Younger individuals understand symbols on packaging better than older individuals – the assumption is that younger people are more familiar with ecological symbols due to ongoing education, internet usage, and greater openness to new ideas compared to older individuals. For older individuals, symbol recognition may be linked to experience, which younger people may lack.
H3: Individuals with higher levels of education understand ecological symbols on packaging better – higher education levels lead to more knowledge gained through years of schooling, both theoretical and practical, providing more experience than individuals with lower levels of education (Abdul-Wahab, 2010).
H4: Understanding ecological symbols increases with greater environmental awareness – individuals who recycle waste must recognize the ecological symbols on packaging. However, the question remains whether individuals who do not prioritize the environmental aspect do so out of negligence or because they are unfamiliar with the ecological symbols.

2. EXPERIMENTAL

To assess comprehensibility, nine standardized symbols commonly found on product packaging were used: the International Symbol for Recyclable Packaging, the Green Dot, “Do Not Litter / Protect Nature!”, the EU Ecolabel, the WWF (World Wildlife Fund) logo, the Plastic Resin Identification Codes, the Separate Waste Collection symbol, FSC (Forest Stewardship Council), and the Compostable symbol (Figure 1). Comprehensibility was evaluated using a symbol recognition method—respondents were asked to describe what they believed the symbol represented, and if they did not recognize the symbol, they were instructed to respond with “I do not recognize it.” Environmental awareness was measured based on statements that respondents rated using a 5-point Likert scale. The survey was conducted via an online questionnaire, with a total of 126 participants (Table 1)



Figure 1: Symbols on product packaging

Table 1: Respondent characteristics

		N
Gender	Male	52
	Female	74
Age	18-34 (young)	96
	35-64 (middle-age)	14
	65+ (older)	16
Education	Secondary education	43
	Bachelor’s or equivalent	39
	Master’s or equivalent	36
	Doctorate or equivalent	8

3. RESULTS

The results show greater environmental awareness among younger people compared to middle-aged and older people (Table 2).

Table 2. Results of respondents' self-assessment of environmental awareness

	Age	N	Mean	Std. Deviation	Std. Error Mean
Environmental awareness	18-34	96	4,1979	,65886	,06724
	35-64	14	3,8216	1,0759	,28756
	65+	16	3,8750	,71880	,17970

The results of understanding symbols depending on the age of the respondents showed that understanding of ecological symbols decreases with increasing age (Table 3).

Table 3. Results of understanding symbols depending on the age of the respondents

					95% Confidence Interval for Mean			
	N	Mean	Std. Deviation	Std. Error	Lower Bound	Upper Bound	Min.	Max.
18-34	96	2,8333	1,67122	,17057	2,4947	3,1720	,00	7,00
35-64	14	2,2143	1,96815	,52601	1,0779	3,3507	,00	6,00
65+	16	,8750	1,58640	,39660	,0297	1,7203	,00	6,00
Total	126	2,5159	1,80548	,16084	2,1975	2,8342	,00	7,00

To check statistical significance within groups, Post Hoc multiple comparison tests Tukey HSD and Games-Howell test were used (Table 4). The tests differed in comparing the mean age with the others, but both tests showed that the results between the younger and older population were statistically significant ($P < 0.01$).

Table 4. Results of Post Hoc Multiple Comparison Tests

						95% Confidence Interval for Mean	
	(I) Age	(J) Age	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
Tukey HSD	18-34	35-64	,61905	,48496	,411	-,5315	1,7695
		65+	1,95833*	,45774	<,001	,8724	3,0443
	35-64	18-34	-.61905	,45496	,411	-1,7695	,5315
		65+	1,33929	,62036	,082	-,1325	2,8110
	65+	18-34	-1,95833*	,45774	<,001	-3,0443	-,8724
		35-64	-1,33929	,62036	,082	-2,8110	,1325
	18-34	35-64	,61905	,55297	,516	-,8091	2,0472
		65+	1,95833*	,43172	<,001	,8699	3,0467
	35-64	18-34	-.61905	,55297	,516	-2,0472	,8091
		65+	1,33929	,65877	,125	-,3017	2,9802
	65+	18-34	-1,95833*	,43172	<,001	-3,0467	-,8699
		35-64	-1,33929	,65877	,125	-2,9802	,3017
*The mean difference is significant at the level 0.05 level.							

Furthermore, the influence of education level on the understanding of environmental symbols on packaging was examined. The results (Table 5) showed that understanding of symbols increases with higher education level up to master's/doctorate. In these results, it is crucial to consider the sample size and its possible impact on the accuracy of the results. The small sample size of respondents with a master's/doctorate degree is not considered relevant and was not taken into consideration.

Table 5. Results of understanding symbols depending on the level of education of the respondents

					95% Confidence Interval for Mean			
	N	Mean	Std. Deviation	Std. Error	Lower Bound	Upper Bound	Min.	Max.
Secundary education	44	2,1591	1,72456	,25999	1,6348	2,6834	,00	7,00
Bachelor's or equivalent	38	2,6053	1,79398	,29102	2,0156	3,1949	,00	7,00
Master's or equivalent	36	3,1389	1,85400	,30900	2,5116	3,7662	,00	7,00
Doctorate or equivalent	8	1,2500	1,03510	,36596	.3846	2,1154	,00	3,00
Total	126	2,5159	1,80548	,16084	2,1975	2,8342	,00	7,00

Finally, the understanding of symbols was examined based on the respondents' ecological awareness. It was assumed that respondents with a higher level of ecological awareness would have a better understanding of ecological symbols. The ANOVA test showed greater understanding of symbols with increasing ecological awareness (Table 6).

Table 6. Results of understanding symbols depending on the level of ecological awareness

					95% Confidence Interval for Mean			
	N	Mean	Std. Deviation	Std. Error	Lower Bound	Upper Bound	Min.	Max.
Medium level of environmental awareness	28	1,3571	1,49603	,28272	,7770	1,9372	,00	7,00
High level of environmental awareness	63	2,5714	1,67249	,21071	2,1502	2,9926	,00	7,00
Highest level of environmental awareness	35	3,3429	1,81404	,30663	2,7197	3,9660	1,00	7,00
Total	126	2,5159	1,80548	,16084	2,1975	2,8342	,00	7,00

Post Hoc Tukey HSD and Games – Howell tests showed that the data were statistically significant between all groups except the group with high and highest environmental awareness, which also showed an increase, but not as statistically significant (Table 7).

Table 7. Results of Post Hoc Multiple Comparison Tests

						95% Confidence Interval for Mean	
	(I) Environmental awareness	(J) Environmental awareness	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
Tukey HSD	(1) Medium-high level of environmental awareness	2	-1,21429*	,38080	,005	-2,1177	-,3109
		3	-1,98571*	,42509	<,001	-2,9942	-,9772
	(2) High level of w awareness	1	1,21429*	,38080	,005	,3109	2,1177
		3	-,77143	,35345	,078	-1,6100	,0671
	(3) Highest level of environmental awareness	1	1,98571*	,42509	<,001	,9772	2,9942
		2	,77143	,35345	,078	-,0671	1,6100
Games-Howell	(1) Medium-high level of environmental awareness	2	-1,21429*	,35261	,003	-2,0626	-,3660
		3	-1,98571*	,41708	<,001	-2,9877	-,9838
	(2) High level of environmental awareness	1	1,21429*	,35261	,003	,3660	2,0626
		3	-,77143	,37205	,103	-1,6636	,1207
	(3) Highest level of environmental awareness	1	1,98571*	,41708	<,001	,9838	2,9877
		2	,77143	,37205	,103	-1,207	1,6636
*The mean difference is significant at the level 0.05 level.							

4. RESULTS DISCUSSION

Previous research indicates that younger individuals exhibit a higher level of environmental awareness compared to the older population (Abdul-Wahab, 2010; Ogunbode, 2012), which confirms the first hypothesis (H1). Considering age as a factor in understanding environmental symbols, the results show that younger individuals have a better understanding of environmental symbols than the older population, thereby confirming the second hypothesis (H2). The level of environmental awareness and familiarity with environmental symbols is often linked to the level of education and knowledge of ecology and sustainability. Individuals with a higher degree of environmental awareness are more conscious of the importance of sustainability and environmental protection, making them more sensitive to information about environmental symbols when purchasing products. This study has demonstrated a connection between the level of education and the comprehension of symbols on packaging, which supports the third hypothesis (H3). A consumer's level of environmental awareness can significantly influence their understanding of packaging symbols. Those with a high level of environmental awareness are familiar with symbols used to indicate the ecological characteristics of products and can recognize symbols related to recycling, energy efficiency, environmental certification, or sustainability. On the other hand, individuals with lower environmental awareness are less familiar with these symbols and their meanings, reducing their ability to recognize them. This may stem from a lack of environmental education or a lower interest in sustainability and environmental protection, thereby confirming the fourth hypothesis (H4).

It is important to note that the comprehensibility of packaging symbols depends not only on the observer's level of environmental awareness but also on the clarity and universality of the symbols themselves. If the symbols are simple, intuitive, and visually well-presented, they can be understood by a broad range of individuals, regardless of their level of environmental awareness. People who have previously interacted with certain symbols or have engaged with environmental topics, such as recycling or waste reduction, are more likely to recognize and understand packaging symbols (Ma, 2018). The findings reveal an unexpected result: a significant proportion of participants—nearly 74%—claimed to recognize a specific symbol and provided responses accordingly. However, further analysis showed that these responses were inaccurate. This result highlights the complexities of human cognition, emphasizing the potential for perception to be misleading. The discrepancy between confidence and correct answers suggests a possible overestimation of one's own knowledge. We assume that participants often avoid leaving answers blank, instead choosing responses that seem logical in order to appear knowledgeable. Furthermore, when comparing our results with previous research by Pam Scholder (1994), interesting similarities emerge. Scholder's study found that participants, on average, correctly identified 4 out of 9 symbols presented, whereas our findings indicate an average of 3.3 out of 9 symbols. Although there is a slight difference in average results, the overall pattern remains consistent. Both studies demonstrate that participants faced challenges in accurately recognizing and recalling symbols.

5. CONCLUSION

Based on the obtained results, there has been a noticeable increase in environmental awareness in recent years, driven by technological advancements and greater access to information. The Internet has become a key platform for spreading knowledge about climate change and sustainability, particularly among younger generations who use it daily as a source of information (Pew Research Center, 2021). According to Boykoff (2011) and Levy and Spicer (2013), digital media and social networks shape public discourse and the understanding of environmental issues. Examples such as Greta Thunberg and the #FridaysForFuture movement highlight the power of online campaigns in raising awareness and mobilizing the public. However, to bring about meaningful ecological change, this awareness must be further strengthened through consistent education and learning—beyond what the Internet alone can offer. The research showed that the majority of respondents understand the recycling symbol, which can be attributed to its standardized design and widespread global use, making it one of the most commonly taught symbols. We propose the introduction of specialized educational programs within the curriculum that would place greater emphasis on other environmental symbols and aspects of ecology, helping to familiarize younger generations with environmental topics.

This study revealed that respondents, regardless of their characteristics, recognized fewer than 40% of the symbols presented, raising important questions. Why do people struggle to understand packaging symbols? To address this, we propose guidelines for further research on this topic. We believe the issue could be examined by designing different types of symbols (either low-structured or high-structured) to determine whether the current symbols provide too much or too little information, impacting their comprehensibility. Additionally, we suggest that future research should involve a larger sample of participants to enable a more in-depth analysis of the relationship between these variables.

6. REFERENCES

Abdul-Wahab, S. A. and Abdo, J. 2010. "The Effects of Demographic Factors on the Environmental Awareness of Omani Citizens." *Human and Ecological Risk Assessment* 16 (2): 380-401.

Arcury, T.A. 1990. "Environmental Attitude and Environmental Knowledge." *Human Organization* 49 (4): 300-304.

Carrión-Bósquez, N., Veas-González, I., Naranjo-Armijo, F., Llamo-Burga, M., Ortiz-Regalado, O., Ruiz-García, W., Guerra-Regalado, W. and Vidal-Silva, C. 2024. "Advertising and Eco-Labels as Influencers of Eco-Consumer Attitudes and Awareness - Case Study of Ecuador." *Foods* 13 (2): 228.

Donato, C. and Adıgüzel, F. 2022. "Visual complexity of eco-labels and product evaluations in online setting: Is simple always better?" *Journal of Retailing and Consumer Services* 67: 102961

Inglehart, R. 1995. "Public Support for Environmental Protection: Objective Problems and Subjective Values in 43 Societies." *Political Science & Politics* 28 (1): 57-72

Jóźwik-Pruska, J., Bobowicz, P., Hernández Vázquez, C.I. and Szalczyńska, M. 2022. "Consumer Awareness of the Eco-Labeling of Packaging." *Fibres and Textiles in Eastern Europe* 30(5): 39-46.

Levy, David L. and Andre Spicer (2013). "Contested Imaginaries and the Cultural Political Economy of Climate Change." Organization, 20(5): 659–678

Ma, G., Rau, P-L.P. and Guo, Z. 2018. "The Effects of Environmental Awareness and Consumption Value on Green Makeup Product Purchase Intentions." *Psychology* 9(7): 1898-1916.

Magnier, L. and Crié, D. 2015. "Communicating packaging eco-friendliness: An exploration of consumers' perceptions of eco-designed packaging." *International Journal of Retail & Distribution Management* 43(4/5): 350-366.

Mitchell, V.W., Walsh, G. and Yamin, M. 2005. "Towards a Conceptual Model of Consumer Confusion." *Advances in Consumer research*, 32: 143-150.

Moon, S.J., Costello, J.P. and Koo, D.M. 2016. "The impact of consumer confusion from eco-labels on negative WOM, distrust, and dissatisfaction." *International Journal of Advertising* 36 (2): 246-271

Ogunbode, C. and Arnold, K. 2012. "A Study of Environmental Awareness and Attitudes in Ibadan, Nigeria" *Human and Ecological Risk Assessment* 18: 669-684.

Pam Scholder, E. 1994. "Do we know what we need to know? Objective and subjective knowledge effects on pro-ecological behaviors." *Journal of Business Research* 30(1): 43-52.

Alec T., Brian K. and Cary F. (2021). "Climate, energy and environmental policy." Pew Research Center

Veltri, G. A., & Atanasova, D. (2017). "Climate change on Twitter: Content, media ecology and information sharing behaviour." Public Understanding of Science, 26(6), 721–737.

Whitehead, J.C. 2006. "Environmental Interest Group Behaviour and Self-Selection Bias in Contingent Valuation Mail Surveys." *Growth and Change* 22 (1): 10-20.

Wierzbiński, B., Surmacz, T., Kuźniar, W. and Witek, L. 2021. "The Role of the Ecological Awareness and the Influence on Food Preferences in Shaping Pro-Ecological Behaviour of Young Consumers." *Agriculture* 11 (4): 345.

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POSTER PRESENTATION

COMPARISON OF A SELF-CREATED VISUAL CORPORATE IDENTITY WITH ONE GENERATED BY ARTIFICIAL INTELLIGENCE

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Abstract: *This study examines the role of generative artificial intelligence (AI) in designing corporate visual identities (CVI) and compares it with traditional design methods. With the growing use of AI in creative industries, the research explores whether AI can replace human creativity or if the human factor remains essential.*

The study investigates the impact of AI on quality, time efficiency, and adaptability. In the experimental part, two CVIs were created for a company specializing in the rental of soft-serve ice cream machines*: one using traditional methods and the other with AI tools. Three AI tools were tested, and feedback was collected via surveys and A/B testing.*

Results show that AI significantly improves automation and time efficiency but requires human input for customization and creativity. While AI delivers quality results, human involvement remains critical for achieving optimal outcomes, highlighting the need for integrated approaches.

Keywords: *generative artificial intelligence, corporate visual identity, graphic design, artificial inteligence tools, soft-serve ice cream*

1. INTRODUCTION

In the last decade, artificial intelligence (AI) has become a key factor in creative industries, including graphic design. This research paper examines the role of artificial intelligence (AI) in designing a corporate visual identity (CVI) and compares it with traditional design methods.

A CVI is a crucial communication element for any company, as it forms the foundation of its identity and marketing communication. Every interaction with a brand represents communication or information that is part of the brand's identity, enhancing recognition and increasing differentiation (1). CVI consists of several fundamental elements, such as colors, typography, slogans, logos, or symbols, which together create a comprehensive representation of the brand (2). All elements must be designed to ensure effective application across various media, both traditional and digital, and to adapt to different business sectors and markets in which the company operates (3).

AI is one of the newest fields of science and engineering, which began serious development shortly after World War II, though the term only became established in 1956. The first work that is now widely recognized as AI was conducted by Warren McCulloch and Walter Pitts in 1943 (4, 5). Throughout history, AI has evolved through various phases: neural networks (1950–1970), machine learning (1980–2010), deep learning (2011–2020), and generative AI (present) (5).

AI is a technology that enables computers and machines to simulate human intelligence and problem-solving capabilities through algorithms. In graphic design, generative AI, utilizing advanced algorithms and machine learning, facilitates the automation of tasks such as logo generation, color scheme selection, and the design of various CVI applications. It serves as a crucial tool for rapidly creating diverse design solutions (6, 7).

With the rapid advancement of AI, a fundamental question arises: can this technology replace human creativity in design, or will the human factor remain essential for achieving optimal results?

The study examines the impact of generative AI on the quality, time efficiency, and adaptability of CVI. It focuses on three hypotheses: (H1) CVI created without AI will be more tailored to the client's preferences, (H2) AI will shorten the design timeline, and (H3) AI will enable a technically refined final product. The research is based on a case study of a specific company for which two CVIs were created—one using a traditional approach and the other utilizing AI.

The significance of the study arises from the increasing use of AI in creative industries. Traditionally, graphic design tasks have been performed exclusively by human designers, whose creativity and adaptability were essential. Advances in AI now allow for the automation of many of these processes, raising questions about the efficiency and suitability of AI compared to human work. This research provides insight into how AI can transform design processes and whether it can achieve results equal to or even superior to those of human designers.

In this study, we conducted a comparative analysis of two approaches to CVI design: the traditional method and the AI-assisted approach. In collaboration with a company specializing in the rental of soft-serve ice cream machines, we developed two CVIs—one using traditional methods and the other utilizing AI tools. The experimental phase included time measurement of each design stage, enabling a comparison of the time efficiency of both approaches.

The AI tools used in the study included generative algorithms for logo creation, color scheme selection, and other graphic elements. Feedback from target users, along with a comparison of time-related data, provided a comprehensive analysis of the efficiency and adaptability of both methods.

2. EXPERIMENTAL

The experimental phase of the study was divided into two parts:

1. CVI design without AI assistance: This approach involved the manual creation of a logo, selection of color schemes, and design of various CVI applications.

2. CVI design using generative AI: The tools used included Looka (8), Design AI (9), and Design.com (10), which enable the automation of certain design processes. In this case as well, the goal was to create a logo, select a color scheme, and design various CVI applications suitable for different media.

The entire design process, from concept to realization, was subject to time measurement.

As part of the CVI, we designed a logo that incorporated both graphic and typographic elements. The client requested that the logo for the company *Točen sladoled* also include the logo of its parent company, *DSM*. In addition to the primary and secondary logos, we designed the following materials: a business card, letterhead, flyer, social media post, graphic for social media stories, profile and cover images for social media, and a web advertisement.

Before initiating the design process, we conducted a market analysis, examining the CVIs of four Slovenian companies operating in a similar industry as our client. Our focus was primarily on the following aspects: logo design, typography and color selection, consistency of CVI elements, and alignment between print and digital materials.

We also conducted research on generative AI tools designed for graphic design. After a thorough analysis of twelve different tools, we selected the three most suitable ones—Looka (8), Design AI (9), and Design.com (10)—to first attempt logo creation. The most effective tool proved to be Design.com, which was subsequently used to develop the remaining CVI elements, including stationery and digital graphics.

The experimental phase also included testing the target audience's satisfaction with both design methods. To achieve this, we conducted a survey among the target audience using an A/B testing method. The goal of this survey was to assess the efficiency and quality of graphic outputs generated by AI compared to those created by human designers.

We aimed to determine how users perceive AI-generated graphic elements and how these compare to those designed by human professionals. Additionally, we explored which design aspects (e.g., professionalism, clarity, creativity, attractiveness) are most important to users across different types of graphic materials and whether AI-generated designs can meet these expectations.

3. RESULTS WITH DISCUSSION

As part of our research, we created two versions of the CVI for the company *Točen sladoled*: one was designed using conventional methods without AI assistance, while the other was developed using AI tools. The fundamental element of any CVI is the logo. In Figure 1, the logo created without AI is presented, whereas Figure 2 displays the logo generated with AI. The AI tools did not provide the option to create a secondary version of the logo, nor did they allow for integration with the logo of the parent company, DSM.



Figure 1: The logo we designed traditionally, without AI, in both primary and secondary versions (positive and negative).



Figure 2: The logo we designed using AI in its primary and only version.

In addition to the logo, we designed several corporate printed materials, including a business card, letterhead, and flyer. For digital media, we created various graphics for social media branding, such as a profile picture, cover image, story, post, and a web advertisement. All of these can be found in Appendices A (1–6) and B (1–6).

We also measured the duration of both design processes. A detailed record of the time measurements for individual design phases of both design processes is presented in Appendices C and D. The AI-assisted design process required significantly less time (1 h 45 min) compared to the traditional design process (19 h 55 min).

The outcomes of our work, as well as those generated by AI, were evaluated through an online survey involving 31 respondents, of whom 13 were male and 18 female. Their ages ranged from 25 to 50 years. Participants received no payment for their participation. Sixty-seven percent of respondents held higher education degrees (associate, bachelor's, or university level). Twenty-four participants reported previous experience with artificial intelligence (AI) before completing the survey. Respondents were asked to rate their agreement with the statement, "Do you believe that artificial intelligence can lead to highly refined products in graphic design?" on a scale from 1 to 5 (1 indicating strong disagreement, 5 indicating strong agreement). Sixteen respondents selected rating 4, twelve selected rating 3, and only three respondents selected rating 5. Thus, respondents generally agreed that AI can create refined products, although their agreement was somewhat cautious.

In the second part of the survey, respondents chose between graphics created by AI and those designed manually. They were also able to provide reasons for their choices. When choosing a logo, 68% preferred manually designed logos, citing more attractive colors, font style, and overall visual appeal. For business cards, 55% preferred AI-generated designs, while 52% found manually designed letterheads more attractive. Regarding social media materials (profile picture, posts, stories, and cover images), most respondents (20 out of 31) preferred manually designed materials, citing more creative and engaging designs better suited for social media communication, as well as the use of product-specific photographs (soft-serve ice cream). When selecting a web advertisement and flyer, 74% preferred manually designed materials due to their greater attractiveness and effectiveness, clearer element layout highlighting the ice cream, and more direct messaging.

In the final question, which asked respondents if they could identify AI-created materials, 55% correctly identified the AI-generated designs.The results are presented in Figure 3.

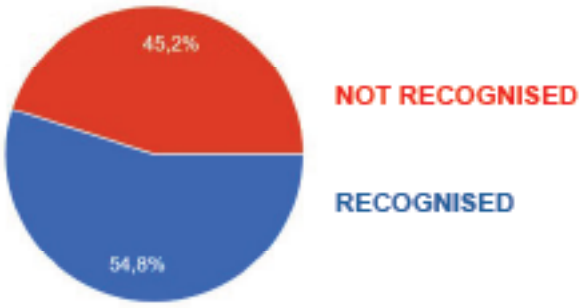


Figure 3: Respondents' recognition of AI-generated work

Unexpected challenges primarily arose with AI tools. Currently, most of them do not support diacritical marks, which presented a significant issue for us. Some tools lack clear definitions of certain concepts, for instance, soft-serve ice cream (with some tools displaying a popsicle instead). The biggest challenge was that the tools are still only available in English and are not optimally adapted for use in other languages. Additionally, some tools are quite complex to use, requiring precise input or selection of appropriate terms to achieve the desired results.

In the broader context, our findings reflect the need for further exploration of the collaboration between AI and human creativity. While AI provides an exceptional tool for accelerating and optimizing certain processes, human designers remain essential for creating and tailoring outcomes to meet the unique requirements of each client. This opens new possibilities for the development of hybrid working methods, where AI and human creativity collaborate, potentially enhancing the efficiency and quality of final products in creative industries.

4. CONCLUSIONS

Based on our findings, we can confirm Hypothesis 1: CVI created without AI will be more tailored to the client's preferences**.** It has been demonstrated that, compared to AI, human design remains more flexible and better able to adapt to client requirements while also delivering higher-quality solutions. This confirms that human creativity and adaptability remain key components of successful client-oriented graphic design.

We can also confirm Hypothesis 2: AI will shorten the design timeline**.** Based on our measurements and final results, the entire design process was significantly shorter when using AI compared to traditional, non-AI design methods.

Hypothesis 3: AI will enable a technically refined final product, can be partially confirmed. Our survey results indicated that respondents preferred products designed by humans. While AI facilitated technically adequate solutions, human intervention was required to achieve a final product that was not only technically refined but also functionally and aesthetically tailored to its specific context of use.

The study confirms that AI provides an effective alternative to traditional graphic design methods, particularly in reducing time constraints. However, human creativity remains crucial for developing customized and unique solutions. The optimal approach appears to be a combination of traditional methods and AI, leveraging the strengths of both.

Future research should focus on integrating AI with traditional methods to maximize their efficiency and adaptability. Additionally, it is recommended to explore the long-term impact of AI on creative industries and its contribution to innovation.

5. REFERENCES

Wiedemann, J. 2009. *Brand identity now!*. Hong Kong: Taschen.
Wiedemann, J. 2009. *Logo design*. Hong Kong: Taschen.
Wheeler, A. 2013. *Designing brand identity: An essential guide for the whole branding team*. New Jersey: John Wiley & Sons.
Russell, J. S., Norving, P. 2010. Artificial intelligence a modern approach. New Jersey: Pearson Education.
Artificial intelligence, what it is and why it matters. URL: https://www.sas.com/en_us/insights/analytics/what-is-artificial-intelligence.html/ (last accessed on 15. 3. 2024).
Generativna umetna inteligenca spreminja ustvarjalni potek dela. URL: https://www.adobe.com/si/products/firefly/discover/how-ai-changes-creative-work.html/ (last accessed on 20. 3. 2024).
Hampus, Dehman. Graphic design, Already Intelligent?: Current possibilities of generative AI applications in graphic design.URL: https://www.diva-portal.org/smash/get/diva2%3A1797022/FULLTEXT02.pdf/ (last accessed on 7. 2. 2025).
Looka. URL: https://looka.com/ (last accessed on 7. 2. 2025).
Design.ai. URL: https://designs.ai/ (last accessed on 7. 2. 2025).
Design.com. URL: https://www.design.com/ (last accessed on 7. 2. 2025)

6. APPENDIECES

Appendix A1: Business card designed without AI (two sided)



Appendix A2: Letterhead designed without AI



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Appendix A3: Flyer designed without AI



Appendix A4: Graphics for social media designed without AI – post (five versions)



Appendix A5: Graphics for social media designed without AI – storie (four versions)



Appendix A6: Graphics for digital media designed without AI: digital advertisement



Appendix B1: Business card designed with AI (one sided)



Appendix B2: Letterhead designed with AI



Appendix B3: Flyer designed with AI



Appendix B4: Graphics for social media designed with AI – post (three versions)



Appendix B5: Graphics for social media designed with AI – storie (three versions)



Appendix B6: Graphics for digital media designed with AI – digital advertisement



Appendix C: Time measurement of CVI creation without AI

Corporate visual identity elements	**Time measured in minutes**	
Meeting with the client	60	
Market and trend research	48	
Creation of a mind map	62	
Color palette (selection, adjustments)	60	
Typography	70	
Logo (inspiration search)	42	**598**
Logo (sketch development)	40	
Logo (creation of initial versions)	180	
Logo (revisions of initial versions and final version selection)	212	
Logo (final version adjustments)	124	
Business card	83	
Letterhead	16	
Social media: posts (5 templates) and stories (4 templates)	62	
Cover page	46	
Digital advertisement	24	
Flyer	66	
Total	**1195 (19 h 55 min)**	

Appendix D: Time measurement of CVI creation with AI

Corporate visual identity elements	Time measured in minutes	
Logo (entry of basic information)	1	**10**
Logo (parameter adjustments, 3x)	3	
Logo (selection)	6	
Business card	12	
Cover page	10	
Social media posts	14	
Social media stories	11	
Profile picture	3	
Digital advertisement	14	
Letterhead	16	
Flyer	15	
Total	**105 (1 h 45 min)**	

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PACKAGING

ORAL PRESENTATION

PROSPECTS FOR THE FUTURE OF PRINTED PACKAGING IN THE CIRCULAR ECONOMY

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Abstract: *The printed packaging market continues to evolve, driven by a number of macro factors. Concern for the environment and a commitment to protecting it has reached an all-time high, resulting in sustainability becoming the primary driver of change for key players in the supply chain. The influence of consumer expectations on the development of printing and packaging is now very significant. There are also accelerating developments in printing processes, smart packaging and communication devices. Drawing on recent conference presentations, journal articles and market reports, the authors present the key drivers of the packaging market: sustainability and regulation, the growth of e-commerce, changing consumer attitudes and lifestyles, digitalisation and innovation.*

Keywords: *Printed packaging, sustainability, digital printing, consumer attitudes in packaging, packaging innovation*

1. INTRODUCTION

Europe remains a key region for the printing industry globally. Despite this, only moderate growth in the overall value of European printing is expected until 2027. But the printed packaging output is expected to grow till 2027 with yearly 1,7% (Figure 1).

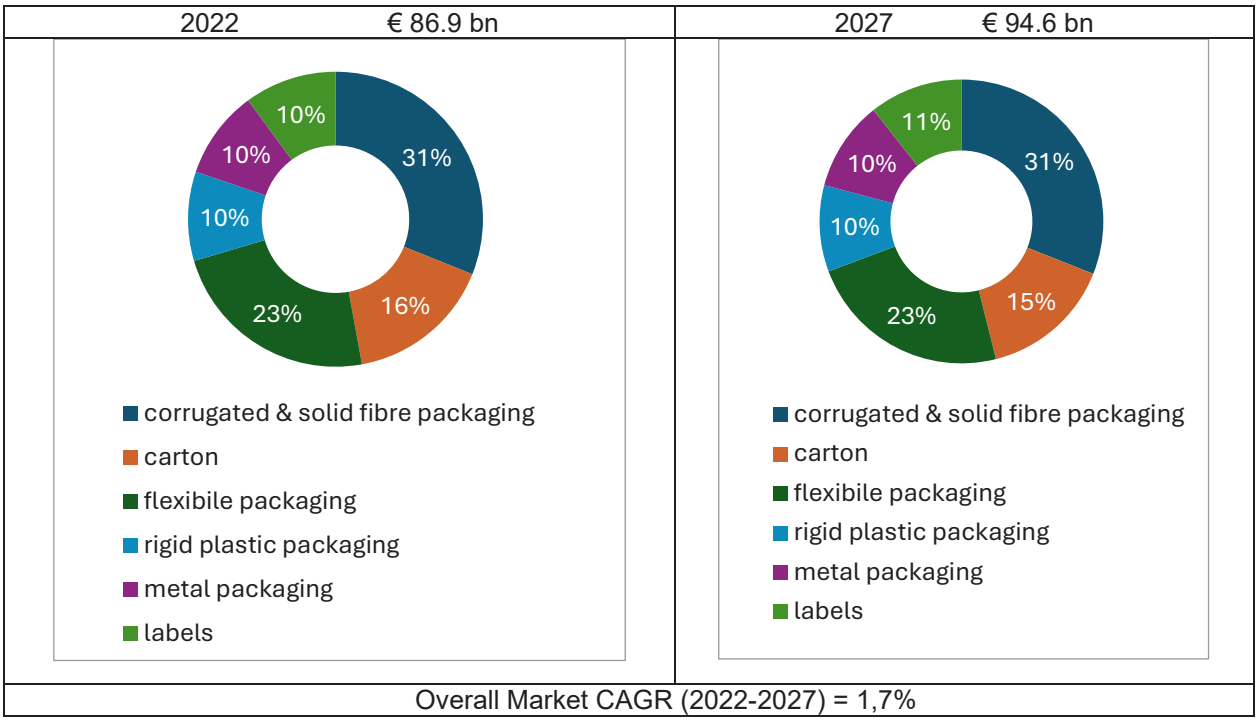


Figure 1: European Package & Label Printing Output by Type, 2022 and 2027
[% share by value, constant 2021 price and € exchange rate basis] (Halam, 2023)

Data (on Figure 1) covers both Western and Eastern Europe, including all EU-27 Member States plus the UK, Norway and Switzerland. Russia and Ukraine have not been included in the analysis due to the current high uncertainty in these markets due to the war. Values have been converted into Euro.

Globally, packaging is a growing sector. This growth is driven by demographic changes and changing consumer lifestyles. Populations are growing in almost every country in the world and there is a significant shift in the proportion of people living in urban and rural areas.

Working-age people are now often referred to as „cash-rich and time-poor“, driving demand for packaging in areas such as ready meals.

Growth is expected to stagnate in Europe. The e-commerce packaging market in Western Europe and Eastern Europe is estimated to reach a total of €11.8 billion in 2028 (Mordor Intelligence, 2023).

Based on recent conference presentations, journal articles and market reports published by various international trade associations, the key trends and drivers in the world of printed packaging can be identified as follows (Ragaert, 2023; Smithers Research, 2023; IMARC, 2023; Mordor Intelligence, 2023).
- Digital printing
- Sustainability and regulation
- Growth of e-commerce
- Digitalisation and innovation
- Consumer attitudes

2. DIGITAL PRINTING

Although printing is perceived to be going through difficult times, it is in fact a highly competitive and dynamic business, especially in the packaging sector. There are huge expectations for the development of digital printing, both inkjet and electrophotography. Digital printing is increasingly used to print labels, corrugated, cartons, flexible, rigid, plastic, metal and glass packaging. In 2020, as the global Covid pandemic disrupted all aspects of human life, digital packaging volumes soared as suppliers were able to respond quickly to changing demands.
Digital printing is gaining ground over analogue printing methods such as lithography, flexography, gravure and embossing as it creates new opportunities - especially for the emerging craft sector (Figure 2). Technological advances have enabled converters and manufacturers to install equipment that is cost-effective and highly productive while meeting the expected quality requirements.

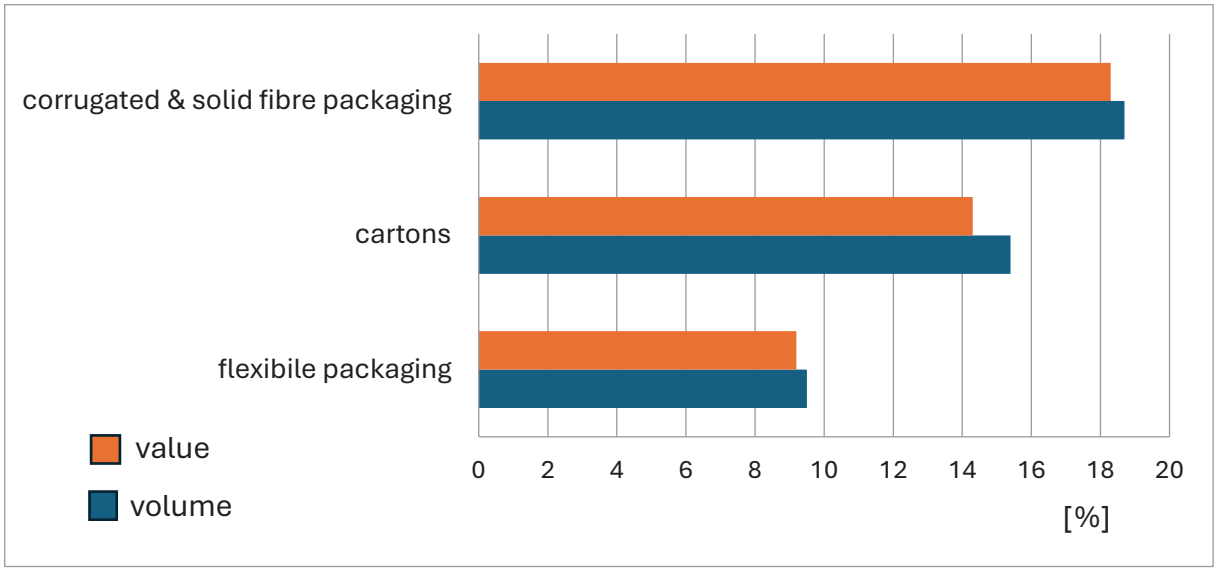


Figure 2: Growth in European digital package printing output by key pack type, 2022-2027 (Smithers, 2023)

Digital printing allows for greater flexibility, helping packaging manufacturers and converters to meet the increasingly tight schedules of their customers. The ability to print variable content enables brands to create new, innovative solutions, delivering higher levels of engagement and new customer experiences that increase brand effectiveness and value (Heidelberger Druckmachinen AG, 2022).

Analogue Print is responding to this challenge with its own developments to improve the performance of offset, flexo and gravure printing for shorter runs, including fixed colour gamut printing, automatic colour correction and registration, streamlined plate and roll preparation, robotic plate loading and many other improvements.

2.1 Market drivers for adoption of digital print for packaging

Among the factors driving the growth of digital printing, the trend towards lower print runs (batch sizes) plays a major role. Differences in set-up costs when producing shorter runs can contribute significantly to variations in cost per print between printing processes. On the other hand, for large print runs, these set-up costs are significantly reduced and the costs of consumables used - ink, coating and other consumables - dominate.
The ‚Amazon' effect - The need and expectation for same-day and next-day delivery is widespread, but not typical in the labelling and packaging sector. It is expected that by 2027, many converters will offer on-demand printing and finishing services (Figure 3). This technology will be exploited not only by craft brands, but also by large companies that will be able to move to smaller and more frequent orders with changes to meet consumer demand. Environmental benefits will come from less set-up waste, printing accurate quantities on demand and eliminating minimum order quantities (Guga, 2023).



Figure 3: Personalized packaging (Hallam, 2023)

2.2 Supply chain changes

Most packaging is produced by processors and delivered to manufacturers or packers/fillers and then to distribution chains. Some big-name brands are re-producing packaging in-house, using digital printing to provide greater flexibility and versatility while controlling costs. Digital technology allows printing to be brought closer to the consumer and there are examples of digital printing being used for on-demand production at manufacturers and in distribution centres where personalised packaging can be tailored to size on demand. Packaging is a direct cost to brands, retailers and distributors, adding promotional messages and advertising can turn packaging from a cost into a revenue generator (Hack, 2023)..

2.3 Market barriers for adoption of digital print

Capability - Digital print successfully replicates most analogue print, except for some spot colours, special-effect inks and coatings. Hybrid systems (and HP Indigo) can handle the special requirements. In the future more digital speciality inks will become available, with alternative methods such as Actega Ecoleaf used to replace metallic inks and foiling for example.

Cost - Much digital is significantly higher cost than analogue new high-performance machines are changing this with lower TCO (*Total Cost of Ownership)*. Price premium for inks falls with bulk supply direct from the equipment

manufacturer, significantly reducing ink cost, particularly for water-based inkjet. Further economies of scale drive down the cost of equipment and the necessary control systems and workflow software.

3. SUSTAINABILITY AND REGULATION

Sustainability is currently the number one concern of consumers and governments, and a top target for the packaging industry and lobby groups. From a printing perspective, digital printing eliminates analogue mould making technology and the associated waste. It will also eliminate potential redundancies in the supply chain. By 2027, it is expected that scientifically rigorous life-cycle analysis measuring key impacts will be available to determine the true performance of digital printing. If there are demonstrable benefits (and there are expected to be), these will provide a significant boost to digital packaging (Nogueira, 2023).

Sustainability is also a key driver in the packaging industry. All stakeholders in packaging: raw material suppliers, processors, distributors, brand owners, retailers and consumers are increasingly focused on aligning their packaging and products with the circular economy (Desgrees du Lou, 2023).

3.1 Circular packaging

The main objective of the circular economy is to keep valuable resources in use and to use them over as many life cycles as possible. This implies a gradual decoupling of economic activity from the consumption of finite (fossil) resources and the diversion of waste out of the system. Initiatives such as EU Vision 2020 promote this new model by extending product life, creating more durable products, reducing manufacturing waste, encouraging consumers to recycle, promoting reuse and strengthening the end market for waste.

The transition to a circular economy is not just about making adjustments to reduce the negative impacts of a linear economy. Rather, it is a fundamental change that builds long-term resilience, creates business and economic opportunities, and delivers both environmental and social benefits (Munroe, 2023).

The Circular Economy Action Plan requires EU countries to ensure that packaging placed on the market complies with the essential requirements of Annex II of the Packaging and Packaging Waste Directive:

- minimise the weight and volume of packaging to achieve the required level of safety, hygiene and acceptability for consumers;
- reducing the content of hazardous substances and materials in packaging materials and their components;
- the design of reusable or recyclable packaging.

3.2 Carbon footprint

Reducing emissions from the production and printing of packaging is at the top of the agenda for industry leaders as they strive to achieve net-zero targets. However, this is a challenging task and the market is currently suffering from a deluge of greenwashing - claims made against products that are factually untrue or unsubstantiated (Hallam, 2023).

The main way to measure the carbon footprint of a label or packaging solution is to carry out a full life cycle analysis (LCA). This is a valuable tool if the methodology is sound and the results are third-party verified, but the results should never be taken at face value. The choice of supplier can be as important a decision as the choice of material, as carbon emissions can vary widely between factories. Suppliers should be aware that carrying out LCA can often be a slow and costly process.

Sustainability is at the forefront of the European Commission‘s regulatory framework for packaging and labelling. This legislation is becoming more stringent and stakeholders in this area need to carefully comply with the requirements already in place.

The EU has developed a comprehensive strategy for regulatory guidelines throughout the life-cycle of consumer packaging. The strategy aims to develop an integrated circular economy model that favours re-use, recycling and reduction. It proposes some anti-plastic sense, but this element focuses on single-use plastic articles rather than on the material itself. Climate change mitigation provides a strong backdrop for setting policy priorities.

3.3 Draft Packaging and Packaging Waste Regulation (PPWR)

As its name suggests, the PPWR (Packaging and Packaging Waste Regulation) is a draft regulation, which has been developed from an earlier version known as the PPWD, which was a directive under EU law. PPWR will be legally enforced across the EU by the end of 2024. The PPWR and packaging is part of the ‚European Green Deal‘, a legal framework that aims to make the region carbon neutral by 2050 (Desgrees du Lou,2023).

The proposed requirements of the PPWR will impose greater responsibility on those who place packaging on the market through Extended Producer Responsibility (EPR). Smithers has a ready market report on this very topic. The food, grocery and beverage industries are expected to be most affected by these developments in PPWR. The proposal on PPWR will go through the EU‘s normal scrutiny procedure, where further amendments will be made.

The current proposal is based on the PPWD impact assessment, which identified three main issues to be addressed.
1. Increasing packaging waste generation.
2. Barriers to recycling and reuse of packaging waste.
3. The low recycling quality of plastic packaging and the use of secondary raw materials.

The overall objective of the proposal is „to reduce the negative environmental impact of packaging and packaging waste while improving the functioning of the internal market“.
The objectives are as follow.

- All packaging materials to be recyclable by 2030.
- To reduce packaging waste by 15% by 2040 (per capita per Member State compared to 2018).
- By 2029, countries should establish a deposit return scheme (DRS) with a collection rate of 90%.
- By 2025, 65% of all packaging waste (by weight) should be recycled.
- Climate neutrality in the packaging sector by 2050.

3.4 Other EU Legislation influencing the label & packaging markets

Action Plan for the Circular Economy

An outline of the EU’s efforts to develop a sustainable, low-carbon, resource-efficient and competitive economy, adopted in 2015. It places packaging waste in a continuum from production to consumption to waste management to recoverable or recyclable resources. It presents a basic legislative blueprint, including not only regulation of the private sector, but also government investment and measurement of progress towards targets.

Compliance criteria for environmental claims

Requires that waste management does not endanger human health or harm the environment, pose a risk to water, air, soil, plants or animals, cause a nuisance through noise or odour, or adversely affect the landscape or places of special interest.

European strategy for plastics in the circular economy

The Plastics Strategy is part of the EU’s transition to a more ‘circular’ economy. Its aim is to improve “the way plastics are currently produced, used and disposed of”, as the status quo fails to reap the economic benefits of a more circular approach and is damaging the environment. The strategy calls for all plastic packaging on the EU market to be reusable or recyclable in a cost-effective way by 2030.

The Single-Use Plastics Directive (SUP Directive)

In February 2021, the European Parliament called on the Commission to consider further measures, such as amending the Single-Use Plastics Directive to ensure that single-use plastics are replaced by reusable products wherever possible. The Commission was also called on to develop standards for reusable packaging and the replacement of single-use packaging.

The Strategic Environmental Assessment (SEA) Directive (2001/42-EC) sets targets for recycled content for certain plastic packaging (drinks bottles), while national plastics taxes linked to the Directive reward recycled content for certain single-use plastics.

Labelling requirements

Labels and packaging are increasingly subject to legislation, requiring more information and, in some sectors, coding to reduce the possibility of counterfeiting. The legislation extends beyond the pharmaceutical industry to consumer goods. Unique codes and tracking and tracing using a simple phone camera app for authentication are being offered as a method of authentication and as a logistical tool for distribution. Many high-value products can be authenticated, although for high-volume, low-value products, some brands are concerned about potential litigation over counterfeit products.

4. THE GROWTH OF E-COMMERCE

The unprecedented growth in e-commerce activity since 2020 has led to a proportionately large increase in demand for transit packaging. This has been coupled with external pressure on retailers from consumers, NGOs and government regulation to reduce the environmental impact of e-commerce packaging. Efforts have focused on: reducing weight; reducing raw material use; increasing recycled content; and eliminating empty spaces. E-retailers are looking at material substitution (plastic to paper) and reusable packaging options.

The global e-commerce packaging market was estimated to be worth $63.60 billion in 2022, growing at an average annual rate of 20.0% since 2017. However, global value growth of 12.5% in 2022 is significantly slower than the rates experienced globally during the peak of the Covid-19 pandemic and the boom in online shopping.
Further growth is expected in the global e-commerce packaging market as e-commerce activity continues to grow, but now at a slower pace, with value sales forecast to grow at a CAGR of around 9.8% through to 2027.

4.1 Key factors shaping the e-com packaging market

1. Environmental concerns about plastics have a negative impact on polybags/bags, both in terms of raw material and overall life cycle. In the EU, retailers are required to use bags with at least 30% recycled content to comply.
2. The growth of paper-based postal parcels will offset some of the slowing growth of polybags.
3. Improved 3D batch scanning technology and fanfold corrugated automated box making machines will improve box production efficiency and reduce empty spaces.
4. Demand for protective packaging in larger formats will remain stable, but smaller formats are not expected to keep pace with growth in other packaging types due to concerns about recyclability and a decline in some core product applications.

4.2 Consumers expect high quality printed (and sometimes personalised) packaging

High levels of consumer expectation now extend to packaging, and they can feel disappointed by e-retailers without a well planned and executed packaging strategy. Packaging is often the brand's first physical contact with the consumer and judgement is often cast at this stage. In a Shorr Packaging survey, 51% of respondents stated that printed or personalised packaging made them feel that the product inside was more valuable. In conventional retail, consumers hold a product as part of the purchase decision process, whereas online consumers only experience a physical product after receipt.

Digital printing has benefits when it comes to personalisation as individual print designs can be made to match the profile of individual customers. This can be achieved when the brand owner/retailer has a well-developed customer database ('big data').

When it comes to flexo the improvements in board qualities, such as white top kraftliners, means that brands can implement what is being termed 'Packvertising' – i.e. printing their corrugated boxes with high quality images to promote the brand and enhance the unboxing experience (Hallam, 2023).

5. DIGITALISATION AND INOVATION

One of the most significant impacts of track and trace packaging on the global market is blockchain technology, which is likely to continue to grow in the future.

5.1 Leveraging blockchain for track and trace packaging

The blockchain technology can be described as a distributed and immutable ledger that can record transactions, track assets and provide greater transparency across the throughout the supply chain. With blockchain technology, data is stored in interconnected blocks that are time-stamped and tamper-proof. Combined with other technologies, such as near field communication (NFC) or the Internet of Things, blockchain technology allows consumers to access the full history of a product, providing significant benefits in areas such as anti-counterfeiting and record-keeping (Gegeckienė, 2022).

Advocates of blockchain technology believe it offers significant benefits to companies and organisations seeking traceability, anti-counterfeiting and brand authentication solutions. Much of its appeal can be attributed to its ability to improve record-keeping and thereby improve supply chain and inventory management. As more and more people now have internet-enabled mobile devices such as smartphones, consumers' ability to quickly and conveniently check the authenticity of goods or supply chain traceability using technologies such as QR codes has increased significantly. For consumer products such as food, blockchain technology is seen as a useful tool to combat contamination and threats to consumer safety, while also offering benefits in terms of innovation and intellectual property (IP), as it is clearer what information has been produced, when and by whom.

5.1 Smart packaging developments

There are several recent examples of smart packaging being used to add value to product offerings.

- Accenture recently partnered with a European luxury brand to create a virtual retail storefront where consumers could enter by scanning or activating the smart packaging of a product. Within the metaverse, consumers could interact with the digital equivalent of the product - the information generated by consumer interactions can be captured and used to inform areas such as sales and manufacturing.
- Developments in smart packaging for the pharmaceutical industry include new time-temperature technologies that increase safety and extend the shelf life of certain products, such as vaccines. In May 2022, Essentra Packaging and Advanced Material Development (AMD) announced that they will collaborate to develop next-generation solutions within the industry to improve patient safety.
- During 2021, the US and Chinese authorities announced that they will develop enhanced food traceability systems to improve food safety through the introduction of smart packaging solutions.
- The adoption of smart packaging with tracking capabilities can often serve to improve the competitiveness of companies in the logistics industry by providing them with information that can help reduce waste and costs and improve productivity.
- A leading Australian company in the smart packaging market is Laava, which specialises in product authentication technology. Its portfolio includes Smart Fingerprints, which uses patented optical technology to apply unique and randomly generated images to labels and other packaging, and is being promoted as an alternative to QR codes. Smart Fingerprints technology has been used on more than two million products and has been adopted in both food and beverage applications in recent years ('t Hart, 2023).

5.2 Packaging format innovation

There are many worthy examples that could be included but the three most prominent developments over the beginning of this decade years have been (Lippitsch, 2023)

- Paper mailing bags for e-commerce
- Paper bottles for the beverage and homecare sectors
- Dry moulded pulp in the foodservice and pharma markets

6. CONSUMER ATTITUDES

Consumers have a negative perception of single-use plastic packaging, which has encouraged the development of alternative materials and packaging. A good example of this is the food sector, where brand owners and retail chains are constantly experimenting with substitutes for single-use plastic packaging, such as compostable bags, paper bags and cellulose nets. It is expected that the recent trend of replacing single-use plastic packaging with reusable renewable materials will continue (Oliver, 2022).

6.1 Consumers are driving the demand for recyclable and compostable packaging

Partly as a response to the media's portrayal of the harmful effects of plastic on the environment, consumers are becoming more aware and passionate about the impact of packaging on the environment. Consumer advocacy is driving action by brand owners and national governments. Many European countries have banned single-use plastic products such as plastic straws, bags, coffee cups and other non-recyclable products. There is also a growing interest in reusable products and efforts are being made to increase recycling in waste collection. The need for education on the need and opportunities for sustainability has also been highlighted.

6.2 Consumers do not like oversized packaging

Consumers are becoming increasingly concerned about the use of oversized packaging for home delivery, forcing brand owners and retailers to respond to this demand with improvements.

Consumers expect printed packaging to take this into account. Sustainable printed packaging can go a long way to adding value to the unboxing experience for the consumer.

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8. REFERENCES

Desgrees du Lou, Maja: Proposal for Regulation on Packaging & Packaging Waste (presentation); Integraf – FTA Europe: Shaping the Future with Packaging Conference, Brussels, March 9th,2023
Guga, Ștefan - Strătilă, Tudor: Amazon and the packaging, publishing and printing industries: an overview, Syntex – UNI Europe – Intergraf, 2023, p.54
Gegeckienė, Laura – Venytė, Ingrida – Karpavičė, Justina – Tambo, Torben – Vaitasius, **Kęstutis** – Pauliukaitis, Darius: Near field communication (NFC) technology int he packaging industry; GRID Internal Symposium on Graphic Engineering and Design – 2022, University of Novi Sad, Serbia, Proceedings, pp. 495 – 501
Hack, Michael –Ward, Jonathan: Rethinking Packaging: A DHL perspective onthe future of packaging in the logistics industry, DHL Customer Solutions & Innovation, Trisdorf, Germany, 2023, p.38
Hallam, Tom: Market Insights: Eurpean Packaging Sector (presentation); Intergraf – FTA Europe: Shaping the Future with Packaging Conference, Brussels, March 9th,2023
Heidelberger Druckmachinen AG: White paper: Packaging printing 4.0. Digitization and its impact on sustainability, agility, and growth. Heidelberg, Germany, 2022. p.11
IMARC: Advanced Packaging Market: Global Industry Trends, Share, Size, Growth, Opportunity and Forecast 2023-2028, Market report, ID: SR112023A6250, 2023
Lippitsch, Susanne: Shaping Packaging for the Future (presentation), Intergraf – FTA Europe: Shaping the Future with Packaging Conference, Brussels, March 10th,2023
Mordor Intelligence: Europe Printed Packaging Market Size & Share Analysis - Growth Trends & Forecasts (2023 - 2028) (https://www.mordorintelligence.com/industry-reports/europe-printed-packaging-market) Last accessed on Oct. 1, 2023.
Munroe, Olga: Sustainable Strategies of UK Reailers – Case Studies (presentation); Intergraf – FTA Europe: Shaping the Future with Packaging Conference, Brussels, March 9th,2023
Nogueira, Francisco: World Without Waste (presentation), Intergraf – FTA Europe: Shaping the Future with Packaging Conference, Brussels, March 9th, 2023
Oliver, Mikah - Vrabič-Brodnjak, Urška – Jestratijevic, Iva: Consumer's socio-Demographics influence between purchase intention and actual behavior of environmentaly friendly grocery packaging, GRID Internal Symposium on Graphic Engineering and Design – 2022, University of Novi Sad, Serbia, Proceedings, pp. 539-546
Ragaert, Peter: Sustainable of Food Packaging: A Muscipliniary Approach (presentation); Intergraf – FTA Europe: Shaping the Future with Packaging Conference, Brussels, March 10th,2023
Smithers Research: An Overview of the European Printed Packaging Market; Market report, 2023
't Hart, Jan: Watermark Holly Grail 2.0 (presentation); Intergraf – FTA Europe: Shaping the Future with Packaging Conference, Brussels, March 10th,2023

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ORAL PRESENTATION

PAPER BAGS MADE FROM ANNUAL PLANTS

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Abstract: *Durable paper is essential for the production of durable paper bags. Although sufficient wood is available in Europe, the technology for obtaining cellulose fibres from annual plants is also of great interest to inventors and manufacturers of cellulose fibres. The advantages of annual plants are easier delignification, lower water consumption and the use of agricultural by-products that would otherwise have to be disposed of in other ways. The main disadvantage of obtaining cellulose fibres from annual plants is that the plants are only available at certain times of the year, which requires large storage capacities. We compared three types of paper produced in Europe that are used to make paper bags. The first paper sample contained only primary wood cellulose fibres, the second sample contained fibres from grass, wood and secondary fibres and the third sample contained cellulose fibres from fallen leaves and secondary cellulose. By comparing the physical-mechanical properties (tear strength, burst strength, tensile strength, sound propagation speed), we wanted to determine whether paper made from annual plant fibres could replace paper made from wood cellulose in the production of paper bags. We assumed that paper made from wood cellulose would be more resistant than others because the wood fibres are longer and therefore improve the physical-mechanical strength of the paper. We were able to confirm this hypothesis, as the paper with primary wood pulp performed better in all measurements except for tear strength, where the grass and wood fibre paper performed better. The paper containing no wood cellulose fibres performed the worst of all three papers tested. Even though the production of paper from annual plant fibres is a welcome innovation, it unfortunately cannot yet replace wood cellulose paper.*

Keywords: *paper bags, cellulose, annual plants, physical-mechanical properties*

1. INTRODUCTION

Shopping bags are the „necessary evil“ of modern consumer society. The formerly ubiquitous polythene bags have now been replaced by reusable bags for more conscious shopping. Paper bags have established themselves as an alternative to plastic bags. Paper for carrier bags must have sufficiently good physical and mechanical properties to withstand the stresses that occur firstly during printing and finishing and then during primary use. Annual plants are widely used as a source of cellulose fibres, especially in tropical countries. In our country, the technology for processing annual plants into cellulose fibres has not yet been massively developed as we have sufficient quantities of wood. Cellulose fibres for packaging paper are obtained from the trunks of coniferous and deciduous trees using the sulphate process. The fibres obtained give the paper excellent physical and mechanical properties, but the processing is energy and technology intensive. There is also a growing trend towards the conservation of forests and the looking for other pulp sources that are easier to process and have less impact on the environment. Two alternatives have emerged in Europe, namely the production of cellulose fibres from grass and leaves. These two alternative raw materials are already being used on an industrial scale for the production of paper and carrier bags. In our research, we determined the physical-mechanical properties of three different papers for carrier bags and established whether papers made from the fibres of annual plants can replace papers made from wood cellulose fibres on an equal footing in this area. Today, paper made from annual plants is once again becoming an alternative to paper made from cellulose fibres obtained from thick trees. This is particularly true in countries where the amount of wood is limited due to natural conditions or forest protection, i.e. as a more environmentally friendly alternative it is also spreading in countries that otherwise have sufficient quantities of wood.

There are several reasons for this:

- reduced availability of wood,
- greater availability of annual plants,
- faster growth of annual plants and
- growth of the paper industry.

The area of forests worldwide is decreasing for various reasons, to which the paper industry also contributes. Despite the tendency to switch to other fibres, it is still necessary for the time being to add wood fibres in order to achieve the desired properties. In areas where there are no forests due to climatic conditions, the lack of wood is an even greater problem. Paper consumption will most likely only increase due to the growth of the world's population and the desire for education (Ainun, 2023). Although the extinction of paper as a medium has long been predicted with widespread digitalisation, it is becoming increasingly clear that this is not true (Možina, 2017). Paper consumption per capita is increasing, and text written on paper is permanent, has greater significance and outlasts all digital recording media, many of which we have already had to replace in the age of digitalisation. The annual plants from which paper fibres are obtained can be divided into three groups depending on their origin:

- agricultural by-products (e.g. wheat or rice straw, bagasse),
- specially cultivated plants (e.g. jute, hemp, kenaf) and
- naturally occurring plants in the environment (e.g. bamboo, reeds).

The extraction of fibres from annual plants can have its own specific problems. They usually have to be harvested by hand, which involves considerable costs. Different plants can only be harvested for a short period each year, so it is necessary to ensure sufficient quantities for uninterrupted production and to provide suitable storage (volume, possibility of spontaneous combustion). We must bear in mind that stored products spoil in the presence of moisture and micro-organisms, which alter their physical, chemical and visual properties. The annual harvest varies from year to year and depends on weather conditions, so the same quantity and quality cannot be guaranteed every year. The targeted cultivation of plants for the production of fibres is controversial, as it consumes resources and agricultural land that could otherwise be used for food production. In order to utilise plants that occur in the natural environment, it is also necessary to carefully consider the impact of mass harvesting on other factors in their natural environment. From an environmental perspective, it therefore makes the most sense to use plants or parts of plants that are by-products or unwanted in the environment and would otherwise have to be composted, incinerated or utilised elsewhere. By focusing on the use of fibres from annual plants, such as straw, they are working in countries that have large agricultural areas but little forest. Ukraine, for example, imports large quantities of wood or recycled paper to produce paper (Tomšič, 2020). In Ukraine, the idea was born to produce paper from the leaves of trees in the urban environment. Table 1 shows the weight percentages of annual plants used for paper production.

Table 1: Proportion of annual plants for paper production (Bajpai, 2021)

Matrial	Proportion [%]
straw	44
bagasse	18
reed	14
bamboo	3
other	21

In Asia, the use of annual plants for the production of paper fibres is widespread, mainly due to the lack of wood resources. China leads the way here, where as much as two-thirds of the world's paper material is produced from non-wood sources. In the USA and Europe, despite the presence of forests, annual plants are used as a source of cellulose fibres to a limited extent, as they reduce the costs of disposing of agricultural by-products (straw, corn stalks) and reduce the impact of their destruction on the environment (Bajpai, 2021).

2. EXPERIMENTAL

2.1 Materials and methods

The measurements were carried out on three paper samples from which paper bags are manufactured. All the papers listed are produced industrially on a paper machine. The samples for kraft and grass paper were taken directly from the paper roll, while the paper made from fallen tree leaves was taken from bags that had already been made. Kraft paper and grass paper were provided to us by Dama d.o.o., where they are used to make carrier bags. We purchased paper bags made from the pulp of fallen tree leaves from the manufacturer Releaf paper, Ukraine. We selected papers that have a similar basis weight and are all intended for the production of paper bags. The three selected papers (Table 2) are suitable for contact with food and, as long as they are not contaminated, can be disposed of normally in waste paper and recycled further.

Table 2: Description of paper samples

Paper sample	Producer	G [g/m^2]	Description
S1	Mondi	110	Unbleached, machine-made, contains only kraft cellulose fibres, no secondary fibres (Gregor Svetec, 2020)
S2	Creapaper	110	Contains grass fibres, wood and secondary cellulose fibres, non-glossy and opaque, with a distinct smell of dry grass
S3	Releafpaper	120	It contains fibres from fallen tree leaves and secondary cellulose fibres

We used the following methods to analyse the properties:

- basic properties (thickness, basis weight, density, specific volume and moisture content) and
- physical-mechanical properties (tear strength and tear index (Schopper), tear strength and tear index (Elmendorf), sound pulse propagation velocity (PPM-5R), tear strength, elongation and tear length, tensile strength, work of rupture, tensile absorption energy and the corresponding index (Instron 6022), modulus of elasticity.

3. RESULTS WITH DISCUSSION

3.1 Basic properties

We measured the basic properties of the paper and thus described the paper samples for paper bags included in the study (Table 3).

Table 3: Basic properties.

		t [mm]	G [g/m^2]	ρ [kg/m^3]	v [cm^3/g]	MC [%]
S1		0.151	107.9	713	1.40	6.4
	S_x	0.003	1.5	16	0.03	1.3
	CV	2.00	1.42	2.23	2.20	20.11
S2		0.185	114.6	622	1.61	4.8
	S_x	0.011	2.4	34	0.09	1.9
	CV	6.12	2.13	5,44	5.51	39.37
S3		0.229	120.4	526	1.90	5.6
	S_x	0.009	1.3	21	0.08	1.1
	CV	3.75	1.07	3,93	4.03	18.81

Contrary to expectations, the smallest deviation in terms of grammage is found in S3 (1.07%), as it looks the least homogeneous of all three (Figure 1). The inhomogeneity of the paper is an undesirable property as its properties are also uneven due to the non-uniform internal structure. In the paper where the fibre concentration is higher, fibre bundles (haze) are visible. This is due to the non-uniformity of the paper suspension and is unavoidable to a certain extent.

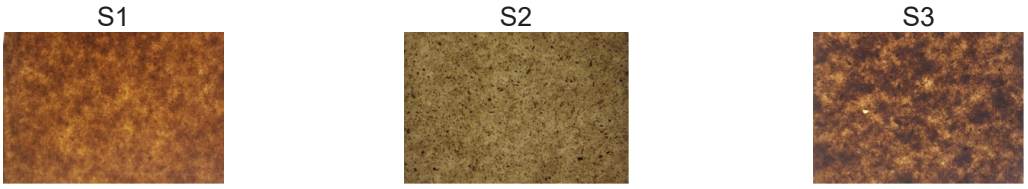


Figure 1: Cloudiness of paper bags specimens

3.2 Physical-mechanical properties

3.2.1 Bursting strenght and burst index

As can be seen in Figure 2, S1 cracked at 280 kPa on side A and 264 kPa on side B, whereas the bursting strength of S2 was twice as high, namely 127 kPa on side A and 116 kPa on side B. S3 had an even lower bursting strength, which was 68 kPa on side A and 80 kPa on side B (Figure 2). S1 achieved a better result because it contains only primary cellulose fibres, which are longer than secondary ones. We can also infer a higher content of fibres from coniferous trees, which are longer than fibres from annual plants and deciduous trees, as is the case with S2, which contains grass fibres and wood fibres, so its bursting resistance is lower (127 and 116 kPa), but still higher than S3 (68 and 80 kPa), which does not contain pimary cellulose fibres from trees. As can be seen from the bursting index, the grammage, i.e. the fibre composition and its source, plays the greatest role.

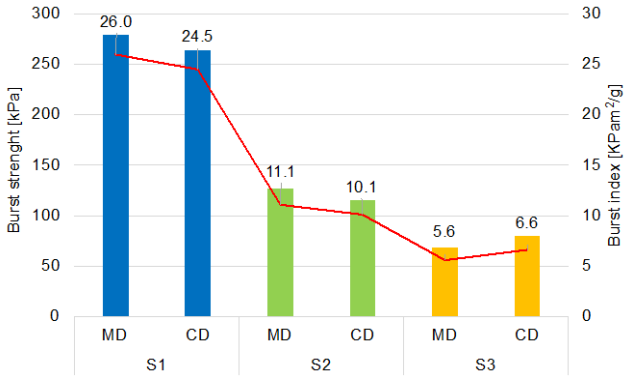


Figure 2: Bursting strenght – Schopper

3.2.2 Tear strenght – Elmendorf

The results of the tensile strength measurements for CD are in all cases higher (592 mN for S1, 606 mN for S2 and 469 mN for S3) than for MD (481 mN for S1, 496 mN for S2 and 418 mN for S3), which is to be expected to a certain extent, i.e. due to anisotropy, where the forces between the fibres are stronger than the connections between the fibres. It is noticeable that the tensile strength S2 (496 mN in MD and 606 mN in CD), i.e. of bagasse paper is greater than S1 (481 mN in MD and 592 mN in CD). The difference is 2% (CD) and 3% (MD). From this we can conclude that the wood cellulose fibres in S2 most likely originate from deciduous trees (Figure 3).

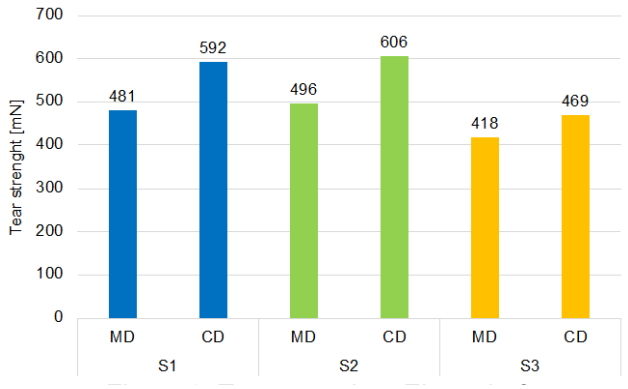


Figure 3: Tear strenght – Elmendorf

3.2.3 Sound velocity

The sound velocity signal is faster in denser matter because there are more covalent bonds. In S1, the paper with the highest density of 713 kg/m^3 (Table 1), the sound signal travelled at a speed of 3.37 km/s, the highest propagation speed of the sound signal among the three samples. The propagation of the sound pulse is faster in the direction of the fibres because the sound pulse propagates along the covalent bonds, which was also demon-

strated in our measurements (Figure 4). The propagation speed of the sound pulse in S2 is 2.77 km/s in MD and 1.78 km/s in CD. In S3, the propagation velocity of the sound pulse was 2.69 km/s in MD and 1.68 km/s in CD. The speed of the sound pulse is reflected in the degree of anisotropy and the degree of order of the molecular structure of the analysed causes of the papers. Annual plants have a lower degree of order in the macromolecular structure.

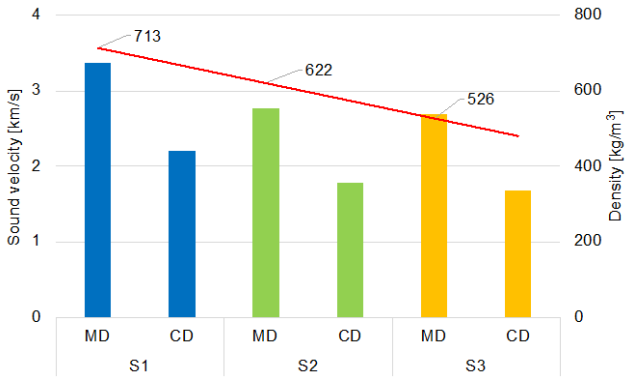


Figure 4: Sound velocity and density of paper bags

3.2.4 Breaking strenght, elongation at break, tensile strenght energy and Young‘s module

The S3 samples were obtained from bags that had already been manufactured, which meant that they were grooved to a certain length. In order for the causes to be comparable, they should not have been mechanically damaged beforehand. For this reason, we used a clamping length of 100 mm when measuring the physical and mechanical properties. The breaking force in [N] (Figure 5a), the elongation at break in [%] (Figure 5b), the tensile strenght energy in [J] (Figure 5c) and the modulus of elasticity in [GPa] (Figure 5d) were measured for selected paper bags that were clamped vertically between the clamps of the dynamometer at a speed of 0.25 mm/s. The results are shown in Figure 5. The breaking force of S1 in MD was 108.92 N (Figure 5a), the highest measured force among all paper samples tested, which is due to the content of primary wood cellulose fibres, i.e. fibres from coniferous trees.

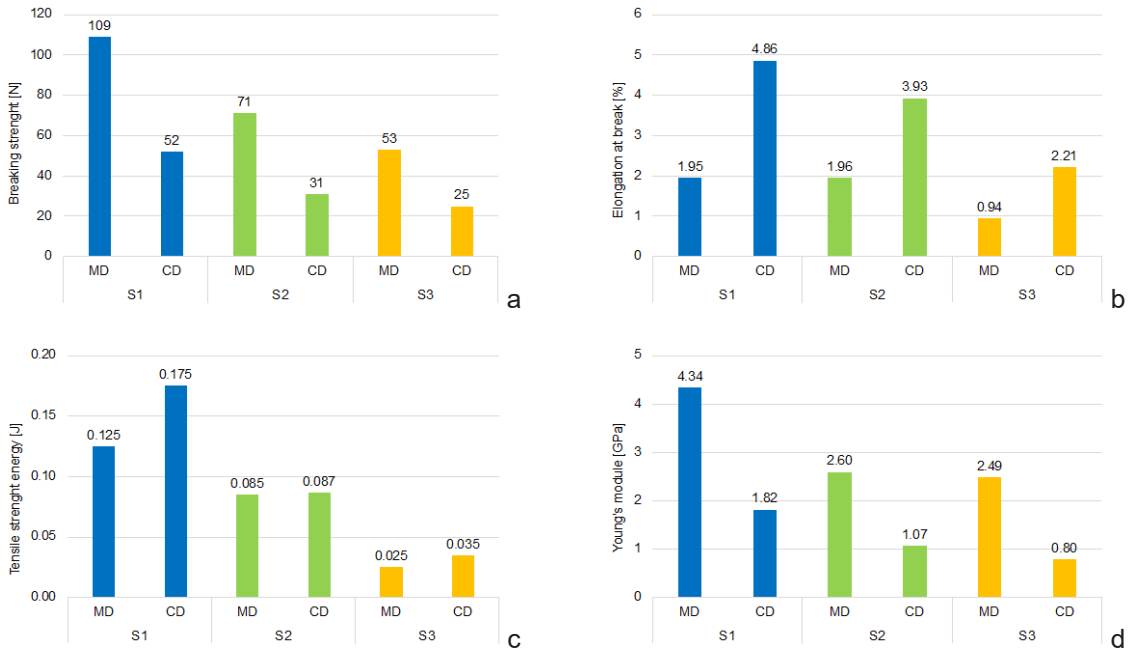


Figure 5: Physical-mechanical properties; a) breaking strenght, b) elongation at break, c) Tensile strenght energy and d) Young‘s module

Since paper is a viscoelastic material in which cellulose is present in crystalline and amorphous form, physical-mechanical loads initially lead to elastic deformation, which depends on the load time. As the load increases, it then passes through the viscoelastic range up to plastic or irreversible deformation. Figure 5b shows a comparison of the strains between the paper bag samples analysed. The elongation at break in MD for S1 and S2 is 1.95% for S1 and 1.96% for S2, while the elongation at break of S3 was half that of S1 and S2, namely 0.94%. For CD, the elongation at break is highest for S1, 4.9%, which means that the 10 cm long test piece was stretched by almost half a centimetre until it broke. High extensibility of paper sacks is a required property of the product, which must ensure adaptability to the contents of the sack. This was also measured by the tensile strength energy, Figure 5c, where the value is most influenced by the raw material composition of the paper for paper sacks, as it is a direct indicator of the extent of bonding between the fibres. Therefore, we also measured the modulus of elasticity, which tells us what stress is required for a given elongation. As we can see from Figure 5d, the highest modulus of elasticity at S1 in MD is 4.34 GPa. This means that the paper S1 can withstand the maximum load in the corresponding direction without being permanently deformed. This is desirable for all printing papers, but especially for paper bag papers, where the main purpose is to stress the paper without physical-mechanical consequences.

1. CONCLUSIONS

The length of the fibres has a direct influence on the physical-mechanical properties of the paper. From the cellulose fibres of coniferous trees, which are obtained using the sulphate process, we obtain a high-quality raw material with long fibres that enable good bonding between the fibres in the paper sheet and greater resistance to physical and mechanical stresses. The measurement results show that the paper made exclusively from kraft pulp (S1) is stronger in terms of physical and mechanical properties than the two papers made from the fibres of the annual plants included in the study. Paper with fibres made partly from grass and partly from wood pulp (S2) was even physically and mechanically stronger than paper made from secondary fibres and fibres from fallen leaves (S3). This shows that the wood fibres obtained by the sulphate process are a valuable raw material that improves the physical and mechanical properties of the paper. The search for alternative sources of cellulose fibres is to be welcomed from the point of view of lower energy consumption, the use of plant parts that would otherwise have to be destroyed, the shortening of transport routes and the reduction of water consumption. We believe that, at least in Slovenia, it would make more ecological sense to use wood that is sufficient for the paper industry if the forest is well managed. Since the length of the fibres also has a significant influence on the quality of the secondary fibre, it is important that the primary cellulose enters the paper manufacturing process with fibres that are as long as possible. If we consider the entire product life cycle of paper sacks made from kraft pulp and sacks made from the fibres of annual plants, we have to weigh up whether a paper sack with better physical-mechanical properties, i.e. a lower probability of tearing during use and a greater chance of being used more than once, has a greater impact on the environment. An important aspect of actual use is also the price, as paper made from the fibres of annual plants has a higher price than paper made from the cellulose fibres of trees. Another important aspect of carrier bags is their size. Large carrier bags, like the ones we see in grocery shops, have to carry loads of several kilogrammes and be made of paper that can withstand physical and mechanical stress. Small bags in clothing shops, jewellery shops, paper shops etc., where they are unlikely to have to carry a large mass, can be made of less physically and mechanically resistant paper. For further research, it would be interesting to find out what types of bags consumers would prefer. In terms of the composition of the paper, we could investigate what proportion of wood cellulose fibres and fibres from annual plants should be used so that the paper retains comparable physical and mechanical properties. We could also experiment with replacing the fibres from deciduous trees in the kraft paper with fibres from annual plants, as the fibres are of comparable length. Paper bags made from cellulose fibres from annual plants are a welcome addition to the market for paper products, but at least for now they cannot completely replace bags made from cellulose fibres from trees.

2. REFERENCES

Ainun, Z. M., Sapuan, S. M. and Ilyas, R. A. 2023. *Pulping and Papermaking of Nonwood Plant Fibres*. Amsterdam: Academic Press, Elsevier.

Bajpai, P. 2021. *Nonwood Plant Fibres for Pulp and Paper*. Amsterdam; Oxford; Cambridge: Elsevier.

Gregor Svetec, D. Franken, G. and Možina, K. 2020. Papir in grafični izdelki iz invazivk. URL: http://www.dlib.si/details/URN:NBN:SI:DOC-KTEVT89R/ (last accessed on 6. 2. 2025).

Možina, K. 2017. "Viscoelastic properties of graphic papers." PhD diss. University of Ljubljana.

Tomšič, A. 2020. "Lastnosti papirja, narejenega iz slame." Diploma thess. University of Ljubljana.

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POSTER PRESENTATION

IMPACTS OF PRINTED INTELLIGENT ELEMENTS ON CARDBOARD PACKAGING RECYCLABILITY: METHOD EVALUATION AND FINDINGS

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Abstract: *This study examines the recyclability of intelligent cardboard packaging, specifically evaluating the impact of printed RFID antennas and thermochromic indicators on recycling outcomes. Three recycling assessment methods were reviewed: the CEPI Recyclability Test Method (version 2), ATICELCA Method, and Eco Paper Loop Method, each offering unique approaches to evaluating fiber recovery, contaminant management, and life-cycle sustainability. The CEPI method was selected to perform the recyclability test on cardboard packaging due to its emphasis on fiber yield, pulp quality, and contaminant separation, aligning with EU recycling mill conditions. Using this method, recycling trials were conducted on two types of cardboard packaging: unprinted cardboard and cardboard with integrated printed intelligent elements. Results revealed a high recyclability score for both samples, with recycling efficiency exceeding 99 %, confirming minimal impact from functional conductive and thermochromic inks on recyclability and the optical properties of hand sheets.*

Keywords: *recycling, intelligent packaging, cardboard, RFID antenna, thermochromic indicator.*

1. INTRODUCTION

The increasing consumption of paper products worldwide has amplified the need for efficient and sustainable recycling systems. Paper recycling not only reduces resource depletion and energy consumption but also minimizes environmental pollution, making it a key pillar of the circular economy. (Defalque, et al., 2021) (Kowalska, et al., 2021) Everyone participating in the paper value chain must be careful, that their actions do not harm the whole chain. Packaging of today must go beyond utility. For the paper value chain, the basic knowledge about the recyclable's lifecycle is not yet sufficient. (Kochersperger, et al., 2024) Sustainable product design emphasizes the use of recycled materials while striving to ensure that all components remain recyclable. (Nordin, et al., 2010) To address the challenges of recycling diverse paper products, several methodologies have been developed, including CEPI (Confederation of European Paper Industries), Eco Paper Loop, and Aticelca. These systems aim to evaluate and optimize recyclability, focusing on quality control, contamination reduction, and the promotion of eco-design principles. Few studies have explored the recyclability of intelligent cardboard packaging. During the recycling process of paper and cardboard, intelligent components like RFID tags and thermochromic indicators remain attached to the packaging and enter the process without prior separation. As the use of intelligent packaging grows, concerns arise regarding its impact on recyclability. However, research on the recycling performance of printed RFID antennas and thermochromic indicators in fiber-based packaging remains limited. (Pevec et al., 2025) Vukoje et. al. showed that irreversible thermochromic inks are difficult to remove through standard deinking flotation. Flotation can reduce paper opacity by removing fillers and possibly optical brighteners but is not ideal for recycling materials like thermochromic indicators. They suggested exploring other methods. (Vukoje et al., 2021)

1.1 Comparison of recyclability test methods

CEPI test method is the relevant test method to be used for standard mills. It defines a laboratory procedure with the most relevant process stages (pulping, coarse and fine screening, sheet formation), while the cleaning step is not included due to a lack of suitable equipment widely available in most EU labs. The test method provides results relevant to the process efficiency (yield, coarse and fine reject amount) as well as to the recycled paper quality (visual impurities and sheet adhesion). CEPI's approach emphasizes standardizing recycling evaluation

across Europe to ensure consistency in results. (CEPI, 2022) By focusing on adhesive stickiness and deinkability, CEPI test method targets two of the most significant challenges in paper recycling, particularly for printed products. These test methods aim to enhance the quality of recycled fibers, reduce operational inefficiencies, and promote environmentally friendly practices within the paper industry. (Defalque, et al., 2021) (Lumme, 2022) For instance, CEPI has worked on a pan-European standardization of the PTS method, which tests adhesion levels and surface changes caused by adhesives during recycling processes. (Lumme, 2022)

The Eco Paper Loop initiative focuses on improving the recyclability of paper-based packaging by evaluating contamination levels, optimizing fiber recovery rates, and recommending best practices for paper collection systems. By integrating recyclability into the product design stage, this initiative not only enhances resource efficiency but also encourages circular economy practices across the European paper industry. (EcoPaperLoop, 2014) (Kowalska, et al., 2021) The project's guidelines, including EcoPaperLoop Method 1 for packaging recyclability, serve as benchmarks for manufacturers aiming to reduce non-paper components and improve recyclability. (EcoPaperLoop, 2014) (Kowalska, et al., 2021)

Aticelca, through its Evaluation System 501:2019, provides a structured framework for classifying paper products based on their recyclability. Rooted in the UNI 11743:2019 standard, this system assigns recyclability grades (A+, A, B, or C) by evaluating process parameters such as adhesive particle size and product quality after recycling. Its primary goal is to encourage manufacturers to adopt eco-design principles and ensure the efficient reprocessing of cellulosic materials. (Aticelca, 2019) The Aticelca system not only fosters collaboration among stakeholders but also highlights the importance of integrating recyclability considerations into product development. (Aticelca, 2019) (Lumme, 2022)

Table 1: Comparison of the recyclability test methods.

	ATICELCA test method	**CEPI test method, Version 2**	**EcoPaperLoop test method**
Disintegration	10 min 3000 revolutions/min, 40°C, 2.5% stock consistency	10 min 3000 revolutions/min, 40°C, 2,5% stock consistency	5 min 40°C, 4% stock consistency
Soluble and colloidal substances	/	Filtrate analysis and COD* (optional)	Filtrate analysis and COD (optional)
Coarse reject (coarse screening)	Somerville fractionator 50 g of OD** material, 5 min, 5 mm holes	Somerville fractionator 50 g of OD material, 5 min, 5 mm holes	Brecht-Holl screening device 10 g of OD material, 5 min, 10 mm holes
Fine reject (fine screening)	Somerville fractionator 5 g of OD material, 5 min, 0,15 mm slots	Somerville fractionator 20 g of OD material, 20 min, 0,15 mm slots	Haindl classifier 10 g of OD material, 5 min, 0,7 mm holes
Sheet adhesion (tackiness)	Adhesion test after fine screening MSA***	Adhesion test after coarse and fine screening MSA (optional)	Adhesion test after fine screening MSA
Visual impurities	Visual impurities after fine screening	Visual impurities after coarse and fine screening	Visual impurities after fine screening

*COD = Chemical Oxygen Demand

**OD = Oven Dry

***MSA = Macrostickies analysis

These methodologies collectively address critical challenges in modern paper recycling, including contamination from adhesives, the need for standardization, and the integration of eco-design principles. By combining the strengths of these systems, the paper industry is advancing toward a sustainable future while aligning with global environmental goals. (Defalque, et al., 2021) (EcoPaperLoop, 2014) (Kowalska, et al., 2021)

2. EXPERIMENTAL

The goal of the study was to select one laboratory test method to perform recyclability test, conduct recycling according to that method, and evaluate recyclability. Due to the increasing presence of smart packaging, a recyclability assessment was performed on the cardboard with the integrated printed intelligent elements as an example of smart cardboard packaging. In practical part of the research, our focus was on the assessment of two elements of intelligent packaging, RFID tag and thermochromic indicator. For the recycling of cardboard packaging the CEPI method was applied. This method was used to assess recyclability by dissolving the samples and determining the coarse reject through a coarse screening process. The concentration after the coarse and fine screening was determined and from obtained recycled fibres the hand sheets were produced on which the adhesiveness test and visual assessment were carried out.

2.1 Materials and method

2.1.1 Materials

The selected base material for smart packaging was coated cardboard, with a grammage of 350 g/m². Cardboard packaging was made with application of starch adhesive. To obtain smart packaging, a screen-printing technique was employed to integrate both the RFID antenna and the thermochromic indicator onto the cardboard. For the RFID antenna, the metallic functional ink CRSN2442 SunTronic Silver 280 was used. For printing thermochromic indicator the Chromatic Technologies (CTI) thermocromic UV Screen Ink, changing color at 30 ◦C, was used. The ink contains leuco dyes, which exist in either a colored or colorless state, depending on temperature. This ink undergoes reversible structural changes when heat disrupts their molecular interactions. When heated above 30°C, interactions between the leuco dye and developer are disrupted, causing the ink to become colorless. Unlike conventional thermochromic coatings that rely on liquid solvents, this ink hardens under UV light, making it more durable and suitable for high-performance printing applications. The recyclability test was performed on cardboard packaging (CP) and smart cardboard packaging (ICP).

2.1.2 Methods

In the experimental part of the research, we tested the recyclability of two different samples according to the CEPI Recyclability Laboratory Test Method, Version 2, October 2022. To conduct the recycling tests, 50 g of oven-dry material was prepared for disintegration, with each sample cut into 3 cm x 3 cm pieces. Disintegration was performed for 10 minutes using conditions reported in Table 1. The entire sample suspension was utilized for coarse screening, starting with 50 g of oven-dry material. After the coarse screening process, presented in Table 1, material retained on the perforated plate was collected and filtered in a Büchner funnel. The coarse reject was then dried using a Rapid-Köthen dryer at 93°C for 10 minutes, followed by oven drying at 105°C until a constant mass was achieved.

The suspension consistency was determined by standard ISO 4119 to produce 60 ± 2 g/m² laboratory sheets using a Rapid-Köthen sheet former for adhesion evaluation after coarse screening. Additionally, 20 g of oven-dry material underwent fine screening. For adhesion testing, the laboratory sheet was layered with a carrier board and cover sheet, dried, and heated at 130°C for 2 minutes. After cooling, it was examined under direct and transmitted light for impurities. Fine screening used a Somerville screen under conditions given in Table 1, with retained material processed as fine reject and analyzed similarly to coarse screening. Finally, the recyclability score was calculated using the coarse reject, fine reject, visual impurities, and sheet adhesion data derived from the accept material after fine screening.

The optical properties of hand sheet were determined using standards. A total of 10 measurements were conducted per sample. For measuring ISO brightness SIST ISO 2470–1:2017 was applied. The opacity was determined by SIST ISO 2471:2011. Color measurements were performed in the CIE Lab* color space, a standard defined by the International Commission on Illumination. This system characterizes color using three coordinates: L*, which indicates brightness on a scale from 0 (black) to 100 (white); a*, which represents the position on the red-green axis; and b*, which indicates the position on the yellow-blue axis.

3. RESULTS AND DISCUSSION

Two samples were compared, the simple cardboard packaging (unprinted cardboard with water soluble glue), marked as CP, and the same packaging, equipped with the printed RFID antenna and thermochromic indicator, marked as ICP. In Table 2 results obtained after performing recyclability test are presented.

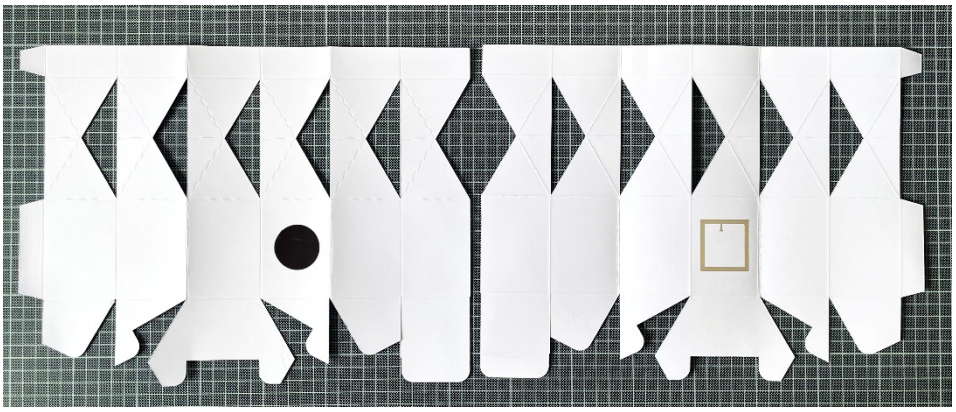


Figure 1: The image shows an example of a sample intelligent cardboard packaging (ICP) from the front and back.

After the coarse screening process, almost no rejects remained on the perforated plate, which aligned with our expectations. Similar to the findings of Aliaga et al. (Aliaga, et al., 2011), we assumed that the printed electronics from the RFID tag would be retained by the sieve, with only a minimal amount making its way into the screened fibers. The calculated percentage of coarse rejects ranged from 0.03% to 0.11%, consisting mainly of small fiber flakes and residual printing ink that became trapped in the gaps between the 5 mm holes after the dewatering process in Somerville.

Table 2: Results of recyclability testing: coarse reject, fine reject, yield, visual impurities after fine screening, sheet adhesion after fine screening and recyclability score for both samples: cardboard packaging (CP) and intelligent cardboard packaging (ICP).

	Coarse reject (%)	**Fine reject** (%)	**Yield** (%)	**Visual impurities after fine screening** (Level)	**Sheet adhesion after fine screening** (Level)	**Recyclability score** (/)
CP	0.03	0.11	99.9	1	1	100/100
ICP	0.05	0.15	99.8	3	1	85/100

Following fine screening, a higher percentage of rejects was anticipated due to the smaller screen plate openings, which allow the passage of good material while capturing more impurities. The fine reject calculations varied between 0.08% and 0.55%. The first sample left almost no visible rejects on the plate, apart from a few minor fiber flakes. However, in the sample containing the thermochromic indicator, numerous small particles of thermochromic ink were retained on the plate. The functional ink of the RFID antenna was not visible to the naked eye on the plate, yet small dots were observed within the screened material.
The hand sheets likely contained minimal amount of adhesive, as there was no noticeable tackiness. The level

of sheet adhesion in both samples was rated as 1, meaning no adhesion issues were detected when processing the recovered material. In the second sample, small dots were also visible on the hand sheet, as previously mentioned in relation to the residues found on the perforated plate, confirming the presence of functional ink. These small impurities were only noticeable upon close examination of the hand sheet and had no significant impact on its optical properties. Consistent with the conclusions of Aliaga et al. (Aliaga, et al., 2011), we found that variations in visual properties were minor and did not interfere with the sample recycling procedures. The consistency of results after fine screening was affected the least by these factors.

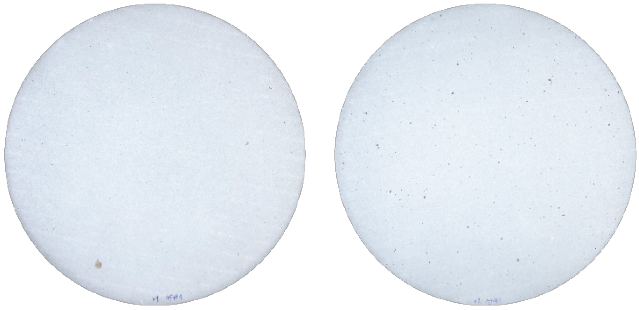


Figure 2: The image of hand sheets after fine screening of samples, photographed using transmitted light.

Table 3: Optical properties of hand sheets produced after fine screening, given as average value and standard deviation.

	L* (/)	a* (/)	b* (/)	ISO brightness [%]	Opacity [%]
CP	96.4±0,04	3.24±0,03	-11.4±0.12	107±0.20	85.9±0.10
ICP	96.5±0,04	3.19±0,02	-11.5±0.07	108±0.19	85.7±0.05

As seen in Table 3, the difference in optical properties between both samples is so minor that it can be considered negligible. Anyway, we can see, that ISO brightness is higher than 100 scale. It means, that our cardboard is treated with optical brightening agents (OBAs) or other chemical additives, which enhance their ability to reflect light, particularly under UV light. As a result, these treatments can cause the paper's ISO brightness to exceed the standard 100 scale.

4. CONCLUSIONS

Our research demonstrated that while thermochromic ink and functional conductive ink had slightly higher levels of fine rejects and minor visual impurities compared to the CP sample, these did not significantly impact the material's recyclability or optical properties. Both tested samples exhibited excellent sheet adhesion, their visual and optical properties remained comparable after the fine screening process and were deemed suitable for standard recycling processes, achieving top-tier performance with recycling efficiencies exceeding 99% and recyclability scores ranging from 85 to 100%. The minor differences in recyclability scores (100/100 for CP and 85/100 for ICP) indicate that the addition of printed electronics and functional inks does not severely hinder the recycling process.

These findings confirmed our initial hypothesis: packaging containing printed RFID antennas and thermochromic indicators maintains high recyclability with negligible effects on the recycling process.

5. REFERENCES:

Aliaga, C., Ferreira, B., Hortal, M., Pancorbo, M., López, J., & Navas. “Influence of RFID tags on recyclability of plastic packaging.” Waste management Volume 31, Issue 6: pp. 1133-1138.
Lumme, E., 2022. “Tahmatestausmenetelmän validointi.” Metropolia Ammattikorkeakoulu.
Aticelca, 2019, Evaluation System 501:2019 – Assessment of the lever of recyclability of materials and products predominantly cellulosic on the basis of the UNI 11743:2019 standard, Milan.
CEPI, 2022b, Cepi recyclability laboratory test method – Harmonised European laboratory test method to generate parameters enabling the assessment of the recyclability of paper and board products in standard paper and board recycling mills, CEPI, Brussels.
Defalque, C., Marins, F., da Silva, A., & Rodríguez, E., 2020. “A review of waste paper recycling networks focusing on quantitative methods and sustainability” Journal of Material Cycles and Waste Management Volume 23: pp 55–76.
EcoPaperLoop, 2014. Enhancing the Quality of Paper for Recycling in Europe: Optimising Paper Products, Packaging and Collection Systems: Outcome – Guidelines and Recommendations, European Union/European Fund for Regional Development, Brussels.
Kochersperger, S., & Schabel, S., 2024. “Recyclability of Paper□Based Composites for Packaging Applications – The Role of Evaluation Methods” Chemie Ingenieur Technik Volume 96, Issue 7: pp. 891-901.
Kowalska, M.A., Donatello, S. and Wolf, O., 2021. “EU Ecolabel Criteria for printed paper, stationery paper, and paper carrier bag products.” Publications Office of the European Union, Luxembourg.
Nordin, N., & Selke, S., 2010. “Social aspect of sustainable packaging.” Packaging Technology and Science Volume 23, Issue 6: pp. 317-326.
Pevec, P., Kapun, T. & Gregor-Svetec, D. 2025. “Recyclability of Intelligent Cardboard Packaging” Sustainability Volume 17, Issue 7: pp 2924.

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POSTER PRESENTATION

SUSTAINABLE GIFT PACKAGING: DESIGN GUIDELINES BASED ON ECO-DESIGN PRINCIPLES

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Abstract: *Sustainable eco-design aims to minimize environmental impacts across a product's entire life cycle, from design and production to use and disposal. This study develops guidelines for sustainable gift packaging, emphasizing multifunctionality, interactivity, and recyclability. The research includes a case study of Tr'glav packaging, part of Bled Local Selection, which integrates Slovenian cultural elements with sustainable and smart packaging design. Packaging from corrugated cardboard without print and paper label are identified as the optimal packaging materials due to their high recyclability. Interactive elements, such as QR codes, RFID tag and augmented reality enhance user engagement while maintaining recyclability of packaging. Additionally, the packaging incorporates reuse strategies, such as transformation into a bee habitat. The findings provide guidelines for designers developing sustainable, interactive packaging aligned with eco-design principles.*

Keywords: *eco-design, guidelines, gift packaging, multifunctionality, interactive packaging*

1. INTRODUCTION

Sustainable eco-design aims to minimize the environmental impact of products throughout their entire life cycle, from design and production, to use and disposal. Key strategies in eco-design focus on reducing energy and material consumption, reusing components, upgrading products, and recycling materials, including waste generated during production, while also considering energy recovery (Brezet, 1997). However, the accumulation of waste is often a result of poor management and design decisions, highlighting the need for more effective sustainable strategies (Urukalo, 2010). In the context of packaging, sustainable design prioritizes waste elimination, material reduction, and the reuse or recycling of packaging at the end of its life cycle, returning materials as raw inputs for further production (Azzi et al., 2012).

Sustainable packaging not only protects products but also serves as a marketing and communication tool, shaping consumer perception and adding value (Snoj, 1981; Dreyfuss, 2003; Pisnik Korda & Snoj, 2006; Yam, 2010). Fundamental concepts in sustainable packaging design include recyclability, multifunctionality, and material efficiency (Kozik, 2020; Radonjič, 2014). At the same time, advancements in smart packaging enable features such as tracking and consumer engagement via QR codes, RFID tags, and augmented reality (AR) (Realini & Marcos, 2014; Restuccia et al., 2010). However, studies suggest that these interactive elements are underutilized unless consumers are specifically encouraged to engage with them (Žurbi & Gregor-Svetec, 2023).

Despite progress in sustainable packaging, the industry faces several challenges, including inefficient waste management, excessive material use, and suboptimal packaging design. Over-decoration and excessive packaging remain prevalent, leading to increased waste production and higher costs (Liu & Wang, 2023). While consumer demand for minimalist and eco-friendly packaging is growing, a lack of clear sustainability information often prevents informed purchasing decisions (Future Market Insights, 2021; Steenis et al., 2017). Regulatory frameworks, such as the European Union Directive 94/62/EC, aim to address these issues by promoting recycling and material reuse. Although the EU has achieved a municipal waste recycling rate of 48% in 2022, challenges persist in sorting and reprocessing complex packaging materials (Statista, 2025).

This study focuses on developing guidelines for sustainable gift packaging that emphasize multifunctionality, interactivity, and recyclability. The research explores innovative design strategies that extend packaging lifespans through reuse while integrating interactive elements to enhance user experience and reduce the reliance on prin-

ted materials. Additionally, it highlights the importance of corrugated cardboard as a widely used and recyclable material, offering an optimal balance between sustainability and mechanical performance (González-García et al., 2016).

By adopting a mixed-method research approach—including literature reviews, case studies, and user research—this study examines a case of sustainable gift packaging developed for the Tr'glav brand, part of the Bled Local Selection initiative (Pogačar, 2023). This case integrates elements of traditional Slovenian culture with modern sustainability and smart packaging technologies, providing valuable insights into the future of eco-friendly and interactive gift packaging.

2. EXPERIMENTAL

The study described in the doctoral dissertation *Design Guidelines for Interactive Sustainable Gift Packaging* employed a structured experimental approach to evaluate the sustainability, functionality, and user perception of the Tr'glav gift packaging. The research combined laboratory material testing, interactive technology integration, and user-centred studies to assess packaging performance. The research methods applied are described in detail in the doctoral dissertation (Pogačar, 2023).

2.1 Material Selection

Materials were selected based on mechanical properties and performance, with consideration for sustainability. The tested materials included corrugated cardboard of various thicknesses and composition, and self-adhesive paper labels of different composition (Pogačar, 2023). Physical tests of corrugated cardboard included measurements of grammage, thickness, and moisture absorption, while mechanical assessments examined tensile strength, bending stiffness, puncture resistance, tear resistance, ECT and FCT. Additionally, durability tests on printed labels assessed resistance to light, moist-heat treatment, and abrasion. These analyses ensured the selection of materials that balance sustainability with durability and functionality.

2.2 Integration and Evaluation of Interactive Technologies

To assess the impact of interactive technologies on user experience and recyclability, the Tr'glav packaging prototypes incorporated QR codes, RFID tags, and AR features. QR codes provided digital product and sustainability information, RFID tags facilitated tracking and logistical optimization, while AR enabled interactive experiences through mobile applications. User interaction studies were conducted to evaluate accessibility, usability, and consumer engagement with these technologies (Pogačar, 2023). Additionally, recyclability impact assessments examined whether interactive elements influenced material recovery processes (Pogačar, 2023). The results provided insights into the feasibility of integrating interactive technologies without compromising packaging sustainability.

2.3 User Research and Consumer Perception Analysis

A combination of quantitative and qualitative methods was used to assess consumer attitudes towards sustainable and interactive packaging (Pogačar, 2023). An online survey was distributed to a diverse Slovenian audience, employing a Likert scale to evaluate sustainability, functionality, and technological features. A total of 207 valid responses were collected and analysed. In addition to the survey, focus groups provided deeper insights into user experience. Two key groups participated: employees from Turizem Bled, who evaluated the packaging's suitability for the tourism industry, and members of Katapult business incubator, who analysed its innovative and commercial potential. Participants engaged directly with the packaging, assessing its visual appeal, ease of use, label clarity, and overall perception of sustainability.

2.4 Field Testing and Real-World Validation

To validate the functional performance and market acceptance of the packaging, real-world field tests were conducted. These trials involved retail environment placements to observe consumer interactions, analysis of handling and durability during transportation, and user behaviour tracking to assess engagement with interactive elements (Pogačar, 2023). Additionally, reuse potential and multifunctionality were evaluated to determine whether consumers repurposed the packaging beyond its initial function.

3. RESULTS WITH DISCUSSION

The collected data from laboratory testing, interactive technology assessments, user experience studies, and field trials were systematically analysed to establish correlations between material properties, digital engagement, and user satisfaction. The findings provided empirical evidence for developing guidelines on sustainable, multifunctional, and interactive packaging solutions. The results of the study demonstrate that sustainable interactive gift packaging can be effectively developed through a strategic combination of environmentally friendly materials, functional structural design, and interactive elements. The integration of these components supports the principles of circular economy, reduces environmental impact, and enhances user engagement (Pogačar, 2019). The findings highlight key material choices, design strategies, and consumer preferences, offering practical guidelines for sustainable packaging development (Pogačar, 2023).

3.1 Material Selection and Performance

Corrugated cardboard is a sustainable packaging material due to its high recyclability, biodegradability, and minimal environmental footprint. However, recycled corrugated cardboard exhibited slightly reduced mechanical strength and limited moisture resistance; nevertheless, its strength and performance were suitable for the selected packaging design (Pogačar, 2023; Pogačar & Gregor-Svetec, 2024).

The study also examined labelling solutions, confirming that a self-adhesive label made from FSC-certified paper with biodegradable adhesive exhibited good print durability and recyclability, making it the most sustainable option (Pogačar et al, 2024). Packaging elements that include plasticized layers or foil coatings were found to hinder recyclability. Therefore, the research strongly recommends adopting a monomaterial approach, ensuring that all components are easily separable and recyclable.

3.2 Structural Design and Functionality

The structural design of the packaging plays a critical role in ensuring durability, multifunctionality, and ease of transport. The results revealed that consumers highly value packaging that can be repurposed or reused after its initial function. A modular system was identified as an effective solution, allowing users to reassemble different parts of the packaging, thereby extending its lifespan (Pogačar & Gregor-Svetec, 2024).

Tests demonstrated that integrated handles and foldable closure mechanisms enhance functionality while reducing the need for additional packaging materials such as gift bags. Furthermore, compact and stackable packaging designs contribute to transport efficiency and material optimization. The study supports a minimalist approach, where excessive decorative elements and unnecessary material usage are eliminated to improve sustainability (Pogačar, 2023; Pogačar & Gregor-Svetec, 2024).

The mechanical durability tests showed that optimizing the structure of corrugated cardboard—by strategically placed folds—significantly enhances resistance to pressure and impact without increasing material consumption. This finding is particularly relevant for ensuring protective functionality while minimizing waste (Pogačar, 2023).

3.3 Impact of Digital and Interactive Elements

The research assessed the feasibility of integrating interactive smart elements within sustainable packaging, focusing on RFID tags, QR codes, and AR. The findings indicate that these features do not compromise recyclability and, in some cases, reduce printed material consumption by shifting product information to digital formats (Pogačar, 2023; Pogačar et al., 2024).

Among the interactive elements, QR codes proved to be the most effective in delivering digital product details, recycling instructions, and promotional content. Printed RFID tags offer advantages in supply chain tracking and inventory management, with no significant impact on recyclability (Pogačar et al., 2024).

AR features were found to increase consumer engagement, particularly among younger demographics. However, their effectiveness depends on consumer familiarity with digital applications. The results suggest that AR integration is most beneficial for brands targeting digitally inclined audiences (Pogačar, 2023).

3.4 Sustainability Beyond Disposal

A key objective of sustainable packaging is to extend its lifecycle beyond single-use functionality. The study identified an innovative secondary-use concept, where the packaging can be repurposed into a solitary bee nesting habitat (Pogačar, 2023). This approach adds environmental value by encouraging biodiversity and aligns with the principles of circular economy and zero-waste design (Pogačar, 2019).

The findings suggest that packaging should incorporate practical reuse possibilities to increase its appeal and functional longevity. Implementing design-for-reuse principles ensures that packaging does not become waste but serves an extended purpose, reinforcing sustainable consumer behaviour (Pogačar & Gregor-Svetec, 2024).

3.5 Consumer Perception and Market Preferences

Consumer feedback collected through surveys and focus groups confirmed that aesthetic appeal, sustainability, and functionality are the most influential factors in packaging perception. Packaging that clearly communicates its environmental benefits received higher preference, reinforcing the need for eco-labelling and transparency in sustainability claims (Pogačar, 2023).

The research found that minimalist design approaches resonate strongly with modern consumers, as excessive decorative elements often create the perception of overconsumption and unnecessary waste. Consumers were more likely to support packaging that visibly aligns with sustainability values while maintaining practical usability and an appealing visual identity (Pogačar, 2023).

4. CONCLUSIONS

A well-balanced integration of eco-friendly materials with optimized design creates sustainable, functional packaging that enhances consumer engagement. Corrugated cardboard, due to its recyclability and strength, remains the most suitable material, with structural reinforcements further improving durability. Monomaterial designs without adhesives support circular economy principles, while structural modifications enhance usability and minimize material waste. Interactive technologies, particularly QR codes and AR, reduce printed materials and improve consumer interaction, with RFID tags adding logistical benefits without compromising recyclability.

Consumer preference for minimalist, clearly labelled, and eco-friendly packaging reinforces the importance of transparent sustainability communication. A holistic approach—combining sustainable materials, functional design, and digital features—drives packaging innovation that meets environmental, functional, and consumer expectations.

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6. REFERENCES:

Azzi, A, Battini, D, Persona, A. and Sgarbosa, F. 2012. “Packaging design: general framework and research agenda.” *Packaging technology and science* 25(8): 435-456.
Brezet, H. 1997. “Dynamics in eco-design practice.” *Industry and Environment*, 20: 21-24.
Dreyfuss, H., 2003. *Designing for people*. New York: Viking.
Future market insights, 2021. Gift Packaging Market. URL: https://www.futuremarketinsights.com/reports/gift-packaging-market (last accessed on 25. 7. 2023).
Ggonzález-García, S., Sanye-Mengual, E., Llorach-Masana, P., Feijoo, G., Gabarrell, X., Rieradevall, J. and Moreira, M.T. 2016. “Sustainable design of packaging materials.” In: *Environmental footprints of packaging*, edited by Muthu, S.S., 23-46. Singapore: Springer.
Kozik, N. 2020. “Sustainable packaging as a tool for global sustainable development. ” In: *SHS web of conferences*, edited by Kliestik, T 74: pp. 1-8. Rajecke Teplice: EDP Sciences.
Liu, L. & Wang, A., 2023. Measures for Excessive Application of Gift Packaging Design Materials. In: *Proceedings of the 2nd International Conference on Culture, Design and Social Development (CDSD 2022)*. Amsterdam: Atlantis Press, pp. 296-302.
Pisnik Korda, A. & Snoj, B., 2006. *Management izdelkov*. Maribor: Ekonomsko poslovna fakulteta, Maribor.
Pogačar, A. 2019. “Razvoj ekološke embalaže kot edina možna pot.” In: *Razvoj embalaže v krožnem gospodarstvu: priročnik*, edited by Volfand, J., Gregor Svetec, D., Požrl. T., 70-72. Celje: Fit media.
Pogačar, A. 2023. “Smernice za načrtovanje interaktivne trajnostne darilne embalaže” PH diss., University of Ljubljana.
Pogačar, A., Bolanča Mirković, I and Gregor-Svetec, D. 2024. “Print durability and recyclability of label paper equipped with printed RFID antenna.” *Sustainability* 16(1): 1-16.
Pogačar, A. and Gregor-Svetec, D. 2024. “Innovative multipurpose gift packaging.” In: *Book of proceedings : 9th International Joint Conference on Environmental and Light Industry Technologies*, edited by Csanák, V., 63-73. Budapest: Óbuda University, Sándor Rejtő Faculty of Light Industry and Environmental Engineering.
Radonjič, G., 2014. *Oblikovanje in razvoj okolju primernejše embalaže*. Maribor: Fakulteta za kemijo in kemijsko tehnologijo.
Realini, C.E. & Marcos, B., 2014. “Active and intelligent packaging systems for a modern society.” *Meat science*, 98(3), pp.404-419.
Restuccia, D., Spizzirri, U.G., Parisi, O.I., Cirillo, G., Curcio, M., Iemma, F., Puoci, F., Vinci, G. & Picci, N., 2010. “New EU regulation aspects and global market of active and intelligent packaging for food industry applications.” *Food control*, 21(11), pp. 1425-1435.
Snoj, B., 1981. *Embalaža-sestavina politik izdelkov in komuniciranja v marketingu*. Ljubljana: ČGP Delo.
Statista, 2024. Recycling rate of municipal waste in the European Union (EU-27) in 2010 and 2022, by country. URL: https://www.statista.com/statistics/1219551/municipal-waste-recycling-eu-by-country/ (last accessed on 31. 1. 2025).
Steenis, N.D., Van Herpen, E., Van der Lans, I.A., Ligthart, T.N. & Van Trijp, H.C., 2017. “Consumer response to packaging design: The role of packaging materials and graphics in sustainability perceptions and product evaluations.” *Journal of cleaner production*, 162, pp. 286-298.
Urukalo, S. 2010. *Odločitev za odgovornost: o oblikovalski etiki in oglaševanju*. Marketing Magazin. Ljubljana: Društvo oblikovalcev Slovenije.
Yam, K.L. ed., 2010. *The Wiley encyclopedia of packaging technology*. Hoboken: John Wiley & Sons Inc.
Žurbi, T. & Gregor Svetec, D., 2023. “Use of QR Code in Dairy Sector in Slovenia.” *SAGE Open*, 13(2), pp. 1-16.

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POSTER PRESENTATION

DESIGNING CARDBOARD PACKAGING FOR CERAMIC PRODUCT TRANSPORTATION AND BRAND IDENTITY DEVELOPMENT

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Abstract: *This research develops an innovative, recyclable cardboard packaging solution for the safe transportation of ceramic products while reinforcing brand identity. The design prioritizes sustainability, functionality, and aesthetic appeal, aligning with modern eco-friendly packaging trends. Corrugated cardboard was selected for its strength, lightweight nature, and high recyclability. The study explores packaging's dual role in product protection and brand communication, integrating eco-design principles and sustainable materials. An experimental approach tested various prototypes, culminating in a refined design featuring a safety belt mechanism for enhanced transit stability. The final solution balances protection, sustainability, and visual appeal, contributing to the advancement of eco-friendly packaging for fragile products.*

Keywords: *cardboard packaging, ceramic product, eco-design, branding.*

1. INTRODUCTION

Packaging is an integral part of our daily lives. Without design and information, packaging would make our everyday routines less practical, less informative and far less appealing. It not only communicates what's inside but also shapes our experience of the product (Gao et. al, 2021, Hi et. al., 2024). Design and information are tightly connected. Well-designed packaging improves the user experience and conveys a sense of quality (Nguyen et al., 2020). But in today's world, good design alone is no longer enough. Despite well-designed packaging, large quantities of products still end up in landfill. This shows how important it is to choose sustainable materials and design packaging that minimises waste.

For ceramic products, the packaging must provide adequate protection to ensure that the items remain intact (Sanchez-Belenguer et.al, 2015, Elkhattat & Medhat, 2022). From personal experience in the ceramic's courses, the finished products are often wrapped in paper and put in a bag, which often leads to breakage during transport (Sundlof & Fasano, 2007). This challenge gave us the idea to develop a more effective and sustainable packaging solution.

This research aimed to explore environmentally friendly and functional packaging solutions for fragile products, focusing on developing a protective yet simple design that is cost-effective and minimizes material use. Cardboard was chosen as the primary material to create packaging that is easy to handle for transporting ceramics while also offering the potential for reuse as storage. A key objective was to analyse the market for fragile product packaging and develop a custom solution specifically for ceramic items. The design needed to balance aesthetics with sustainability, minimizing ink consumption while maintaining visual appeal. Additionally, a brand identity was created, guided by eco-design principles.

The primary challenge was designing packaging that could accommodate the unique nature of handcrafted ceramics. Unlike mass-produced items, ceramics made in courses and workshops vary in shape and size, requiring a flexible packaging solution. Market research revealed that most existing packaging is designed for products with fixed dimensions. While many innovative box designs exist, very few offer adaptability. To address this gap, we developed a packaging solution consisting of an outer box that appears conventional but incorporates an internal structure with adjustable cardboard inserts. These inserts provide additional stability when needed, ensuring that ceramics remain secure during transport—from the place of production to their destination.

The final packaging design is a corrugated cardboard box, suitable for most ceramic course projects. It features a handle for easy carrying and an innovative fastening system that allows the box to be attached to a car seatbelt or bicycle basket to increase stability during transport.

2. EXPERIMENTAL

2.1 Materials

The cardboard we used for the packaging was E-wave, uncoated, white cardboard, with a thickness of 1.5 mm and grammage 320 g/m^2. Before the box was assembled it was laminated with a vinyl sticker on which the brand image was printed.

2.2 Methods

Various tools were used for the production of the box and the design. Adobe programmes (Adobe Systems Inc., USA) such as Photoshop and Illustrator were used to design the box. For the box construction Engview Packaging Suite (Engview Systems Corp., Bulgaria) was used. Cutter Esko Konsgberg X20 (Esko, Belgium) was used for the cutting and production of final box. Canon imagePROGRAF PRO-4000S (Canon Inc., Japan) was used for the print on vinyl label.

3. RESULTS WITH DISCUSSION

3.1 Designing the brand name, logo and packaging construction

For the brand name, we wanted something modern, easy to remember and easy to pronounce internationally. The name itself evokes associations with a figure, i.e. a shape, structure, sculpture, statue. The name Figulina comes from a Latin word whose direct translation is pottery. Phonetically, Figulina sounds youthful and like a kind of diminutive, which gives it a soft sound. We experimented with very different ideas for the logo. We tried out different illustrated characters to represent the brand, word logos in very different styles. We wanted to capture youth, playfulness, simplicity and originality in the logo. Examples of sketches can be seen in Figure 1a. We wanted to incorporate the duality of clay, which can be very soft at first and then very hard and sharp at different stages of its life. Clay can withstand very high temperatures that harden it, but at the same time it can crack quickly when struck, during and after firing, if handled carelessly. That is why in the sketches above we see in many cases sharp and rounded edges, regular and irregular shapes on individual logos. We have mainly stuck to shapes that ultimately represent the letter “f” or the word Figulina, the brand name.



a) b) c)

Figure 1: a) sketches for the logo, b) moodboard of the first idea, c) moodboard of the second idea

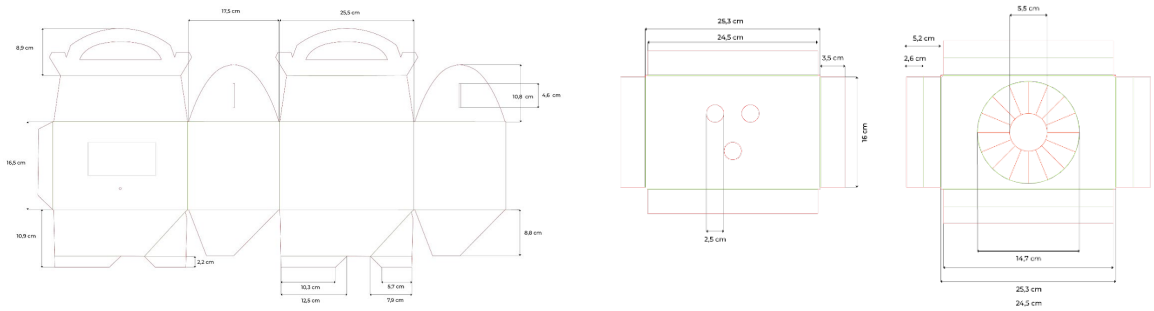
As shown in Figure 2a, we first drew sketches of the desired packaging, then we drew constructions of the whole packaging. To make our products even safer during transport to your home, we have come up with various solutions to protect our ceramic products even better against mechanical damage. We have produced different solutions, which we have tested for their stability during the transport of the products (Figure 2b).



a) b)

Figure 2: a) first construction of the desired packaging, b) solutions for additional packaging safety with a seat belt.

After the first cut, we adjusted the construction, corrected all errors and drew the final box with belt solution and inner part customisation (Figure 3a-b). The packaging consists of the outer part where are two pieces of cardboard inserts (Figure 3b), which are optional and can be used as needed. The insert on the right-hand side in Figure 3b is used when we want to give the product more stability, for example for taller products such as bowls, vases, cups, etc. The insert on the left-hand side (Figure 3b) is used to support products that do not reach exactly to the top edge of our packaging. This keeps the product more stable and in place. The packaging must be glued in three parts. One is the flap on the far left of the envelope that connects all sides of the box, the other two sections are at the bottom of the box. This ensures that the bottom does not collapse when you are carrying heavier products.

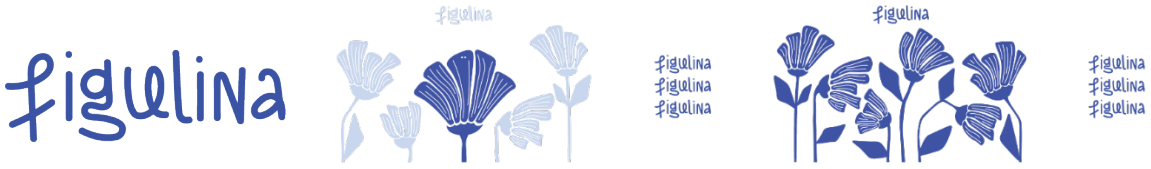


a) b)

Figure 3: a) final construction of the packaging, b) solution for additional packaging safety.

3.2 Final logos, packaging design and the box

We spent a lot of time designing a symbol to represent the letter “F”, but in the end we decided on a word logo made up of letters that we designed ourselves. The advantages of word logos are quick recognisability, simplicity and versatility of use, which would be very useful for a new business. Here’s how we went about creating the logo: First, we wrote down on a piece of paper the words we wanted to associate with the logo. These words were youth, uniqueness, creativity, freedom, simplicity and organisation. First, we started with shapes and composed abstract logos from geometric and more organic shapes, which together would form the letter f (Figure 4). Due to the nature of the letter f, which did not appear stable enough in our design attempts, we discarded this idea. We then focussed on a word logo that would be written in a slightly different, original way. Like every ceramic product, it is shaped by hand.



a) b)

Figure 4: a) final logo, b) final packaging design.

In Figure 5, the illustrations on the box were designed to convey two key messages: first, that the packaged products are fragile and should be handled with care, and second, that the box itself serves as a visually appealing representation of the beauty of the products it protects. This reminded us of extremely valuable ceramic products that are highly recognisable all over the world. It is Chinese porcelain, which is easily recognised by the white of the ceramic and the blue of the floral patterns on it. To match the logo, we modernised the flowers and used a simpler design with fewer details. The blue and white ceramic was originally invented in China but quickly spread around the world. Today it is one of the most famous products in the history of Chinese porcelain. It is generally ceramic decorated with cobalt blue colour, usually applied with a brush. Its charm lies precisely in the colour combination, which spread at the end of the 19th century and became an essential element of a beautiful home.



Figure 5: Final packaging with printed design.

Since the safe transport of fragile products like ceramics was a primary concern, we developed an effective packaging solution featuring inner components that are securely fixed yet removable when needed (Figure 6a-c).



a) b) c)

Figure 6: a) inner part of the packaging, b) inner part wih added product in the packaging, c) upper safety cover cardboard.

In the end, we decided in favour of the solution for fastening to the belt, which is shown in Figure 7a. At the same time, we managed to incorporate the brand image into this solution, as can be seen and added also. The elastic cords highlight intricate details (Figure 7b) in the flower, which are also reflected throughout the design. This solution is user-friendly—simply pull the elastic over the belt and secure it onto the golden rivet at the bottom.



a) b)

Figure 7: a) fixed packaging during the transport, b) detail of the fastening solution, incorporated into design.

The designed packaging is functional, aesthetically perfect and flexible. Above all, its flexibility gives it an advantage over existing packaging on the market. There is not much flexible cardboard packaging for fragile products on the Slovenian market. Our final packaging is very suitable for a wide range of ceramic products and also allows the user to additionally protect the products with paper. It is flexible in the sense that we can store the products in it in various ways. In the case of a tall vase, we used an insert with recesses to help provide stability to taller products with a diameter of 5.5 to 14 cm. Our box enables the storage of products up to 16.5 cm high and 25.5 cm wide. With the second insert, we reduced the risk of tipping damage and offer the option of storing products on two levels. The insert is placed on top and with the sides on the surface we ensure that it stays in place.

4. CONCLUSIONS

Our research demonstrated that corrugated cardboard can be used to create packaging that meets all our requirements. Designed with sustainability in mind, the packaging is made from recycled and recyclable materials, minimizing its environmental impact. Throughout the development process, we explored various design solutions, prototyping and testing them under real conditions. To ensure stability during transport, we tested the box in a moving car with three different seatbelt-locking mechanisms. The most effective and eco-friendly solution was selected and integrated into the final design.

Beyond the technical aspects of cardboard packaging, we also explored the significance of branding and market positioning. Our findings were implemented in the design process, successfully demonstrating that functionality, aesthetics, and sustainability can be harmoniously integrated into packaging for ceramic products. In the future, this concept could be expanded into a series of packaging solutions in different sizes, accommodating a wider range of products. We hope our design will contribute to making the transportation of fragile ceramic items more secure and convenient.

5. REFERENCES

Elkhattat, D., & Medhat, M. 2022. Creativity in packaging design as a competitive promotional tool. Information Sciences Letters, 11(1), 135-145.
Gao, Z., Dong, W., & Xiaomin, J. 2021. Research on the reduction design of fragile product cushion packaging under the green development concept. In IOP Conference Series: Earth and Environmental Science, vol. 657, No. 1, 01205.
Nguyen, V., Nguyen, N., Schumacher, B., & Tran, T. 2020. Practical application of plan–do–check–act cycle for quality improvement of sustainable packaging: a case study. Applied Sciences, 10(18), 6332.
Sanchez-Belenguer, C., Vendrell-Vidal, E., Sánchez-López, M., Díaz-Marín, C., & Aura-Castro, E. 2015. Automatic production of tailored packaging for fragile archaeological artifacts. Journal on Computing and Cultural Heritage (JOCCH), 8(3), 1-11.
Sundlof, B., & Fasano, B. 2007. Ceramics in Packaging. Global Roadmap for Ceramic and Glass Technology, 397-418.
Xi, H., Guo, C., Yang, J., Wang, X., Wang, B., Huang, S., & Wang, Z. 2024. Cushioning Performance of a Novel Polyurethane Foam Material Applied in Fragile Packaging. Acta Mechanica Solida Sinica, 1-11.

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POSTER PRESENTATION

SUSTAINABLE PRODUCTION OF BACTERIAL NANOCELLULOSE FROM KOMAGATAEIBACTER XYLINUS USING CITRUS PEEL AND GAMMA IRRADIATION

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Abstract: *Bacterial nanocellulose (BNC) is a promising natural biopolymer with unique structural and functional properties that make it valuable for various technological applications. However, large-scale production is limited by low yields and high costs of conventional culture media. In this study, cost-effective strategies to improve BNC production using agribusiness by-products, especially citrus peels, as alternative carbon sources are investigated. Additionally, gamma irradiation was used to improve the properties of BNC as it effectively modifies materials without chemical initiators. The results showed that irradiation affected the growth of Komagataeibacter xylinus and altered the morphology of BNC, improving its physical and chemical properties. The use of citrus peels offered an environmentally friendly, scalable approach to BNC production. This research emphasises the potential of waste materials and irradiation technology for sustainable BNC synthesis with improved properties.*

Keywords: *Bacterial nanocellulose, ionizing radiation, biowaste, citrus peel.*

1. INTRODUCTION

Biomaterials play a crucial role in a variety of scientific and industrial applications, ranging from biomedical engineering to sustainable packaging. However, both natural and synthetic biomaterials are associated with limitations such as high cost, limited availability and potential toxicity, driving the search for innovative and environmentally friendly alternatives (Sarma, 2013; Arif, 2022). Among the emerging biopolymers, bacterial nanocellulose (BNC) has gained much attention due to its unique molecular structure, nanofibrillar network, excellent mechanical properties and biocompatibility. These properties make BNC a valuable material for applications in biomedicine, electronics, food packaging and tissue engineering. Despite its favourable properties, large-scale production of BNC faces significant challenges, mainly due to the low production yields and high costs associated with conventional culture media. Although conventional media such as Hestrin and Schramm (HS) provide optimal conditions for BNC biosynthesis, they are expensive and often unsuitable for industrial applications. Therefore, the search for cost-effective, sustainable alternatives for BNC production is crucial to enable commercial viability. Recent studies have investigated the potential of agro-industrial by-products as nutrient sources for microbial fermentation, offering both economic and environmental benefits (Hadidi et. al., 2024, Valenzuela et.al., 2024). In particular citrus peels, which are abundant as waste materials in the fruit processing industry, contain important carbon sources that could support bacterial cellulose biosynthesis in a cost-effective manner. In addition to optimising culture media, improving the physicochemical properties of BNC is essential for expanding its applications. Radiation technology has proven to be a promising approach for the modification of biomaterials, as it enables structural changes without chemical additives or hazardous by-products. In contrast to conventional surface treatments, gamma irradiation penetrates the material and generates reactive intermediates that can affect the polymer structures. Previous research has shown that high-dose irradiation can enhance enzymatic hydrolysis, change the crystallinity of cellulose and improve water solubility (Li, 2020). In addition, it has been reported that multiple irradiations and low-dose irradiation can significantly increase the yield of BNC, demonstrating its potential to increase production efficiency (Al-Hagar, 2022). In this study, we investigated the use of agro-industrial wastes, especially citrus peels, as an alternative carbon source for BNC production by *Komagataeibacter xylinus*. We also analysed the effects of gamma irradiation on BNC yield and structural properties. The morphology, mechanical properties

and physicochemical attributes of BNC produced in citrus peel-based media were compared with those of BNC synthesised in conventional HS media. This study distinguishes itself by combining citrus peel-based media and gamma irradiation to enhance bacterial nanocellulose (BNC) production. The objectives are to: 1) explore citrus peels as a carbon source for BNC production, 2) evaluate the effects of gamma irradiation on BNC yield and properties, and 3) compare BNC produced in citrus peel-based and conventional media. This research aims to advance sustainable and scalable BNC production.By integrating waste materials and advanced processing methods such as irradiation, this research contributes to ongoing efforts to develop sustainable, scalable and high-performance biomaterials.

2. EXPERIMENTAL

2.1 Materials

For BNC production, a strain of *Komagataeibacter xylinus* (Brown 1886), obtained from the culture collection of Leibniz institute (DSMZ), was used. The standard culture medium used in the experiments was the HS described by Hestrin and Schramm (1954) and modified by Hungund and Gupta (2010). The liquid medium contained 2.0% glucose (w/v), 0.5% yeast extract (w/v), 0.5% peptone, 0.27% Na_2HPO_4 (w/v), and 0.15% citric acid (v/v). To formulate desolid medium, 1.8% agar (w/v) was added. The pH was adjusted to 5.0. The medium was stored at 4°C in a refrigerator. The citrus peel media was prepared as follows: citrus peels were boiled in 1L of water for one hour. The mixture was filtered to remove insoluble material. In 1L of the prepared citrus juice, 0.5% yeast extract (w/v), 0.5% peptone, 0.27% Na_2HPO_4 (w/v), and 0.15% citric acid (v/v) were added. To formulate a desolid medium, 1.8% agar (w/v) was added. The pH was adjusted to 5.0. The process of growing the bacterial strain, forming the incubation and irradiation process was the same as for the HS media. The strain cultures were treated with gamma-ray. 0.2 and 0.5, kGy with singular and dual doses in parallel. The samples which underwent the irradiation treatment were then left to grow for 7 days and sub-cultured twice in fresh (HS) medium and /citrus media for 7 days each time to obtain the third generation, which re-irradiated with the corresponding radiation doses. The bacterial culture was incubated 28 ℃ for 10 days statically.

At the end of the incubation session, the BNC films were collected and washed twice in boiling distilled water, and twice in 0.1 M NaOH solution, 15 min each time, prior to applying distilled water many times until the neutral pH of the BNC hydrogels was restored. The neutral hydrogels were maintained in distilled water in 4 ℃ until further examination. The wet BNC were dried in the oven for 5 hours at 60°C.

2.2 Methods

For the final material analysis, a scanning electron microscope (SEM) (Jeol Ltd., Japan) was used at different magnifications with a voltage of 10 kV, along with dynamic mechanical analysis (DMA). The viscoelastic properties of bacterial cellulose were investigated using DMA Q800 (TA Instruments, ZDA). The tension mode of deformation was performed with the amplitude of 10 µm and at the frequency of 10 Hz of oscillation. Dynamic frequency sweep tests were carried out from 0 to 250 ◦C in temperature, with a 3 ◦C/min heating rate.

3. RESULTS WITH DISCUSSION

Scanning electron microscopy (SEM) analysis (Figures 1–3) revealed that gamma radiation influenced the formation of thinner nanofibers, with an average diameter below 100 nm, particularly in HS and orange media. This reduction in fibre diameter suggests a notable alteration in the nanostructure, likely due to the impact of gamma radiation on polymerization and cross-linking processes during BNC formation.

Additionally, all irradiated samples exhibited an increased presence of bacterial traces, implying that while gamma irradiation affects nanofiber formation, it does not eliminate bacterial contamination. This bacterial presence may result from incomplete sterilization or suggest that modifications to the BNC fibril surface properties after irradiation enhance bacterial adhesion. The combined effects of thinner fibers, increased porosity, and bacterial traces highlight the intricate relationship between radiation and microbial cellulose synthesis.

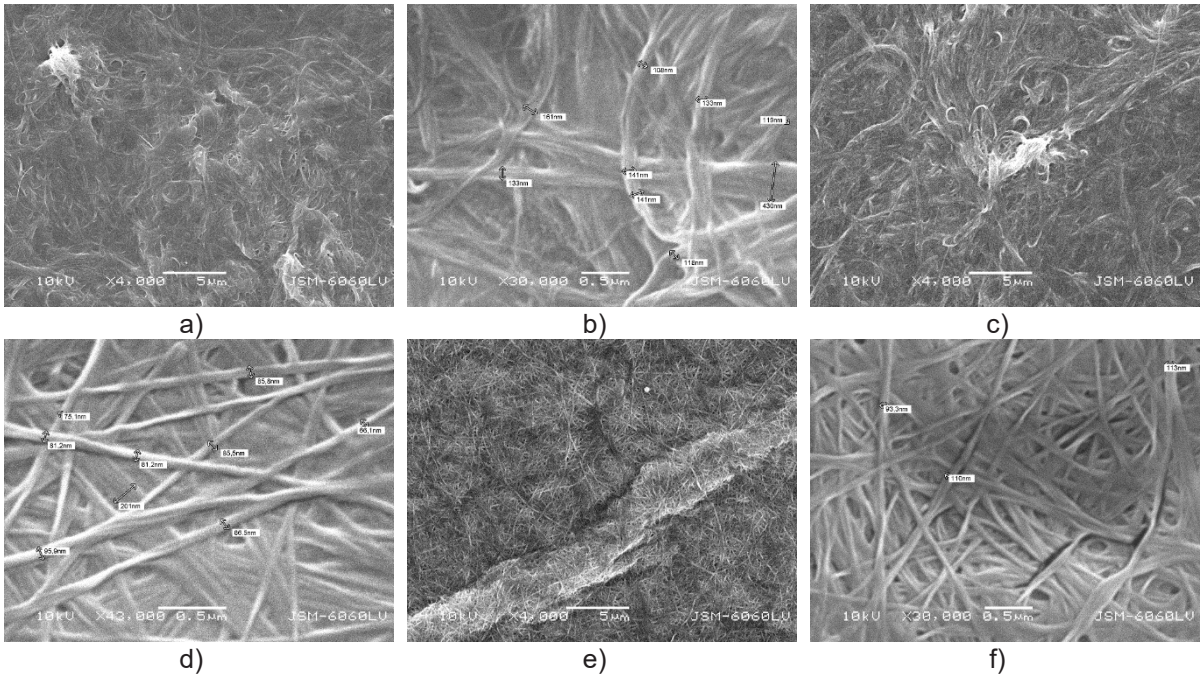


Figure 1: SEM of a) BNC – control, b) BNC – control – with added diameter values of nanofibers, c) BNC-2x200Gy, d) BNC-2x200Gy – with added diameter values of nanofibers, e) BNC - 2 x 500 Gy, f) BNC - 2 x 500 Gy – with added diameter values of nanofibers in HS media

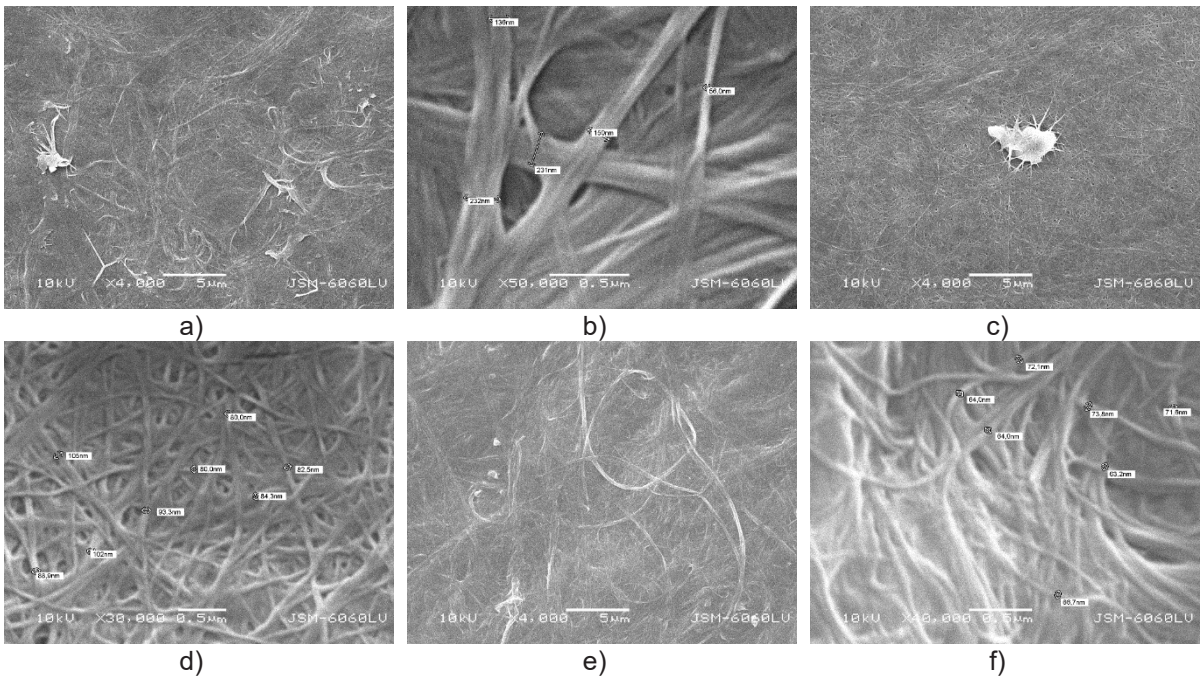


Figure 2: SEM of a) BNC – control, b) BNC – control – with added diameter values of nanofibers, c) BNC-2x200Gy, d) BNC-2x200Gy – with added diameter values of nanofibers, e) BNC - 2 x 500 Gy, f) BNC - 2 x 500 Gy – with added diameter values of nanofibers in orange media

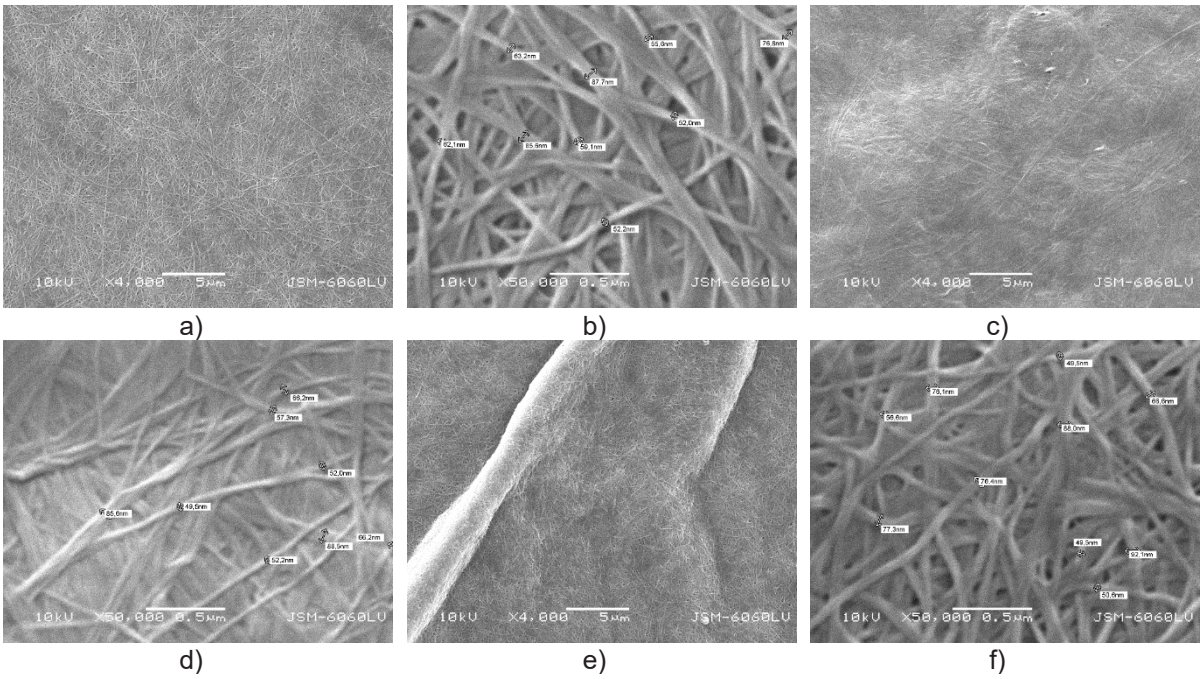


Figure 3: SEM of a) BNC – control, b) BNC – control – with added diameter values of nanofibers, c) BNC-2x200Gy, d) BNC-2x200Gy – with added diameter values of nanofibers, e) BNC - 2 x 500 Gy, f) BNC - 2 x 500 Gy – with added diameter values of nanofibers in tangerine media

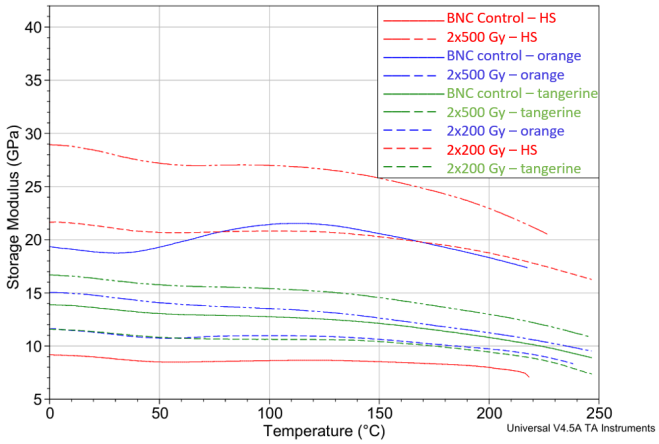


Figure 4: Dependence of storage modulus versus temperature for different media (HS, orange peel, tangerine peel) and irradiation conditions

Since the storage modulus represents the mechanical energy stored by the material during a loading cycle (Figure 4 and Table 1), the loss tangent (tan delta) (Figure 5) describes the material's damping characteristics and reflects the extent of chain mobility influenced by oscillatory loading and temperature. This parameter provides insight into the temperature range in which the material should not be subjected to significant mechanical loads. For most samples, this critical region falls between 20–80°C, where tan delta increases, reaches a peak, and then decreases. The subsequent rise in tan delta above 150°C is attributed to increased material viscosity due to thermal expansion. This behaviour defines how the material absorbs and dissipates energy. Irradiation doses affected the elastic modulus (Table 1). In all cases, samples exposed to double irradiation doses exhibited an increase in elastic modulus not only at ambient temperature (25°C) but also across the entire heating range compared to the control. Changes in the elastic behaviour (storage modulus) of the samples result from alterations

in crystallinity and fibre network entanglement. The increased stiffness of irradiated HS, orange, and tangerine samples can be attributed to higher crystallinity, where molecular chains are arranged in a more ordered lattice structure. Additionally, increased fibril connectivity within the bacterial cellulose (BC) network contributes to this stiffness. This enhanced connectivity arises from multiple interactions, including hydrogen bonding, electrostatic forces, hydrophobic interactions, van der Waals forces, and entanglement. The close packing and strengthened interactions restrict polymer chain mobility, thereby increasing BC toughness. The rigid BC fibrils provide greater resistance to applied forces, maintaining their structural integrity under mechanical stress. Some inconsistencies in the results require further investigation.

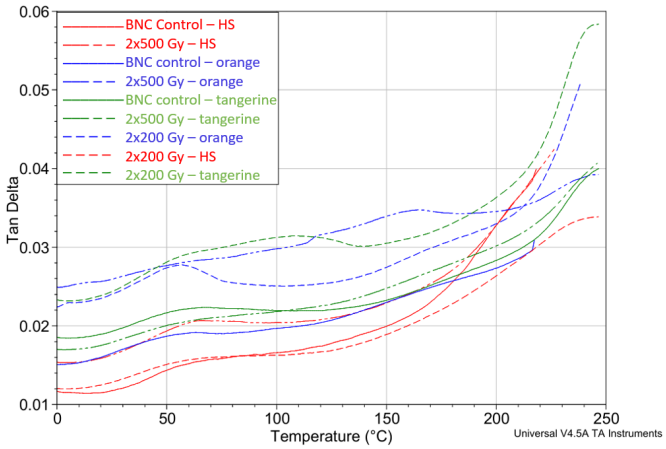


Figure 5: Dependence of tan delta versus temperature for different media (HS, orange peel, tangerine peel) and irradiation conditions

Table 1: The results of elastic modulus, E' at room temperature (23 °C)

Sample	Elastic modulus, E' [GPa]
BNC control – HS	8.92
2x200 Gy – HS	21.26
2x500 Gy – HS	28.31
BNC control – orange	18.81
2x200 Gy – orange	11.24
2x500 Gy – orange	14.72
BNC control– tangerine	13.56
2x200 Gy – tangerine	11.30
2x500 Gy – tangerine	16.29

4. CONCLUSIONS

Gamma irradiation significantly enhances the mechanical properties of BNC by increasing stiffness, fibril connectivity, and crystallinity, which improves toughness and reduces polymer chain mobility. These changes also reveal a temperature-sensitive region, suggesting that mechanical loading should be minimized in specific conditions, while persistent bacterial traces indicate that complete sterilization may not be achieved. The use of biowaste-based media offers a sustainable, cost-effective approach to BNC production, which could facilitate large-scale applications. The remarkable modifications induced by gamma irradiation improve BNC's suitability for diverse applications. Its enhanced properties make it ideal for biomedical engineering (e.g., wound dressings, tissue scaffolds, drug delivery systems), sustainable packaging, flexible electronics, and food packaging. Additionally, the environmentally friendly production process of BNC supports circular economy principles and improves its performance, offering a viable solution for large-scale, sustainable material production.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Al-Hagar, O.E.A. and Abol-Fotouh, D. 2022. A turning point in the bacterial nanocellulose production employing low doses of gamma radiation. Sci. Rep. 12: 7012.

Arif, Z.U., Khalid, M.Y. ,Sheikh, M. F., Zolfagharian, A., Bodaghi, M, 2022. Biopolymeric sustainable materials and their emerging applications. J. Environ. Chem. Eng. 10: 108159.

Hadidi, M., Aghababaei, F., Gonzalez-Serrano, D. J., Goksen, G., Trif, M., McClements, D. J., & Moreno, A. 2024. Plant-based proteins from agro-industrial waste and by-products: Towards a more circular economy. International Journal of Biological Macromolecules, 129576.

Hestrin S., Schramm M. 1954. Synthesis of cellulose by Acetobacter xylinum. Preparation of freeze-dried cells capable of polymerizing glucose to cellulose. Biochem. J. 58 345–352. 10.1042/bj0580345

Hungund B. S., Gupta S. G. (2010). Improved production of bacterial cellulose from Gluconacetobacter persimmonis GH-2. J. Microb. Biochem. Technol. 2 127–133.

Li, T.; Wang, L., Chen, Z., Li, C., Li, X. and Sun, D. 2020. Structural changes and enzymatic hydrolysis yield of rice bran fiber under electron beam irradiation, Food Bioprod. Process. 122: 62−71

Sharma, C., Dinda, A.K., and Mishra, N.C. 2013. Fabrication and characterization of natural origin chitosan-gelatin-alginate composite scaffold by foaming method without using surfactant, J. Appl. Polym. Sci. 127: 3228–3241.

Valenzuela, M., Ciudad, G., Cárdenas, J. P., Medina, C., Salas, A., Oñate, A., ... & Tuninetti, V. 2024. Towards the development of performance-efficient compressed earth blocks from industrial and agro-industrial by-products. Renewable and Sustainable Energy Reviews, 194, 114323.

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POSTER PRESENTATION

A GLOBAL ASSESSMENT OF COSMETIC PACKAGING TRENDS AND CONSUMER PREFERENCES

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Abstract: *This study explores the shift towards sustainable packaging in the cosmetics industry, focusing on the baby cosmetics sector. As the environmental impact of traditional packaging grows, the demand for eco-friendly solutions is rising. Analysing packaging claims from 2050 brands, including 76 specializing in baby cosmetics, the study identifies key trends. While sustainability efforts are promising, a lack of transparency raises concerns about actual environmental benefits, emphasizing the need for clear labelling and stronger regulations. Consumer preferences play a crucial role, as awareness of environmental issues grows. However, knowledge gaps persist regarding the true sustainability of materials, types of packaging, highlighting the need for brands to educate consumers and provide transparent information. The research highlights the importance of industry-wide collaboration among companies, regulators, and consumers to establish sustainable practices as the norm. Ultimately, it calls for transparency, innovation, and responsibility, urging the cosmetics industry to prioritize sustainability, minimize environmental impact, and align with consumer expectations for a more eco-conscious future.*

Keywords: *Consumer preferences, packaging solutions, sustainable statements, industry collaboration, consumer education.*

1. INTRODUCTION

In the cosmetics industry, there is a clear shift towards sustainable packaging solutions, driven by increasing environmental concerns and growing consumer demand for environmentally friendly products (Le Pera et. al, 2023; Patel, 2023). This movement is particularly pronounced in the area of baby cosmetics, where parents are increasingly focussing on products that ensure the safety of their children and have as little impact on the environment as possible. Recent analyses show that many of baby cosmetics brands have introduced recyclable, refillable or bio-based packaging alternatives, reflecting a commendable commitment to environmental protection (Vrabič Brodnjak & Jestratijević, 2023). However, transparency remains a critical issue, namely many of brands not disclosing their packaging materials, highlighting the need for clearer labelling and stricter regulations. As environmental awareness increases, many new generation parents are favouring brands that use biodegradable materials or are committed to eco-friendly practises (Savale et. al., 2023; Rosi et al., 2024). This trend emphasises the importance of sustainable packaging in meeting consumer expectations and promoting environmental awareness in the baby cosmetics industry. The global biodegradable packaging market is expected to grow at a CAGR of 15.3% from 2023 to 2028, driven by rising demand in the cosmetics industry and other factors (Golden et. al., 2024). This growth is indicative of a broader industry trend towards sustainability, with companies exploring innovative materials and designs to reduce their environmental footprint. Despite this progress, there are still challenges. A significant number of brands lack transparency around their packaging materials, leading to consumer scepticism about the actual environmental benefits of supposedly sustainable products. This opacity underlines the urgent need for standardised labelling and a legal framework to ensure that sustainability claims are both accurate and verifiable. At the same time, consumer preferences are increasingly influencing market dynamics (Reddy et. al., 2023). As awareness of environmental issues grows, parents are more inclined to choose brands that demonstrate a genuine commitment to sustainability. However, there are still gaps in knowledge regarding the actual sustainability of different materials, which emphasises the need for brands to educate consumers and provide transparent information. Case studies within the industry showcase successful sustainable packaging initiatives that demonstrate the feasibility and benefits of such practises for brand reputation and consumer trust (Tjalsma,

2024). These examples serve as valuable role models for other companies looking to implement environmentally friendly solutions. The study emphasises the importance of industry-wide collaboration between companies, regulators and consumers to establish sustainable practises as the norm. Ultimately, it calls for transparency, innovation and responsibility and urges the cosmetics industry to prioritise sustainability, minimise environmental impact and adapt to consumer expectations for an environmentally conscious future.

2. EXPERIMENTAL

This systematic review examined international baby cosmetic brands promoting sustainable packaging. Using data mining, only primary sources (official websites, sustainability reports) were included, while secondary sources (social media, press articles) were excluded. From an initial 2048, only 79 were registered as a baby cosmetic brand, three were removed due to non-English websites or irrelevant sources, resulting in a final sample of 76 brands covering shampoos, lotions, and creams across Europe, America, Australia, and Asia. Thematic content clustering guided data analysis through five research stages: (1) search planning, (2) execution, (3) screening, (4) analysis, and (5) synthesis. To minimize researcher bias, a structured research protocol was established, outlining the study's purpose, objectives, and methodology. Data collection was automated using a Python 3.6 web scraper. In the second stage, the web scraper accessed the internet via Hypertext Transfer Protocol (HTTP), identifying 79 baby cosmetic brands promoting sustainable packaging. The third stage involved manual verification and screening of websites to ensure data quality. Only primary sources were included, and non-eligible websites were excluded, resulting in a final sample of 76 brands. In the fourth stage, thematic content clustering was applied as a qualitative analytical method. Two researchers conducted thematic coding, resolving discrepancies through discussion. Finally, the findings were synthesized and reported, providing insights into sustainable packaging trends within the baby cosmetics industry.

3. RESULTS WITH DISCUSSION

The dilemma with cosmetics packaging lies in the balance between sustainability, functionality and aesthetics. While eco-friendly materials such as biodegradable plastics, refillable containers and glass packaging offer environmental benefits, they often come with higher costs, shelf-life concerns, and limited availability. Many brands advertise with "green" claims to attract conscious consumers, but a lack of transparency and clear regulations raises concerns about greenwashing. In addition, consumers are looking for sustainable options but may favour convenience and affordability. This tension emphasises the need for innovation, stricter regulations and consumer education to ensure that sustainability in cosmetic packaging is both effective and truly beneficial for the environment and human health. An analysis of the types of packaging used by cosmetics brands revealed notable trends in both material choice and packaging design. To better understand these trends, the research categorized cosmetic products according to FDA regulations (US Food and Drug Administration) as outlined in Table 1 (Vrabič Brodnjak, Jestratijević, 2024).

Table 1: Categories of cosmetic products based on the FDA.

Categories	Cosmetic products
1.	Baby Products
2.	Bath Preparations
3.	Eye Makeup Preparations
4.	Fragrance Preparations
5.	Hair Preparations (non-colouring)
6	Hair Colouring Preparations
7.	Makeup Preparations (not eye)
8.	Manicuring Preparations
9.	Oral Hygiene Products
10.	Personal Cleanliness
11.	Shaving Preparations
12.	Skin Care Preparations
13.	Suntan Preparations

Baby cosmetic products were divided into three main categories: Baby shampoos, lotions/oils/powders/creams and other baby care products. Baby shampoos are specially formulated for baby's delicate skin and hair and often do not contain harsh chemicals that could cause irritation or dryness. Many baby shampoos are also tear-free to avoid discomfort if the product accidentally gets into the baby's eyes. Lotions, oils, powders and creams are designed to moisturise and protect your baby's skin. These products help to soothe dry skin, prevent diaper rash and provide relief from various skin conditions. Like the baby shampoos, they are gentle and safe for baby's sensitive skin. Other baby products include a wide range of products that do not fall into the first two categories, such as baby lip balm for chapped lips, baby toothpaste that must not be swallowed, and wet wipes for diaper changes or cleaning baby's face and hands. These products are designed to be gentle and non-irritating to baby's skin. Results of categories that brands are using is presented in Figure 1.

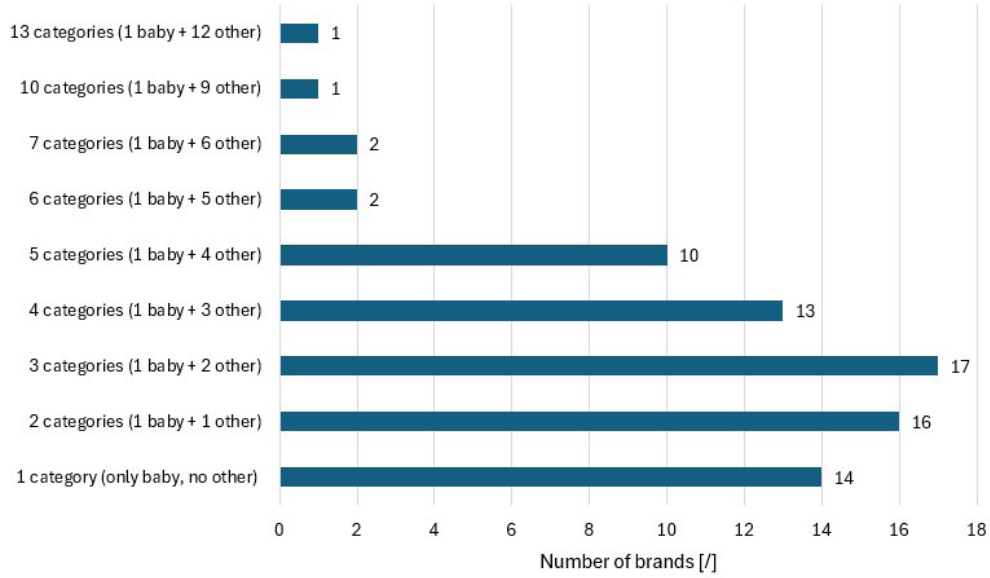


Figure 1: Number of brands and cosmetic categories based on FDA.

Seventeen of the brands analysed belong to 3 cosmetics categories, including the baby cosmetics category. There are only 6 brands that include 6 or more categories of different cosmetic products but also offer baby cosmetics. Worldwide, only 14 cosmetics brands have only 1 cosmetics category, and that is baby cosmetics.

Sustainable packaging solutions, such as the use of biodegradable or compostable materials, recycled materials and designs that minimise the use of materials, energy and resources, are increasingly favoured in the industry. Other sustainable practises include the use of renewable energy in production and efforts to reduce emissions through improved supply chain and logistics management.

The most common packaging type was the tube, used by 68 brands (28.33%), especially for products such as toothpaste, sunscreen and facial cleanser, as it is lightweight and user-friendly. Containers, commonly used for creams and lotions, were the second most common packaging type, used by 62 brands (25.83%). Boxes, typically used as secondary packaging, ranked third with 50 brands (20.83%), followed by bottles, commonly used for shampoos, conditioners and body washes, used by 48 brands (20%). Pouches were used by 11 brands (4.58%) and envelopes by only 1 brand (0.42%). In addition, 2 brands (0.83%) did not define their packaging type.

Of the 76 brands analysed, 30 brands (39%) did not specify the materials used in their packaging, while 46 brands (61%) reported using recyclable or bio-based packaging materials (Figure 2). This reflects an increasing trend towards sustainability in the cosmetics industry. However, the high proportion of brands that do not provide information on their packaging materials shows a lack of transparency.

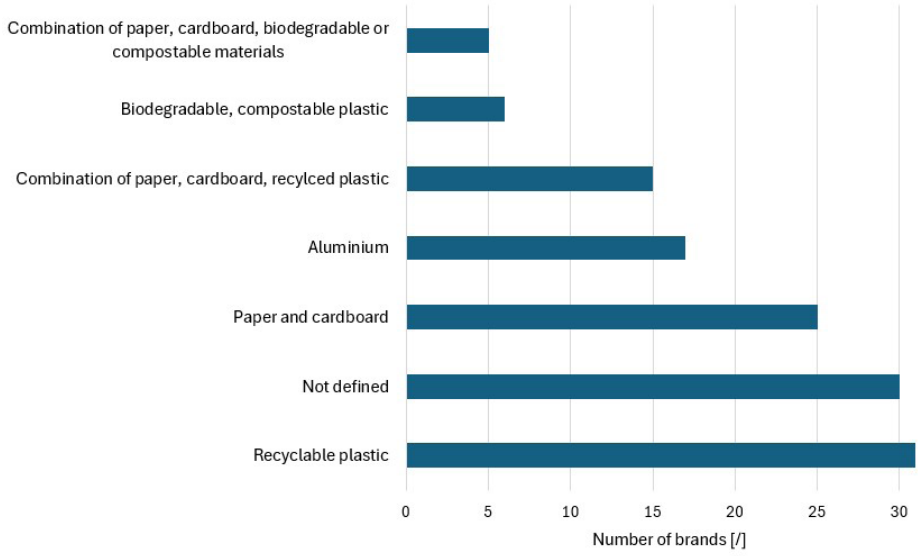


Figure 2: Number of brands and specified materials in their packaging solutions.

The high percentage of brands with undefined packaging materials raises concerns about accountability and highlights the need for better regulation and standardisation within the industry. These findings suggest that while there is a clear movement towards more sustainable packaging options, cosmetics companies need to make greater efforts to fully adopt these practises and provide transparent information to consumers. Such measures are crucial to move the industry towards more sustainable and environmentally friendly packaging solutions. In addition to the packaging types, the study analysed the materials used, identifying both sustainable and non-sustainable options. Among the brands analysed, recyclable plastic proved to be the most commonly used material, used by 31 brands. Despite its recyclability, issues such as contamination and inadequate recycling infrastructure can compromise the environmental benefits of this material. Paper and cardboard, known for their renewability and biodegradability, were the most important materials for 25 brands, signalling a positive shift towards sustainability. Aluminium, a durable but energy-intensive material, was used by 17 brands. Biodegradable and compostable plastics, which are considered environmentally friendly alternatives, were used by 6 brands, signalling a growing

interest in sustainable innovation. A combination of materials, including paper, cardboard and recycled plastic, was used by 15 brands, while a further 5 brands combined paper, cardboard and biodegradable or compostable materials, further increasing their sustainability efforts. However, a worrying trend was observed as 30 brands did not define their primary packaging material, raising questions of transparency around sustainability claims. The results show that the cosmetics industry is taking different approaches to sustainable packaging. Whilst many brands have introduced recyclable, biodegradable or renewable materials, the lack of transparency and continued use of unsustainable materials remains a challenge. Promoting clear labelling and informed consumer choices will be key to making further progress in sustainable packaging practises.

3.1 Consumer perception of packaging in the cosmetics industry

In terms of consumer preferences, there is a clear global shift towards sustainable packaging, with an increasing number of consumers prioritizing eco-friendly options. However, consumer perceptions are often influenced by convenience and cost, which can sometimes lead to a preference for non-sustainable options despite an expressed desire for more environmentally responsible choices. This tension between sustainability and convenience highlights the need for brands to find a balance that meets both consumer demands and environmental goals.

A significant challenge identified in the assessment is the lack of transparency in packaging materials and sustainability claims. Consumers are often confused about the environmental benefits of different materials, such as recyclable plastics and biodegradable options. This confusion is exacerbated by the prevalence of greenwashing, where brands make unsubstantiated sustainability claims to attract eco-conscious consumers. Clear labelling, material transparency, and sustainability certifications are essential to building trust and enabling consumers to make informed choices. Notably, in the baby cosmetics sector, consumer preferences are even more pronounced, with parents prioritizing safety and sustainability. The desire for non-toxic packaging materials, such as BPA- and phthalate-free plastics, is central to purchasing decisions. In this segment, packaging that is hygienic, convenient, and easy to use is critical, and there is a growing demand for refillable or reusable packaging options. Favourite packaging types, such as tubes and containers, meet consumer expectations in terms of ease of use and convenience.

The choice of material also plays a crucial role in consumer perception. While recyclable plastics are used by many brands, they often cause confusion among consumers who do not fully understand the limitations of recycling due to contamination or lack of infrastructure. Paper and cardboard packaging, on the other hand, is generally well received as it is considered environmentally friendly and biodegradable. Although aluminium is durable, it raises concerns due to the high energy consumption during production. Biodegradable and compostable plastics are gaining traction with environmentally conscious consumers, but limited awareness of their actual degradation process remains a challenge. Consumers are also strongly influenced by the transparency of packaging. When brands fail to disclose their primary packaging materials, this can lead to scepticism and a lack of trust in sustainability claims. Clear labelling, sustainability certifications and material composition claims are crucial to boost consumer confidence. In addition, aesthetics and a high-quality packaging experience are still important, as many consumers associate high-quality packaging with product effectiveness and luxury. In the area of baby cosmetics, the perception of packaging is even more sensitive, as parents prioritise safety, sustainability and the protection of ingredients. Parents expect baby cosmetics packaging to be free from harmful chemicals such as BPA and phthalates to ensure that the materials do not leach into the skincare products. Tubes and pump bottles are among the preferred packaging types for baby shampoos, lotions and creams as they are hygienic and easy to handle. The issue of sustainability is particularly important in this sector, as parents are more likely to opt for brands that prioritise environmentally friendly packaging (Vrabič Brodnjak & Jestratijević, 2024). Paper and cardboard packaging are perceived as safer alternatives for outer packaging, while biodegradable plastics are seen as a responsible innovation. However, similar to cosmetics in general, consumers still lack knowledge about the actual environmental benefits of the different materials. The functionality of the packaging also plays an important role in the purchasing decision. Parents prefer leak-proof, easy-to-use designs that can be operated with one hand during baby care. Brands that offer refillable or reusable packaging solutions are also gaining traction as they cater to growing environmental awareness and offer consumers long-term cost savings. For both general and baby cosmetics, consumer perception is a complex interplay of sustainability, safety, convenience and brand trust.

To improve the perception and acceptance of sustainable packaging, brands need to focus on clear communication, education and innovative design solutions that meet consumer expectations. Given the complexity of balancing sustainability with functionality and aesthetics, it is essential for brands to work together, share best practices, and align on standards that promote environmental responsibility. Collaboration between companies can lead to innovative solutions that address the challenges of cost, material availability, and waste reduction. Regulators play a crucial role in setting clear and enforceable standards that prevent greenwashing, ensuring that sustainability claims are transparent and reliable. At the same time, consumer education is key to fostering informed decision-making and driving demand for genuinely sustainable packaging options. By working together, these stakeholders can create a unified approach that accelerates the adoption of sustainable packaging practices and drives the cosmetics industry toward a more environmentally responsible future.

4. CONCLUSIONS

The cosmetics industry's pursuit of sustainable packaging has seen significant progress but still faces challenges. Many brands have adopted eco-friendly materials like recyclable plastics, biodegradable alternatives, and paper-based packaging, but continued reliance on unsustainable materials and lack of transparency hinder further progress. Consumer demand for sustainable packaging is growing, but perceptions are influenced by convenience, material transparency, and environmental impact, with many consumers unaware of the actual benefits and limitations of materials. Clear communication and education on sustainable practices are essential. In the baby cosmetics sector, safety, sustainability, and functionality are especially important, with parents preferring non-toxic, easy-to-use, and hygienic packaging, with a growing interest in refillable or reusable options. A global assessment of packaging trends shows increasing use of sustainable materials but highlights low consumer awareness of the environmental impact. Greenwashing adds to consumer confusion, underscoring the need for transparency and industry-wide collaboration. Clear labelling, sustainability certifications, and education will boost consumer confidence and enable informed purchasing decisions. For the cosmetics industry to meet the demand for sustainable packaging and contribute to environmental sustainability, brands, regulators, and consumers must collaborate effectively. Integrating clear labelling, consumer education, and innovative design will be key to driving meaningful change. Aligning sustainability with consumer expectations and ensuring transparency will help the industry make significant strides towards a responsible future.

5. REFERENCES

Golden, J. S., Handfield, R. B., Daystar, J., & Pires, S. 2024. An Economic Impact Analysis of the US Biobased Products Industry: 2023 Update.

Le Pera, A., Sellaro, M., Grande, G., Bencivenni, E., & Migliori, M. 2023. "Effect of quality of separately collected glass, paper plus cardboard and lightweight packaging waste on environmental, energetic and economic sustainability of the material recovery facility operations". *Journal of Cleaner Production*, 425, 138973.

Patel, K. R. 2023. "Harmonizing sustainability, functionality, and cost: navigating responsible packaging innovations in modern supply chains". *American Journal of Economic and Management Business* (AJEMB), 2(8), 287-300.

Reddy, K. P., Chandu, V., Srilakshmi, S., Thagaram, E., Sahyaja, C., & Osei, B. 2023. "Consumers perception on green marketing towards eco-friendly fast moving consumer goods". *International Journal of Engineering Business Management*, 15, 18479790231170962.

Rossi, M., Cappelletti, F., Manuguerra, L., Mundo, M., & Germani, M. 2024. "Ecodesign Strategies for Packaging: a Simplified Approach to Evaluate Environmental Benefits". *Procedia* CIRP, 122, 330-335.

Savale, T. K., Byram Anand, P., Perumalla Varalaxmi, A. B., & Quaye, J. A. 2023. Green Marketing Strategies: Assessing Consumer Perception and Adoption of Eco-friendly Products. *Remittances Review*, 8(4).

Tjalsma, D. 2024. The Supermarket of the Future: A Case Study on the Transition towards Sustainable Packaging (Master's thesis, University of Twente).

Vrabič-Brodnjak, U., & Jestratijević, I. 2024. The future of baby cosmetics packaging and sustainable development: A look at sustainable materials and packaging innovations–A systematic review. *Sustainable Development*, 32, 2208–2222.

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POSTER PRESENTATION

PACKAGING PAPERS' ANTIMICROBIAL PROPERTIES THROUGH NATIVE CHEMICAL ADDITIVES TREATMENT OR COATING

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Abstract: *Study evaluates the antimicrobial properties of packaging paper treated with lavender essential oil, silver nanoparticles (AgNPs) and chitosan coatings. These additives are known for their antimicrobial efficacy due to their physicochemical properties. A cellulose mixture (80:20 bleached softwood and hardwood) was used, with the base paper prepared by adding wet-end chemicals. Antimicrobial activity was tested against nine microorganisms, including Gram-positive and Gram-negative bacteria, yeasts and fungi. The results showed that paper treated with lavender oil exhibited decreasing antimicrobial activity, with efficacy ranging from 42.9% to 67.2%. AgNP-treated paper (3 mL/20 cm²) demonstrated the highest antibacterial protection (81.6% for S. aureus, 75.8% for E. coli), with lower efficacy at lower concentrations. Chitosan-coated paper (2 g/m²) provided the most consistent protection (79% on average) for all microorganisms tested. Gram-positive bacteria, yeasts and fungi were more sensitive to chitosan. The results emphasize the potential of these treatments for antimicrobial packaging applications.*

Keywords: *Lavender oil; silver nanoparticles; chitosan; packaging paper; antibacterial.*

1. INTRODUCTION

The rising concerns about food safety, shelf-life extension, and environmental sustainability have led to increased interest in antimicrobial packaging materials. Foodborne pathogens and spoilage microorganisms pose significant challenges to the food industry, leading to contamination, foodborne illnesses, and economic losses (De Matteis, 2023). Traditional packaging materials primarily act as passive barriers, offering no antimicrobial functionality. To address these challenges, active packaging technologies have been developed to enhance the protective functions of packaging materials by incorporating antimicrobial agents that inhibit microbial growth directly on the surface of packaged products. Among various antimicrobial agents, natural additives and nanomaterials have gained significant attention due to their potential to replace synthetic preservatives, which are often associated with health risks and regulatory restrictions. Essential oils (EOs), silver nanoparticles (AgNPs), and polysaccharide-based coatings, such as chitosan, have emerged as promising antimicrobial agents due to their biocompatibility, biodegradability, and broad-spectrum antimicrobial activity. These compounds can be incorporated into packaging materials as coatings, embedded into films, or applied as surface treatments to enhance their antimicrobial effectiveness. Lavender (*Lavandula angustifolia Mill.*) essential oil has been widely studied for its antimicrobial properties, primarily due to its high content of bioactive compounds such as linalool and linalyl acetate (Kuorwel, 2011; Predoi, 2018). These compounds exhibit strong antibacterial and antifungal activities by disrupting microbial cell membranes and inhibiting enzymatic functions. Similarly, AgNPs have been extensively used for their antimicrobial efficiency, attributed to their ability to release silver ions, which interact with microbial cell walls, disrupt metabolic pathways, and ultimately lead to cell death (Kumar, 2021). Chitosan, a naturally occurring biopolymer derived from chitin, has been recognized for its antimicrobial and film-forming properties. Due to its cationic nature, chitosan interacts with negatively charged microbial membranes, causing membrane destabilization, leakage of intracellular contents, and microbial inactivation (Zhang, 2023).

While the antimicrobial potential of these agents has been extensively studied in various applications, their direct integration into paper-based packaging materials remains underexplored. Paper packaging is widely used in the food industry due to its renewability, biodegradability, and recyclability. However, its porous structure makes it

susceptible to microbial contamination, necessitating the development of antimicrobial modifications to enhance its functionality. In this study, we investigate the antimicrobial performance of packaging paper treated with lavender essential oil, AgNPs, and chitosan coatings. The antimicrobial efficacy of these treatments was evaluated against nine microbial strains, including Gram-positive and Gram-negative bacteria, yeasts, and fungal species, to determine their potential application in active packaging systems.

The findings from this study contribute to the growing body of knowledge on antimicrobial packaging materials and provide valuable insights into the practical application of natural and nanomaterial-based antimicrobial agents in paper-based packaging. By comparing the effectiveness of these treatments, we aim to identify the most suitable antimicrobial approach for improving the safety and shelf life of packaged products while maintaining the sustainability of paper-based packaging solutions.

2. EXPERIMENTAL

2.1 Materials and Preparation Procedures

For paper samples preparation, in ratio 80:20, a cellulose mixture from two kraft bleached wood-free pulps was used. Both, softwood cellulose - SCA, Sweden and hardwood cellulose - Svilosa AD, Bulgaria were separately refined using laboratory Valley beater, according to ISO 5264-1:1979. The average beating degree of the pulp mixture obtained was 30 °SR (Schopper Riegler value), in accordance with ISO 5267-1:1999/Cor 1:2001. For the base paper samples obtaining, two wet-end chemical additives were added sequentially: alkylketendimer sizing agent - 1% of o.d.f (Kemira® Fennosize KD 157YC) and cationic retention additive - 0.025% of o.d.f. (cationic modified polyacrylamide with 11.106 g/mol molecular weight and +1.05 charge density delivered by Ciba® Percol® Co. Rapid-Köthen laboratory paper-sheet machine (Birkenau, Germany) was used for the laboratory papermaking process. With base weight of 50 g/m^2 and in according to ISO 5269-2:2004 samples were prepared and dried under 90 kPa pressure at 95 °C temperature with duration of 7 min.

The experimental investigations were conducted with nine paper samples, described in Table 1.

Table 1: Composition of investigated paper samples.

Paper samples	Description	CSAgNPs Treatment (mL/20 cm^2)	Lavender treatment (mg/cm^2)	Chitosan coating (g/m^2)
OP	Mixture of only pulp	-	-	-
BP (control)	Base paper	-	-	-
BP/CSAgNPs 1	Base paper treated with silver water	1	-	-
BP/CSAgNPs 2		2	-	-
BP/CSAgNPs 3		3	-	-
BP/LEO	Base paper treated with lavender essential oil	-	0.8	-
BP/Ch 0.5	Base paper coated with chitosan	-	-	0.5
BP/Ch 1		-	-	1
BP/Ch 2		-	-	2

By sparing onto the obtained 20 cm^2 base paper samples silver nanoparticles treatment with 1-, 2- and 3-mL consumption of Arcol® colloidal silver solution containing silver nanoparticles suspended in a liquid base (CSAgNPs), delivered from Gal ET was applied from 20 cm distance and is having concentration of 10 mg/L = 0.00001 g/L.

Using a sprayer on both sides of pre-weighed paper squares of 5x5 cm the lavender essential oil (LEO) was applied and let dry at room temperature (25°C) for 30 minutes. The dried paper samples were weighed again and the amount of essential oil was calculated. Results indicated that the average amount of lavender EO was 0.8 mg/cm^2. The relative density () of the used LEO is 0.8862 ± 0.05, its refractive index () is 1.4626±0,02, polarization

coefficient (α) is -8±0,02 and acid number, (mg KOH/g oil) 0,9±0,04. Thirty-five ingredients were identified in the used LEO, representing 99.69% of the total amount of substances. Ten of them are in concentrations above 1%, and the remaining twenty-five ingredients are in concentrations below 1%. In an amount above 4% are six compounds: linalyl acetate (36.05%), β-linalool (27.67%), terpinene-4-ol (6.13%), β-cis-ocimene (5.52%), lavandulyl acetate (4.87%), β-car-yophyllene (4.68%). According to ISO 3515 /2017, β-trans-ocimene (1.79%) is below the lower limit (2.0–5.0%) and terpinene-4-ol (6.13%) is above the upper limit (2.0–5.0%). The main components in lavender oil are linalool and linalyl acetate, and their total amount is 63.72% (Todorova, 2023).

Fluka® 28191 (BioChemika, Japan) crayfish chitosan (2-Amino-2-deoxy-(1->4)-β-D-glucopyranan) with medium viscosity and acetic acid - 99.8% with M = 60.05 g/mol was used for the base paper coating. At constant stirring at 300 rev/min for 24 h on a magnetic stirrer and heating to 50 °C in the first 2 h, 1 g of chitosan (Ch) was dissolved in 1% (v/v) aqueous acetic acid (100 mL) to complete dissolving. The obtained chitosan solution was with viscosity of 300 $mPas^{-1}$. Laboratory coating machine K Control Coater (RK PrintCoat, UK) was used for the paper samples' coating process, done at ambient temperature. Stainless steel wet film deposit K-bar 120 μm with wire diameter 1.52 mm was used. The drying of the coated samples was done in a vacuum dryer with P = 0.08 MPa at t = 50 °C till its complete drying. The resulting chitosan coating layers were, respectively 0.5 g/m^2, 1 g/m^2 and 2 g/m^2.

2.2 Antimicrobial Testing

The antimicrobial testing was performed with nine microorganisms – two Gram-positive bacteria (*Staphylococcus aureus* ATCC 6538; *Bacillus cereus* ATCC 10876), three Gram-negative bacteria (*Escherichia coli* ATCC 8739; *Pseudomonas aeruginosa* ATCC 9027; *Salmonella abony* NTCC 6017), two yeast (*Candida albicans* ATCC 10231; *Saccharomyces cerevisiae* ATCC 2601) and two fungal strains (*Aspergillus brasiliensis* ATCC 16404; *Fusarium moniliforme*). For bacteria growth, samples were cultured in an incubation chamber at 30-35 °C for 24-48 h and at 20-25 °C for 48-72 h for yeast and 120 h for fungal. From each bacterial test microorganism a 24 h culture was prepared. Vegetative material was taken using a wire loop and suspended in 10 mL of saline (0.9% sodium chloride solution (0.154 mol/L). The cell concentration of the suspensions prepared were of about 103 CFU/mL. Analogously, the yeast and mould suspensions, with 48 h cultivation time for yeast and 120 h for mould, respectively. In aseptic conditions with sterile tweezers, each paper sample was placed in a petri dish. On each square with sterile pipette 0.1 mL of the prepared cell suspensions was dropped and carefully spread over the surface, then placed in an incubation chamber for 2 h at 30-35 °C. Aseptically with a sterile pipette, in every petri dish were dropped 20 mL of soybean casein agar for bacteria or Sabouraud-dextrose agar for yeast and moulds. For bacteria growth, samples were cultured in an incubation chamber at 30-35 °C for 24-48 h and at 20-25 °C for 48-72 h for yeast and 120 h for mould. The colonies grown in the petri dishes were counted by a colony counter. The effect on the growth of test microorganisms was evaluated by the antimicrobial efficiency the antimicrobial efficiency calculated by the Equation 1:

$$\%Efficiency = \frac{N_0 - N_1}{N_0} \times 100 \quad , (1)$$

Where N_0 was the number of the colony-forming units in the control sample, while N_1 – in the treated and coated samples.

One-way ANOVA with a confidence level of 95% ($p<0.05$) statistical analysis was carried out using Microsoft® Excel 2016 with ToolPak data analysis.

3. RESULTS WITH DISCUSSION

The applicability in the forms of treatments, films or coatings of native chemical additive such as essential oils, silver nanoparticles (AgNPs) or polysaccharides such as chitosan have attracted great interest in the field of antimicrobial packaging due to their unique physicochemical properties, especially their high surface-to-volume ratio, which enhances their interaction with microbial cells (De Matteis, 2023). Lavender (Lavandula angustifolia Mill.) is a popular raw material for widely used aromatic products. Its' essential oil has a high content of linalyl acetate and linalool characterizing its' antimicrobial efficiency (Kuorwel, 2011; Predoi, 2018). The antimicrobial mechanism of AgNPs primarily involves the release of silver ions, which can penetrate microbial cell membranes, disrupt cell function and ultimately lead to cell death (Kumar, 2021). Chitosan's unique properties arise from its cationic nature, which allows it to interact with negatively charged microbial cell membranes, leading to the destruction of the cell wall and the death of the microbes (Zhang, 2023). The inhibition efficiency of the CSAgNPs and LEO treated paper samples against Gram-positive and Gram-negative bacteria, yeast and fungal strain are presented in Table 2, while the chitosan coating efficiency in Table 3.

Table 2: Inhibition efficiency of the CSAgNPs and LEO treated paper samples against Gram-positive and Gram-negative bacteria, yeast and fungal strain.

Sample	Tested microorganisms		Inhibition efficiency of CSAgNPs and LEO treatments (%)			
			BP/ CSAgNPs 1	BP/ CSAgNPs 2	BP/ CSAgNPs 3	BP/LEO
A	Gram-positive bacteria	*Staphylococcus aureus* ATCC 6538	47.5	67.3	81.6	62.9
B		*Bacillus cereus* ATCC 10876	11.7	31.5	40.4	51.3
C	Gram-negative bacteria	*Escherichia coli* ATCC 8739	46.8	66.0	75.8	67.2
D		*Pseudomonas aeruginosa* ATCC 9027	16.3	20.4	38.8	54.8
E		*Salmonella abony* NTCC 6017	27.7	35.7	45.6	42.9
F	Yeast	*Candida albicans* ATCC 10231	18.6	34.4	37.1	53.1
G		*Saccharomyces cerevisiae* ATCC 2601	33.4	41.1	51.2	56.6
H	Fungal strain	*Aspergillus brasiliensis* ATCC 16404	15.1	28.3	35.5	44.3
I		*Fusarium moniliforme*	27.1	33.8	36.9	49.2

3 mL/20cm^2 CSAgNPs treated paper samples (BP/CSAgNPs 3) inhibited the growth of the Gram-positive bacterium *S. aureus* with 81.6% and the Gram-negative bacterium *E. coli* with 75.8%. The inhibition efficiency is weaker compared to Gram-negative *S. abony* (45.6%) bacterium and the yeast *S. cerevisiae* (51.2%). This type of paper has around and below 40% antimicrobial activity against Gram-positive bacterium *B. cereus* (40.4%), *P. aeruginosa* (38.8%), yeast *C. albicans* (37.1%), fungal strain *A. brasiliensis* (35.5%) and *F. moniliforme* (36.9%). Less effective is the treatment of the paper with 1 and 2 mL/20cm^2 of CSAgNPs - 27.13 and 39.83%, respectively. The CSAgNPs treatment is most efficient for the Gram-positive bacteria (with about 106%), followed by the Gram-negative with an efficiency of about 77% and 74.8% for the fungal strains and yeast from 70%. The order of the group's effectiveness is confirmed while comparing the microorganisms group, except for the yeast and fungal strain, with exchanged positions.

The inhibition efficiency of the LEO treated paper is in the range of 62.9% and 51.3% against Gram-positive bacteria *S. aureus* and *B. cereus*. Against Gram-negative bacteria it is in the range of 67.2% for *E. coli*, 54.8% at *P. aeruginosa* and 42.9% for *S. ebony*. Against yeasts and molds LEO has an effectiveness reaching 53.1% for *C. albicans* and 56.6% for *S. cerevisiae* to 44.3% against *A. brasiliensis* and *F. moniliforme* of 49.2%.

Most effective inhibition efficiency against the tested bacteria, yeasts, and fungal strains from the chitosan coated samples was calculated for the 2 g/m^2 (BP/Ch 2) paper samples with an average of 79%. At BP/Ch 1 and BP/Ch 0.5 the effectiveness was 72.38% and 54.67%, respectively. Coating layer of 2 g/m^2 inhibit the Gram-positive bacteria *S. aureus* and *B. cereus* and the Gram-negative bacterium *E. coli*, the yeasts *C. albicans* and *S. cerevisiae*,

and the fungal strains *A. brasiliensis* and *F. moniliforme* by 80–90%. It has a weaker effectiveness against the Gram-negative bacteria *P. aeruginosa* (56.3%) and *S. ebony* (48.6%). The efficiency of the 1 g/m^2 coating is lower against the Gram-negative bacteria *P. aeruginosa* (54.8%) and *S. ebony* (47.4%), but is found to be about 80% effective against the Gram-positive bacteria *S. aureus*, *B. cereus*, the Gram-negative bacterium *E. coli*, the yeasts *C. albicans*, *S. cerevisiae* and the fungal strain *A. brasiliensis* and *F. moniliforme*. As lower the chitosan coating is applied (BP/Ch 0.5), the lowest inhibition efficiency is observed.

Table 3: Inhibition efficiency of the chitosan coated paper samples against Gram-positive and Gram-negative bacteria, yeast and fungal strain.

Sample	Tested microorganisms		Inhibition efficiency of chitosan coating (%)		
			BP/Ch 0.5	BP/Ch 1	BP/Ch 2
A	Gram-positive bacteria	*Staphylococcus aureus* ATCC 6538	76.4	78.5	86.5
B		*Bacillus cereus* ATCC 10876	31.2	79.5	88.2
C	Gram-negative bacteria	*Escherichia coli* ATCC 8739	51.8	73.7	89.5
D		*Pseudomonas aeruginosa* ATCC 9027	32.3	54.8	56.3
E		*Salmonella abony* NTCC 6017	20.2	47.4	48.6
F	Yeast	*Candida albicans* ATCC 10231	62.9	81.7	82.6
G		*Saccharomyces cerevisiae* ATCC 2601	76.6	82.8	89.9
H	Fungal strain	*Aspergillus brasiliensis* ATCC 16404	65.9	70.1	82.4
I		*Fusarium moniliforme*	74.7	82.9	87.1

4. CONCLUSIONS

Colloidal silver solution containing silver nanoparticles suspended in a liquid base on consumption of 3 mL/20cm^2 paper treatment inhibited the growth of the Gram-positive bacterium *S. aureus* with 81.6% and the Gram-negative bacterium *E. coli* with 75.8%. Packaging paper treatment with lavender essential oil is characterized with sufficient inhibition efficiency reaching 67.2% for Gram-negative bacterium *E. coli*. The antifungal effect of the obtained treated paper is more pronounced than the antibacterial one. Most effective inhibition efficiency against the tested bacteria, yeasts, and fungal strains from the chitosan coated samples was calculated for the 2 g/m^2 (BP/Ch 2) paper samples with an average of 79%. At BP/Ch 1 and BP/Ch 0.5 the effectiveness was 72.38% and 54.67%, respectively. The practical aspect of this research highlights the potential of various treatments for enhancing the antimicrobial properties of packaging materials. Colloidal silver solution, with silver nanoparticles, can significantly inhibit the growth of both Gram-positive and Gram-negative bacteria, making it a promising treatment for antimicrobial packaging. Additionally, packaging paper treated with lavender essential oil demonstrates notable effectiveness against E. coli, while chitosan-coated paper samples show a high level of inhibition, particularly at a concentration of 2 g/m^2. This suggests that incorporating silver nanoparticles, essential oils, or chitosan coatings into packaging materials could be an effective strategy for improving food safety and extending shelf life.

5. REFERENCES

De Matteis, V., Cascione, M., Costa, D., Martano, S., Manno, D., Cannavale, A., Mazzotta, S., Paladini, F., Martino, M., Rinaldi, R. 2023. "Aloe Vera Silver Nanoparticles Addition in Chitosan Films: Improvement of Physicochemical Properties for Eco-Friendly Food Packaging Material" *J. Mater. Res. Technol.* 24: 1015–1033.
Kumar, S., Basumatary, I.B., Sudhani, H.P.K., Bajpai, V.K., Chen, L., Shukla, S., Mukherjee, A. 2021. "Plant Extract Mediated Silver Nanoparticles and Their Applications as Antimicrobials and in Sustainable Food Packaging: A State-of-the-Art Review Trends" *Food Sci. Technol.* 112: 651–666.

Kuorwel, K.K., Cran, M.J., Sonneveld, K., Miltz, J., Bigger, S.W. 2011. "Essential Oils and Their Principal Constituents as Antimi-crobial Agents for Synthetic Packaging Films" *Journal of Food Science 76* (9): R164–R177.
Predoi, D., Iconaru, S., Buton, N., Badea, M., Marutescu, L. 2018. "Antimicrobial Activity of New Materials Based on Lavender and Basil Essential Oils and Hydroxyapatite" Nanomaterials 8 (5): 291.
Todorova, D.; Yavorov, N.; Lasheva, V.; Damyanova, S.; Kostova. 2023. "Lavender Essential Oil as Antibacterial Treatment for Packaging Paper" *Coatings*. 13: 32.
Zhang, W., Hadidi, M., Karaca, A.C., Hedayati, S., Tarahi, M., Assadpour, E., Jafari, S.M. 2023. "Chitosan-Grafted Phenolic Acids as an Efficient Biopolymer for Food Packaging Films/Coatings" *Carbohydr. Polym*. 314: 120901.

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2D AND 3D PRINTING

ORAL PRESENTATION

ENHANCING PRINTABILITY AND RUNNABILITY RELATED FACTORS IN VARIOUS INKJET PRINT HEADS WHILE PRINTED ON VARIOUS PAPER SUBSTRATES

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Abstract: *This study is aimed to investigate the printability and runnability aspects of various grades of printing paper and the impact of their surface properties on print quality in different inkjet technologies (DOD, CIJ). Various print-related parameters such as; colour cast, colour non-uniformity, print sharpness, graininess, hickeys, moire, banding, dimensional stability, print consistency, and runnability were measured using the standard observer method on a 5-point Likert scale. Twenty observers visually assessed the print quality for each parameter, and the data was statistically analysed using the TOPSIS method. Scanning Electron Microscope (SEM) test of the selected papers was performed at 1000X magnification for analysis of paper surface characteristics. It was found that excellent print consistency and colour uniformity were observed on all of the selected papers. Surface properties of paper, such as porosity and roughness, played a crucial role in graininess, consistency, and sharpness of prints, with gloss papers exhibiting favourable results. The results of the study clearly demonstrated that an explicit correlation could be established between porosity, cobb values and sharpness of print.*

Keywords: *Inkjet Printing, Drop-On-Demand Inkjet, Continuous Inkjet, Banding, Print consistency, Print Sharpness.*

1. INTRODUCTION

Inkjet printing is a versatile non-impact printing method known for its high-resolution output and precision. The fundamental principle of inkjet printing involves the deposition of minuscule ink droplets onto a substrate to form images or text. These droplets, which can be as small as a few picoliters, are controlled and directed through nozzles using advanced hardware and software systems, enabling excellent colour gamut and image sharpness (Hudd, 2010). For optimal results, the substrate's morphological properties (porosity, roughness, and smoothness) and chemical properties (pH and surface energy) must be compatible with the ink. Incompatibilities can cause defects such as absorption issues, uneven ink spreading, adhesion, wicking, improper wetting or drying (Rosalen & Backhaus, 2019).

Inkjet printing can be mainly categorized into two types: 1) Continuous Inkjet (CIJ) and 2) Drop-on-Demand (DOD). DOD is further categorized into Piezoelectric Inkjet (PIJ) and Thermal Inkjet (TIJ) (Shah et al., 2021). The CIJ technology utilizes an electric field for the continuous production and deflection of electrically charged droplets to create an image on the substrate. A major drawback of CIJ is the tendency of ink to bleed and blur, especially on porous surfaces (Ha et al., 2019). The size and frequency of the droplets are affected by different factors, such as the surface tension of ink, the nozzle orifice, and pressure applied (Askeland, 2015).

In contrast, in DOD technology ink droplets are ejected only when they are required, which significantly reduces ink wastage while offering high-resolution printing. In TIJ technology, the drops are generated and jetted on to substrate at a very high speed by heating the ink using voltage control. After heating, the ink produces a drive bubble (vapour of ink) where after a certain time the drive bubble expands and jets the ink droplet through the orifice of the printhead. Very small droplets of ink are generated (Kipphan,2001; Hoath, 2016; Askeland 2015). In PIJ technology, a special type of piezoelectric crystal/disk is used that generates a pressure which ejects the

ink droplet from the orifice of the printhead. This technology makes use of the piezo ceramic property to deform under voltage variation. The pressure in the ink chamber is controlled using electric voltage which assists the ink droplet to eject onto the substrate. The size of the droplet is controlled very precisely by means of the electrical pulse (Kippan 2001; Askeland 2015; Kraushaar, 2018).

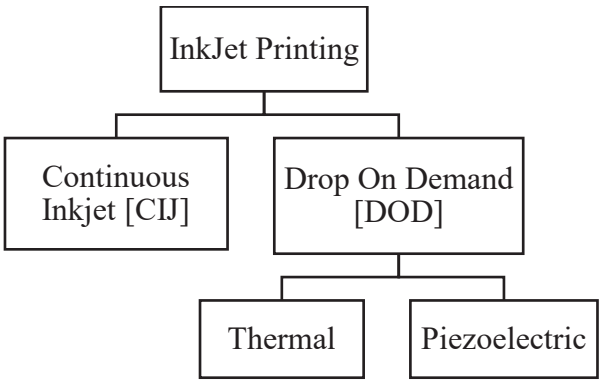


Figure 1: Classification of Inkjet Printing

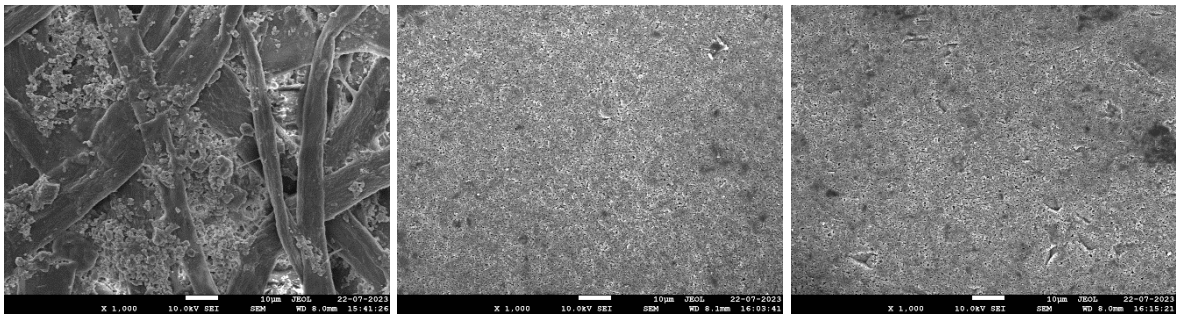
Printability and runnability are two important aspects to measure print quality in inkjet printing. Printability depends on various paper-related factors during printing and also depends on the inherent quality of the paper, while runnability refers to the smooth passage of paper through the printing machine. Both, impact print quality and cost. Inkjet printing with its ability to use thin liquid inks, faces significant challenge in achieving high print quality due to the influence of substrates wetting characteristics on final dot size. Effective selection of substrate, tackling dot spread and adressing processing needs helps to ensure, both printability and runnability in inkjet printing process. Coated papers with enhanced smoothness, gloss and brightness typically yield superior print quality as compared to uncoated papers (Pedersen et al., 2010; Boora & Baral, 2023). Print quality depends on paper and ink properties, print head specifications, and colour management software used. Proper ink retention on the surface of substrate is crucial for achieving desired density as well as colour saturation on final print (Svanholm & Ström, 2004).

Several studies have been conducted to investigate the factors influencing print quality in inkjet printing. Researchers including Bartleson (1982), Petersson (2005) and Pedersen et al. (2010, 2011) examined the perceived image quality by human observers through psychophysical experiments based on the extensive research on the existing quality attributes including lightness, blur, resolution, colour reproduction, tone reproduction, colour cast, sharpness, print consistency, graininess, gloss, mottle, and roughness. Finally, to represent overall quality the attributes were reduced to six comprehensive attributes; the colour, lightness, contrast, sharpness, artefacts and physical quality attributes. The properties of ink (viscosity, surface tension, density, drop volume) and printed surface (surface energy) impact droplet setting in inkjet printing. In capillary imbibition, properties such as ink contact angle, pore size/distribution, connectivity, permeability, and tortuosity within the porous layer are crucial (Kettle et al.,2010). Additionally, Gast and Tse (2001) conducted a subjective survey on print quality, specifically focusing on noise, banding, blur, colour rendition and tone reproduction, which revealed preferences and cultural differences in colour rendition. Evaluation of print quality can be done through both; human perception assessment, where the human visual system plays a key role in subjective judgment, and the use of measurement instruments for objective assessment (Gast & Tse, 2001).

2. MATERIALS AND METHODS

For this study, three categories of paper, comprising uncoated (90 g/m2), gloss coated (88 g/m2), and matt coated (90 g/m2), were selected for printing using continuous (CIJ), piezo (PIJ), and thermal (TIJ) inkjet printheads. The selection of papers was based on three broad categories commonly utilized in inkjet presses. The surface properties of the papers, including thickness, porosity, burst factor, roughness, gloss, brightness, Cobb value, and opacity, were measured in a standardized paper-testing laboratory. A Scanning Electron Microscope (SEM) analysis of the selected papers was conducted at the Central Instrumentation Lab (CIL), GJUS&T, Hissar to de-

termine the surface properties of the papers. Figure 2 illustrates SEM images of the selected paper samples at 1000X magnification.



a. Uncoated Paper b. Matt Coated Paper c. Gloss Coated Paper

Figure 2. SEM images of Paper Types Used for Printing at 1000X

2.1 Preparation of Test Chart:

A test master was designed consisting of all the elements, which were instrumental in the measurement of various print quality factors. The elements incorporated in the test chart are;

- Four-colour black, micro points, fine lines, ISO images (ISO 400, ISO 800, ISO 102400).
- University logo.
- Colour control strips having solids to measure Solid Ink Density (SID), grey scales, and 40%-80% tints to measure Tone Value Increase (TVI).

2.2 Printing Process:

Printing was performed on UC, MC, and GC paper using three types of calibrated inkjet printing machines under controlled press-room conditions, equipped with the following printheads;

- **Continuous Inkjet (CIJ)**: Stream Jet.
- **Piezoelectric Inkjet (PIJ)**: Oce Canon (Kyocera KJ4B).
- **Thermal Inkjet (TIJ)**: Hewlett Packard (A53 HDNA).

Each paper sample was printed on an 11″ × 17″ sheet.

2.3 Evaluation of Print Quality:

The print quality was assessed on a Likert scale from **1 (lowest)** to **5 (highest)**. The evaluation was performed by:

- **Standard Observers Method**: Twenty individuals who have prior knowledge of printing, were selected using the Farnsworth-Munsell (FM) hue test. Factors such as colour cast, colour non-uniformity, graininess, moiré, hickeys, sharpness, consistency, and banding was assesed by the standard observers.
- **Viewing Conditions**: Standard conditions with a D-50 light source.

2.4 Data Analysis

To analyze the data:

- **MATLAB™ 2023** was used for numerical simulations to evaluate print-related parameters.
- **TOPSIS Analysis** (Technique for Order Preference by Similarity to an Ideal Solution) was employed to determine the performance of inkjet heads and paper combinations.

3. RESULTS WITH DISCUSSION

The print performance of different paper substrates i.e. UC, MC and GC printed using three inkjet technologies i.e. M-I, M-II, and M-III was evaluated across key print quality metrics. The data collected through standard observer assessments was subjected to statistical analysis to indicate trends in printability and runnability.

3.1 Analysis of Print-Related Parameters

Banding and Colour Cast: Banding and colour cast values were consistently low across all selected machines, with the highest observed value being 1.56 for GC on M-II. MC exhibited better performance than UC and GC with minimal banding and colour cast values across all machines, demonstrating its balanced surface properties. In contrast, UC showed slightly higher banding and colour cast values due to its rougher surface and higher porosity.

Graininess and Print Sharpness: MC and GC performed better than UC in terms of graininess and sharpness. The average values of sharpness for MC and GC ranged between 4.34 and 4.81, while sharpness values were moderate (3.40–3.43) for UC. Graininess was significantly higher on UC (2.19–2.23), conforming to its SEM results that clearly showed greater surface irregularities compared to coated substrates. Table 1 represents the average values of different print related factors as assessed by the standard observers. The same was used as Decision Making Matrix for TOPSIS analysis.

Table 1: Average values as assessed by standard observes and Decision Making Matrix for TOPSIS

	M-I						M-II						M-III					
	Banding	Colour Cast	Colour non-uniformity	Graininess	Print consistency	Print Sharpness	Banding	Colour Cast	Colour non-uniformity	Graininess	Print Consistency	Print Sharpness	Banding	Colour Cast	Colour non-uniformity	Graininess	Print consistency	Print Sharpness
UC	1.54	1.37	1.06	2.21	4.71	3.43	1.32	1.38	1.04	2.23	4.12	3.4	1.52	1.45	1.05	2.19	4.12	3.4
MC	1.22	1.54	1.24	1.51	4.75	4.37	1.24	1.50	1.05	1.56	4.77	4.34	1.19	1.53	1.16	1.49	4.78	4.26
GC	1.4	1.22	1.35	1.39	4.16	4.82	1.56	1.20	1.05	1.42	4.93	4.81	1.06	1.20	1.66	1.47	4.77	4.76

Colour Non-Uniformity and Print Consistency: Across all machines, colour non-uniformity values were close to the minimum, whereas, print consistency values were close to maximum, indicating excellent consistency in colour reproduction. These attributes exhibited negligible variation across the selected substrates and machines, reflecting the robustness of the inkjet systems used.

3.23 Machine-Specific Performance

The evaluation of machine-specific performance revealed the following results as displayed in Table 2, where, R_i is the closeness coefficient between various machines and ideal solution.

Table 2: Closeness co-efficient and rank for the proposed system in relation to machines

	UC		MC		GC		Overall Performance (Machine)	
	R_i		R_i		R_i		R_i	Rank
M-I		2		3		2	0.4569	2
M-II		1		1		1	0.623	1
M-III		3		2		3	0.3779	3

CIJ (M-I): Delivered consistent performance with low banding and colour cast values, particularly on MC and GC. However, sharpness and graininess values for UC were moderate due to its surface roughness.

PIJ (M-II): Achieved the highest performance, with superior sharpness (4.81 on GC) and high print consistency (4.93). Its precise droplet control enabled better print quality across all substrates.

TIJ (M-III): Demonstrated results similar to CIJ, performing well on MC and GC but showing limitations on UC due to substrate absorption and roughness characteristics.

3.3 Substrate-Specific Performance

The performance of the paper substrates varied significantly. Table 3 represents the substrate-specific performance through TOPSIS analysis:

Table 3: Closeness co-efficient and rank for the proposed system in relation to papers

	M-I		M-II		M-III		Overall Performance (Paper)	
	R_i		R_i		R_i		R_i	Rank
UC		3		3		2	0.3584	3
MC		2		2		1	0.802	1
GC		1		1		3	0.6415	2

Gloss Coated Paper (GC): Consistently ranked as the best-performing substrate for sharpness and print consistency. It achieved high scores across all machines, particularly in M-I and M-II.

Matt Coated Paper (MC): Showed balanced performance, excelling in both printability and runnability. It exhibited minimal banding and colour cast values while maintaining high sharpness and consistency.

Uncoated Paper (UC): While satisfactory for basic applications, UC showed limitations in sharpness and graininess, with performance significantly influenced by its rough surface and high porosity.

4. CONCLUSIONS

The study focused on various critical factors that influence print quality and consistency of inkjet printing on different paper types. The results of the study demonstrated that GC exhibited minimal colour cast and superior colour uniformity, followed by UC and MC. Paper quality directly affected colour consistency due to varying ink absorption. Banding, chracterized by printed output lines, was influenced by paper type and inkjet technology. Surface properties of paper, such as porosity and roughness, played a crucial role in graininess, consistency, and sharpness of prints, with gloss papers exhibiting favourable results. The results of the study clearly demonstrate that an explicit correlation could be established between porosity, cobb values and sharpness of print. The greater the porosity of the paper the lower are the sharpness values. It is evident from the results the porosity values of UC being the maximum (140.0) in comparison to MC and GC which is 127.8 and 108, respectively, results in lower sharpness values of 3.43 for UC and relatively higher values of 4.37 and 4.82 on MC and GC, respectively printed under M-I. The same is true for M-II and M-III as well. Coated papers generally exhibit better performance than uncoated ones in terms of printability, with specific paper attributes like porosity, roughness, brightness, and gloss exerting substantial influence on print quality. The high surface roughness values of UC (14.9) in comparison to MC (11.9) and GC (10.0) resulted in the relatively higher values of graininess on UC. The TOPSIS results elucidated that GC performed better on M-I and M-II, while MC exhibited overall better printability and runnability. In terms of machine performance, M-II exhibited excellent printability and runnability in comparison to M-I and M-III.

5. REFERENCES

Askeland, R. A. (2015). Inkjet Print Engines. Handbook of Digital Imaging, 1-31.

Bartleson, C. J. The Combined Influence of Sharpness and Graininess On the Quality of Colour Prints. The Journal of Photographic Science, 30(2), 33-38 (1982).

Boora, S., & Baral, A. K. (2023). Critical Analysis of Printability of Different Types of Paper Substrates while printed with Piezoelectric and Thermal Inkjet Presses. European Chemical Bulletin

Gast, G.; Tse, M. K.; A Report On a Subjective Print Quality Survey Conducted at Nip16. In Nip & Digital Fabrication Conference (Vol. 2001, No. 2, Pp. 723-727). Society for Imaging Science and Technology (2001, January).

Ha, Y. B., Park, J. Y., & Kim, H. J. (2019). Influence of the Physical Properties of Digital Printing Paper on the Printing Quality. 51(2), 108-120.

Hoath, S. D. (Ed.). (2016). Fundamentals of Inkjet Printing: The Science of Inkjet and Droplets. John Wiley & Sons.

Hudd, A. (2010). Inkjet Printing Technologies (pp. 3-18). World Scientific Publishing, Hackensack, NJ, USA.

Kettle, John & Lamminmäki, Taina & Gane, Patrick. (2010). A Review of Modified Surfaces for High Speed Inkjet Coating. Surface and Coatings Technology. 204. 2103-2109.

Kipphan, H. (Ed.). (2001). Handbook of Print Media: Technologies and Production Methods. Springer Science & Business Media.

Kraushaar. (2018). Process Standard Digital (PSD). Fogra Research Institute for Media Technologies.

Pedersen, M., Bonnier, N., Hardeberg, J. Y., & Albregtsen, F. (2010). Attributes of Image Quality for Colour Prints. Journal of Electronic Imaging, 19(1), 011016-011016.

Pedersen, M.; Zheng, Y.; Hardeberg, J. Y. (2011, May).; Evaluation of Image Quality Metrics for Color Prints. In Scandinavian Conference On Image Analysis (PP. 317-326). Springer, Berlin, Heidelberg

Petersson, J. A. (2005).; Review of Perceptual Image Quality

Rosalen, S., & Backhaus, J. (2023). Comparing Quality Attributes of Coated Cardboards for Inkjet Printing by using Different Methods. Journal of Print and Media Technology Research, 8(4), 211–226.

Shah, M. A., Lee, D. G., Lee, B. Y., & Hur, S.; Classifications and Applications of Inkjet Printing Technology: A Review. IEEE Access, 9, 140079-140102 (2021).

Svanholm, E., & Ström, G. (2004). Influence of polyvinyl alcohol on inkjet printability.

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ORAL PRESENTATION

INNOVATIVE APPROACHES TO COLOR REPRODUCTION ON 3D PRINTED FLAT AND LOW-RELIEF SURFACES

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Abstract: *This study investigates color printing techniques for 3D-printed objects and their potential in 4D printing applications. It compares direct UV inkjet printing with indirect electrophotographic (EP) heat transfer, highlighting key differences in color reproduction. UV inkjet printing provides a wider color gamut, particularly in blue and green tones, while EP heat transfer minimizes dot gain and deformation. Both methods exhibit strong adhesion, though surface texture influences print sharpness. For 4D printing, UV inkjet printing proves superior due to its ability to print on both sides and on low-relief surfaces, whereas EP heat transfer is limited to single-sided applications on flat surfaces. The integration of 2D printing into 4D printing enhances customization, aesthetics, and interactivity. Additionally, flat 3D-printed geometries improve storage, transport, and material efficiency. The study also presents a practical example: a UV inkjet-printed mobile phone stand that undergoes a complex shape transformation upon thermal activation. Results confirm that UV inkjet printing ensures high-quality prints without visible irregularities, making it a promising method for 4D printing.*

Keywords: *4D printing, 3D printing, UV inkjet, Electrophotography, colour reproduction*

1. INTRODUCTION

The origins of 3D printing trace back to Slovenian professor Dr. Igor Grabec, who pre-patented a three-dimensional recorder in 1969 (Muck, 2015). However, it was not until the 1980s that 3D printing technologies became commercially viable. Charles Hull pioneered stereolithography (SLA) in 1983, and Scott Crump developed the widely used Fused Deposition Modeling (FDM) for thermoplastics in 1988 (Abar, 2024). Over the last decade, advancements in 3D printing have enabled the fabrication of highly complex structures with increasing precision (Ngo et al., 2018; Jandyal, 2022).

A significant area of research within 3D printing is multicolor and full-color printing (Formlabs, 2024). Achieving accurate and consistent color reproduction on 3D surfaces presents numerous challenges, influenced by factors such as printing technology, material properties, and surface characteristics (Jiangping, 2021; Singh, 2017; Taufik, 2017; Tan, 2020; Zang, 2012). These challenges have led to the exploration of new materials, including smart and programmable materials, which have contributed to the evolution of 4D printing (Chen, 2024).

4D printing, which incorporates time as the fourth dimension, was first conceptualized by Skylar Tibbits in 2013, followed by the establishment of the Self-Assembly Lab at MIT in 2014. This technology enables 3D-printed objects to transform over time when exposed to environmental stimuli (Pivar, 2022; Pivar, 2024). The integration of color printing into 4D printing remains an emerging field, requiring further investigation into how different color application methods interact with dynamic material transformations.

This study investigates two distinct methods of color reproduction on 3D-printed samples, particularly their practical applications and potential integration into 4D printing. The methods analyzed are direct UV-inkjet printing and indirect thermal transfer of electrophotographic (EP) toner. The research aimed to evaluate print quality, adhesion, and the achievable color gamut of each method, as well as their suitability for 4D printing applications.

For this study, white PLA filaments were used to fabricate flat and low-relief (bas-relief) samples using an FDM-based ZMorph VX 3D printer. Two color application methods were employed: direct UV-inkjet printing and indirect thermal transfer of EP toner. The comparison of these methods revealed distinct advantages and limitations.

A crucial aspect of the research extended these methods to programmable 4D printing, where flat 3D-printed structures transform into complex shapes under external stimuli, such as heat.

2. EXPERIMENTAL

2.1 3D printing process

3D printing of 70 × 130 mm samples with a thickness of 0.3 mm was carried out using a ZMorph VX 3D printer (ZMorph S.A., Poland) equipped with a heated build plate. The samples were printed from white PLA filament sourced from Plastika Trček d.o.o. (Slovenia, Ljubljana). White PLA was selected to achieve a wider color gamut in printed reproductions. The PLA was printed directly onto temperature-resistant Avery Zweckform 3560 polyester film, obtained from CCL Industries Inc. (Canada, Toronto). Two variations were tested: one with an unprinted polyester film and another pre-printed with a color test image. The 3D printing process was optimized using a 0.4 mm nozzle diameter, an extrusion temperature of 215°C, and a build plate temperature of 30°C. The first layer was printed at 0.1 mm, while subsequent layers were set to 0.2 mm. A rectilinear infill pattern with a 0° orientation ensured structural consistency. Printing parameters were carefully adjusted to ensure strong adhesion between the PLA and polyester film, as well as to achieve a smooth surface, which is crucial for optimal printability. These factors also played a key role in facilitating effective toner transfer from the polyester film to the PLA material.

In addition to samples with flat surfaces, samples with low-relief surfaces were also printed. To generate these low-relief textures, the Fuzzyfictator plugin in Slicer software was utilized. This approach enabled an assessment of how the color printing process performs on slightly textured or rough surfaces, providing valuable insights into print quality, adhesion, and color accuracy on non-flat geometries.

2.2 Colour printing process

In the first step, color test images were printed onto the 3D-printed samples using two methods. The indirect printing process involved heat transfer of EP toner from polyester film during the 3D printing process, while the direct printing process applied UV inks onto the flat geometry of the 3D-printed samples. Both methods utilized digital printing techniques and identical test images.

For indirect printing, a Xerox Versant 280 EP digital printer (Xerox, U.S.) was used to print test images onto polyester film. For direct printing, an Apex UV6090 UV LED inkjet flatbed printer (Apex, China) with Nazdar 260 UV LED inks was employed. The test images were designed to evaluate key print quality attributes using validated methods. They included color patches for spectrophotometric measurements, optical density, and tonal value assessments, as well as geometric quality elements and ink adhesion tests. Five samples were printed for each method.

In the second step, the same color printing processes were applied to low-relief, textured surfaces, following the same methodology as in the first step.

2.3 Printing evaluation

Densitometric and spectrophotometric measurements were performed using an X-Rite Exact spectrodensitometer under D50 illumination, with a 2° standard observer, 45:0 measurement geometry, and white backing. Optical density, tonal values, and CIELAB color values were determined for both printing methods. Adhesion of UV ink and EP toner to PLA was assessed using the cross-cut method with a Byko-Cut device (BYK-Gardner GmbH, Germany). Cuts were made at a 45° angle to the filament direction and inspected with a Dino-Lite AM4113ZT digital microscope (AnMo Electronics Corporation, Taiwan). Adhesion quality was evaluated based on the ISO 2409 classification. Geometric irregularities of printed elements were analyzed using ImageJ 1.54 (open-source software). Images, captured with a Dino-Lite AM4113ZT microscope at 50x magnification, were used to assess edge sharpness and physical gain on 0.3 mm-wide lines, comparing measured areas and perimeters to digital reference values. Dot deformation was evaluated by measuring roundness of 0.4 mm dots, comparing results to an ideal reference value of 1, calculated using equation (1).

$$\text{Roundness} = 4 \times \text{area}/(\pi \times \text{major_axis}^2)$$

2.4 Practical example of a smart structure

To demonstrate the practical use of programmable 3D structures in everyday life, a smart mobile phone stand was used as an example. This stand transforms from a flat shape into a functional 3D form upon activation. The structure was printed with color graphics on both sides using a UV inkjet printer, enabling double-sided printing, unlike thermal transfer printing, which only allows printing on one side. After printing, the programmable 3D structure was thermally activated in 80°C water, triggering its transformation.

The stand was fabricated using a combination of active PLA and passive PRO-PLA thermoplastics. The active sections featured a rectilinear pattern with 99% infill density, while the passive ones had a 30% infill density. Printing parameters were set at 195°C for the nozzle and 30°C for the build plate.

With a thickness of 2.4 mm, the stand comprises three active elements and one passive element in the global system. Locally, one active element is printed on the top side, enabling upward bending, while the other two are on the bottom side, also facilitating upward bending. This programmed structure transforms into its final shape upon thermal activation. All active elements were printed with a 0.1 mm layer height and a filament orientation of 0°, with varying lengths to achieve different bending angles, determined experimentally.

A schematic representation of the programmable 3D structure is shown in Figure 1.

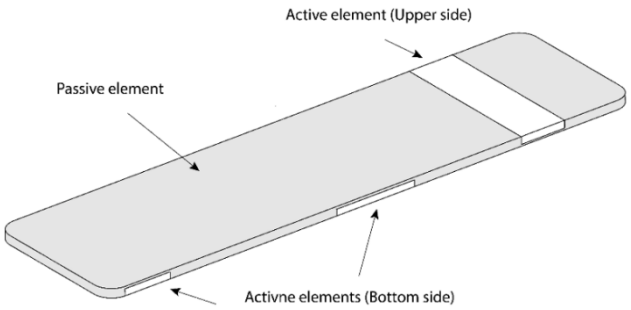


Figure 1: Schematic representation of the flat geometry of a programmable 3D structure.

3. RESULTS WITH DISCUSSION

3.1 Densitometric analysis

Table 1 presents the optical density measurements of solid tone (100% TV) process colors. Heat transfer printing generally shows higher optical density values, except for cyan, which is higher with UV inkjet printing. The highest optical density is observed for black in heat transfer printing, indicating a greater dynamic range compared to UV inkjet printing. Standard deviations confirm stable ink transfer in both methods, suggesting that the surface properties of the 3D-printed samples and printing parameters did not negatively impact ink performance.

Table 1: Average values and standard deviations of the optical density.

Colour	Optical density [/]	
	UV inkjet	Heat transfer (EP)
C	2.44 (±0.024)	2.29 (±0.028)
M	1.61 (±0.011)	2.14 (±0.050)
Y	1.71 (±0.015)	2.02 (±0.037)
K	1.71 (±0.004)	2.54 (±0.034)

Figure 2 illustrates the relationship between the reference and measured tone values for all process colors. The study found that dot gain is generally higher in UV inkjet printing, with magenta showing the lowest gain (24.3%). Cyan, yellow, and black range between 31.9% and 34.4% at 50% tonal value.

In heat transfer printing, dot gain is lower for all colors except magenta, with values between 25.2% and 28.1% at 50% tonal value. This suggests that heat transfer printing produces sharper details across light, medium, and dark tones.

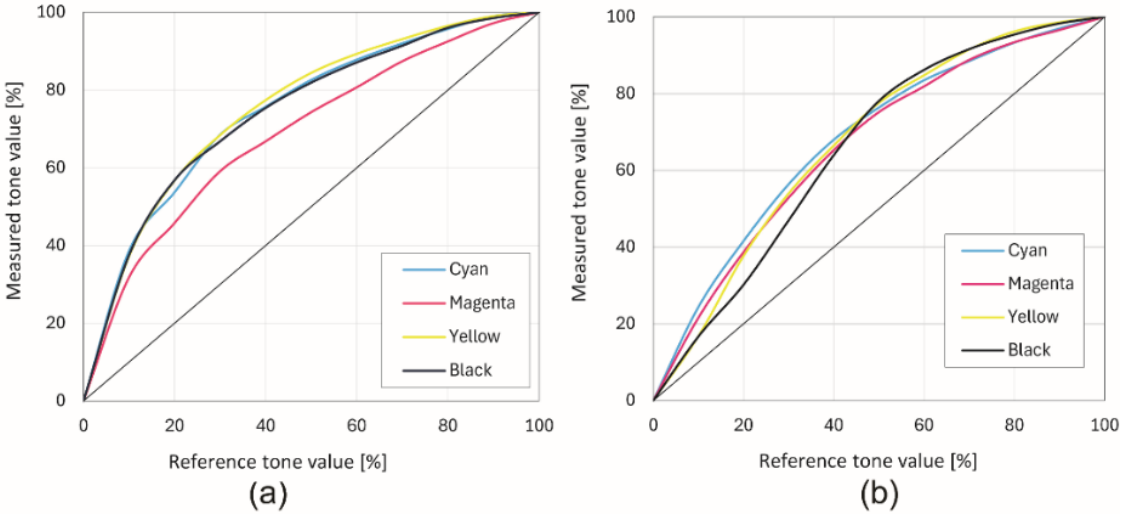


Figure 2: Dependence between the reference value and the measured tonal value for both printing processes. (a) UV inkjet printing and (b) heat transfer (EP) printing.

3.2 Spectrophotometric analysis

Based on measured CIELAB values (Table 2), color gamut diagrams were created for both printing processes (Figure 3). A larger gamut indicates better color reproduction. Comparison shows that UV inkjet prints have a slightly larger gamut than EP prints.

Detailed analysis reveals that UV inkjet printing enhances magenta, blue, and green tones, while EP printing achieves more saturated yellow tones.

Table 2: CIELAB colour values for both printing processes.

Colour	UV inkjet			Heat transfer (EP)		
	L*	a*	b*	L*	a*	b*
C	45.53	–35.86	–49.67	46.88	–32.81	–52.71
M	47.33	74.89	–5.95	41.50	74.17	6.01
Y	85.54	–4.91	90.82	87.18	–8.27	100.25
K	17.80	1.80	5.02	13.52	–0.42	–1.36
R	46.69	66.78	52.36	40.29	70.37	44.71
G	39.80	–78.45	18.23	39.28	–73.18	24.46
B	16.90	23.98	-49.15	14.46	17.51	–38.14

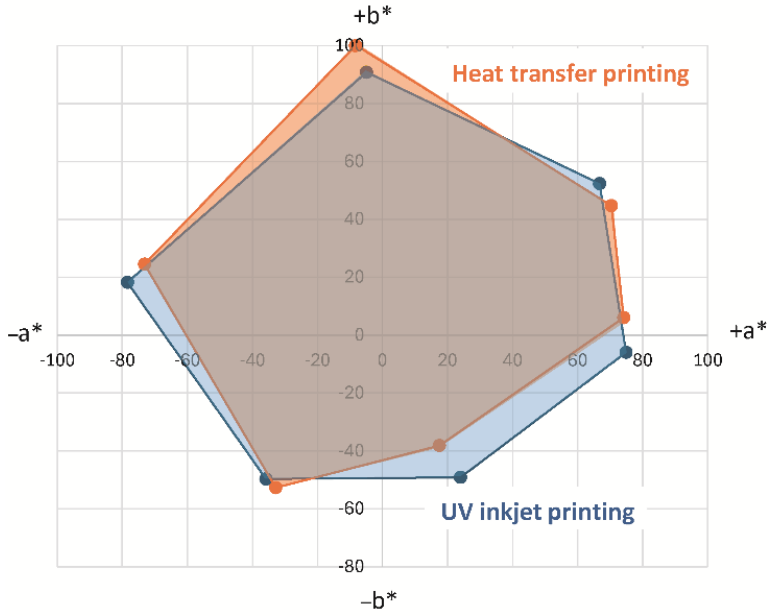


Figure 3: Colour gamut for both printing processes.

3.3 Ink adhesion

The optical images of the cross-cut pattern show that the adhesion of the UV ink and the EP toner to the 3D printed samples is very good. The adhesion of the UV ink achieves ISO classification 0 with smooth cut edges and no detached ink. The adhesion of the EP toner achieved ISO classification 1, with slightly damaged chipped edges and up to 5% detached ink. The analysis of the adhesion showed that both printing processes are suitable for printing on the 3D printed PLA material.

3.4 Image analysis

Image analysis revealed geometric irregularities in both printing processes, as shown in Figures 4. Dot roundness measurements confirm that UV inkjet printing results in greater deformation, with an average roundness of 0.821 (±0.027), while heat transfer printing achieves a more circular dot shape at 0.975 (±0.012), nearing the ideal value of 1. This deformation in UV printing is attributed to droplet distribution and ink spreading between filament layers.

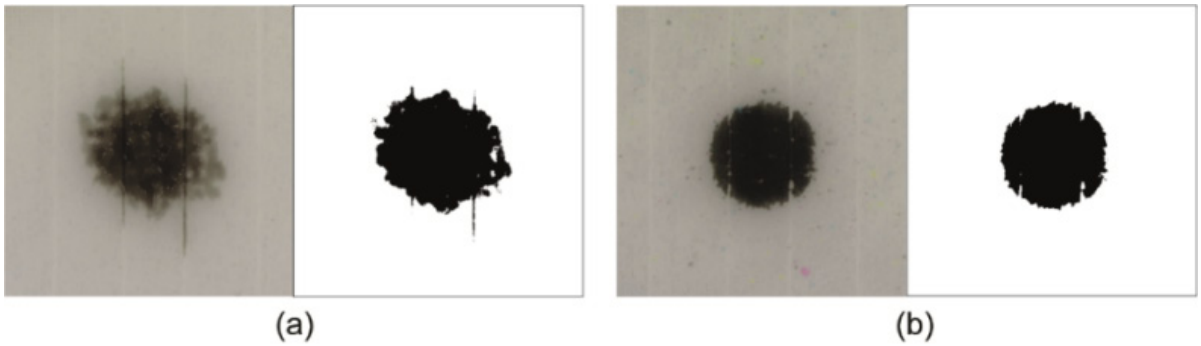


Figure 4: Visual comparison of microscopic images of printed dots with both printing processes: (a) UV inkjet and (b) heat transfer printing.

Line area measurements show a physical increase in both printing processes compared to the ideal reference value (2.1 mm²), with UV inkjet printing exhibiting a greater expansion (2.58 ±0.022 mm²) than heat transfer printing (2.33 ±0.003 mm²). The perimeter of printed lines also increases significantly, indicating poor edge sharpness 23.99 ±1.400 mm for UV inkjet and 20.96 ±0.428 mm for heat transfer (EP).

Edge deformation in UV printing occurs due to ink spreading into filament channels before curing, while in heat transfer printing, the toner does not fully transfer into these channels, leading to lower edge sharpness.

3.5 Colour printing on low-relief surfaces

Colo printing on low-relief surfaces revealed that EP toner transfer during 3D printing on rough surfaces was uneven, resulting in poor print quality (Figure 5 (b)). In contrast, samples printed with a UV inkjet printer exhibited good print quality, with all elements clearly visible (Figure 5 (a)).

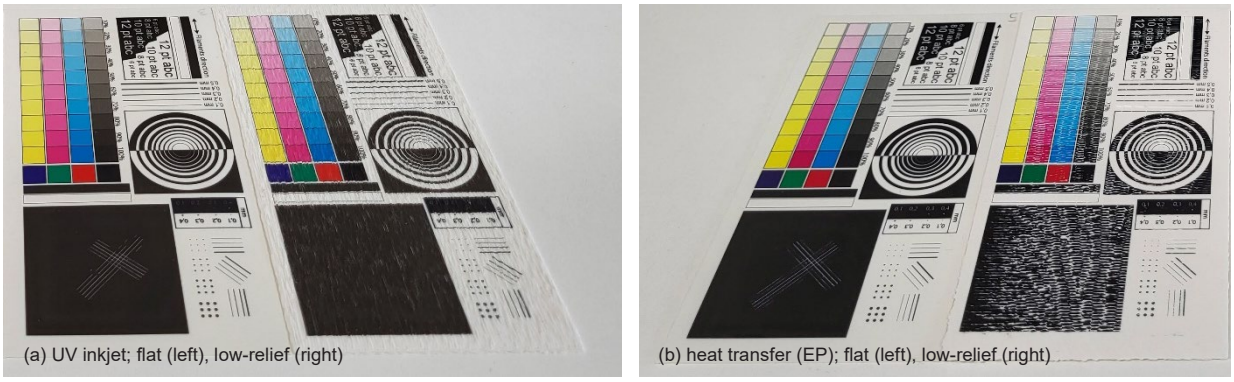


Figure 5: Visual comparison of images of printed test forms on flat (left) and low-relief (right) surfaces with both printing processes: (a) UV inkjet and (b) heat transfer (EP) printing.

3.6 Practical example of a smart structure

A practical example, printed on both sides with color graphics using a UV inkjet printer, showcases the complex transformation of programmable 3D structures (Figure 6). This structure changes shape out of plane in both upward and downward directions, with varying degrees of transformation (different angles). The deformation is enabled by three active elements of different lengths, printed locally at specific points on the 3D structure.

Two active elements, measuring 13.0 mm and 22.5 mm in length and printed on the underside, bend downwards at angles of 82° and 145°, respectively. Meanwhile, an active element of 13.0 mm in length, printed on the top side, bends upwards at 82°. Throughout the transformation, the passive element connecting the active components remains stable, ensuring dimensional stability during thermal activation and practical use afterward.

Results confirm that programmable 3D structures maintain stability for practical applications, and UV inkjet printing delivers high-quality prints without visible irregularities.

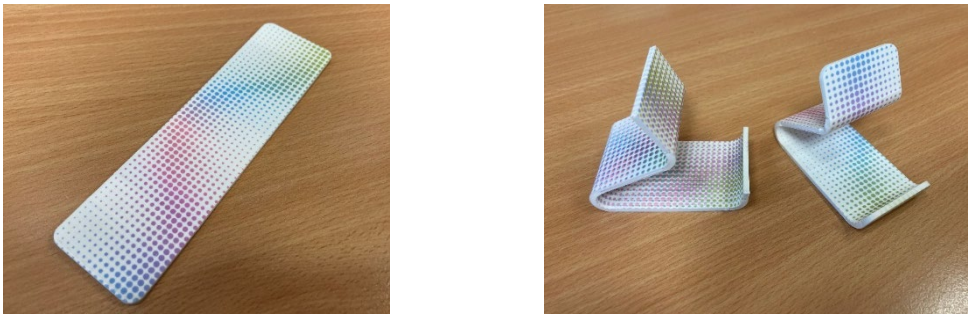


Figure 6: Smart structure in flat geometry (left) and thermally activated mobile phone stand (right).

4. CONCLUSIONS

This research provides valuable insights into color printing techniques for 3D-printed objects, highlighting their potential for 4D printing applications. The comparison of direct UV inkjet printing and indirect electrophotographic printing reveals key differences in color reproduction quality. While electrophotographic heat transfer minimizes dot gain and deformation, UV inkjet printing offers a wider color gamut, particularly in blue and green tones, making it advantageous for specific applications. Both methods demonstrate good adhesion to 3D-printed surfaces, but surface texture impacts print sharpness.

For 4D printing, UV inkjet printing is the superior choice, as it allows double-sided printing, whereas heat transfer (EP) printing is limited to one side. The integration of 2D printing into 4D printing represents a significant step forward, enabling personalization, aesthetic enhancements, and interactive functionality. Additionally, the flat geometry of 3D objects optimizes storage, transport, and material efficiency, reducing plastic waste by eliminating the need for support structures.

Both direct and indirect color printing techniques can achieve satisfactory print quality on flat surfaces. However, for low-relief textures or double-sided printing, UV inkjet printing remains the only viable option. Selecting the appropriate printing method depends on the specific requirements of the final product.

The expansion of research into 4D printing paves the way for groundbreaking innovations, particularly in the use of active elements for dynamic morphing. Future studies should focus on enhancing accuracy and efficiency, unlocking new industrial applications in 3D and 4D printing.

5. REFERENCES

Abar, M. B., Kelly, C., Allen, N. B., Gall, K. 2024. "Historical perspectives on 3D printing." *Clinical Applications of 3D Printing in Foot and Ankle Surgery*, Highlander, P. D., 1-16. United States: Elsevier.

Barreto dos Santos, B. M., Littlefair, G., Singamneni, S. 2023. "From 3D to 4D printing: A review." *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2023.05.707

Chen, J., Virrueta, C., Zhang, S., Mao, C., Wang, J. 2024. 4D printing: "The spotlight for 3D printed smart materials." *Materials Today*. https://doi.org/10.1016/j.mattod.2024.06.004

Formlabs. 2024. *Guide to Color 3D Printers*. Available from: https://formlabs.com/eu/blog/guide-color-3d-printers/ [Accessed 15th September 2024]

Jandyal, A., Chaturvedi, I., Wazir, I., Raina, A., Ul Haq, M. F. 2022. 3D printing – A review of processes, materials and applications in Industry 4.0. *Sustainable Operations and Computers*, 3, 33-42. https://doi.org/10.1016/j.susoc.2021.09.004

Jiangping, Y., Guangxue, C., Hua, L., Hartmut, P., Kaida, X. 2021. Challenges in Color Reproduction on 3D Printed Objects. *Materials & Design*, 209, 109943. https://doi.org/10.1016/j.matdes.2021.109943

Muck, D., Križanovskij, I. 2015. *3D tisk: Tehnologije 3D-tiska, priprava 3D-modelov za tisk, pojmovnik.* Pasadena.

Ngo, T., Kashani, A., Imbalzano, G., Nguyen, K., Hui, D. 2018. Additive manufacturing (3D printing): a review of materials, methods, applications and challenges. *Composites Part B: Engineering*, 143, 172-196. https://doi.org/10.1016/j.compositesb.2018.02.012

Pivar, M., Gregor-Svetec, D., Muck, D. 2022. Effect of Printing Process Parameters on the Shape Transformation Capability of 3D Printed Structures. *Polymers*, 14, 117. https://doi.org/10.3390/polym14010117

Pivar, M., Vrabič-Brodnjak, U., Leskovšek, M., Gregor-Svetec, D., Muck, D. 2024. Material Compatibility in 4D Printing: Identifying the Optimal Combination for Programmable Multi-Material Structures. *Polymers*, 16, 2138. https://doi.org/10.3390/polym16152138

Singh, R., Singh, S., Singh, I. P., Fabbrocino, F., Fraternali, F. 2017. Investigation for surface finish improvement of FDM parts by vapor smoothing process. *Composites Part B: Engineering*, 111, 228-234. https://doi.org/10.1016/j.compositesb.2016.11.062

Tan, L., Zhu, W., Zhou, K. 2020. Recent progress on polymer materials for additive manufacturing. *Advanced Functional Materials*, 30(43), 22. https://doi.org/10.1002/adfm.202003062

Taufik, M., Jain, P. K. 2017. Laser assisted finishing process for improved surface finish of fused deposition modelled parts. *Journal of Manufacturing Processes*, 30, 161-177. https://doi.org/10.1016/j.jmapro.2017.09.020

Yang, X., Wei, X. F., Huang, B. Q., Zhang, W. 2012. Study on the Printability of UV-Curable Inkjet Ink on Different Printed Materials. *Applied Mechanics and Materials*, 262, 324-328. https://doi.org/10.4028/www.scientific.net/AMM.262.324

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POSTER PRESENTATION

INFLUENCE OF LOW TEMPERATURE ON MECHANICAL STABILITY OF INKJET PRINTS

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Abstract: *Inkjet printing technology has become established in many areas due to its accessibility and flexibility. However, the quality and resistance of the print depend on several factors which can affect the product during transport, storage, and use. In the present research, we analysed the influence of low temperature on the mechanical durability of prints to demonstrate the conditions of storing food packaging. The resistance to rubbing was determined for inkjet prints that were previously exposed to a constant low temperature for a certain period of time or alternately to room temperature and low temperature. The resistance of prints to mechanical stress was tested in accordance with appropriate standards and the colour differences that appeared on the prints after rubbing were evaluated. The results showed that exposure to low temperatures did not exhibit any serious destructive effect on the mechanical durability of the prints.*

Keywords: *inkjet, printing, low temperature, resistance, durability*

1. INTRODUCTION

Due to its accessibility and flexibility, inkjet printing has become an established technology in many areas, from document printing to photos and art. However, the print's quality and resistance depend firstly on the appropriate formulation of the ink and the dyes and pigments used. Special attention must also be paid to the selection of the printing material, since the absorption of the ink and thus the quality of the final print strongly depend on the chemical and surface properties of both ink and the substrate (Magdassi, 2010; Hoath, 2016).

The resistance of print is influenced by many interconnected external factors to which the graphic product is exposed during transport, storage and use. In the past, the research was focused mainly on the phenomenon of photodegradation and the destructive influence of light. The light fastness of colourants and colour prints is influenced by several factors, for example by the structure and concentration of the dye or pigment, the degree of aggregation, the size of the pigment particles, the chemical and physical properties of the printing material, the spectral distribution of the radiation of the light source, the composition of the atmosphere, including relative humidity and impurities present in the air (Zollinger, 2003).

In the past, research on the photodegradation processes considered the influence of the structure of the ink and printing material as well as numerous factors that contribute to the degradation process, such as heat, moisture, light, impurities, and microorganisms (Venosa, 2011; Pastorelli; 2014; Izdebska, 2016). Many of the processes that accompany the decomposition of organic materials are temperature dependent and research has shown that the decomposition rate is proportional to the increase in temperature (Feller, 1994; Blaznik, 2017). Additionally, the decomposition process is accelerated by moisture; therefore, the cumulative effect of light, heat and moisture is particularly destructive and can significantly shorten the lifespan of a print (Bamfield, 2001; Bevk, 2023; Blaznik, 2022; Wypych, 2008). On the other hand, we noticed no systematic study regarding the durability of prints at lower temperatures in the absence of light.

The aim of our research was therefore to examine the influence of low temperature on the mechanical durability of inkjet prints. The resistance to rubbing was determined for the samples that were previously exposed to constant low temperature for a certain period of time or alternately to room temperature and low temperature, and the results were compared with the values for samples that were stored at room temperature. The resulting colour differences and the durability of the prints were evaluated based on spectrophotometric analysis and the CIELAB parameters.

2. EXPERIMENTAL

2.1 Preparation of printed samples

Prints were prepared with a Canon Image PROGRAF W8400 inkjet printer (Canon, Japan) using paper with a matte coating, with a grammage of G = 180 g/m^2 and CIE whiteness of W = 121.2. The samples contained four fields of cyan, magenta, yellow and black (CMYK) with 100% coverage (C100, M100, Y100, K100) and four fields with 50% coverage (C50, M50, Y50, K50).

2.2 Exposure pf prints to low temperature and temperature changes

The prints were exposed to different temperatures in the dark during three time intervals: 6, 12 and 18 days respectively at a constant temperature of 6, –12 or 23 °C or alternately at a temperature of 6 °C and 23 °C, with an interval of 24 hours.

2.3 Durability of prints to rubbing

The durability of prints to rub was tested using the Rub Tester RT-01 (Labthink, USA) in accordance with the ASTM D 5264 – 98 Standard. The print was placed on the lower plate of the apparatus and an unprinted piece of the same paper was fixed on a counterweight (m = 1.8 kg). Based on previous experiments, 200 cycles of passes were determined for each sample.

2.4 Colorimetric properties of prints before and after rubbing

The mechanical resistance to rubbing was evaluated based on the colour differences that appeared on the samples after rubbing and were calculated using the CIELAB equation for colour differences (Equation 1) (Bračko, 2022). The CIELAB coordinates of the prints were measured with an Eye-One spectrophotometer (X-Rite, USA) in accordance with the ISO 13655 standard. The values were also measured before rubbing on prints that were kept at room temperature in the dark, and these values were used as a standard in further calculations. The results represent the average of five measurements and are shown in Figure 1.

$$\Delta E^*_{ab} = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (1)$$

2.5 CIE whiteness and tint of whiteness after exposure of paper to temperature changes

CIE whiteness, W, and tint of whiteness, T_w, (Equations 2–3) (Bračko, 2022) of paper samples after exposure to low temperatures for 6, 12, and 18 days, respectively, were determined in accordance with the ISO 11475 standard based on measurements with an Eye-One spectrophotometer (X-Rite, USA). The results represent the average of five measurements and are shown in Tables 1–3.

$$W = Y + 800(x_0 - x) + 1700(y_0 - y) \quad (2)$$

$$T_W = 1000(x_0 - x) - 650(y_0 - y) \quad (3)$$

3. RESULTS AND DISCUSSION

Figure 1 shows the mechanical durability of prints after exposure or storage for 6, 12 or 18 days at a constant temperature of 23 °C, 6 °C or –12 °C or at an alternating temperature of 6 and 23 °C, expressed as colour difference, ΔE^*_{ab}.

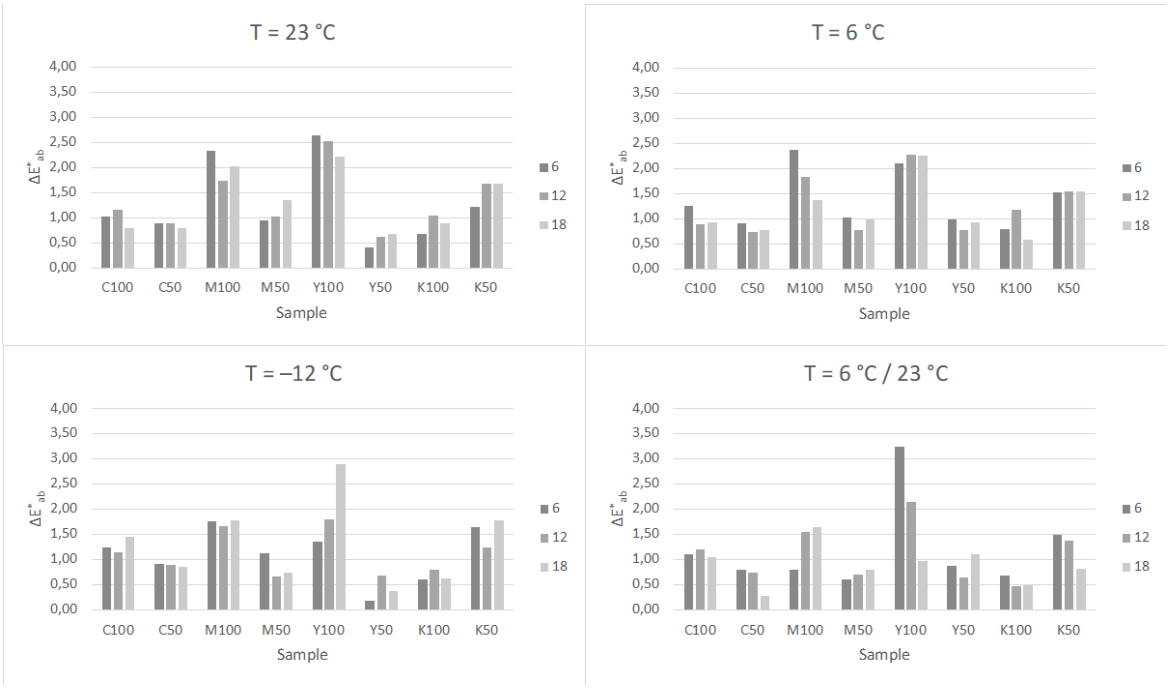


Figure 1: Durability of prints to rubbing after exposure to low temperature for 6, 12 and 18 days, respectively, expressed as colour difference, ΔE^*_{ab}.

The results show that for a given combination of selected paper and ink (C, M, Y, K), low temperature and the process of cooling or even freezing and heating and subsequent thawing does not significantly affect the durability of the print to rubbing, as the colour differences are small or moderate and do not exceed 3.25 ΔE^*_{ab} units. The resulting changes are comparable to the results obtained at room temperature. Nevertheless, certain changes and trends can be observed.

Colour prints (C, M, Y) with a higher ink application (100%) are generally slightly less durable than prints with a lower ink application (50%). After rubbing, slightly more significant colour differences appear on samples C100, M100 and Y100, regardless of the temperature and duration of exposure (for C prints up to 0.77 ΔE^*_{ab} units (T = alternating, t = 18 days), for M prints up to 1.38 ΔE^*_{ab} units (T = 23 °C, t = 6 days), for Y prints up to 2.51 ΔE^*_{ab} units (T = –12 °C, 18 days)). The exception is the yellow print after 18 hours of exposure to alternating temperature, where the change of Y50 is practically the same as that of Y100.

On the other hand, black prints with 50% coating (K50) are less durable than K100 as after rubbing larger colour differences can be observed, regardless of the temperature and duration of exposure. The largest changes of the K50 sample occur at T = –12 °C, where the colour differences reach ΔE^*_{ab} = 1.78 after 18 days.

Longer exposure time (12 or 18 days compared to 6 days) to low temperature, even for prints with 50% application, does not significantly worsen resistance to rubbing; colour differences increase slightly after 18 days in the case of Y100, T = –12 °C (ΔE^*_{ab} increases by 1.53 units), M100, T = alternating (ΔE^*_{ab} increases by 0.85 units) and K50, T = 23 °C (ΔE^*_{ab} increases by 0.46 units).

There are minor differences in durability between prints of different colours with 100% application: the most resistant print is C100 (ΔE^*_{ab} = 0.79 – 1.15), and the least resistant is Y100 (ΔE^*_{ab} = 1.36 – 3.25). In the case of 50% application, the permanence of colour prints (C, M, Y) is very similar. Colour differences resulting from rubbing

range from ΔE^*_{ab} = 0.40 (Y50, T = 23 °C) to ΔE^*_{ab} = 1.12 (M50, T = –12 °C) after 6 days of exposure. The resistance of colour prints is slightly better than black (K50), where colour differences after 6 days of exposure range from ΔE^*_{ab} = 1.21 to 1.65 units.

On average, the changes in the prints are minor to moderate and do not exceed 3.25 ΔE^*_{ab} units, and the results at lower temperatures are comparable to the results at room temperature (Table 1).

Table 1: Average colour differences, ΔE^*_{ab}, after exposure of CMYK samples to low temperatures (T = 23, 6, –12 °C or alternating) and rubbing.

Exposure T/t	ΔE^*_{ab}					
	6 days		12 days		18 days	
	100%	50%	100%	50%	100%	50%
23 °C	1.67	0.86	1.62	1.08	1.48	1.12
6 °C	1.63	1.11	1.54	0.99	1.29	1.06
–12 °C	1.24	0.97	1.35	0.87	1.69	0.94
6/23 °C	1.46	0.95	1.35	0.86	1.05	0.75

We also checked how the optical properties of the printing material i.e. paper change during storage (Tables 2 and 3). The effect of low temperatures is small and practically identical at all temperatures: the whiteness of the paper slightly decreased during the storage both at room and at lower temperature (from 0.6 to 1.2 units after 6 days and 1.2 to 1.6 units after 18 days). The paper has a minimal reddish tint (T_w = –0.6), which deepens only slightly (T_w = –0.9) after 6, 12 or 18 days of exposure to low temperature, but the changes are so small that they would hardly be noticeable to the naked eye.

Table 2: CIE whiteness, W, after exposing paper samples to low temperature.

Exposure T/t	W			
	0	6 days	12 days	18 days
23 °C	121.2	120.0	120.2	120.0
6 °C	121.2	120.4	119.4	120.6
–12 °C	121.2	120.6	119.9	119.6
6/23 °C	121.2	120.6	119.6	119.8

Table 3: Tint of whiteness, T_w, after exposing paper samples to low temperature.

Exposure T/t	T_w			
	0	6 days	12 days	18 days
23 °C	–0.63	–0.89	–0.88	–0.83
6 °C	–0.63	–0.81	–0.92	–0.90
–12 °C	–0.63	–0.84	–0.88	–0.87
6/23 °C	–0.63	–0.83	–0.89	–0.88

4. CONCLUSIONS

The present research analysed the influence of low temperatures on the mechanical durability of inkjet prints. The resistance to rubbing was tested for prints previously exposed to constant low temperature for a certain period, or alternately to room temperature and low temperature. The results were compared with the values for samples stored at room temperature before rubbing. According to the results, exposure to low temperatures did not cause serious destructive effects on the durability of the prints. Colour differences due to mechanical stress were small or moderate and did not exceed 3.25 ΔE^*_{ab} units on average, and results at lower temperatures were comparable to those at room temperature. Colour prints (CMY) with a higher ink application (100%) were generally slightly less durable than those with lower ink application (50%). On the other hand, black prints with 50% coating were less durable than those with 100 % coverage regardless of the temperature and duration of exposure. A very important factor in the degradation process is the printing material, which, in our case, showed excellent durability. In the future, expanding the research and systematically analysing its impact would be reasonable.

5. REFERENCES

Bamfield, P. 2001. *Chromic phenomena: technological applications of colour chemistry.* Cambridge: The royal society of chemistry.

Bevk, E., Blaznik, B. and Bračko, S. 2023. "Impact of protective glass on photodegradation of ink-jet printed documents." Journal of cultural heritage. 62 (7/8): 356–362.

Blaznik, B., Možina, K. and Bračko, S. 2013. "Stability of ink-jet prints under influence of light." Nordic Pulp and Paper Research Journal 28: 111–118.

Blaznik, B., Gregor-Svetec, D. and Bračko, S. 2017. "Influence of light and temperature on optical properties of papers." Cellulose chemistry and technology 51 (7/8): 755–764.

Blaznik, B., Kovač, F., Bizjak, G. and Bračko, S. 2022. "Fastness of dye-based ink-jet printing inks in aqueous solution in the presence and absence of oxygen." Color research and application 47 (5): 1193–1199.

Bračko, S. and Blaznik, B. 2022. *Osnove merjenja barv. Ljubljana*: Univerza v Ljubljani, Naravoslovnotehniška fakulteta.

Feller, R. L. 1994. *Accelerated aging: photochemical and thermal aspects*. Los Angeles: Getty Conservation Institute.

Hoath, S. D. 2016. *Fundamentals of Inkjet Printing.* Weinheim: Wiley-VCH.

Izdebska, J. 2016. Aging and degradation of polymers. Printing on polymers. Editors Izdebska, J. and Thomas, S. Oxford: William Andrew Publishing.

Magdassi, S. 2010. The Chemistry of Inkjet Inks. Singapore: World Scientific Publishing.

Pastorelli, G., Cucci, C., Garcia, O., Piantanida, G, Elnaggar, A., Cassar, M. and Strlič, M. 2014. "Environmentally induced colour change during natural degradation of selected polymers." Polymer Degradation and Stability 56:198–209.

Venosa, A., Burge, D. and Nishimura, D. 2011. "Effect of light on modern digital prints: photographs and documents." Studies in Conservation 56: 267–280.

Wypych, G. 2008. *Handbook of material weathering.* 4th ed. Toronto: ChemTec Publishing.

Zollinger, H. 2003. *Color Chemistry: Syntheses, properties and applications of organic dyes and pigments.* 3rd ed. Weinheim: Verlag Helvetica Chimica Acta.

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POSTER PRESENTATION

SCREEN PRINTING WITH DYES FROM INVASIVE ALIEN PLANTS

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Abstract: *The research presents a comparative study on the applicability of natural dyes from three different invasive alien plants, namely goldenrod, Himalayan balsam and Japanese knotweed, for screen printing on different papers and shows the possible influence of printing pastes with different pH values in the formulation of printing inks on the final colour and durability of prints. Commercially available cellulose papers made from primary and secondary cellulose fibres as well as innovative papers made from the stems of Japanese knotweed were used for printing. The printed substrates were evaluated on the basis of colour measurements and fastness properties. The results confirmed that the inks made from natural dyes produced with both printing pastes can be successfully used for screen printing on all papers and exhibit very good rub resistance. However, the lower light fastness of the prints made with the dyes from the petals of Himalayan balsam and the leaves of Japanese knotweed limits their use for outdoor paper products. The different pH of the printing paste also had a great influence on the colour of the prints of all dye extracts and on the fastness of the prints made with the Japanese knotweed leaves. The prints made with the yellow dye extract from goldenrod flowers showed the best fastness properties on all the papers tested.*

Keywords: *natural dye, invasive alien plant, printing, paper.*

1. INTRODUCTION

Invasive alien plants pose an ecological problem as they grow on a large scale and displace native plants. The possibility of using them as a source of natural dyes for dyeing textiles, printing on textiles and paper, and coating wood has therefore been the subject of several studies (Gorjanc, 2016; Gorjanc, 2019; Topič, 2017; Klančnik, 2021; Klančnik, 2021; Klančnik, 2024; Horvat, 2020).

In our study, the dye extracts from the yellow petals of goldenrod, the green leaves of Japanese knotweed and the pink petals of Himalayan balsam were used to produce screen printing inks. The research work represents a comparative study of the possible influence of printing pastes with slightly different pH values in the formulation of printing inks on the final colour and durability of the prints. For this purpose, the pigment printing paste with a pH value of 7.4, which was produced by mixing individual components such as acrylic thickener and acrylic binder in distilled water, and the commercially produced printing paste with a pH value of 8.1 were used for comparison. The inks produced from three dye extracts using two different printing pastes were printed by flat screen printing on two papers made from Japanese knotweed stems of different grammages and on two commercially available papers, one made from primary cellulose fibres and one from recycled cellulose fibres. The colour of the prints was evaluated spectrophotometrically, and the abrasion and light resistance of the prints was tested. The printing of papers with dyes from Himalayan balsam (Klančnik, 2021) and Japanese knotweed leaves (Klančnik, 2024) has already been demonstrated, but not in comparison to printing with the dye from goldenrod and the printing pastes with different pH values.

2. EKSPERIMENTAL

2.1 Dye extracts

The dye extracts from the leaves of Japanese knotweed, form the petals of goldenrod and Himalayan Balsam were obtained from National Institute of Chemistry (Ljubljana, Slovenia).

2.2 Printing Ink Preparation

For the screen printing inks, the already commercially prepared pigment printing paste Transparent Elastil FGI (AchitexMinerva Ltd., Vaiano Cremasco, Italy) with a pH value of 8.1 was used and the printing paste, which we prepared by mixing the individual ingredients according to the following recipe: 150 g Binder SE conc. (Achitex-Minerva Ltd., Vaiano Cremasco, Italy), 18 g thickener Clear MCS (AchitexMinerva Ltd., Vaiano Cremasco, Italy) and up to 1000 g demineralized water to form a homogeneous paste with a pH value of 7.4. The dye extract from goldenrod petals was added in the following concentrations: 1 and 3 g per 100 g of the printing paste we produced with pH 7.4 and per 100 g of the commercially available Transparent Elastil printing paste with pH 8.1. The dye extracts from the Japanese knotweed leaves and Himalayan balsam petals were added in concentrations of 1 and 3 g per 100 g of Transparent Elastil printing paste with pH 8.1 and in a concentration of 3 g per 100 g of the printing paste with pH 7.4. The formulated inks are shown in Figure 1.

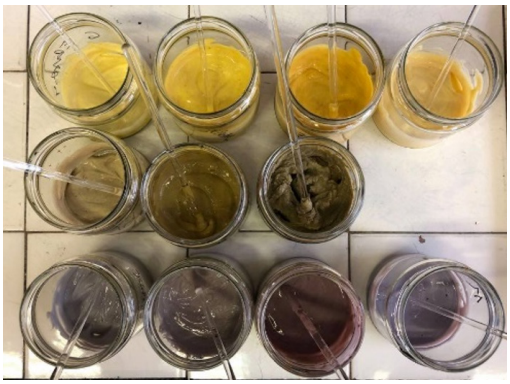


Figure 1: The printing inks produced with dye extracts from goldenrod (in the first row), with dye extracts from Japanese knotweed leaves (in the second row) and with dye extracts from Himalayan balsam (in the third row).

2.3 Printing Materials

The following papers were used for printing: Japanese knotweed papers in two grammages, 200 and 240 g/m², produced by the Pulp and Paper Institute (Ljubljana, Slovenia), hereafter referred to as J.k. 200 and J.k. 240, where J.k. 200 contains approx. 30 % Japanese knotweed fibres and J.k. 240 approx. 40 % fibres from Japanese knotweed, the remainder being commercially available cellulose fibres, and paper made from primary cellulose fibres with the trade name IQ premium (manufactured by Mondi Group Ltd, Vienna, Austria), grammage 200 g/m², referred to as Paper 1, and recycled paper from an unknown manufacturer, grammage 200 g/m², referred to as Paper 2.

2.4 Printing

The printing inks were applied by the semi-automatic screen-printing machine SD 05 (RokuPrint Ltd., Darmstadt, Germany) with the flat printing screen made of polyester fabric with 77 threads/cm and a thread diameter of 55 µm with three strokes of squeegee. The prints were dried at room temperature overnight and then cured at 150 °C for 5 minutes.

2.5 Spectrophotometric Measurements

Colour measurements of the prints were made using the Eye-One i1 Pro spectrophotometer (X-Rite, Grand Rapids, MI, USA) with 45/0 plane geometry, illuminant D65, 10° standard observer and a 4.5 mm diameter aperture. The CIELAB colour coordinates: L* (lightness), a* (red-green value), b* (yellow-blue value) in the range of 380 to 730 nm were measured, the average of three measurements for each print was taken, and h_{ab} (hue) and C^*_{ab} (chroma) were calculated.

2.6 Colour Fastness Tests

The abrasion resistance of the ink layer on papers was tested according to ASTM D 5264 using the digital ink rub tester RT-01 (Labthink Ltd., Neu-Isenburg, Germany) at an abrasion pressure of 1.81 kg and at an abrasion frequency of 1.8 s^{-1} with 500 strokes. The transfer of ink from the prints to the white paper (Paper 1) used as a receptor, and the damage of printed surface after rubbing were visually assessed. The colour fastness of the prints to artificial light (xenon arc fading lamp) was tested according to ISO 105-B02: 2014 using the Xenotest Alpha tester (Atlas, Rancho Cucamonga, CA, ZDA) under the following conditions: 35 °C, 35% relative humidity and 72 h, together with the standard blue reference scale. The colour change of the exposed prints was visually assessed using the blue wool references with ratings from 1 to 8, with 8 being the best value.

3. RESULTS WITH DISCUSSION

The prints produced with inks made from the dye extract of goldenrod flowers were light yellow, there were no major differences in colour and fastness properties when different printing pastes were used, except on white paper made from primary cellulose fibres, where the printing paste with a pH of 7.4 gave more yellowish and saturated prints than the commercially produced printing paste with a pH of 8.1 (Table 1).

Table 1: Colour values of prints produced with goldenrod dye extract

Colour values	1 g/100 g paste of pH 7.4	3 g/100 g paste of pH 7.4	1 g/100 g paste of pH 8.1	3 g/100 g paste of pH 8.1
On J.k. 200				
				
L*	82.81	82.98	83.07	83.40
a*	0.89	0.50	1.22	0.82
b*	16.52	18.80	15.76	17.67
C^*_{ab}	16.54	18.81	15.81	17.69
h_{ab} (°)	86.92	88.48	85.57	87.34
On J.k. 240				
				
L*	74.26	74.62	73.67	74.36
a*	4.08	4.23	4.32	3.80
b*	22.61	22.21	23.68	23.21
C^*_{ab}	22.97	22.61	24.07	23.52
h_{ab} (°)	79.77	79.22	79.66	80.70
On Paper 1				
				
L*	92.82	92.70	91.95	92.43
a*	-0.30	-2.60	-0.07	-1.24
b*	-3.27	4.79	-2.11	-0.19
C^*_{ab}	3.28	5.45	2.11	1.25
h_{ab} (°)	264.76	118.49	268.10	188.71

On Paper 2				
				
L*	92.07	90.97	90.73	90.38
a*	-1.41	-3.19	-2.00	-2.96
b*	5.67	12.85	8.86	12.79
C^*_{ab}	5.84	13.24	9.08	13.13
h_{ab} (°)	103.97	103.94	102.72	103.03

All prints made with the goldenrod extract inks showed excellent resistance to dry abrasion (Table 2). The best light fastness of the prints among all dye extracts was achieved with these inks, the light fastness of the prints according to the blue scale was on average grade 6, on white paper even grade 7 with both printing pastes. Only on recycled paper the prints of the goldenrod extracts became darker after exposure to light.

Table 2: Fastness properties of prints made with goldenrod dye extract

Fastness	1 g/100 g paste of pH 7.4	3 g/100 g paste of pH 7.4	1 g/100 g paste of pH 8.1	3 g/100 g paste of pH 8.1
On J.k. 200				
Dry rubbing (assessment of printed surface)	No change	No change	No change	No change
Dry rubbing (assessment of white paper)	No ink transfer	No ink transfer	No ink transfer	No ink transfer
Light fastness (blue reference)	6-7	6	6	6
On J.k. 240				
Dry rubbing (assessment of printed surface)	No change	No change	No change	No change
Dry rubbing (assessment of white paper)	No ink transfer	No ink transfer	No ink transfer	No ink transfer
Light fastness (blue reference)	5-6	5	5	5
On Paper 1				
Dry rubbing (assessment of printed surface)	No change	No change	No change	Slightly rubbed
Dry rubbing (assessment of white paper)	No ink transfer	No ink transfer	No ink transfer	No ink transfer
Light fastness (blue reference)	8	7	7	7
On Paper 2				
Dry rubbing (assessment of printed surface)	No change	No change	No change	No change
Dry rubbing (assessment of white paper)	No ink transfer	No ink transfer	No ink transfer	No ink transfer
Light fastness (blue reference)	5 darker	6 darker	5 darker	5 darker

The prints made with the dye extract from the leaves of Japanese knotweed were yellowish-green, lighter when the printing paste with a pH of 7.4 was used and more intense when the commercial printing paste with a pH of 8.1 was used (Table 3).

Table 3: Colour values of prints produced with Japanese knotweed

Colour values	1 g/100 g paste of pH 7.4	3 g/100 g paste of pH 7.4	1 g/100 g paste of pH 8.1	3 g/100 g paste of pH 8.1
On J.k. 200				
				
L*	/	79.56	80.97	75.30
a*	/	0.03	0.90	0.68
b*	/	26.26	21.32	29.91
C^*_{ab}	/	26.26	21.34	29.92
h_{ab} (°)	/	89.93	87.58	88.70
On J.k. 240				
				
L*	/	70.39	75.99	69.14
a*	/	3.65	2.93	3.91
b*	/	30.22	25.06	30.84
C^*_{ab}	/	30.44	25.23	31.00
h_{ab} (°)	/	83.11	83.33	84.09
On Paper 1				
				
L*	/	87.48	90.29	83.58
a*	/	-2.54	-1.03	-2.89
b*	/	16.93	3.60	22.36
C^*_{ab}	/	17.15	3.74	22.55
h_{ab} (°)	/	98.53	105.97	97.37
On Paper 2				
				
L*	/	88.48	89.21	84.64
a*	/	-2.42	-2.21	-3.78
b*	/	17.96	13.19	24.92
C^*_{ab}	/	18.12	13.37	25.20
h_{ab} (°)	/	97.68	99.51	98.63

The prints made from Japanese knotweed extract using the printing paste with a pH value of 7.4 were more resistant to dry rubbing and light (fastness grade 4) than the prints made using the commercial printing paste with a pH value of 8.1, while the prints on the Japanese knotweed papers were rubbed off after the rub resistance test and the light fastness of the prints of a higher concentration on all papers deteriorated sharply (grade 2).

Table 4: Fastness properties of prints made with Japanese knotweed

Fastness	1 g/100 g paste of pH 7.4	3 g/100 g paste of pH 7.4	1 g/100 g paste of pH 8.1	3 g/100 g paste of pH 8.1
On J.k. 200				
Dry rubbing (assessment of printed surface)	/	No change	No change	Slightly rubbed
Dry rubbing (assessment of white paper)	/	No ink transfer	No ink transfer	No ink transfer
Light fastness (blue reference)	/	4	4-5	2
On J.k. 240				
Dry rubbing (assessment of printed surface)	/	No change	No change	Slightly rubbed
Dry rubbing (assessment of white paper)	/	No ink transfer	No ink transfer	No ink transfer
Light fastness (blue reference)	/	3	4-5	2
On Paper 1				
Dry rubbing (assessment of printed surface)	/	Slight shine	No change	No change
Dry rubbing (assessment of white paper)	/	Slight ink transfer	No ink transfer	No ink transfer
Light fastness (blue reference)	/	4	2	2
On Paper 2				
Dry rubbing (assessment of printed surface)	/	No change	No change	No change
Dry rubbing (assessment of white paper)	/	Slight ink transfer	No ink transfer	No ink transfer
Light fastness (blue reference)	/	4-5	5-6	3

The colour of the prints made from the petals of the Himalayan balsam was strongly influenced by the printing pastes with different pH values. The prints made with the printing paste with a pH of 7.4 were more intense purplish brown, while the prints made with the commercially prepared printing paste with a pH of 8.1 were more brown (Table 5).

Table 5: Colour values of prints produced with Himalayan balsam

Colour values	1 g/100 g paste of pH 7.4	3 g/100 g paste of pH 7.4	1 g/100 g paste of pH 8.1	3 g/100 g paste of pH 8.1
On J.k. 200				
				
L*	/	77.56	80.71	76.36
a*	/	4.17	2.30	3.69
b*	/	14.26	15.46	17.67
C^*_{ab}	/	14.86	15.63	18.05
h_{ab} (°)	/	73.70	81.54	78.20
On J.k. 240				
				
L*	/	69.46	71.31	68.15
a*	/	6.65	4.90	5.95
b*	/	21.52	22.69	23.18
C^*_{ab}	/	22.52	23.21	23.93
h_{ab} (°)	/	72.83	77.81	75.60
On Paper 1				
				
L*	/	81.27	89.79	83.31
a*	/	4.03	1.66	2.22
b*	/	3.69	-3.81	5.81
C^*_{ab}	/	5.46	4.16	6.22
h_{ab} (°)	/	42.48	293.54	69.09
On Paper 2				
				
L*	/	85.73	89.45	84.05
a*	/	1.04	-0.39	0.44
b*	/	5.74	5.78	10.51
C^*_{ab}	/	5.83	5.79	10.52
h_{ab} (°)	/	79.73	93.86	87.61

The rub resistance test showed that the prints on papers with the Himalayan balsam dye extract rubbed off a little, except on white paper made from primary cellulose fibres, where the resistance with both printing pastes was excellent (Table 6). The light fastness of the prints made with the Himalayan balsam dye extract was only 3 on average with both printing pastes, except on the recycled paper where the light fastness of the prints was better with a grade of 4-5.

Table 6: Fastness properties of prints made with Himalayan balsam

Fastness	1 g/100 g paste of pH 7.4	3 g/100 g paste of pH 7.4	1 g/100 g paste of pH 8.1	3 g/100 g paste of pH 8.1
On J.k. 200				
Dry rubbing (assessment of printed surface)	/	Slightly rubbed	No change	Slightly rubbed
Dry rubbing (assessment of white paper)	/	No ink transfer	No ink transfer	No ink transfer
Light fastness (blue reference)	/	3-4	5-6	3-4
On J.k. 240				
Dry rubbing (assessment of printed surface)	/	Slightly rubbed	No change	Slightly rubbed
Dry rubbing (assessment of white paper)	/	No ink transfer	No ink transfer	No ink transfer
Light fastness (blue reference)	/	3	5	3
On Paper 1				
Dry rubbing (assessment of printed surface)	/	No change	No change	No change
Dry rubbing (assessment of white paper)	/	No ink transfer	No ink transfer	No ink transfer
Light fastness (blue reference)	/	2	5	2
On Paper 2				
Dry rubbing (assessment of printed surface)	/	Slightly rubbed	No change	Slightly rubbed
Dry rubbing (assessment of white paper)	/	No ink transfer	No ink transfer	No ink transfer
Light fastness (blue reference)	/	4-5	4-5	4-5

4. CONCLUSIONS

The research results confirmed that the printing inks made from natural dyes using pigment printing pastes can be successfully used for screen printing on various papers and have very good rub resistance. However, the lower light fastness of the prints made with the dyes from Himalayan balsam petals and Japanese knotweed leaves limits their use for outdoor paper products. The different pH value of the printing paste also had a great influence on the colour of the prints of all dye extracts and on the fastness of the prints made with the leaves of Japanese knotweed. The prints made with the yellow dye extract from goldenrod flowers showed the best fastness properties on all the papers tested.

5. REFERENCES

Gorjanc, M., Savić, A., Topalić-Trivunović, L., Mozetič, M., Zaplotnik, R., Vesel, A. and Grujić, D. 2016. “Dyeing of plasma treated cotton and bamboo rayon with Fallopia Japonica extract.” *Cellulose* 23: 2221–2228.
Gorjanc, M., Kert, M., Mujadžić, A., Simončič, B., Forte-Tavčer, P., Tomšič, B. and Kostanjšek, K. 2019. “Cationic pretreatment of cotton and dyeing with Fallopia Japonica leaves.” *Tekstilec* 62:181–186.
Horvat, M., Iskra, J., Pavlič, M., Žigon, J. and Merela, M. 2020. “Wood dyes from invasive alien plants.” *Les* Wood 69: 37–48.
Klančnik, M. 2021. “Screen Printing with Natural Dye Extract from Japanese Knotweed Rhizome.” *Fiber Polym*. 22: 2498–2506.
Klančnik, M. 2021. “Printing with Natural Dye Extracted from Impatiens glandulifera Royle.” *Coatings* 11: 445–457.
Klančnik, M. 2024. “Printing with Natural Dye Extract from Japanese Knotweed Leaves.” *Fibers Polym*. 25: 4771–4785.
Topič, T., Gorjanc, M. and Kert, M. 2018. “The influence of the treatment process on the dyeability of cotton fabric using goldenrod dye.” *Tekstilec* 61: 192–200.

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POSTER PRESENTATION

REPRODUCTION OF COLOUR PATCHES ON TEXTILE AND PAPER MATERIALS

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***Abstract**: This study compares the colour reproduction capabilities of two Canon inkjet printers: the older imagePROGRAF W8400 and the newer imagePROGRAF PRO-4000S. Using the same paper (EMBLEM Water Coated Paper 180) and a textile substrate (Blackout VI DirectTex), we evaluated colour accuracy, colour gamut size and overall print quality. The results showed that the PRO-4000S with its extended eight-ink system produced a significantly larger colour gamut and more accurate colours compared to the older six-ink W8400. On paper, colour differences were minimal, but on textile material, colour accuracy decreased due to the limitations of the substrate. This underlines the importance of substrate-specific colour management strategies and adapted ICC profiles to optimise colour consistency when printing on different materials.*

***Keywords:** ICC profiles, colour accuracy, colour differences, inkjet printing, Canon imagePROGRAF.*

1. INTRODUCTION

Today's rapid technological advances are changing the industry, and the printing industry is no exception. Innovations in digital printing, ink formulations and materials science are revolutionising the way we reproduce colour, enabling greater accuracy, efficiency and adaptability across a wide range of applications and materials.

Technological advances such as faster presses, improved ink technology and hybrid printing solutions are enhancing production efficiency and quality. The global market for commercial printing is driven by the increasing demand for printed marketing materials such as brochures, leaflets and packaging. Digital printing is the fastest growing segment, driven by innovations in inkjet, laser printing and AI integration. Despite challenges such as rising raw material costs and the switch to digital media, the market is finding opportunities in environmentally friendly processes such as soya-based inks and recycled paper. (Grand View Research, 2024)

Like many industry leaders, Canon utilises its research and development departments to continuously develop printing technologies. Through continuous investment in research and development (R&D), Canon develops new ink formulations, improves printhead precision and expands media compatibility. The result of these efforts are innovations such as a wider colour gamut, better colour consistency and faster print production. The LUCIA PRO ink system, for example, has significantly improved colour fidelity and durability and meets the high demands of professional photographers, artists and print service providers. With faster print speeds and improved media handling, including the ability to print on various materials such as textiles, canvas and technical papers, Canon's imagePROGRAF line continues to push the boundaries of modern printing. These technological advances fulfil the market's growing demand for high-quality, reliable and efficient printing solutions and demonstrate how strategic R&D investment can drive innovation in the industry and meet evolving customer needs. (Canon, 2025) Accurate colour reproduction has become a critical requirement in industries ranging from commercial printing and packaging to textiles and industrial applications. Customers and brands expect visually consistent prints that perfectly match digital designs, which requires colour management and precise printer calibration. The need for colour accuracy extends beyond traditional media as new substrates–such as synthetic papers, synthetic, speciality and technical textiles, flexible films, and textured surfaces–are being introduced to expand the possibilities

of print applications. Each of these materials has specific requirements for ink absorption, reflectivity and colour gamut compatibility, requiring bespoke colour profiling and workflow optimisation.

When printing, it is crucial to know the properties of the substrate, as they significantly influence the quality and durability of the final print. Unlike paper, textile materials have a wider range of variables, including fabric structure, raw material composition, thread density and physical properties such as yarn diameter, fabric thickness and whiteness. In contrast, paper substrates have precisely defined properties such as grammage, thickness, brightness, smoothness and absorbency. These properties all influence the final print quality, so it is important to take them into account when making accurate comparisons and evaluations. A thorough understanding of these properties is essential for industries seeking high-quality, reproducible prints with accurate detail and colour reproduction. (Mendizza, 2024)

2. EXPERIMENTAL

2.1 Printers and printing substrates

To asses the advances in printing technology, we first carried out a comparative analysis of prints made with an older Canon imagePROGRAF W8400 printer and a newer Canon imagePROGRAF PRO-4000S (Figure 1). Both printers are inkjet printers and use water-based inks. The W8400 uses a six-colour ink system with cyan, magenta, yellow, black, light cyan and light magenta, while the PRO-4000S uses an advanced eight-ink configuration that includes photo black, matte black, cyan, magenta, yellow, photo cyan, photo magenta and grey. This comparison allowed us to assess the improvements in colour accuracy, colour gamut size and overall print quality resulting from advances in printing technology.



Figure 1: Canon imagePROGRAF W8400(left), Canon imagePROGRAF PRO-4000S (right) (Canon, 2025)

In the first part of our study, both printers used the same paper substrate to ensure consistency in the evaluation process. The chosen substrate was EMBLEM Water Coated Paper 180 (manufactured by Dataplot, Germany), a high-quality printing paper with a grammage of 180 g/m². This paper is ultra-white, has a heavy matt coating and is specifically designed to improve colour reproduction and ink adhesion, making it an ideal choice for accurate colour evaluation (Dataplot, 2021). By maintaining identical printing conditions, we wanted to isolate and emphasise the differences in performance due to the printers themselves.

In the second part of our study, we wanted to evaluate the print quality of the newer printer, Canon imagePROGRAF PRO-4000S, on different substrates to assess its adaptability and performance. In particular, we compared prints on a paper substrate with those on a textile substrate to determine how the material properties affect colour reproduction, colour fidelity and consistency. The textile substrate we chose was Blackout VI DirectTex (manufactured by Pongs, Germany), a high-quality fabric designed for direct printing applications. This material is

characterised by a dense, opaque structure that minimises light transmission. This makes it suitable for applications that require vibrant colours and high contrast. (Pongs, 2024)

By analysing prints on EMBLEM Water Coated Paper 180 and Blackout VI DirectTex, we wanted to determine the printer‘s strengths and limitations when working with different substrates and which materials deliver the most accurate and consistent colour results.

2.2 Colour management and the printing process

To ensure repeatability, we created ICC profiles for both printers and the substrates tested. We used a spectrophotometer (i1Pro 2) and i1Profiler software to create custom ICC profiles that allowed us to accurately calibrate and characterise each printer-substrate combination. We created profiles for both the Canon imagePROGRAF W8400 and Canon imagePROGRAF PRO-4000S on EMBLEM Water Coated Paper 180 and for the Canon imagePROGRAF PRO-4000S on Blackout VI DirectTex. This ensures consistent and reproducible colour reproduction across different print runs. By minimising variations due to device-specific characteristics, ink interactions and substrate properties, we have created a reliable basis for comparing colour accuracy, gamut size and overall print quality.

The i1Pro 2 spectrophotometer (manufactured by X-Rite) is standardised according to ISO 13655:2017, an international standard that defines the spectral measurement conditions for graphic arts applications. This standard specifies the use of the CIE 1931 standard colorimetric observer, which is based on a 2° field of view and simulates human colour perception under controlled conditions. In addition, the measurements were performed under a D50 illumination source, which corresponds to a standardised daylight condition with a correlated colour temperature of approximately 5000 K (ISO, 2017). This ensures consistency and comparability of colour data across different devices and printing environments. By adhering to these standardised methods, we have ensured the reliability of our colour profiling process and enabled an objective assessment of each printer’s performance in terms of colour accuracy and gamut size.

2.3 Colour chart

To measure colour consistency, we selected the patches from the ColorChecker Classic test chart. The ColorChecker Classic is a widely recognised and standardised colour reference chart used in colour calibration and profiling. It consists of 24 colour patches, each representing a specific, carefully selected colour covering a range of hues, tones, and saturations commonly used in imaging and printing processes. These colour patches include a variety of primary and secondary colours, grayscale, and skin tones, making them a comprehensive tool for evaluating a printer‘s ability to accurately reproduce colours. (calibrate, 2025; Lindbloom, 2025) Using Adobe Illustrator, we designed the patches based on the ColorChecker Classic test chart and ensured that each patch exactly matched the intended colour values to enable accurate colour evaluation (Figure 2).

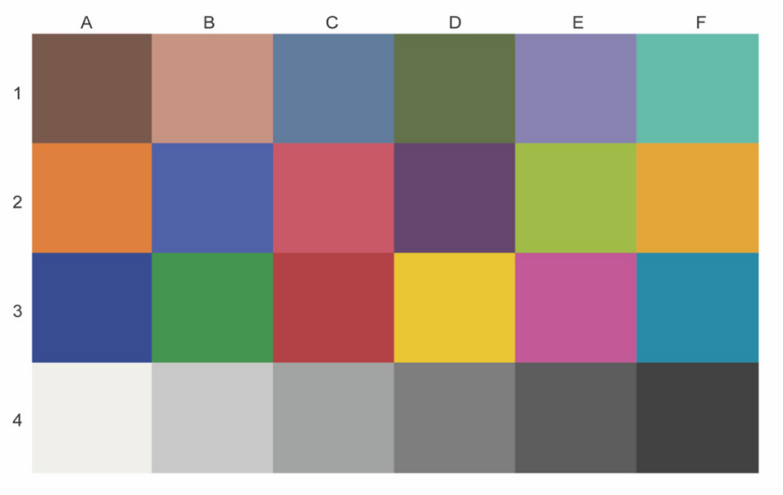


Figure 2: ColorChecker Classic test chart, patches created in Adobe Illustrator

3. RESULTS WITH DISCUSSION

3.1 Visual comparison of the colour profiles

To visually compare the colour gamuts of the ICC profiles, we used the macOS-based application ColorSync Utility. This tool enables the visualisation and comparison of ICC profiles and provides a detailed representation of the colour gamut of the individual printers (Apple, 2025). First, we compared the colour gamuts of the Canon imagePROGRAF W8400 and the Canon imagePROGRAF PRO-4000S using EMBLEM Water Coated Paper 180 as substrate. The colour gamut of the profile created with the older W8400 is visibly smaller (Figure 3, left). As this printer uses fewer colours, the result is a smaller colour gamut that is reproduced. In contrast, the newer Canon imagePROGRAF PRO-4000S has a much wider colour gamut, thanks to its extended ink set (Figure 3, right). With this extended ink set, the PRO-4000S can reproduce a much wider range of colours.

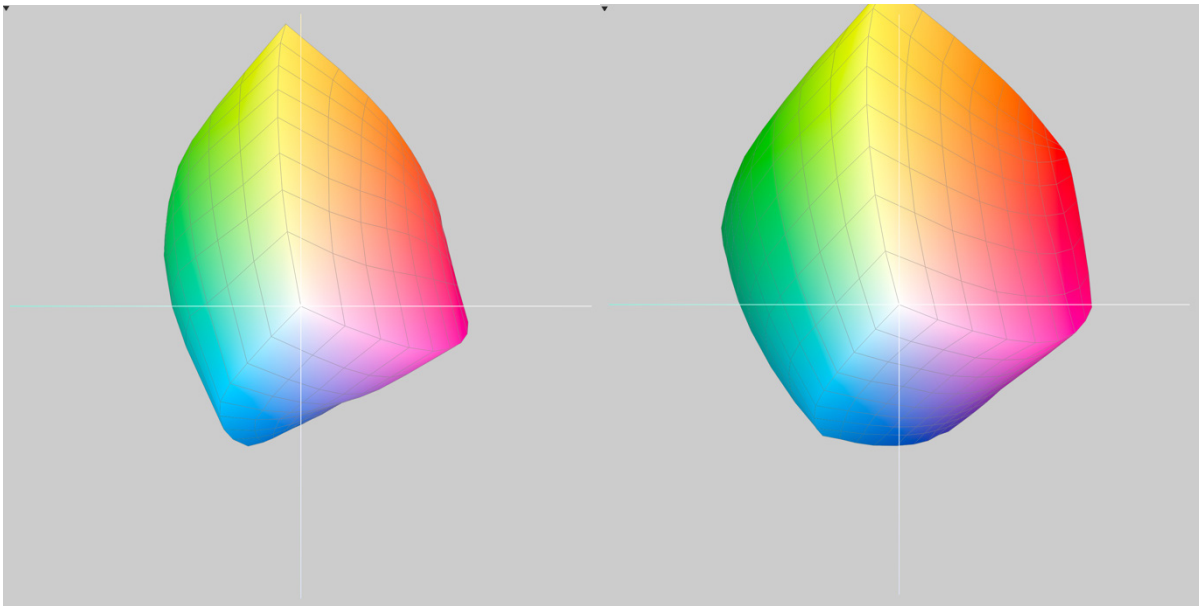


Figure 3: Colour gamut of an ICC profile made on Canon imagePROGRAF W8400 (left), Colour gamut of an ICC profile made on Canon imagePROGRAF PRO-4000S

In the second part of the study, we compared the ICC profiles created for the newer Canon imagePROGRAF PRO-4000S with two different substrates: paper and textile. This comparison allowed us to assess how the characteristics of the substrate, e.g. texture, material composition and coatings, affect colour reproduction and colour fidelity. The results show that the paper substrate EMBLEM Water Coated Paper 180 has a wider colour gamut (Figure 4, left) compared to the textile substrate Blackout VI DirectTex (Figure 4, right). This suggests that the paper substrate allows for a wider colour gamut, probably due to its smoother surface and more uniform ink absorption, while the textile substrate has a more limited colour gamut due to its porous nature and texture.

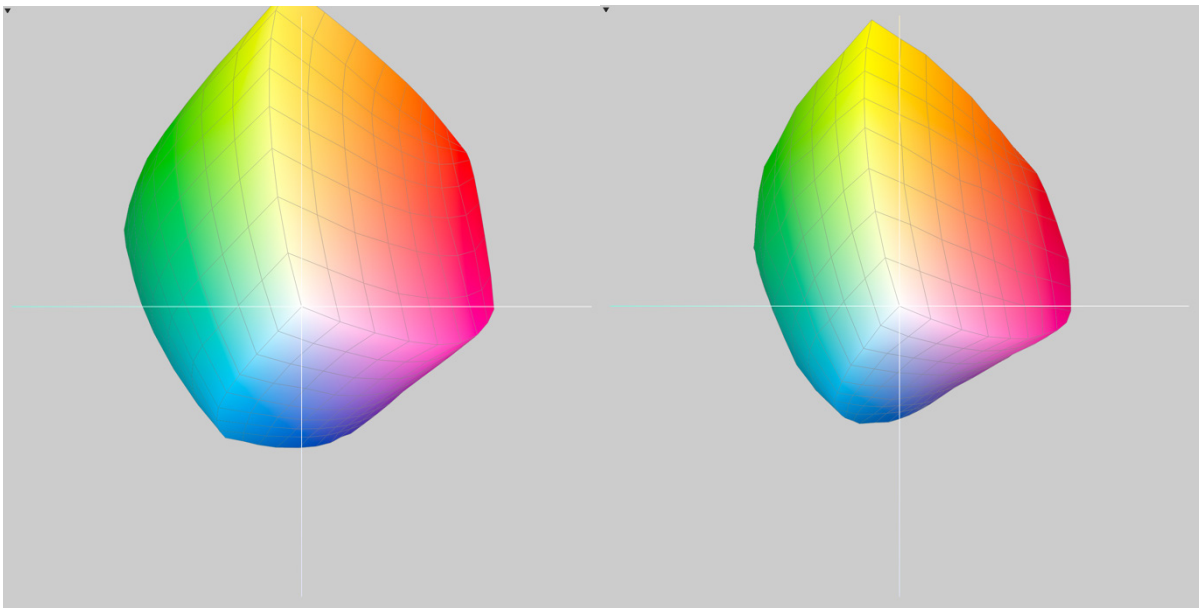


Figure 4: Colour gamut of an ICC profile made on the Canon imagePROGRAF PRO-4000S for paper substrate (left) and textile substrate (right)

3.2 Colour differences

For all patches on the ColorChecker Classic test chart, we measured the $L^*a^*b^*$ values and calculated the ΔE_{00} colour differences (Luo, 2001). The values for the colour differences can be divided into four groups. The first group includes colour differences from 0 to 1, where the difference is not perceptible to the naked eye. The second group ranges from 1 to 3, which represents a small colour difference. The third group includes differences from 3 to 6, where the colour difference is visible to the naked eye, and the fourth group consists of differences of more than 6, which indicates a significant colour difference.

For the prints made with the Canon imagePROGRAF W8400 on paper substrate the average colour difference for all 24 patches was 4.2, with the lowest value being 1 and the highest 9. Most of the colour differences fall into the third group, where the differences are visible to the naked eye, with some patches exceeding a value of 6 and thus falling into the fourth group, which indicates large colour deviations. Figure 5 shows the printed patches.

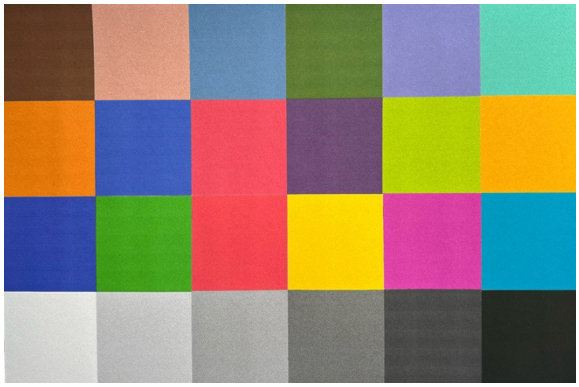


Figure 5: Patches on the paper substrate made with Canon imagePROGRAF W8400

The average colour difference of the patches made with the Canon imagePROGRAF PRO-4000S was 2.3, with the lowest value being 0.4 and the highest 5.1. The majority of the patches fall into the second group, where the differences are small but perceptible on closer inspection. Only a few patches reach the third group, which shows a general improvement in colour accuracy compared to the older printer. Figure 6 shows the printed patches.



Figure 6: Patches on paper substrate made with Canon imagePROGRAF PRO-4000S

For the textile substrate printed with the Canon imagePROGRAF PRO-4000S the average colour difference was 7.8, with the highest value being 14 and the lowest 2.7. The highest colour differences can be observed here, with most patches in the third and fourth group, i.e. the deviations are easily visible. Several patches exceed the value of 6, indicating a significant loss of colour accuracy due to substrate limitations. Figure 7 shows the printed patches.

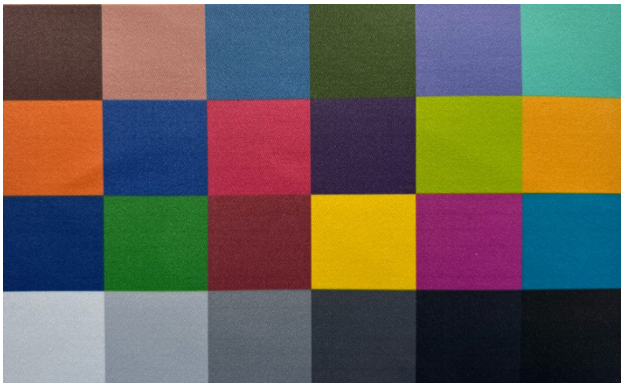


Figure 7: Photo of the patches on paper substrate made with Canon imagePROGRAF PRO-4000S

The analysis of the colour differences shows that the colour accuracy varies greatly depending on the printer and the substrate used, which is reflected in the classifications of the colour difference groups. The highest colour differences are found on the textile substrate. This is primarily due to the limitations of ink application and the physical properties of the textile substrate. Unlike paper, which allows for precise ink deposition and controlled absorption, textiles exhibit higher ink diffusion, uneven absorption and variations in surface texture, all of which contribute to greater deviations from the reference colours. In addition, the smaller colour gamut of the textile substrate limits the ability to reproduce highly saturated and accurate colours.

These results underline the importance of substrate-specific colour management strategies. Optimising ink application techniques, using appropriate print profiles and adjusting colour compensation settings are crucial for minimising perceptible colour differences when printing on different substrates.

4. CONCLUSION

The experimental analysis of colour differences in conjunction with visual comparisons of the colour gamuts, highlights significant differences in colour reproduction accuracy between the older Canon imagePROGRAF W8400 and the newer Canon imagePROGRAF PRO-4000S, as well as with different substrates.

The results show that the newer Canon imagePROGRAF PRO-4000S with its expanded eight-ink configuration offers a significantly larger colour gamut and improved colour accuracy compared to the older six-ink Canon imagePROGRAF W8400. The wider colour gamut enables more accurate colour reproduction, and the newer printer‘s ability to reproduce a wider colour gamut contributes to more accurate prints. The paper substrate, EMBLEM Water Coated Paper 180, also contributes to better colour reproduction due to its smooth surface and even ink absorption. This substrate showed a wider colour gamut and smaller colour differences, especially on the PRO-4000S, where most colour differences were in the small or low range (between 1 and 3).

In contrast, the study showed a remarkable decrease in colour accuracy when printing on the Blackout VI DirectTex textile substrate. The textile substrate showed a more limited colour gamut and larger colour differences (more than 6). The inherent irregularities in the diffusion and absorption of the ink in the textile material, combined with the limited colour gamut of the substrate, contributed to larger deviations from the reference colours. These results highlight the challenges of consistent and accurate colour reproduction on textiles.

The results emphasize the importance of substrate-specific colour management strategies. Optimising ink application, using customised ICC profiles and carefully adjusting colour compensation settings are critical to minimising colour differences when working with different substrates. This study highlights that achieving colour consistency is not only dependent on the printer itself, but is also significantly influenced by the properties of the substrate, underlining the need for tailored approaches to colour management in the printing process.

5. REFERENCES

Apple. Title: ColorSync Utility User Guide. URL: https://support.apple.com/en-gb/guide/colorsync-utility/welcome/mac (last accessed on 1. 2. 2025).
Calibrate. Title: ColorChecker Classic Mini. URL: https://calibrite.com/product/colorchecker-classic-mini/ (last accessed on 1. 2. 2025).
Canon. Title: Canon USA. URL: https://www.usa.canon.com (last accessed on 1. 2. 2025).
Dataplot. 2021. *Data sheet EMBLEM Water Coated Paper 180.* Henstedt-Ulzburg: Dataplot.
Grand View Research. 2024. *Commercial Printing Market Size, Share & Trends Analysis Report By Printing Technology (Digital Printing, Lithography Printing), By Application (Packaging, Advertising), By Region, And Segment Forecasts, 2025 - 2030.* San Francisco: Grand View Research.
ISO. 2017. *ISO 13655:2017 Graphic technology — Spectral measurement and colorimetric computation for graphic arts images*. ISO.
Lindbloom, B. Title: Bruce Lindbloom. URL: http://www.brucelindbloom.com (last accessed on 1. 2. 2025).
Luo, M. R., Cui, G. and Rigg, B. 2001. "The Development of the CIE 2000 Colour Difference Formula: CIEDE2000. " *Color Research and Application,* vol. 26, no. 5, pp. 340–350, 2001.
Mendizza, A. 2024. "Characterisation of prints made with inkjet printer Canon imagePROGRAF PRO- 4000s." master's thesis, University of Ljubljana.
Pongs Technical Textiles GmbH. 2021. *DirectTex® Blackout VI*. URL: https://atech.co.uk/consumables-printable-fabrics/pongs-directtex-blackout-vi-pd-801.html (Retrieved 27. 1. 2024).

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PHOTOGRAPHY AND COLORIMETRY

ORAL PRESENTATION

COMPARATIVE STUDY OF NOISE REDUCTION TECHNIQUES FOR PHOTOGRAPHIC IMAGE ENHANCEMENT

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Abstract: *The quality of digital photographs is influenced by various factors, including noise, which can reduce image quality. Noise refers to unwanted artifacts that do not originate from the scene itself, distracting the viewer from important details. While noise is always present in digital photography, it can be minimized in cameras with larger pixels. Noise arises from physical effects like the photonic nature of light and thermal energy in the camera sensor. Despite being a characteristic in analog photography, noise is generally seen as undesirable in digital images, prompting the development of various noise reduction techniques. This research compares manual and artificial intelligence-based methods for noise removal, analyzing their effectiveness across different software. The study examines seven photos with varying noise levels and lighting conditions, using both RAW and JPG formats. Results show that AI-based software offers faster processing, better image clarity, and enhanced detail, offering significant advantages over manual methods.*

Keywords: *digital photography, noise, image processing, artificial intelligence-based techniques*

1. INTRODUCTION

Image quality is significantly affected by noise, which complicates feature extraction, analysis, recognition, and precise measurements. Noise is inherently present in digital images throughout the processes of capture, encoding, transmission, and editing. Various fields, including robotics, education, biometrics, medical and biomedical imaging, remote sensing, security, and surveillance, require clear, noise-free images for accurate processing. Effective noise removal is a complex task that depends on identifying the specific type of noise. Numerous methods have been developed to reduce noise and restore the image to its original quality (Al Mudhafar, 2022) (Owotogbe, 2019).

Noise in photographs appears as artifacts that do not originate from the actual scene content. It is one of the undesirable effects that degrade image quality. A noisy photograph distracts the viewer, drawing attention to grainy areas instead of essential image elements (Image Engineering, 2023). Digital cameras always introduce some degree of noise, but it can be exceptionally low in cameras with larger pixel sizes (pixel pitch ≥ 3 μm) (Imatest, 2023). While signal processing improvements have successfully minimized noise, it remains a challenge in compact digital cameras and mobile phone cameras with small pixel sensors. At high ISO values, noise reduction algorithms can cause a visible loss of fine details and textures.

Noise is most noticeable in uniform areas of an image and is particularly prominent in darker regions (shadows). It belongs to the category of local quality attributes, meaning that its perception depends on viewing conditions, such as observation distance and image size (DxOmark, 2023).

Various types of noise can appear in digital photographs. It can be randomly distributed, exhibit a fixed pattern, or appear as banding lines (Kuzmenko, 2023). Common noise types include Gaussian noise, salt-and-pepper noise, speckle noise, and shot noise (Poisson noise) (Lendave, 2023). When addressing noise removal in digital photography, the most critical distinction is between luminance noise and chrominance noise. Luminance noise is evenly distributed across the image, more visible in darker areas, and easier to remove. Chrominance noise, on

the other hand, is more prominent at high ISO values and appears unevenly across the image (Karlović, 2012). Reducing noise in digital images is a challenging task because noise is linked to high-frequency content, such as fine details. The goal is to balance noise suppression while preserving critical image information. Various filtering techniques are commonly used for noise reduction. Noise reduction should ideally be performed before sharpening, and for better results, edge masking and channel-specific noise reduction are recommended. Since noise is typically most dominant in the blue channel, the strongest reduction should be applied there (Wang, 2004).

Recently, artificial intelligence-based tools have been developed to effectively recognize noise intensity and automatically remove it while preserving sharp details. These tools present an alternative to traditional noise reduction methods. The aim of this study is to test and compare different software solutions for noise reduction. Some programs require users to manually assess the noise level and adjust the necessary values for optimal correction, while others perform the entire process automatically.

2. EXPERIMENTAL

The experimental part of this study consists of comparing the obtained results of noise removal from photographs using manual methods, i.e., applying filters where the user visually assesses the noise level and selects the appropriate correction values accordingly, and AI-based methods through multiple different software solutions to evaluate their capabilities. This is followed by an assessment of the quality of the processed images using metrics, as well as an analysis and discussion of the obtained results. The software selected for testing includes Adobe Photoshop 2021, Adobe Lightroom 2023, DxO PureRAW 3, Luminar Neo, Noiseware, Neat Image, and ON1 NoNoise AI. Photographs with varying content and levels of noise were used to better assess the noise removal capabilities and processing quality of the software. Seven images were selected, differing in content, the amount of noise present, and the lighting conditions during capture. Additionally, the two most common photo formats, NEF (RAW) and JPG, were chosen. Figure 1 presents the photographs used for noise correction in the experimental part of the study.

Each photograph was first processed in Adobe Photoshop. Both JPG and RAW images were edited using the Reduce Noise filter. The masking capabilities of the software were also analyzed. Based on the amount of noise present, the necessary manual adjustments were selected. Afterward, noise correction was performed in the other listed software, where the automatic correction mode was tested. Adobe Photoshop, Adobe Lightroom, DxO PureRAW 3, Noiseware, and ON1 NoNoise AI offer direct processing of RAW images, while Luminar Neo and Neat Image require prior conversion of RAW images to JPG format.

In addition to the visual assessment of the quality of the corrected photographs, the applicability of the SSIM (Structural Similarity Index Measure) metric was examined for monitoring and analyzing noise correction in images (Wang, 2004). The SSIM metric produces both a numerical value and a visual map, indicating areas where greater or lesser differences are present in the images. A comparison was conducted between all corrected images, with each one being compared to every other, resulting in a distance matrix. This matrix can be further utilized for data processing, in this case, Multidimensional Scaling (MDS).

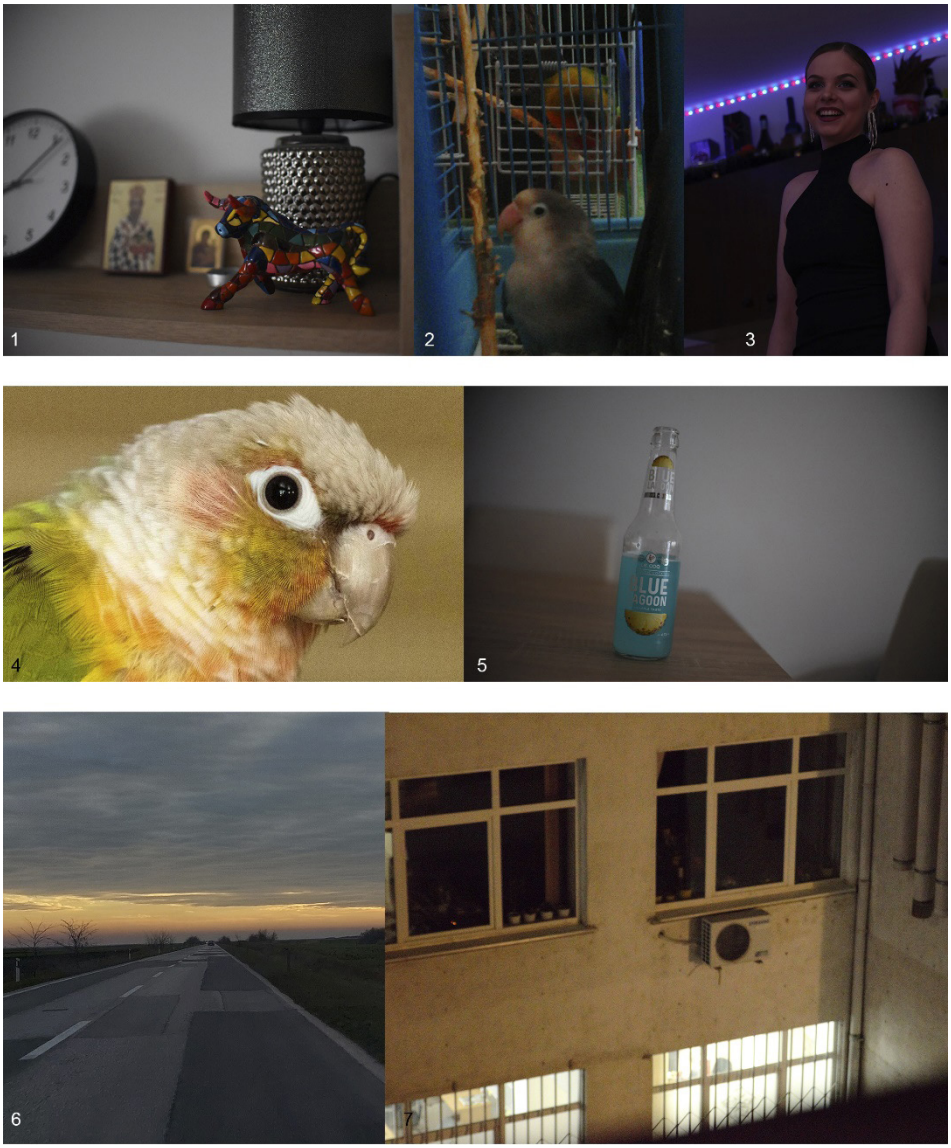


Figure 1: Display of photographs used for correction in the experimental part of the study

3. RESULTS

Based on the analysis of the obtained samples, we conclude that software, depending on the content of the images, produces different processing results. Manual processing is most commonly done with software like Adobe Photoshop and Luminar Neo, while automatic processing is handled by software such as Adobe Lightroom, Noiseware, Neat Image, ON1 NoNoise AI, and DxO PureRAW 3. Satisfactory noise reduction results are provided by ON1 NoNoise AI, Neat Image, and Noiseware for JPG format images, while for RAW format, Neat Image, Adobe Lightroom, and DxO PureRAW 3 stand out. However, some software may also affect other aspects of the photo during reduction, thus altering it. The third example is shown in Figure 2, where it is clearly visible that noise correction in artificial intelligence-based software also applies additional adjustments. In Figure 2 under a), a crop of the original photograph is shown for comparison of the results. In example b), the image processed with the software ON1 NoNoise AI is presented, where during the automatic noise reduction, the software also corrects the color and brightness. In examples c) and d), the noise reduction results are adequate, with the difference being that the software DxO PureRAW 3 lightens the image and makes it cleaner, while the software Neat Image slightly darkens the image but preserves the details.

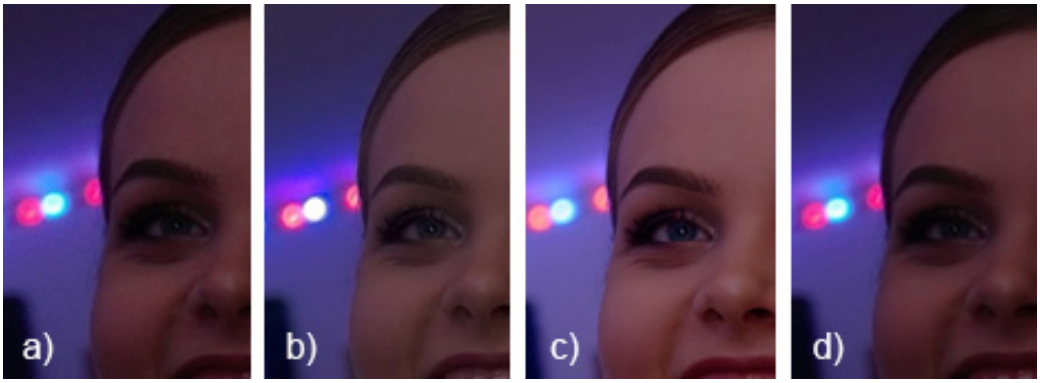


Figure 2: Part of: a) original third photograph and its processing in the software: b) ON NoNoise AI, c) DxO PureRAW 3, and d) Neat Image

Based on visual inspection of all seven processed images, DxO PureRAW 3 (for RAW format images), Noiseware, and Neat Image deliver the most effective and accurate noise reduction results. All three software programs operate on the principle of artificial intelligence and automatic noise removal, leading to the conclusion that this technology has advanced and surpassed manual noise reduction methods, which require additional time in the photo editing process. AI-based noise reduction software can effectively detect the amount of noise present and remove it while preserving details, which is of crucial importance. In addition to noise reduction, some software also provides additional correction options, including color and brightness adjustments, significantly optimizing the processing workflow and enhancing the overall image quality. Based on the obtained SSIM values, it can be concluded that this metric does not consider only a single quality attribute but, as stated, compares the structural differences between pixels in the images. For example, when comparing the original photograph with the correction applied in DxO PureRAW 3 (Figure 3), the lowest SSIM value (0.5702) is obtained, even though this correction appears significantly better than that of another software with a higher SSIM value. The differences in characteristics between software solutions, such as DxO PureRAW 3 and other programs, stem from its ability to perform additional automatic corrections, including distortion and brightness adjustments. These corrections are effectively illustrated in the generated structural similarity (SSIM) map, which highlights the significantly enhanced performance of DxO PureRAW 3 compared to other tools. These automatic corrections, in addition to noise reduction, were also observed in RAW format images processed with ON1 NoNoise AI and DxO PureRAW 3.

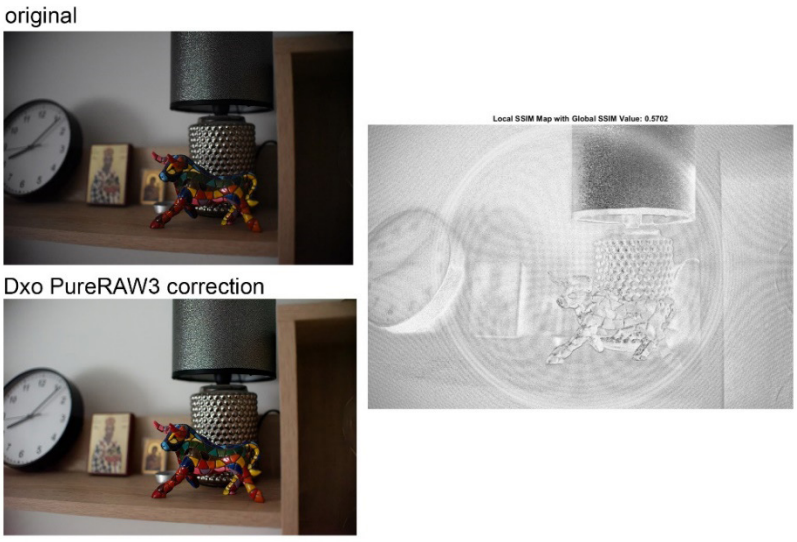


Figure 3: The first photograph and its processing in DxO PureRAW 3, compared using the SSIM metric

Based on the MDS analysis, it can be concluded that the SSIM values provide a distribution across multiple dimensions rather than a single expected one. The samples are distributed along the x- and y-axes within the range of -1.5 to +1.5, indicating that they cannot be approximated or classified based solely on one dimension, such as noise.

Figure 4 presents the results of the MDS analysis for the first example, where the samples are distributed between -2 and +2 on both axes. Additionally, more than two dimensions—quality attributes observed using the SSIM metric—have been identified.

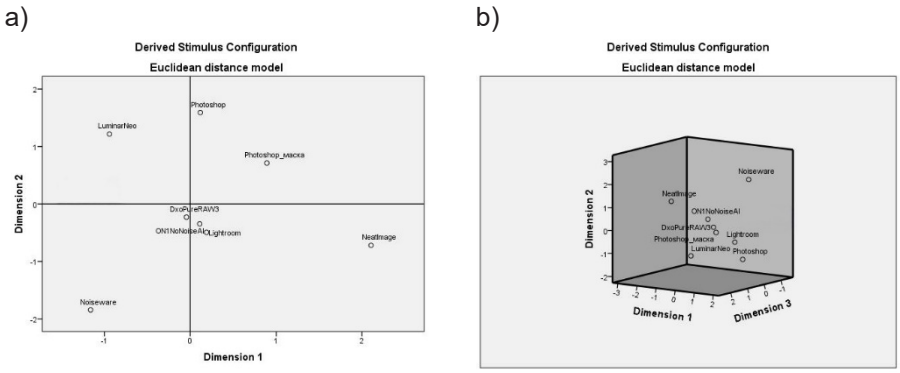


Figure 4: The results of the MDS analysis for the first example

4. CONCLUSIONS

The analysis of noise reduction capabilities across seven different software solutions on both RAW and JPG formats highlights significant differences in performance. AI-based software solutions generally outperform manual methods in terms of speed and quality of noise reduction, preserving more image details while delivering cleaner results.

Among the tested software, Neat Image demonstrated exceptional performance in noise removal, while DxO PureRAW 3 provided high-quality results but was limited to RAW format. Adobe Lightroom's AI-based processing yielded satisfactory results for RAW images but underperformed with JPG images due to manual processing limitations. Noiseware and ON1 NoNoise AI provided decent noise reduction but occasionally introduced blurring and loss of details. In contrast, Adobe Photoshop and Luminar Neo, relying primarily on manual noise correction, required additional adjustments and filters to achieve satisfactory results, making them less efficient compared to AI-driven alternatives.

The application of SSIM metrics enabled a quantitative assessment of noise correction effectiveness, providing insights into the differences between processed images. The findings confirm that AI-driven noise reduction methods are more efficient and practical, offering a significant advantage over manual techniques due to their speed and superior image clarity.

Future research should focus on improving AI noise reduction algorithms to better balance noise removal with detail preservation, especially in JPG images. Additionally, exploring the integration of hybrid AI-manual correction workflows could offer enhanced control and flexibility in noise reduction processes.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Al Mudhafar, R. A. and El Abbadi, N. K. 2022. “Noise in Digital Image Processing: A Review Study.” 3rd Information Technology To Enhance e-learning and Other Application (IT-ELA), Baghdad, Iraq, 2022, pp. 79-84, doi: 10.1109/IT-ELA57378.2022.10107965.
Dxomark. What is noise? URL: https://www.dxomark.com/glossary/noise/ (last accessed on 03.07.2023).
Image Engineering. Noise. URL: https://www.image-engineering.de/library/image-quality/factors/1080-noise (last accessed on 06.06.2023).
Imatest. Noise in photographic images. URL: https://www.imatest.com/support/docs/23-1/noise/ (last accessed on 06.06.2023).
Karlović, I., Tomić, I. and Rilovski I. 2012. Digital Rephotography. Novi Sad: Faculty of Technical Sciences, pp. 149-150.
Kuzmenko. Understanding Image Noise. URL: https://retouchingacademy.com/qualities-of-digital-images-understanding-image-noise (last accessed on 03.07.2023).
Lendave. A Guide to Different Types of Noises and Image Denoising Methods. URL: https://analyticsindiamag.com/a-guide-to-different-types-of-noises-and-image-denoising-methods/ (last accessed on 03.07.2023).
Owotogbe, J. S., Ibiyemi, T. S. and Adu, B. A. 2019. “A Comprehensive Review On Various Types of Noise in Image”. Processing International Journal of Scientific & Engineering Research 10 (11), ISSN 2229-5518
Wang Z, Bovik A.C., Sheikh H.R. and Simoncelli E.P. 2004. “Image quality assessment: from error visibility to structural similarity.” IEEE Trans Image Process 13(4):600–612. https://doi.org/10.1109/TIP.2003.819861

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POSTER PRESENTATION

COMPARISON OF SHADOWS CREATED WITH GEOMETRIC PROJECTION, 3D RENDERING AND PHYSICAL EXPERIMENT FOR DIFFERENT PHOTOGRAPHIC LIGHT SOURCES

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Abstract: *In this study, the accuracy of shadows generated by different photographic light sources is evaluated using three methods: geometric projection, 3D rendering and physical experiments. Shadows play an important role in visual perception and are crucial for achieving photorealism in computer graphics, virtual reality and photography. The study uses halogen, LED and xenon light sources, all with and without light-shaping attachments. The geometric projection defines fully, partially and non-illuminated areas based on the light source geometry, but neglects material properties. 3D rendering using Elixxier set.a.light 3D software computationally simulates light dispersion, while physical experiments provide real-world validation. The comparative analysis focusses on shadow harshness and fidelity. The results show that no single method is universally accurate, with physical experiments providing the most reliable reference. The results contribute to the improvement of shadow rendering algorithms and the enhancement of visual realism in digital applications.*

Keywords: *geometrical shadow projection, shadow rendering, photographic light sources, light harshness*

1. INTRODUCTION

Shadows are a fundamental aspect of visual perception. They are created when an object obstructs a ray of light and prevents it from reaching a projection surface. The resulting shadow contains valuable information about the properties of the object, the light source and the projection surface, provided that two of these three properties are known. Shadows are not just the absence of light; they are dynamic entities that can reveal intricate details about the scene in which they are located. In art, shadows and the contrast they create with light are often used to evoke certain visual effects, commonly referred to as “creating a mood” (Buryk and Bratitsel, 2024). Beyond their artistic applications, shadows play a crucial role in the visual understanding of object shapes, surface properties and spatial positioning within images (Corpon, 1962).

The study of shadows extends beyond the realm of art and into the domain of science and technology, particularly in computer graphics and virtual environments. Achieving photorealism in virtual environments is a complex task that requires the accurate simulation of light and shadow. Shadows are essential for creating a sense of depth and realism in rendered scenes, and their accurate representation is crucial for applications ranging from video games to architectural visualisation and virtual reality. For this reason, shadows have been studied extensively, with a particular focus on improving the quality of rendered shadows to ensure they closely resemble real-world shadows (Osti et al., 2019).

In the past, early algorithms for shadow rendering relied on geometric projection methods that were limited to uniform projection planes. While these methods were computationally efficient, they often failed to capture the complexity of real-world shadows, especially in scenes with complicated geometries and varying material properties. Over time, more advanced techniques, such as shadow volumes, have been developed to overcome these limitations. Shadow volumes take into account the complexity of the scene and the material properties of objects, resulting in a more accurate shadow rendering (Liu, 2009). However, these methods are computationally intensive, and researchers continue to seek a balance between the quality of shadow rendering and the computational resources required to achieve it (Sattler et al., 2005).

Despite significant advancements in shadow rendering algorithms, no single method has achieved universal accuracy in all contexts. Various algorithms have been proposed to represent shadows as realistically as possible, each with its strengths and limitations (Hasenfratz et al., 2003). For example, some methods excel in rendering hard shadows with sharp edges, while others are better suited for soft shadows with gradual transitions between light and dark regions. The challenge is to develop algorithms that can accurately simulate the wide range of shadow types that can be observed in the real world scenarios, from the sharp shadows cast by a point light source to the soft, diffused shadows created by large, area light sources (Ritschel et al., 2009).

This study aims to evaluate the accuracy of shadows generated by different photographic light sources using three distinct methods: theoretical (geometric projection), virtual (3D rendering) and experimental (physical experiment). Each method offers a unique approach to shadow generation, and by comparing their results we can gain insight into the strengths and limitations of each technique. Various light sources are used in the study, including halogen, LED and xenon, all with and without light-shaping attachments such as softboxes. These attachments are designed to modify the properties of the light beam, resulting in shadows with different characteristics.

In the first method, geometric projection, the shadow areas are calculated based on the geometry of the light source and the occluding object. This approach defines areas of full illumination, partial illumination (penumbra) and complete shadow (umbra). While geometric projection provides a straightforward and computationally efficient method for generating shadows, it often overlooks the material properties of the light source and its attachments, which can significantly affect the accuracy of the resulting shadows (Štampfl & Ahtik, 2024). For example, the use of a softbox can scatter the light and create softer shadows with less defined edges, a phenomenon that the geometric projection may not fully capture.

In the second method, 3D rendering, the shadows are simulated in a virtual environment using specialized software. In this study, we use the Elixxier set.a.light 3D software, which was specially developed for the high-precision creation of photo scenes with predefined light sources. This software uses complex algorithms to realistically simulate the behaviour of lighting technology, including the dispersion of light and the interaction between light and objects. The virtual environment allows for precise control over lighting conditions and enables the generation of shadows that are very similar to those in the real world scenarios. However, the accuracy of these shadows depends on the accuracy of the software's algorithms and the quality of the input data, such as the properties of the light sources and the materials of the objects in the scene. (Elixxier, 2024)

In the third method, the physical experiment, the shadows are captured in a real photo studio environment. This approach provides a ground truth against which the results of the geometric projection and 3D rendering methods can be compared. The experimental setup includes a variety of light sources and light-shaping attachments, allowing for the generation of shadows with different properties. By capturing these shadows using a high-resolution camera, we can analyse their properties and compare them to the shadows generated by the other two methods.
The images from all three methods — geometric projection, 3D rendering and physical experiment — are analysed for their shadow properties. A comparative evaluation of shadow quality allows us to assess the accuracy of each method in simulating realistic shadows under different lighting conditions. This analysis includes both visual and numerical assessments of shadow harshness , a metric that quantifies the sharpness or softness of shadow edges (Štampfl & Ahtik, 2024). By examining the differences in shadow harshness between the three methods, we can identify areas where improvements in shadow rendering algorithms are needed.

2. EXPERIMENTAL

We have created three sets of six images, each set corresponding to one of the analysed imaging methods: geometric projection, 3D rendering and a physical experiment. The six images within each set represent three different light sources – halogen, LED and xenon, used once without and once with a light-shaping attachment designed to soften the original light beam.

2.1 Generating shadowed images

To obtain shadows produced by different light sources, we applied a method proposed in our previous research (Štampfl and Ahtik, 2024). This involves using a 50 × 50 cm grey plane with ArUco markers as a projection plate

and placing a 6 × 8 cm vertical plane as an occluder, which produces a shadow when illuminated with a light source placed 120 cm away and 10 cm above the origin of the plane. The setup can be seen in Figure 1, which also shows a camera mounted above and perpendicular to the projection plane, capturing the shadow. We have followed the geometry of the setup in all three approaches to image generation.

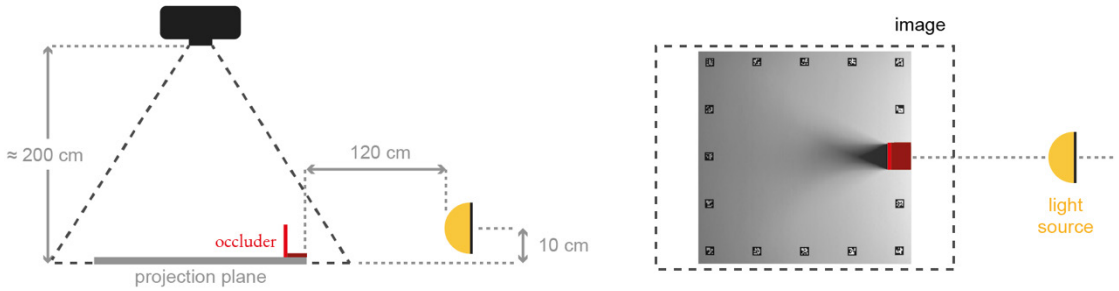


Figure 1: Shadow capture method in 3D environment and physical experiment.

The setup in Figure 1 was set up in a photographic studio with a black background to minimise the ambient reflections of the positioned light source. We used a Nikon D850 DSLR camera in manual mode with a Nikkor 50 mm/1.8 lens. The aperture was set to f/5.6 to maximise the sharpness of the lens. For the virtual environment, we used the Elixxier set.a.light 3D software (version 2.5), which was specially developed to mimic photo studio conditions and can be controlled in the same way. The projection plane and occluder were imported as 3D objects created in Blender software (version 2.91.2) and placed into the scene to scale. A 50 mm lens was also used here to render the image. For the theoretical shadows, we used Adobe Illustrator (version 29.0.1) to create vector images of the geometric projections, taking into account the geometry of the entire scene.

2.2 Light source properties

Three light sources were analysed in two different setups – with and without a light-shaping attachment. The light sources were first determined according to their availability for the physical experiment and then matched with the available light sources in the 3D environment. For the geometric projections, we used the exact geometry of the light sources and light-shaping attachments from the physical experiment.

We used a Kaiser Studiolight H with a halogen bulb with a diameter of 2 cm as the halogen light source for the experiment. To soften the original light beam, we used a square softbox with a side length of 70 cm and a depth of 45 cm. In 3D, we used a Godox AD 200 Pro with a bare bulb, while adding a softbox with the same side dimensions but 35 cm deep.

For the LED light source, we used a square Lupo Superpanel dual-colour LED panel with 30 cm sides. A softbox with a depth of 30 cm and a side length of 40 cm was used as a light-shaping accessory. As no identical light source was available in the 3D programme, we used an Arri S30-C LED panel measuring 35.5 × 30 cm, with the side barndoors set to −5° and the top and bottom barndoors set to 0°. To soften the light, there was again no attachment available. We therefore moved the light source 30 cm closer to the scene and adjusted the side flaps of the barndoors to 10° and the top and bottom flaps to 5°, which corresponded to the final dimensions of the physical light shaper.

For the xenon light source we used an Elinchrom ELC PRO HD 500 flash unit with a 7 cm diameter bulb. The light was attenuated by a square softbox with a side length of 66 cm and a depth of 35 cm. In the virtual environment, we used a 500Ws flash unit with a light bulb and a square softbox with a side length of 60 cm and a depth of 32 cm.

2.3 Image processing

Three shadow generating techniques and six light source combinations resulted in 18 test images. Each scene was also captured without an occluder, resulting in an image without shadows that allowed us to remove the background from the virtual and experimental images. To ensure comparability, we used code written in the Python programming language to first register all 32 images to the reference image using the ArUco markers on the projection plane. We then cropped them to the same area to make the image processing less computationally demanding but retain the shadow information. In the next step, we subtracted the shadowed image from its non-shadowed pair, while the resulting image was inverted to show the positive shape of the shadow. For visual analysis, we equalized the inverted shadow images to avoid the contrast effect on our visual perception of shadow harshness.

These images were then analysed using the harshness method proposed in our previous study (Štampfl and Ahtik, 2024). First, we thresholded each image and determined the centroid of the most prominent shape at each threshold. The centroid coordinates for all 256 thresholds per image were then combined into datasets that were denoised and plotted to check for possible errors. The derivatives for each dataset were calculated and the breakpoint between umbra and penumbra was determined. In this way, the height of the umbra and the width of the penumbra were determined and the final harshness H calculated.

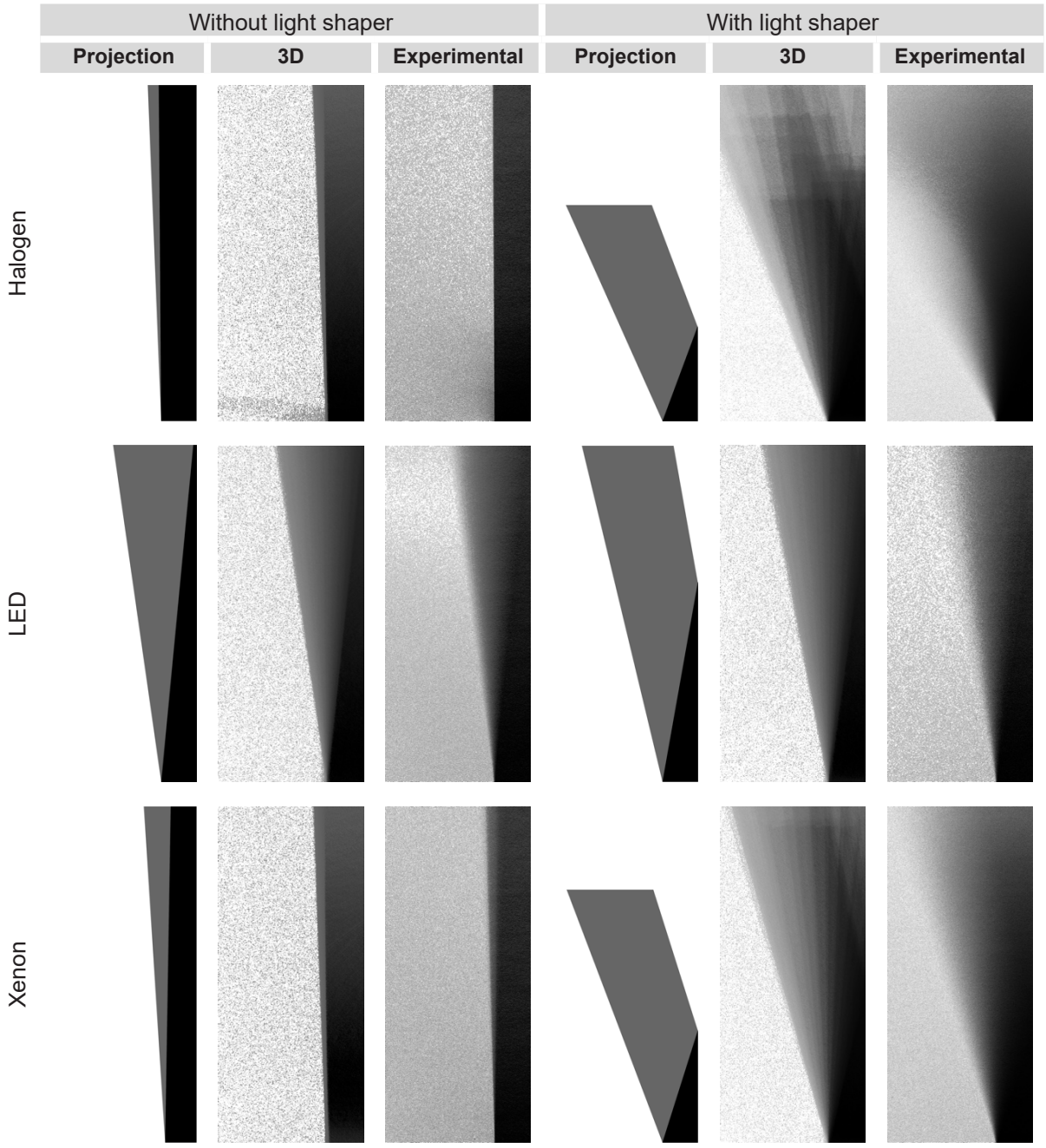
3. RESULTS AND DISCUSSION

The obtained results are divided into two sections. The first section, the visual analysis, examines the final equalized images visually, describing and comparing the umbra and penumbra shapes among the three approaches used for generating shadows. The second section, the numerical analysis, evaluates the results obtained from shadow harshness determination using a previously proposed method.

3.1 Visual analysis

In Table 1, equalized shadow images are presented for the three tested light sources with and without the light-shaping attachment in place. The image of geometric projection can be compared to the 3D rendered version and from the real-life studio experiment. In general, we can observe a great deal of resemblance between the three corresponding images, apart from the high amount of noise in the areas of full illumination for 3D and experimental images, suggesting that the selected light sources had an adequate level of resemblance within 3D and real-life environment.

Table 1: Equalized shadow images for all six light sources from geometrical projection, 3D rendered shadows and shadows from experiment.



When analysing the images from each of the six light source combinations, we can see a similar but not identical shadow rendering when comparing the three methods. In the cases where the differences occur between the geometric projection and 3D or 3D and experimental images, this could indicate that the light sources used in both approaches were not similar enough, while it is possible that it indicates a generally different shadow rendering due to the method.

Comparing the three images from geometric projection and different light sources without a light-shaping attachment, it is clear how the size of the light source affects the ratio of umbra to penumbra. Halogen has the widest umbra, which remains the same width across almost the entire y-axis. This is due to the size of the light source, as the bulb has a diameter of 2 cm. This is followed by xenon with a bulb of 7 cm in diameter, which results in umbra that becomes narrower in the upper area (y=0). This is due to the wider source point, which begins to

cross-illuminate the region. This becomes particularly clear when comparing the described images with the image for the LED light source, where the umbra width reduces almost to zero, which is due to a much wider light source. In these cases, the width of the penumbra is in inverse proportion to the width of the shadow, as it is largest in the upper part of the image for the LED light source and smallest for the halogen lamp.

The relationship between projected and 3D shadows is identical for halogen and LED, with only a slight difference in harshness of the transition between umbra and penumbra and from penumbra to fully illuminated surface. On the other hand, xenon in 3D is identical to the halogen pair and not to its geometric projection. This would lead us to believe that the xenon light source in 3D does not match the experimental version. However, if we compare them with the experimental shadow, they are again identical, but with an additional softness at the transitions in the shadow regions. On the other hand, the experimental shadow for halogen differs from its pair for projection and 3D, as it shows no penumbra at all and acts entirely as a point source, while the LED samples can be treated as identical, but with a difference in the harshness of the transitions. This shows that the geometric projection for simple light sources is not always completely accurate, especially in cases with pulsating light (xenon) or with a light source smaller than the occluder (halogen). In practise, the latter act as a pure point light source so that no penumbra is created. These differences are also realised in the 3D environment, where the ray tracing takes over both real scenarios, but still relies on the basic geometry. The halogen example is misinterpreted as a point source, while pulsating light and continuous sources such as in the LED example are displayed correctly.
The statement regarding the tested 3D environment, which uses both real-life situations and geometric projections to achieve a balance between physical accuracy and fast real-time visualisation, becomes particularly clear when comparing the three images for halogen and xenon light source with a light-shaping attachment. The 3D version generally appears as soft as its experimental pair, but the transitions are not as smooth, with quadrilateral shapes clearly visible in the penumbra. Interestingly, this is not visible in the combination for LED, which we believe is due to the fact that no light shaper was actually in place, as we only adjusted the positioning and size of the light source to match the experimental version with a light shaper. This leads us to the conclusion that both the geometric projection and 3D rendering approaches struggle to visualise softened shadows accurately, especially due to the complexity of penumbra rendering.

3.2 Numerical analysis – harshness

Figure 2 shows the results of harshness *H* for all three shadow rendering approaches. As described in previous research (Štampfl and Ahtik, 2024), the geometric projection is insufficient, especially when visualising softer shadows. With a visual analysis, we have shown that 3D rendering also lacks precision when light-shaping attachments are applied to the original light source, in our case softboxes. These difficulties also carry over to the harshness values, where the results are similar for light sources without light-shaping attachments, while they differ in value and tendency when comparing the combinations with attached attachments.

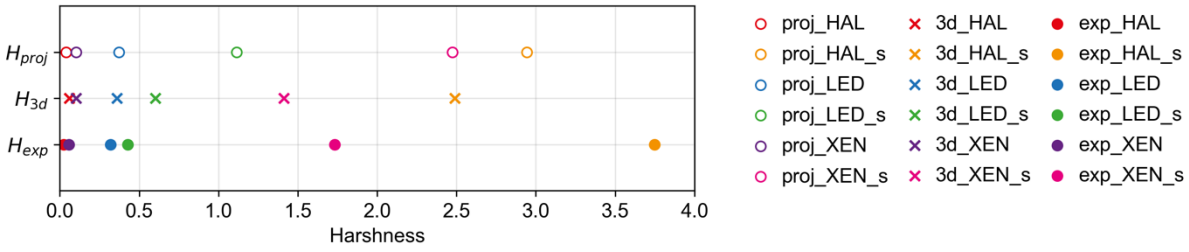


Figure 2: Harshness H for shadows from geometrical projection (proj), 3D environment (3d) and experiment (exp) for halogen (_HAL), LED (_LED) and xenon (_XEN) light sources with (_s) and without a light-shaping attachment.

For light sources without light-shaping attachments, the results are thus similar for all three approaches, while the harshness of the experimental shadows is always the lowest of the three results: for halogen, H_{proj}, H_{3d} and H_{exp} are 0.04, 0.05 and 0.02, for xenon 0.10, 0.10 and 0.06 and for LED 0.37, 0.36 and 0.31. These results are consistent with the visual assessments, where the shadow harshness is visually the same for halogen and xenon, while it is much softer for LED.

When you add a light-shaping attachment, the differences in harshness for the three shadow rendering approaches tested no longer follow the observed trend. The results of H_{proj}, H_{3d} and H_{exp} for LED_s are 1.11, 0.60 and 0.43, which is still the lowest harshness for the experimental shadow but the highest for the geometric projection. On the other hand, HAL_s and XEN_s show the lowest harshness for the 3D rendered shadow (H_{3d} is 2.49 and 1.41, respectively), while H_{exp} is higher in both cases (H_{exp} is 3.75 and 1.73, respectively), but not the highest for XEN_s. These inconsistent differences not only demonstrate again the complexity of rendering soft shadows, but also test the robustness of the harshness determination method for such light sources.

Figure 3 shows the data sets of centroid coordinates for each light source, both for the examples from the 3D rendering and for the experiment. For a better understanding of the data, they are superimposed on an image of the experimental shadow. It is clear that the data sets for light sources without a light-shaping attachment match regardless of the method used (3D or experimental), while the other three data sets (_s) show larger offsets or completely different trends. While the differences for LED_s and XEN_s are mostly only seen in the offset, HAL_s shows a different trend in the generated penumbra region. This could indicate that inaccurate penumbra generation in 3D is in comparison to the experimental approach also the reason harshness result for the 3d_HAL_s sample does not match the trend shown by the other 3D and experimental pairs.

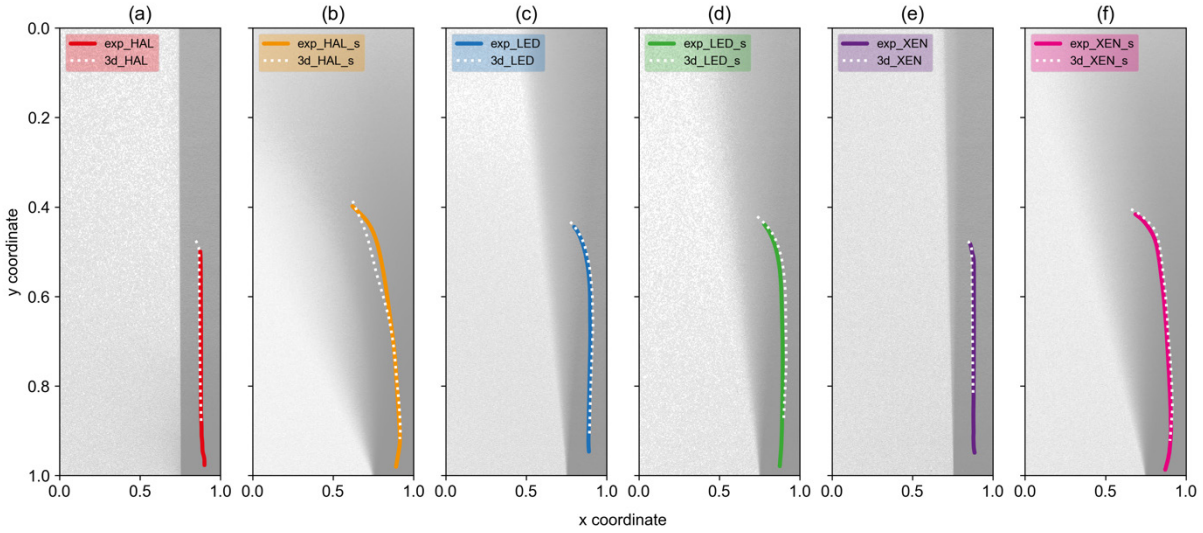


Figure 3: Data sets of centroid coordinates (x,y) during harshness determination, which numerically indicate the differences in shadow generation between 3D rendering and experimental method.

4. CONCLUSION

This study provides a comparative evaluation of shadows generated by geometric projection, 3D rendering and physical experiments under different lighting conditions. The results highlight the strengths and limitations of each method, emphasising that while geometric projection is computationally efficient, it often fails to capture the complexity of real-world shadows, particularly when light-shaping attachments are involved. 3D rendering, on the other hand, offers a high degree of control and precision, but is dependent on the accuracy of the underlying algorithms and input data. Physical experiments serve as a valuable reference as they provide the most reliable representation of shadows in the real world.

The results show that no method of artificial representation is universally accurate. Geometric projection provides a basic approximation but is not accurate enough in complex scenarios, while 3D rendering, while promising, requires algorithmic refinements to better simulate soft shadows and varying light intensities. The experimental approach remains the benchmark for assessing shadow realism, offering crucial insights for improving virtual shadow generation techniques.

This research contributes to ongoing efforts to improve the accuracy of shadows in digital environments. By refining 3D rendering algorithms and integrating experimental findings, future developments can improve photorealistic shadow rendering in computer graphics, virtual reality and cinematography. These findings will help optimise computational efficiency while maintaining high visual fidelity, benefiting a range of industries that rely on realistic shadow rendering.

5. REFERENCES

Buryk, R. and Bratitsel, M. 2023. “Harmony of Light and Shadow: Key Aspects of Lighting in Portrait Photography.” *Scientific Journal of Polonia University* 61 (6): 38–49.

Corpon, C. 1962. Light as a Creative Medium. *Art Education* 15 (5): 4–7.

Eisemann, E., Schwarz, M., Assarsson, U., and Wimmer, M. 2011. *Real-Time Shadows*. AK Peters/CRC Press.

Elixxier Software. set.a.light 3D – Lighting Simulator for photographers & filmmakers. URL: https://www.elixxier.com/en/set-a-light-3d/ (last sccessed on 31. 1. 2025).

Hasenfratz, J., Lapierre, M., Holzschuch, N. and Sillion, F. 2003. “A Survey of Real-time Soft Shadows Algorithms.” *Computer Graphics Forum* 22 (4): 753–774.

Liu, N. and Pang, M. 2009. “A Survey of Shadow Rendering Algorithms: Projection Shadows and Shadow Volumes.” *Second International Workshop on Computer Science and Engineering*, 488–492.

Osti, F., Santi, G. and Caligiana, G. 2019. “Real Time Shadow Mapping for Augmented Reality Photorealistic Rendering.” *Applied Sciences* 9 (11): 2225.

Ritschel, T., Grosch, T., and Seidel, H.P. 2009. “Approximating Dynamic Global Illumination in Image Space.” *ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games*, 75-82.

Sattler, M., Sarlette, R., Mücken, T. and Klein R. 2005. “Exploitation of human shadow perception for fast shadow rendering.” In *Proceedings of the 2nd symposium on Applied perception in graphics and visualization (APGV ‘05),* 131–134. New York: Association for Computing Machinery.

Štampfl, V. and Ahtik, J. 2024. “Shadow Segmentation with Image Thresholding for Describing the Harshness of Light Sources.” *IEEE Transactions on Image Processing* 33: 3428–3440.

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POSTER PRESENTATION

REFLECTANCE SPECTRA RECONSTRUCTION FROM FLATBED SCANNER-BASED RGB VALUES USING ARTIFICIAL NEURAL NETWORK

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Abstract: *Spectral description of colours using multi or hyper-spectral cameras is costly. Thus, algorithms for mapping RGB images captured with cheaper commercial cameras into spectral data are being developed. A straight mathematical approach for spectral reconstruction is not feasible if capturing conditions and camera characteristics are partially unknown. Our approach proposes to capture RGB values of a colour patch reference set with known spectral values in the same acquisition conditions as the image of interest and train the single-layer artificial neural network using Matlab with Levenberg-Marquardt and a faster scaled conjugate gradient learning algorithms varying the hidden layer neurons number to perform RGB to spectrum mapping. Images obtained with a flatbed scanner avoid the problem of uneven illumination and lens-related geometric and refractive distortions using cameras and expand the possibility of capturing in more expansive ProPhoto colour space and 16-bit resolution compared to the Adobe RGB 8-bit capturing utilised in our previous work.*

Keywords: *spectral reconstruction, flatbed scanner, artificial neural networks*

1. INTRODUCTION

A multispectral or, even better, a hyperspectral camera can be applied to describe colour images with spectral data (Cucci 2019) instead of RGB values captured by a commercial or professional camera. As such devices are costly, they are only found in better-equipped laboratories and professional applications. Capturing colour images with an RGB camera is significantly cheaper, and active research is underway to develop algorithms for mapping RGB into spectral values (Slavuj 2013, Cao 2017, Zhao 2020).

The reconstruction of reflectance spectra (hereafter RS) from RGB values is mathematically feasible if the light source's properties, the imaging device's optical properties, and its sensors' characteristics are known. If any of this information is unknown, the information for the mapping must be obtained in other ways. Our approach proposes to capture, in addition to the images, the RGB values of a set of colour patches whose RS are known and to teach an artificial neural network (hereafter ANN) to map their colours to RS using a learning set (hereafter LS) of RGB-reflectance spectrum pairs.

When capturing images with a commercial camera, as discussed in our previous work (Lazar 2019, Lazar 2022), it is necessary to ensure uniform and time-invariant illumination and to perform geometry and spherical aberration correction before further processing. For this reason, we have chosen to use a flatbed scanner instead of a commercial camera in this study, where uniform illumination and the absence of geometric and refractive distortions due to lenses are guaranteed.

Matlab offers a range of different learning algorithms for modelling ANNs. Specifically, for the function approximation, Matlab's Deep Learning Toolbox module offers a choice between a faster scaled conjugate gradient backpropagation (hereafter BP) learning algorithm that can harvest the parallel computing power of the Graphics Processing Unit (GPU) and a slower Levenberg-Marquardt (hereafter LM) learning algorithm that, although only executed on the CPU, converges faster and finds more efficient models. In previous research, we have observed the dependence of the performance of the models on the size of the LS since when retrieving images with a camera, it is necessary to capture a reference set of colour samples of a suitable (smaller) size under the same

lighting conditions, ideally simultaneously. When using a scanner, simultaneous acquisition of the image and the reference set is not necessary, so only two learning sets with a larger number of colour patches were used in our study. For modelling, single-layer ANNs were applied, which, according to the results of our previous studies, were modelled within a modified range of the number of neurons in the hidden layer. The flatbed scanner allows the description of colours in different colour spaces, where we used Adobe RGB (1998) and the more extensive ProPhoto RGB, and 16-bit RGB readings in addition to 8-bit ones. In the experiment, the influence of different parameters on the performance of the ANN models was monitored, and the performance of the scanner-based modelled ANNs was additionally compared with the performance of camera-based ANNs modelled in our previous experiments (Lazar 2020, 2022) using learning sets with RGB values of three commercial cameras.

Our hypotheses in this study are as follows:

1. RS reconstruction from RGB values of the scanned image is feasible.
2. RS reconstruction from a scanned RGB image will outperform that from an RGB photograph.
3. RS reconstruction from an image at 16 bits per colour channel will perform better than that at eight.
4. RS reconstruction from an image scanned in ProPhoto will be better than from an image scanned in Adobe RGB colour space.
5. ANN models for RS reconstruction trained with the LM algorithm will perform better than those trained with the BP algorithm.
6. ANN models for RS reconstruction learned on a larger training set will perform better than models learned on a smaller one.

2. EXPERIMENTAL

Our study focuses on the reconstruction of reflectance spectra from RGB flatbed scanner readings by supervised learning of a single-layer ANN implemented with the Matlab Neural Network Toolbox on a general-purpose PC. In the ANN model learning, the inputs are RGB values of the scanner readings, and the outputs are vectors of spectral reflectance components - the spectrophotometer readings.

As a source of colourimetric data, we used The Munsell Book of Color Matte Collection with 1301 colour samples of different chroma, value and hue values, which also include natural colours such as earth, skin, foliage and a set of neutral tones. The 40 sheets are divided into a 2.5-step Munsell hue circle (2.5; 5; 7.5; 10 for R, YR, Y, GY, G, BG, B, PB, P and RP), with an additional four sheets containing neutral tones and lightly tinted greys. Each patch was measured with an X-Rite i1Pro 2 spectrophotometer at five points (near the corners and at the centre of the patch), and RS vectors with 107 components were obtained at wavelengths from 376,66 to 730 nm in steps of 3,33 nm, with a maximum standard deviation for the five measurements of less than 0,4 %. Averages were calculated from the five measurements on the patch, and the RS was subsampled to 36 components from 380 nm to 730 nm in steps of 10 nm.

The sheets of the Munsell Matte Collection were scanned at 300 DPI using an Epson Perfection V750 Pro flatbed scanner with manual settings, i.e. filters, sharpening, and corrections turned off. Each sheet of samples was captured in 24 and 48-bit RGB mode, i.e. with 8 and 16 bits per channel, and in Adobe RGB and ProPhoto RGB colour space. The median RGB values of each colour patch were obtained on the inner 50% square of the patch. The complete set consisting of RGB-reflectance pairs for all 1301 Munsell Matte patches was assembled, with three RGB values and 36 values for each reflectance spectrum. Two learning sets were formed before training a series of ANNs through a supervised learning algorithm - the subset of 90% and 50% of a complete set. The learning set was randomly partitioned into training, validation and test sets in a 70:15:15 ratio before every ANN model training.

ANN learning algorithms search for the minima of a cost function, which may be global or local. Therefore, training was repeated 21 times for each combination of ANN parameters to find the best-performing models, varying the size of the hidden layer from 18 to 75 neurons in step 3. The odd number (21) was chosen to compute some additional statistics not mentioned in the paper. The calculations for both learning algorithms (BP and LM) were performed for two training set sizes (650 and 1711 RGB-RS pairs), with colour readings in two colour spaces (ProPhoto and Adobe RGB) and with 8 and 16-bit precision. Data on the best results and averages were collected, and the results were compared and visualised. Almost 80 hours of 6-core CPU parallel processing time and more

than 4 hours of GPU time were spent. The Matlab Parallel Computing Toolbox supports CPU parallel computing. ANN modelling on all CPU cores was activated using the useParallel training option.

3. RESULTS WITH DISCUSSION

In our experiment, as the number of hidden layer neurons increased from 18 to 75 in step 3 for both ANN learning algorithms, we monitored the training time, the number of epochs, i.e. the number of repeated learning cycles with the whole LS, and the time required per single epoch (Figure 1), and in particular, we compared the average and best MSE performances of the RS reconstruction utilising ANN models.

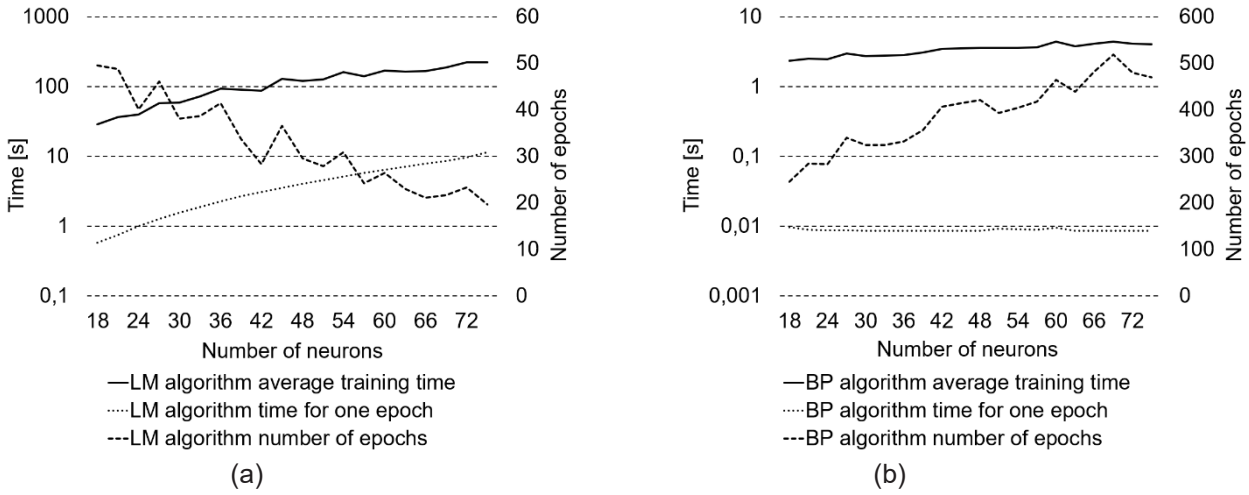


Figure 1: Average training time, average time for a single epoch and average number of epochs used to train an ANN with a larger LS of 1171 RGB16 ProPhoto input values using LM (a) and BP algorithm (b)

When scanning colour images with a flatbed scanner, the illumination is provided by a smoothly moving array of calibrated LED lamps, which ensures uniform illumination along the entire image acquisition, whereas a commercial camera captures the whole image simultaneously, but it is more difficult to ensure uniform illumination due to shadows, reflections and, e.g. in the case of spotlights, the uneven distance between the lamp and the surface. Therefore, a comparison was made between the RS reconstruction efficiencies of ANNs modelled with RGB data from three commercial cameras used in previous studies and ANNs modelled with 8- and 16-bit RGB input readings from a flatbed scanner for both modelling algorithms, two LS sizes and the ProPhoto and Adobe RGB colour spaces. Some of the 16 combinations are shown in Figure 2 to Figure 5.

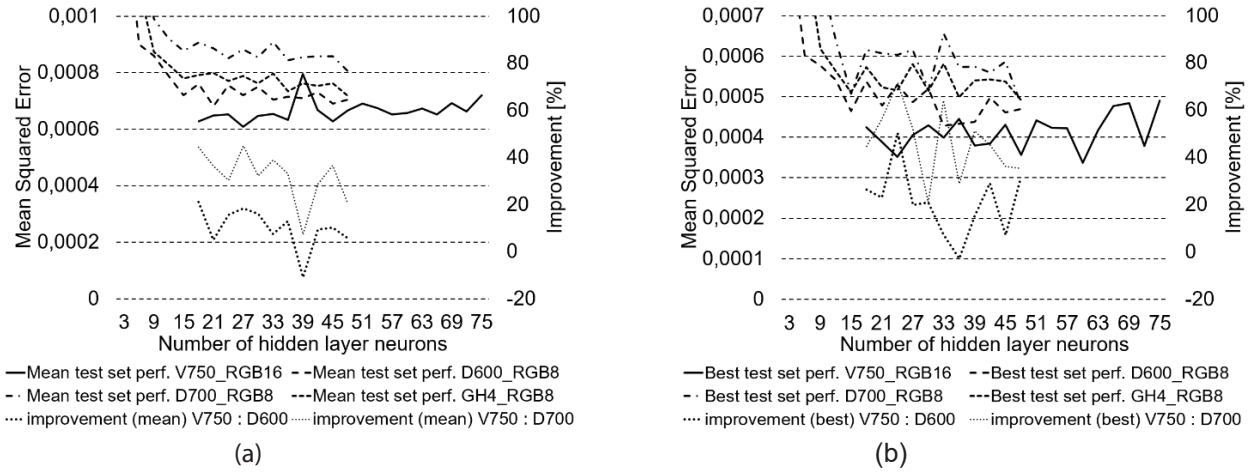
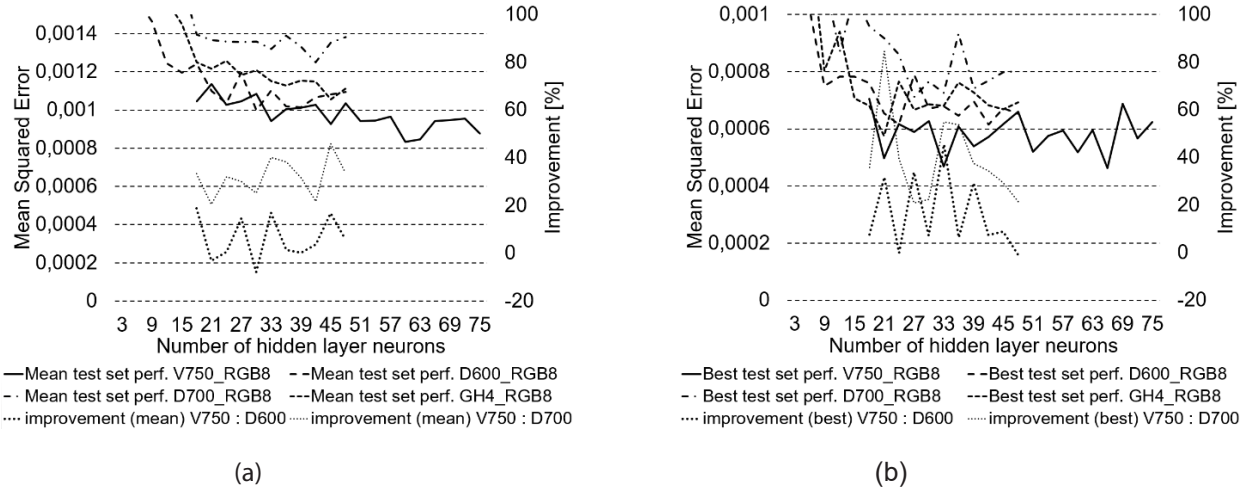
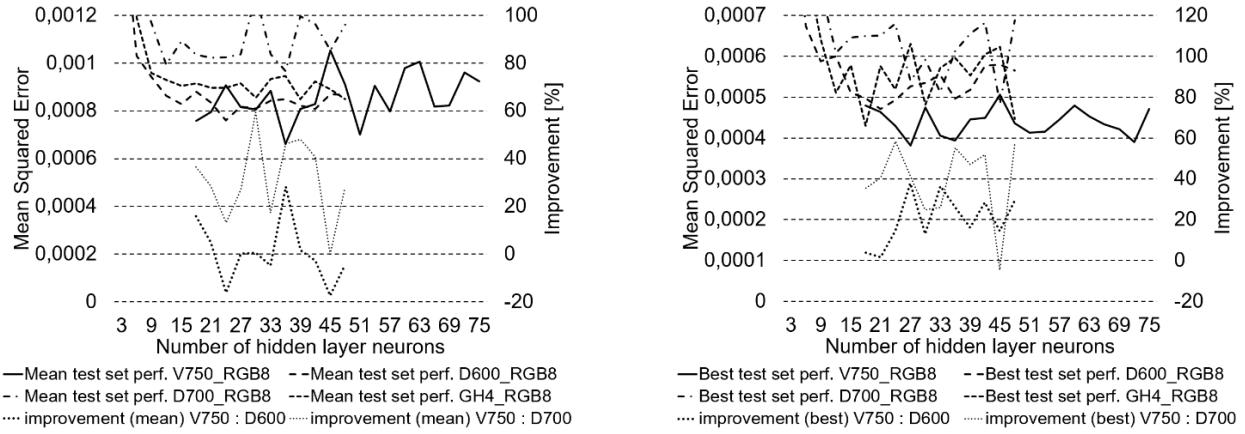


Figure 2: Comparison of test set mean (a) and best (b) MSE performance of ANNs modelled with LM algorithm, large LS (1171), and RGB8 AdobeRGB data of three commercial cameras versus RGB16 ProPhoto data of V750 scanner



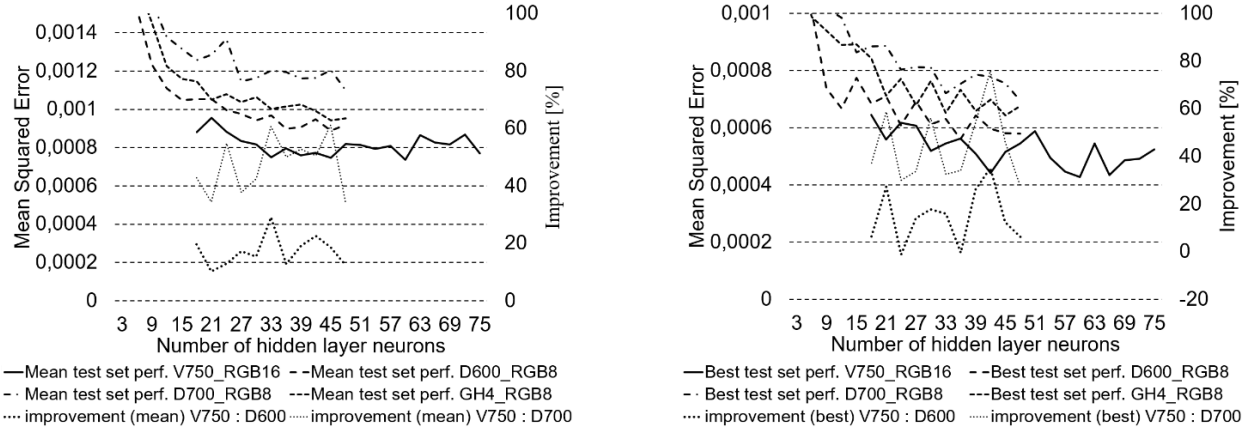
(a) (b)

Figure 3: Comparison of test set mean (a) and best (b) MSE performance of ANNs modelled with BP algorithm, medium LS (650), and RGB8 AdobeRGB data of three commercial cameras versus RGB8 ProPhoto data of V750 scanner



(a) (b)

Figure 4: Comparison of test set mean (a) and best (b) MSE performance of ANNs modelled with LM algorithm, medium LS (650), and RGB8 AdobeRGB data of three commercial cameras versus RGB8 AdobeRGB data of V750 scanner



(a) (b)

Figure 5: Comparison of test set mean (a) and best (b) MSE performance of ANNs modelled with BP algorithm, large LS (1171), and RGB8 AdobeRGB data of three commercial cameras versus RGB16 AdobeRGB data of V750 scanner

In addition to comparing the performance of ANNs for reconstructing RSs trained with RGB values captured by the camera and the scanner, we were also interested in the performance of models trained with the LS of samples captured by the scanner alone, observing four variables, namely the influence of bit depth, the extent of the colour space, the choice of the learning algorithm, and the size of the LS, as described below.
Assuming that a larger bit depth will improve the performance of the ANN models, we compared the models trained with 8- and 16-bit RGB data, observing both average and best performances when training with LM or BP algorithms, two LS sizes and two colour spaces. The comparison shows a slight improvement when using 16-bit RGB values only when observing the best performances of the models with the LM algorithm and scanning in the ProPhoto space. The improvement is not pronounced, as the performances overlap in places, and it is only noticeable when comparing linear approximations (Figure 6). In all other cases, i.e. when modelling with the BP algorithm in ProPhoto space and with both algorithms in Adobe RGB colour space, the performances overlap significantly. Examples of overlapping results for the 8- and 16-bit models are shown in Figure 7.

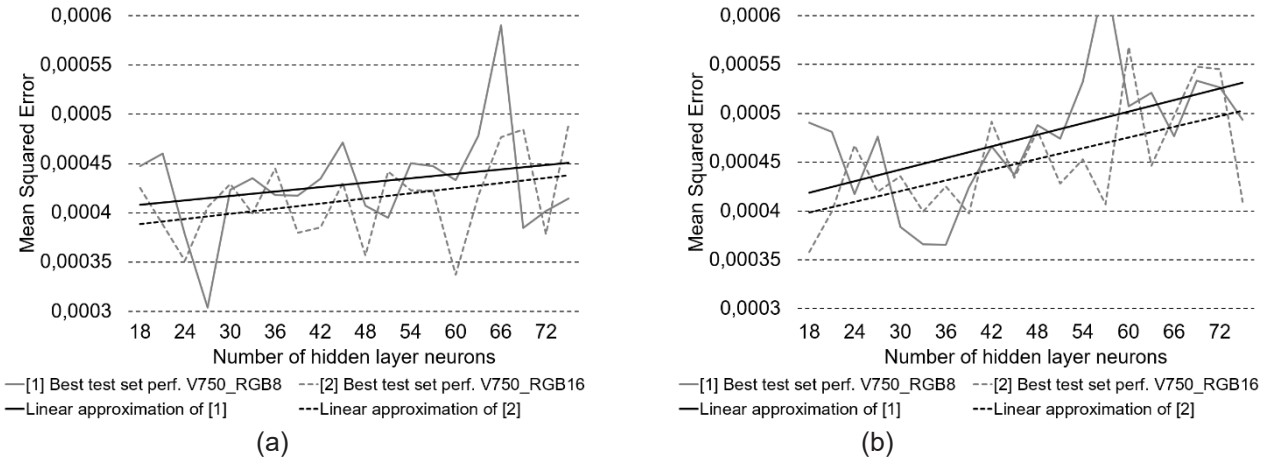


Figure 6: Comparison of RGB8 vs RGB16 test set best MSE performance of ANNs modelled with LM algorithm, V750 scanner ProPhoto large (a) and medium LS (a)

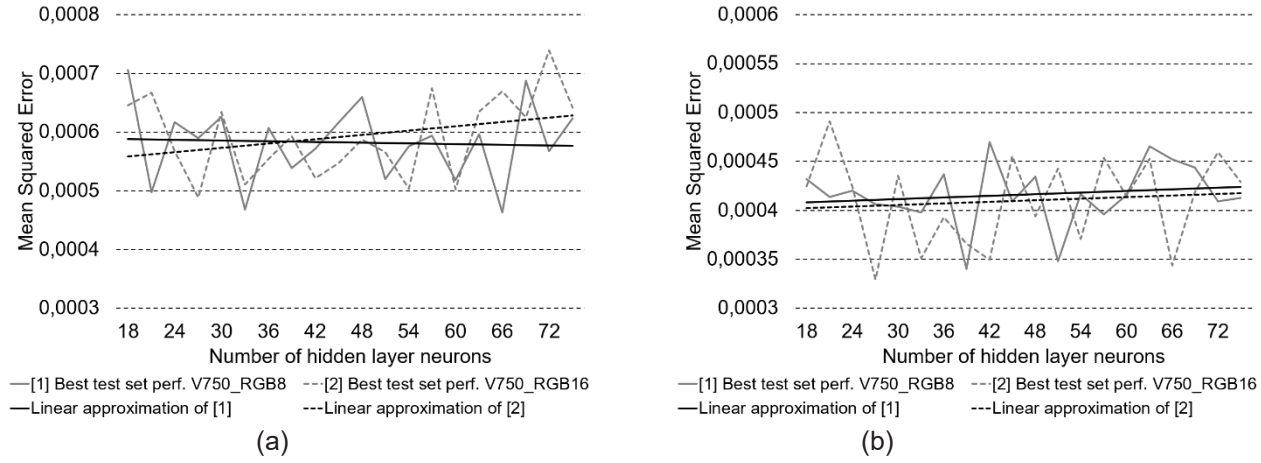


Figure 7: Comparison of RGB8 vs RGB16 test set best MSE performance of ANNs modelled with V750 scanner ProPhoto RGB medium LS and BP algorithm (a) and Adobe RGB large LS and LM algorithm (b)

A professional scanner allows for capturing colours in the larger ProPhoto colour space and in the slightly narrower Adobe RGB colour space (#image of both colour spaces). As the performance of models trained with input values captured in the larger colour space was expected to be better, a comparison of the performance of the models trained with RGB values described in the two selected spaces was made. Figure 8 shows the overlapping performance of the models both when trained with BP, 8-bit depth and smaller LS, and when trained with LM, 16-bit depth and larger LS.

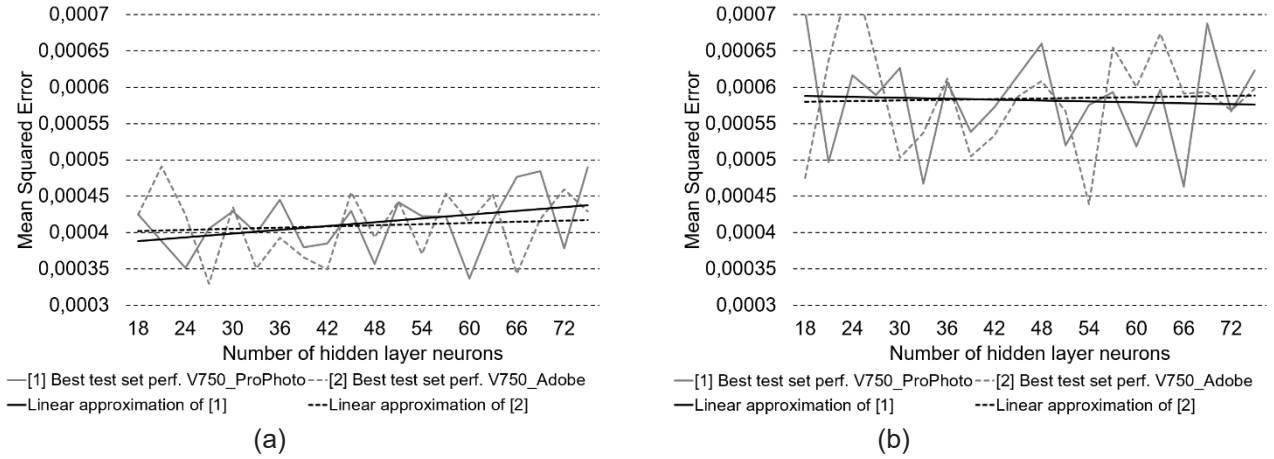


Figure 8: Comparison of ProPhoto vs AdobeRGB test set best MSE performance of ANNs modelled with V750 scanner RGB16 large LS and LM algorithm (a) and RGB8 medium LS and BP algorithm (b)

When modelling ANNs for function approximation, we compared the performance of the models trained by the two algorithms at both bit depths, colour spaces and LS sizes. Comparisons of the best performances between LM and BP models at large learning sets, 16-bit resolution, and ProPhoto colour space, and at smaller learning sets, 8-bit resolution and Adobe RGB space, are shown in Figure 9.

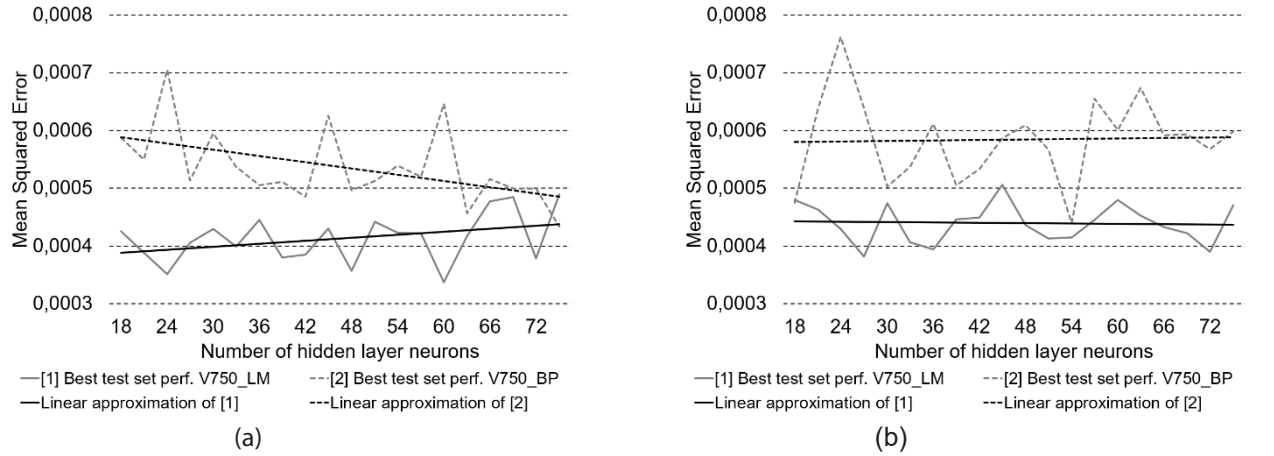


Figure 9: Comparison of LM vs BP algorithm test set best MSE performance of ANNs modelled with V750 scanner ProPhoto RGB16 large LS (a) and Adobe RGB8 medium LS (b)

When training ANNs, building a sufficiently large LS is necessary to ensure adequate model reconstruction performance and, therefore, to capture a sufficient number of reference colour samples. In our study, we monitored two sizes of the LS, a smaller one with 650 and a larger one with 1171 colour samples. A comparison of the average performances of the two sizes of the LS for ANNs modelled with BP and 8-bit RGB readings in the ProPhoto colour space and the best performances of the two sizes of the LS for models with LM, 16-bit resolution in the Adobe RGB space is shown in Figure 10.

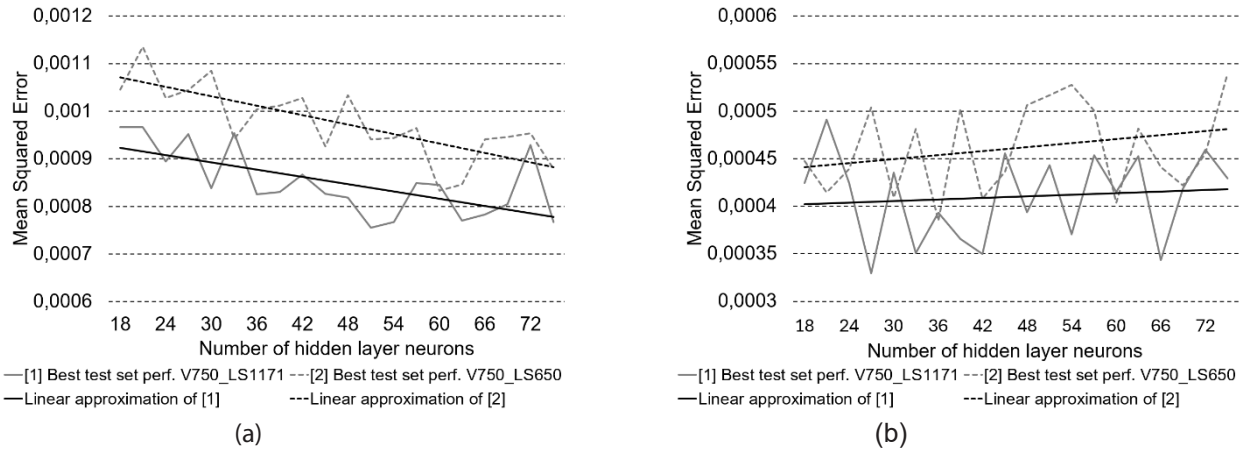


Figure 10: Comparison of Large vs medium LS best test set MSE performance of ANNs modelled with V750 scanner ProPhoto RGB8 and BP algorithm (a) and Adobe RGB16 values and LM algorithm (b)

4. CONCLUSIONS

As the number of neurons in the hidden layer increases, the complexity of the model - the number of synapses - increases linearly according to the formula $(N_i + N_o) * N_h$, where N_i is the number of input neurons, N_o is the number of output neurons and N_h is the number of neurons in the hidden layer. At the same time, as the capacity to accumulate "knowledge" increases, the learning time also increases linearly. As the number of neurons increases, the number of epochs, i.e. the ANN learning cycles with the whole LS, decreases in the LM algorithm, and the time for each epoch increases. In the BP algorithm, however, as the number of neurons increases, the number of epochs increases, and the time to learn each epoch is almost constant.

Most MSE performance comparisons of the ANN models trained with the scanner RGB readings and the RGB readings from the three cameras show an improvement in both the average and best performances when using the scanner. The improvement in performance using the scanner is noticeable for both learning algorithms and is more prominent for the larger LS. When observing the average performances of the ANN models trained with the smaller LS of scanned RGB readings, there is a partial overlap with the best performances of the ANN models trained with the RGB readings of the Nikon D600 camera. However, the best MSE performances of the former are still noticeably better than those of the models using cameras, which confirms our *second hypothesis* and, consequently, our *first hypothesis*.

From the overlap of the MSE performance of the 8- and 16-bit models, we can conclude that a larger bit depth for both ANNs trained with BP and ProPhoto RGB input values and for both algorithms and Adobe RGB input values does not help to improve the performance of the ANN models for the reconstruction of the reflectance spectrum. A partial improvement is only observed when modelling the ANN with the LM algorithm and the LS of values described in a more extensive colour space. The *third hypothesis* regarding the performance improvement of ANN models trained with a LS of 16-bit RGB input values compared to 8-bit is thus only partially confirmed.
Despite the expectation that models trained with colour values scanned in the ProPhoto RGB space will perform better than those scanned in Adobe RGB, the MSE performances of the two overlap significantly. The difference in performance is probably not pronounced because most of the colour samples are within the range of the Adobe RGB space, and the colours of the learning sets are adequately described in both cases, leading to comparable performance of the two types of models. The *fourth hypothesis* that the reconstruction of RS from an image scanned in the ProPhoto colour space will be better than one scanned in the Adobe RGB space has not been confirmed.

As shown in our previous experiments with AdobeRGB colour space and 8-bit resolution photos, even when using a scanner to capture the input colour values, the ANN models trained with the LM algorithm outperform the BP models for all combinations of the observed parameters. The linear approximation of the average and best ANNs performance ranges from 50% better performance for LM models with fewer neurons to 20% better for the largest observed number of neurons, confirming our *fifth hypothesis*.

As the number of colour samples increases, the LS increases, and so does the amount of knowledge the ANN absorbs. In previous research, due to the aim of capturing reference samples with the camera in a practical way, we have observed the impact of several different sizes of the LS, ranging from the smallest, with 195 samples, to the largest, with 1171 samples. When capturing images with the camera, a set of reference samples must be captured in parallel each time due to the variable illumination. This is unnecessary for scanner image capture, as the reference samples are captured only once. The best ANN is found and then used to reconstruct the RS from the scanned RGB values over a longer period of time. Therefore, it makes sense to use a larger LS here, and we chose to compare the training performance with a medium-sized one with half of the total available Munsell Matte Collection colour samples and a LS that includes 90% of the samples. As expected, the learning performance with the more extensive LS is noticeably better. Comparison of the linear approximation of the mean MSE performance values shows an improvement between 10% and 25% with the larger LS, while the improvement when observing the best MSE performance is smaller but still reaches up to 20%, confirming our *sixth hypothesis*.

Finally, it can be said that the reconstruction of RS from scanned images using ANN is feasible, so our *first hypothesis* was confirmed as well. It is comparable and even superior to the performance of RS reconstruction from camera images, both in terms of improved results and ease of implementation. Due to the constant illumination, ANN modelling and best-fit model search only need to be performed once, unlike camera image acquisition, where the lighting conditions may change with each acquisition. The use of a good quality scanner, therefore, allows successful reconstruction of the RS, but the question is whether the performance would also be adequate, e.g. using a cheaper flatbed scanner for home use or perhaps a scanner in a multifunction photocopier, which may be the subject of further research.

5. REFERENCES

Cao, B., Liao, N., Cheng, H. 2017 “Spectral reflectance reconstruction from RGB images based on weighting smaller color difference group.” Color Research & Application 42(3): 327-332.

Cucci, C., Casini, A. 2019. “Hyperspectral imaging for artworks investigation.” Data Handling in Science and Technology” 32: 583–604.

Lazar, M., Javoršek, D., Hladnik, A. 2020. “Study of camera spectral reflectance reconstruction performance using CPU and GPU artificial neural network modelling.” Tehnički Vjesnik, 27: 1204–1212.

Lazar, M., Hladnik, A. 2022. “Exploiting Nonlinearity between Parallel Channels of Multiple Cameras for Accurate ANN Reconstruction of Reflectance Spectra.” Tehnički Vjesnik, 29: 765–774.

Slavuj, R.; Green, P. 2013. “To develop a method of estimating spectral reflectance from camera RGB values.” Colour and Visual Computing Symposium (CVCS). IEEE, 2013: p. 1-6

Zhao, J., Kechasov, D., Rewald, B., Bodner, G., Verheul, M., Clarke, N., Clarke, J. L. 2020. “Deep learning in hyperspectral image reconstruction from single RGB images—A case study on tomato quality parameters.” Remote Sensing, 12(19): 3258.

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SUBSTRATES AND STANDARDIZATION

ORAL PRESENTATION

SLOVENIAN INSTITUTE FOR STANDARDIZATION AND WORK OF TECHNICAL COMMITTEES GRAPHIC TECHNOLOGY, PACKAGING - SALES AND GROUPED AND PULP, PAPER, BOARD AND PRODUCTS

Mojca Lampič[1]

[1]Slovenian Institute for Standardization, Slovenia

Abstract: *My presentation will focus on working activities of SIST – Slovenian Institute for Standardization, Ljubljana, Slovenia – EU, where several various active technical committees are established, among many others as well technical committee SIST/TC GRT Graphic technology, SIST/TC EPO Packaging – sales and grouped and SIST/TC VPK Pulp, paper, board and products. In the presentation I am briefly presenting some basic rules in the field of standardization that are important for the experts working procedures, pointing out the general importance of standards, why they are needed in modern world, where are their main advantages of use in business environment (companies), that is on different levels, and in various (specific) areas. I am also identifying certain most relevant and important principles of standardization, the process of creating standardization documents, ways of adopting standards (by adoption, with translation) and specifying the types of standardization documents. In conclusion I am referring to the work of SIST/TC GRT, SIST/TC EPO and SIST/TC VPK..*

Keywords: *SIST, rules, standards, SIST/TC GRT, SIST/TC EPO, SIST/TC VPK.*

1. THE SLOVENIAN INSTITUTE FOR STANDARDIZATION (SIST)

The Slovenian Institute for Standardization (SIST) is the Slovenian national body responsible for the preparation and issuance of SIST Slovenian standards.

It represents Slovenia's interests in international standards organizations such as ISO and IEC, as well as European ones such as CEN, CENELEC, ETSI.

Members of the Slovenian technical committees (SIST/TC) have the opportunity to equally participate in all standardization activities, in Slovenia, Europe and the world and can collaborate to create European and international standards.

2. THE BASIC RULES OF THE SIST

Standardization principles:

- participation by all interested parties is voluntary;
- the content of the Slovenian national standards has consensus – agreement in principle of a significant part of interested parties;
- preventing the dominance of individual interests over the common interest of interested parties;
- Slovenian national standards transparency require work transparency and accessibility for the public;
- taking into account the techniques and rules that have been achieved through international and European standardization.

Professional technical work is carried out within the framework of SIST in technical working bodies (TDT), i.e.:
- technical committees (SIST/TC),
- sub-committees (SIST/SC) and
- working groups (SIST/WG).

The professional technical work in SIST supervises:
- members of the technical education board that specializes in electrical engineering and
- members of the board of technical experts in the general field.

Members of the board technic are responsible for the following tasks:

- establish, reform and dissolve TDT to determine the rules for professional work,
  - decide in case there is a misunderstanding between the SIST technical committees or within the technical committees,
  - they take care of standards in the field, where there are no active SIST technical committees.

Participation in technical working bodies means the possibility of:

- expert's representing the interests of the institution from which she/he comes to participate in the preparation of international, European and original national standards,

  - expert's, based on the application, participation in the working groups of international or European organizations for standardization,
  - expert's participation in voting decisions on the content of international, European and original national standards,
  - receiving working material of draft standards (prEN, FprEN),
  - tracking technical progress, reflected in standards,
  - knowledge and experience exchange at meetings etc.

The basic rules on the establishment and working method of technical working documents are:

- quorum at the meeting,
- consensus on essential issues,
- when approving standardization documents, 75% votes of the members present are required,
- resolutions are adopted by the majority of votes of the members present,
- meetings with presence/correspondence/hybrid.

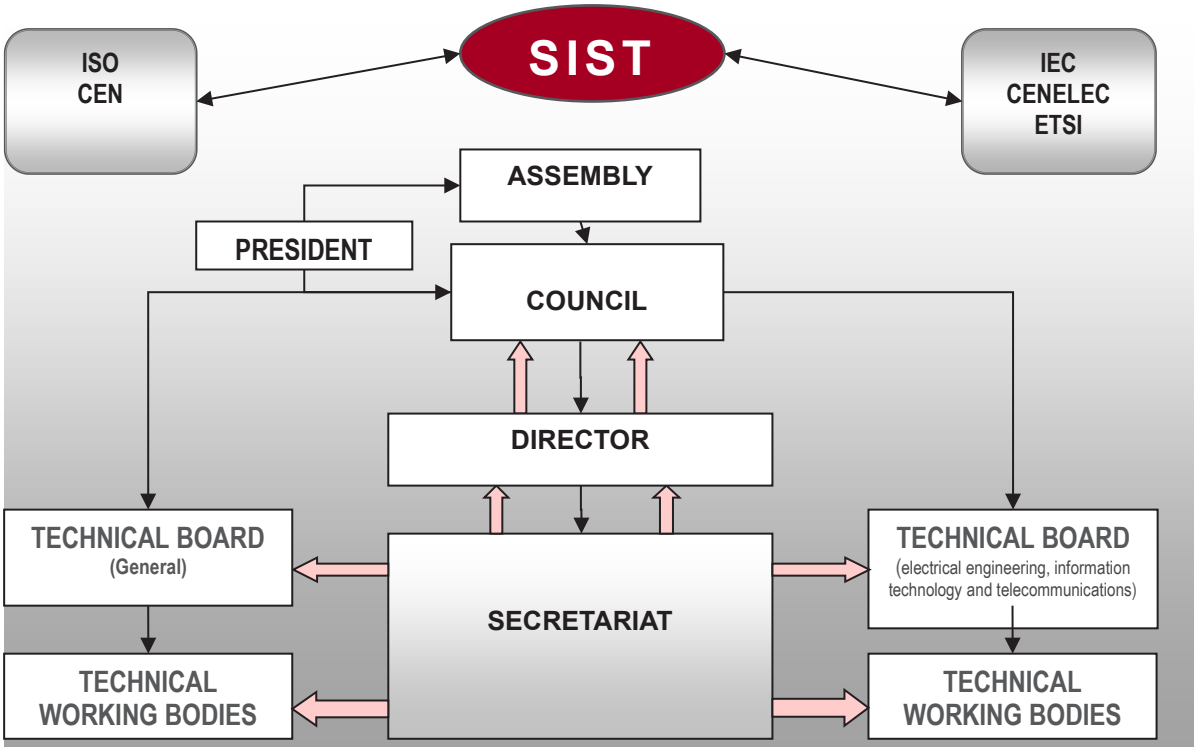


Figure 1: SIST Bodies

3. THE BENEFITS OF HAVING STANDARDS

A standard is a document created by consensus and approved by a recognized authority which defines rules, guidelines or characteristics for activities and their results and is intended for general and repeated use and aimed at achieving an optimal level of regulation in a given field.

4. ADVANTAGES COMPANIES CAN GAIN FROM USING STANDARDS

- better efficiency, fewer costs, and less waste,
- ensure the high quality and safety of products,
- the compatibility between products or services,
- the access to the EU internal market and the reputation of companies; the use of the EN standard in European countries has a potential internal market of more than 500 million (potential) consumers

5. ADVANTAGES OF PARTICIPATING IN THE STANDARDIZATION PROCESS

- co-creation of national standards in Slovenia,
- the possibility of impacting the content of European and international standards,
- accessible experts information about the most up-to-date (recent) techniques,
- achieving access to draft standards and working materials that are not freely accessible,
- establishing and developing business connections in meetings,
- harmonized terminology.

6. STANDARDS PREPARATION

- in the Slovenian national standardization sistem there are almost 36.000 valid standards,
- professional standardization work takes place in technical committees (SIST/TC),
- currently 81 SIST/TC are active (47 among them in the general field of standardization),
- the preparation time of the standard is approximately 2 years, the revision of the standard is in principle every 5 years,
- during the public enquiry there is the possibility of free access to draft standards.

7. TYPES OF STANDARDIZATION DOCUMENTS

- International ISO,
- European EN,
- National SIST (SIST EN, SIST ISO),
- Technical specifications TS,
- Reports TR,
- Guide (Guide - V).

8. STANDARDS ADOPTION METHODS

Members of CEN, CENELEC and ETSI must adopt all European standards within 6 months.
International standards and other national standards are adopted by initiative.

The methods of adoption of standards are the same in all cases;

- method of adoption,
- translation method,
- original Slovenian standard.

9. ALL INTERESTED PARTIES CAN JOIN THE TECHNICAL COMMITTEES

All interested parties can join the technical committee with a written application and a signed access declaration.

Members of the technical committee have the following rights and benefits:

- they participate in the technical committee,
- ability to influence the content of Slovenian national, European and international standards,
- ability to represent national interests in European and international standardization,
- they have access to information that is otherwise not freely available (intellectual property).

10. TECHNICAL COMMITTEE SIST/TC GRT GRAPHIC TECHNOLOGY

In the committee there are currently 4 experts involved in a standardization work.

At the European level, they monitor the work of:
CEN/SS F14 - Graphical Technology, Sign-boards and Nameplates
CEN/SS F18 - Micrographics
CEN/TC 198 - Printing and paper machinery - Safety
CEN/TC 198/WG 1 - Printing and paper converting machines - Drafting of safety standards
CEN/TC 198/WG 2 - Paper Machinery
CEN/TC 198/WG 3 - Paper making machines - Noise

At the international level, they monitor the work of:

ISO/TC 130 - Graphic technology
ISO/TC 42 – Photography.

European technical committees also cooperate with international technical committees and therefore European standards are in the field of graphic technology as well adopted as international standards.

SIST/TC GRT adopts European and International standards as Slovenian national standards. Experts also participate in public enquiry of draft standards and formal voting of European and international final draft standards.

By 1 February 2025 in the field of graphic technology, there will have been issued 166 Slovenian standards.

For the year 2025, the members of SIST/TC GRT Graphic technology plan to translate following standards:
SIST ISO 12637-1:2010 Graphic technology - Vocabulary - Part 1: Fundamental terms
SIST ISO 12637-2:2010 Graphic technology - Vocabulary - Part 2: Prepress terms
SIST ISO 12637-3:2010 Graphic technology - Vocabulary - Part 3: Printing terms
SIST ISO 12637-4:2010 Graphic technology - Vocabulary - Part 4: Postpress terms.

11. TECHNICAL COMMITTEE SIST/TC EPO PACKAGING - SALES AND GROUPED

In the committee there are currently 6 experts involved in a standardization work.

At the European level, they monitor the work of:
CEN/TC 120 - Sacks for the transport of food aid
CEN/TC 194 - Utensils in contact with food
CEN/TC 253 - Self adhesive tapes
CEN/TC 261 - Packaging

At the international level, they monitor the work of:

ISO/TC 122 - Packaging
ISO/TC 51 - Pallets for unit load method of materials handling
ISO/TC 52 - Light gauge metal containers
ISO/TC 63 - Glass containers
ISO/TC 87 – Cork.

Experts also participate in public enquiry of draft standards and formal voting of European final draft standards.

By 1 February 2025 in the field of packaging - sales and grouped, there will have been issued 353 Slovenian standards.

12. TECHNICAL COMMITTEE SIST/TC VPK PULP, PAPER, BOARD AND PRODUCTS

In the committee there are currently 7 experts involved in a standardization work.

At the European level, they monitor the work of:
CEN/TC 172 - Pulp, paper and board.

At the international level, they monitor the work of:

ISO/TC 6 - Paper, board and pulps
ISO/TC 6/SC 2 - Test methods and quality specifications for paper and board.

Experts also participate in public enquiry of draft standards and formal voting of European and international final draft standards.

By 1 February 2025 in the field of packaging – sales and grouped, there will have been issued 139 Slovenian standards.

For the year 2025, the members of SIST/TC VPK Pulp, paper, board and products plan to translate following standards:

SIST ISO 4046-1:2016 Paper, board, pulps and related terms - Vocabulary - Part 1: Alphabetical index
SIST ISO 4046-2:2016 Paper, board, pulps and related terms - Vocabulary - Part 2: Pulping terminology
SIST ISO 4046-3:2016 Paper, board, pulps and related terms - Vocabulary - Part 3: Paper-making terminology
SIST ISO 4046-4:2016 Paper, board, pulps and related terms -- Vocabulary -- Part 4: Paper and board grades and converted products
SIST ISO 4046-5:2016 Paper, board, pulps and related terms - Vocabulary - Part 5: Properties of pulp, paper and board.

Standard SIST EN 643:2014 Paper and board - European list of standard grades of paper and board for recycling has been translated into Slovenian language.

In this field was also issued the original Slovenian technical specification SIST-TS 1190:2017 Paper and board (paperboard, cardboard and corrugated board) – Archive quality.for preparation of the record, document, books, and for protection of document materials on paper.

13. REFERENCES:

mag. Marjetka Strle Vidali, 2024. *Secretariat Quality Manual, Edition 22.* Ljubljana: SIST.
SIST, Standardizacija. URL: https://www.sist.si/standardizacija (Retrieved 27 January 2025).
SIST, E-Dostopi/E-Katalog. URL: https://members.sist.si// (Retrieved 27 January 2025).
SIST, e-Publikacije. URL: https://www.sist.si/e-sporocila.html (Retrieved 27 January 2025).
SIST, *Navodilo o postopku sprejemanja slovenskih nacionalnih standardov in drugih dokumentov s področja slovenske nacionalne standardizacije,* 26.10.2005.

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ORAL PRESENTATION

STARCH-BASED FILMS REINFORCED WITH BACTERIAL NANOCELLULOSE AS PH INDICATORS IN SMART PACKAGING

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Abstract: *The aim of this research was the production of starch-based films with the addition of anthocyanins from red cabbage and bacterial nanocellulose (BNC). BNC was added in different concentrations in polymer composites, as it can be used as an additive that could improve the properties of the produced films. The mechanical, surface and colorimetric properties of the produced films were evaluated. It was expected that a higher BNC concentration would improve the mechanical properties and have little effect on the colorimetric and surface properties of the indicators. The optimal concentrations of starch and BNC, and the colorimetric response of the films were defined. The study has shown that BNC can stabilize the anthocyanins at different pH values and prolong their stability, but may reduce the range of colorimetric changes in the films, which should be taken into account in the preparation of the proposed films.*

Keywords: *Starch-based films, bacterial nanocellulose, pH indicators, smart packaging.*

1. INTRODUCTION

Bacterial nanocellulose (BNC) is an emerging material with significant potential for bio-based smart packaging applications due to its unique properties and compatibility with sustainable practices (Bhargava, 2020; 2020; Ashfaq, 2022). BNC is fully biodegradable, making it an environmentally friendly alternative to synthetic polymers. Research into the production of starch-based films with the addition of bacterial nanocellulose (BNC) has shown great potential in smart packaging applications. In the production of polymer composite films and by adding a natural pigment, pH indicators can be produced to visually monitor food quality in the packaging container by detecting pH fluctuations in the packaging environment (Brockgreitens, 2016; Vasuki, 2023). Embedded starch/BNC films with a pH sensing element can provide a visible color change in response to volatile amines or acids produced by microbial activity on the food surface and provide real-time food quality information. They could be used to monitor the freshness of perishable products such as meat, fish and dairy products (Liu, 2022). The production of starch-based indicators can vary depending on the starch source, pH sensing element and plasticizer used, as well as the desired film properties (Pounds, 2021).

Previously published studies have shown that it is possible to produce a pH indicator from potato and maize starch with the addition of BNC and anthocyanins extracted from red cabbage (Mahović Poljaček, 2024a, Mahović Poljaček, 2024b). Anthocyanins extracted from red cabbage are known for their vivid color changes in response to different pH values. The aim of these studies was to determine the changes in intermolecular interactions between the components of the films (starch, anthocyanins and BNC) and their influence on the physical, surface and colorimetric properties, which are important for the use of the produced films as pH indicators in smart packaging. It was determined that further research should be carried out, such as analyzing the mechanical and other properties of the produced films relevant to their use in smart packaging applications.

The aim of this research was the production of starch-based films with the addition of pH-sensitive elements, anthocyanins extracted from red cabbage, and BNC, in different concentrations. The mechanical, visual and

colorimetric properties of the produced films were evaluated. In addition, the produced films were immersed in different pH buffers to observe and determine the colorimetric response of the polymer composite films at changing pH values.

2. EXPERIMENTAL PART

2.1 Film forming solutions

Two sets of polymer composites were produced. The first consisted of potato starch (PS) (extra pure, CAS: 9005-25-8) (Carl Roth, Karlsruhe, Germany) and the other of maize starch (MS) (extra pure, CAS: 9005-25-8). BNC was prepared from the cellulose-rich biofilm formed after acetic acid fermentation of apple juice according to the previously published method (Lavrič, 2020). The prepared BNC was obtained in a suspension containing 0.6 % of the dry matter of the BNC. The dry matter content of the BNC suspension was calculated according to (ISO 638-2:2022) and the BNC suspension was isolated at a concentration of 20 %, 40 %, 60 %, 80 % and 100 % (v/v) for the preparation of the starch-based films. Samples without BNC were also prepared as a reference. The film-forming solutions were prepared by dissolving the starches in distilled water with the addition of glacial acetic acid (CAS: 64-19-7) (1 % v/v) and glycerol (purity 99.5 %, CAS: 56-81-5) in various concentrations. Glycerol was added to the potato and maize solutions at a concentration of 20 % (v/v) and 15 % (v/v), respectively. Acetic acid was added at a concentration of 5 % (v/v) for PS-based films and 3 % (v/v) for MS-based films.

- Anthocyanins were extracted from the outer leaf debris of fresh red cabbage (Brassica oleracea L.) available in the local market. The extraction method and the calculation of the total monomeric anthocyanin pigment content of red cabbage were performed according to the previously published procedure (Mahović Poljaček, 2024a). The concentration of anthocyanins added to the film-forming solutions was 12% (v/v) for the PS film solution and 14% (v/v) for the MS film solution, based on the previously performed experiments and their color response in different pH buffers (Mahović Poljaček, 2024b).

- The production of each starch-based film took about 30 minutes with constant stirring at elevated temperature; the film-forming potato starch solution was heated to 60 °C and the maize starch solution to 80 °C to achieve a complete gelatinization process. The film-forming solutions were then poured into Petri dishes, dried and stored in a ventilated climate chamber at 25 °C and 50 % relative humidity (RH) for seven days. The starch-based films produced and their designation are summarized in Table 1.

Table 1: Starch-based films produced in the research

Starch type	BNC (%)	Designation	Starch type	BNC (%)	Designation
Potato (PS)	0	PS_0BNC	Maize (MS)	0	MS_0BNC
	20	PS_20BNC		20	MS_20BNC
	40	PS_40BNC		40	MS_40BNC
	60	PS_60BNC		60	MS_60BNC
	80	PS_80BNC		80	MS_80BNC
	100	PS_100BNC		100	MS_100BNC

2.2 Methods

The mechanical properties were measured using the Zwick Roell Z010 tensile testing machine with 20 N measuring cell (class 0.5, ISO 7500-1) and the testXpert testing software (version II V3.2, Zwick GmbH & Co. KG). The tensile properties of the films were determined in accordance with modified ASTM D 882 and expressed as tensile strength (TS, in MPa), Young's modulus of elasticity (YM, in MPa) and elongation at break in percent (ε, %). The size of the sample was set to a width of 20 mm and tested at a test speed of 25 mm/min; the clamping length was set at 40 mm. The test was carried out at 23 °C and 50 % RH. The colorimetric properties of the prepared films were measured before and after immersion in different pH buffer solutions using the Techkon SpectroDens spectrodensitometer (TECHKON GmbH) (illuminant D50/2°, M1 filter). The CIE L*a*b* values were calculated and the

relative CIE L*a*b* values (with paper as white point) were displayed. The results shown are the average values of ten measurements. Photographs were taken of films immersed in different buffer solutions with different pH values to observe the visual change in the films produced.

3. RESULTS AND DISCUSSION

3.1 Mechanical properties

The mechanical properties provide an important indication of the influence of the addition of BNC in the film-forming solutions on the properties of dried starch-based films. These results are important for predicting the behavior of indicators on the surface of packaging materials. The results of the mechanical properties are shown in Table 2. The results of the modulus of elasticity, tensile strength, elongation at break and thickness are shown.
The results show that the tensile strength of the potato-based films decreases with the addition of 40 % BNC and increases slightly with further additions of BNC (60, 80 and 100 %). These values indicate that 40% BNC reduces the ultimate strength of the samples and the higher amount of BNC increases it. This trend is consistent with the studies of Tavares de Almeida et al. (Tavares de Almeida, 2024), in which the mechanical strength of potato starch films showed considerable variation with the addition of BNC in the film-forming solution. Nevertheless, it was found that the addition of BNC mainly increased TS and YM, while EAB was reduced. Similar results are shown in the publication by Jeevahan et al. (Jeevahan, 2019), which indicate a strong interaction of BNC with the starch matrix. The results of mechanical measurements performed on maize-based films showed a similar trend in YM and TS results with differences in EAB percentage. A BNC content of 40 % in the film forming solution leads to lower elongation of the samples, and a higher BNC content (60 and 80 %) leads to higher elongation of the samples as the stress required for deformation is higher compared to potato-based films.

Table 2: Properties of starch-based films with BNC variation

Film sample	Young's Modulus (MPa)	Tensile Strenght (MPa)	Elongation at Break (%)	Thickness (µm)
PS_0BNC	0.085±0.004	0.4445±0.056	34.197±1.793	953
PS_40BNC	0.086±0.002	0.375±0.025	27.276±2.283	1189
PS_60BNC	0.164±0.032	0.499±0.005	15.450±1.233	1139
PS_80BNC	0.164±0.004	0.479±0.009	15.69±0.321	1447
PS_100BNC	0.176±0.009	0.522±0.038	14.683±3.123	1347
MS_0BNC	0.059±0.003	0.613±0.015	50.504±1.044	761
MS_40BNC	0.108±0.004	0.663±0.009	39.538±0.442	767
MS_60BNC	0.129±0.015	0.757±0.006	54.069±1.178	553
MS_80BNC	0.176±0.011	0.895±0.013	53.611±0.569	629
MS_100BNC	0.153±0.013	0.702±0.001	48.563±2.089	576

Figure 1 shows the standard force-elongation curve; Figure 1.a shows the influence of BNC concentration on the properties of potato-based films and Figure 1.b on the properties of maize-based films. According to the measurement results, the maize-based films showed higher potential elongation than the potato-based films, indicating greater flexibility, probably due to the better interaction of BNC with maize starch compared to potato starch. It can be said that maize-based films may have greater potential for the production of pH indicators due to the higher elasticity and ultimate strength of the films produced.

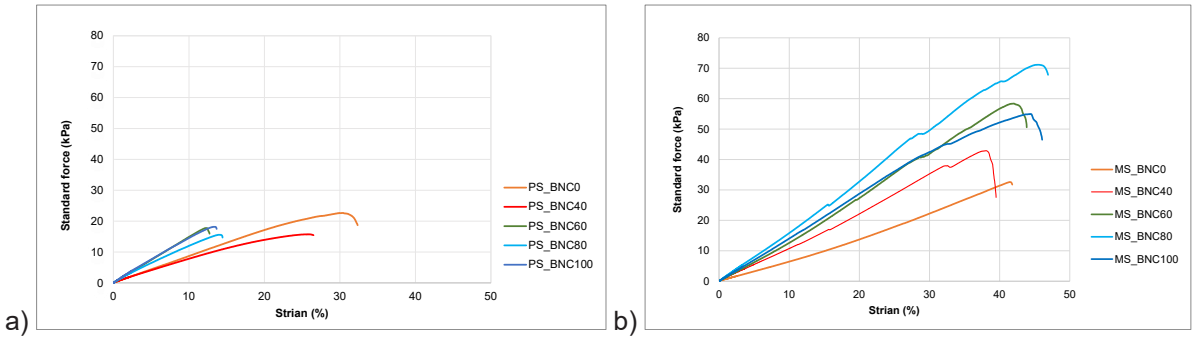
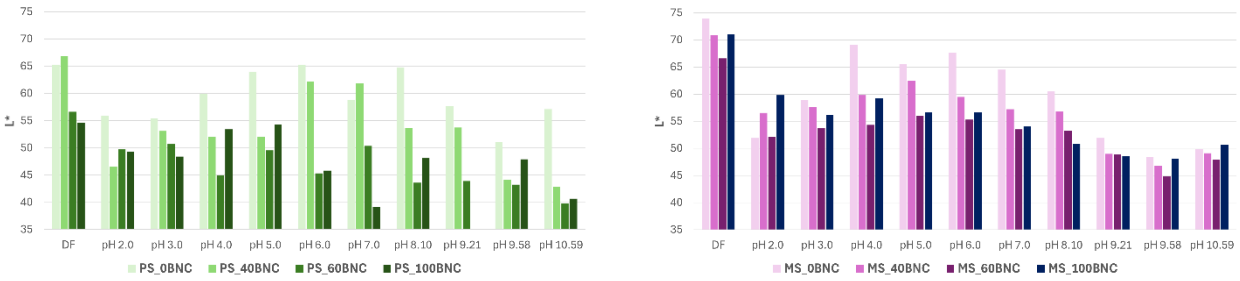


Figure 1: Standard force – strain curve for a) potato-based fims and b) maize-based fims

3.2 Colorimetric measurements

Figures 2.a -2.b present the lightness (L*) values of the PS-based and MS-based films with different BNC contents. The films containing BNC generally exhibited a decrease in L* values across the entire tested pH range compared to the films without BNC. This reduction was notably more significant in the PS-based films (Figure 2.a) and generally for the samples with higher BNC content in buffer solutions with alkaline pH. The observed decrease in lightness of the samples with a higher concentration of BNC can be attributed to the optical properties of the BNC (i.e., decreased optical transparency of the samples with higher BNC portion (Almeida, 2023), and to the pronounced swelling of the films in buffers of pH above 9.



a) b)

Figure 2: Lightness (L*) at different pH values (2.0–10.59): a) PS-based films, b) MS-based films

Figures 3-4 present the changes in CIE a* and b* values of the produced films. To emphasize and compare the trends of the CIE a*/b* shifts in different pH environments, a fourth-degree polynomial trendline has been added to the plots. The point labelled „DF“ represents the dry film not immersed in the buffer solutions.

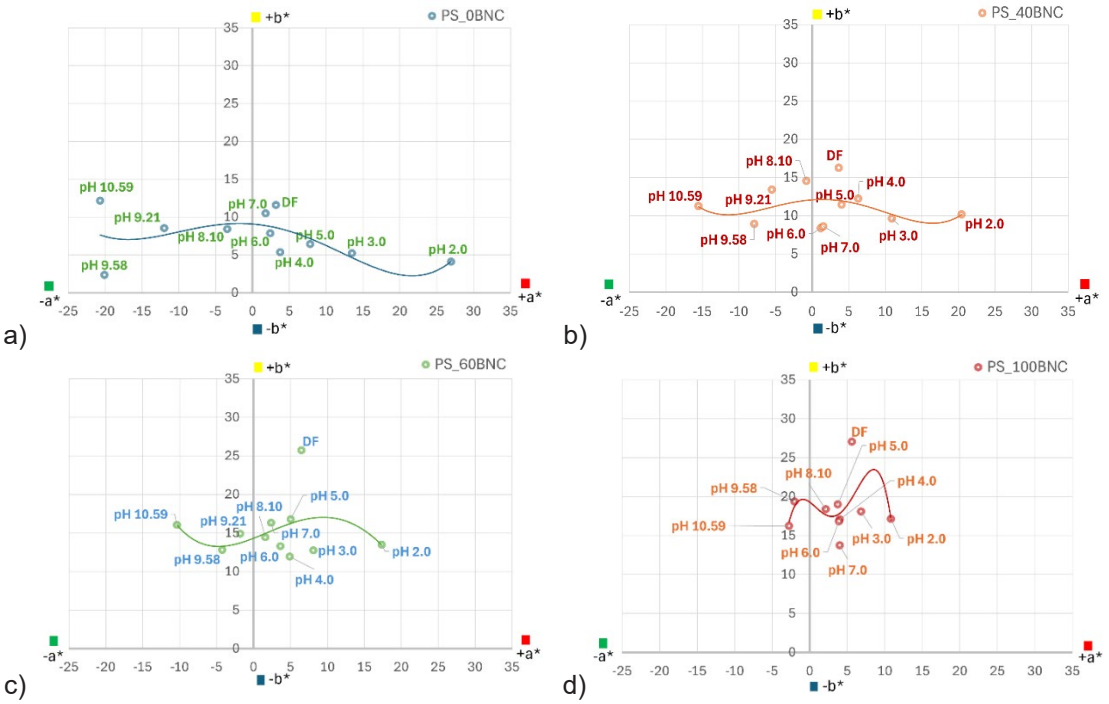


Figure 3: CIE a*/b* diagrams for PS-based films at different pH values:
a) 0% BNC, b) 40% BNC, c) 60% BNC, d) 100% BNC

The changes in the pH-dependent range of a* and b* values of both PS-based and MS-based films were predominantly influenced by the concentration of BNC in the films, regardless of the starch type.

The trendlines of data points in the CIE a*/b* plots (Figure 3-4) showed a noticeable shift towards +b* values with increased concentration of BNC in the films. This occurrence is not dependent on the type of starch and can be attributed to the hue of used BNC. Color shifts occurring in the films as a consequence of the changed pH of the environment start from pink hues at acidic pH, across the mildly yellow hues at neutral pH, towards blue-green hues at alkaline pH. The results of the color shifts are aligned with the previous research. However, the addition of BNC in concentrations higher than 40% significantly decreased the span of the +a*/-a* color shift. Specifically, the span of measured CIE a* values for the sample PS_0BNC was 47.60, and it decreased to 13.59 for PS_100BNC. The span of measured CIE a* values for the sample MS_0BNC was 52.07, and was decreased to 8.79 for the sample MS_100BNC. Therefore, the addition of BNC in high concentrations has impaired the colorimetric response and color vividness of the produced films.

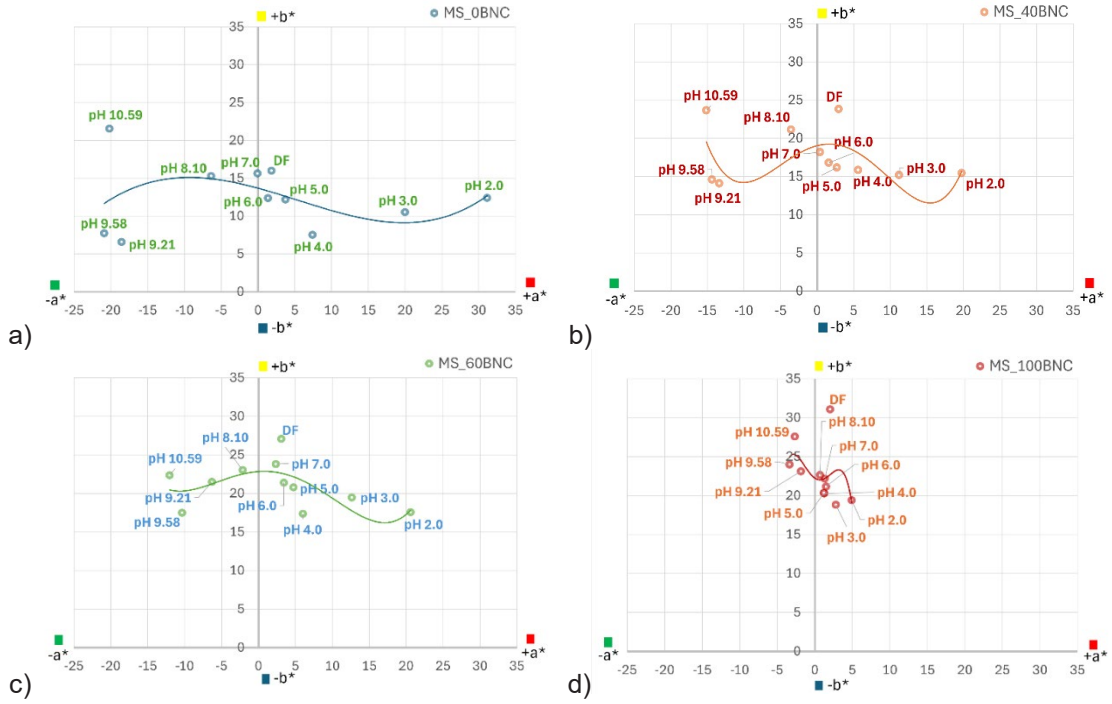


Figure 4: CIE a*/b* diagrams for MS-based films at different pH values:
a) 0% BNC, b) 40% BNC, c) 60% BNC, d) 100% BNC

The results obtained from this research indicate that BNC can stabilize anthocyanins during exposure to varied pH, which is aligned with the previous research (Mahović Poljaček, 2024a). BNC can form a network that protects anthocyanins from degradative factors, thereby extending their stability and lifespan. However, because of the interaction of BNC and anthocyanins; and due to the optical and colorimetric properties of BNC, the range of colorimetric changes occurring in the films when exposed to an environment with varied pH could be significantly reduced. Therefore, the concentration of BNC in starch-based films with anthocyanins should be carefully adjusted to maximize both the functional properties of the produced films and their colorimetric response.

4. CONCLUSION

This research aimed to produce starch-based films incorporating pH-sensitive anthocyanins from red cabbage and varying concentrations of BNC. Mechanical, visual, and colorimetric properties were evaluated, along with the films' responses to different pH buffers. Results indicated that adding 40% BNC initially reduced the tensile strength of PS-based films, while higher concentrations (60-100%) slightly increased it. Similar trends were observed in MS-based films, with higher BNC (60-80%) content leading to increased elongation, suggesting greater flexibility. MS-based films demonstrated better flexibility than PS-based films, likely due to improved BNC-starch interactions. The study found that BNC could stabilize anthocyanins in varying pH conditions, extending their stability, but might reduce the range of colorimetric changes in the films. Therefore, BNC concentration in films should be optimized for the desired functional properties and maximized colorimetric response.

5. REFERENCES

Almeida, T., Karamysheva, A., Valente, B.F.A., Silva, J.M., Braz, M., Almeida, A., Silvestre, A.J.D., Vilela, C., Freire, C.S.R. 2023. "Biobased ternary films of thermoplastic starch, bacterial nanocellulose and gallic acid for active food packaging." Food Hydrocoll. 144: 108934.
Ashfaq, A., Khursheed, N., Fatima, S., Anjum, Z., Younis, K. 2022. "Application of nanotechnology in food packaging: Pros and Cons."Journal of Agriculture and Food Research 7: 100270.
Beluhan, S., Herceg, F., Pavunc, A.L., Djaković, S. 2022. "Preparation and Structural Properties of Bacterial Nanocellulose Obtained from Beetroot Peel Medium." Energies 15(24): 9374.
Bertoft, E. 2017. "Understanding Starch Structure: Recent Progress," Agron. 7(3): 56.
Bhargava, N., Singh Sharanagat, V., Mor, R.S., Kumar, K. 2020. "Active and intelligent biodegradable packaging films using food and food waste-derived bioactive compounds: A review." Trends in Food Science & Technology 105: 385-401.
Brockgreitens, J., Abbas, A. 2016. "Responsive Food Packaging: Recent Progress and Technological Prospects." Compr. Rev. food Sci. food Saf. 15: 3-15.
ISO 638-2:2022 Paper, Board, Pulps and Cellulosic Nanomaterials - Determination of Dry Matter Content by Oven-Drying Method - Part 2: Suspension of Cellulosic Nanomaterials 2022. Available online: https://www.iso.org/standard/83615.html (accessed on 21 July 2024).
Jeevahan, J., Chandrasekaran, M., Sethu, A. 2019. "Influence of nanocellulose addition on the film properties of the bionanocomposite edible films prepared from maize, rice, wheat, and potato starches." AIP Conference Proceedings 2162: 020073.
Lavrič, G., Medvešček, D., Skočaj, M. 2020. "Papermaking properties of bacterial nanocellulose produced from mother of vinegar, a waste product after classical vinegar production." Tappi J. 19: 197-203.
Liu, D., Zhang, C., Pu, Y., Chen S., Liu, L., Cui, Z., Zhong, Y. 2022. "Recent Advances in pH-Responsive Freshness Indicators Using Natural Food Colorants to Monitor Food Freshness." Foods 11(13):1884.
Mahović Poljaček, S., Tomašegović, T., Strižić Jakovljević, M., Jamnicki Hanzer, S., Murković Steinberg, I., Žuvić, I., Leskovac, M., Lavrič, G., Kavčić, U., Karlovits, I. 2024. "Starch-Based Functional Films Enhanced with Bacterial Nanocellulose for Smart Packaging: Physicochemical Properties, pH Sensitivity and Colorimetric Response." Polymers 16(16): 2259.
Mahović Poljaček, S., Tomašegović, T., Jamnicki Hanzer, S., Strižić Jakovljević, M., Murković Steinberg, I., Žuvić, I., Lavrič, G., Kavčič, U., Karlovits, I. 2024. "Immobilization of anthocyanins by bacterial nanocellulose in production of indicators for pH-controlled smart packaging" In Proceedings GRID 2024, edited by Pál, Magdolna, 443-453. Novi Sad: University of Novi Sad.
Mustafa, F., Andreescu, S. 2022. "Nanotechnology-based approaches for food sensing and packaging applications." RSC Adv. 10: 19309-19336.
Pounds, K., Jairam, S., Bao, H., Meng, S., Zhang, L., Godinez, S., Savin, D.A., Pelletier, W., Correll, M.J., Tong, Z. 2021. "Glycerol-Based Dendrimer Nanocomposite Film as a Tunable pH-Sensor for Food Packaging." ACS Appl. Mater. Interfaces 13: 23268–23281.
Tavares de Almeida, N., Pereira, A.L.S., de Oliveira Barros, M., Mattos, A.L.A., Rosa, M.d.F. 2024. "Enhancing Starch Film Properties Using Bacterial Nanocellulose-Stabilized Pickering Emulsions." Polymers 16(23): 3346.
Vasuki, M.T., Kadirvel, V. and Narayana, G.P. 2023. "Smart packaging - An overview of concepts and applications in various food industries." Food Bioeng. 2: 25-41.

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ORAL PRESENTATION

SCREEN-PRINTED IRREVERSIBLE THERMOCHROMIC INDICATORS UTILISING SINGLE AND MIXED LEUCO DYE SYSTEMS

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Abstract: *Effective temperature control is essential in various industrial applications to prevent equipment from overheating and to ensure product quality. A cost-effective solution is the use of screen-printed irreversible temperature indicators with thermochromic systems based on leuco dyes. In this study, the effectiveness of temperature indicators with mixtures of two leuco dye systems with different colour transition temperatures was investigated. Five different indicators with blue and green leuco dyes and their mixtures were produced. For all samples, the colour parameters (L*, a*, b*, chroma and hue angle) were measured as a function of temperature and their thermal behaviour evaluated. Single-dye indicators showed sharp colour transitions within narrow temperature ranges, while mixed-dye indicators showed gradual colour transitions.*

Keywords: *Thermochromism, thermochromic inks, leuco dyes, screen printing, colourimetry.*

1. INTRODUCTION

Temperature control plays a critical role in numerous industrial applications, especially in scenarios where overheating poses a significant risk to equipment performance and longevity (Almubarak, 2017). Effective monitoring and management of temperature is essential to prevent equipment failure and ensure the safety and efficiency of industrial processes. On the other hand, in some production processes, certain heating thresholds must be met for each product (Panayiotou, 2017; Tadini, 2022). In both cases, conventional temperature sensors based on electrical components are often unsuitable. This limitation is particularly evident when temperature measurements are required on surfaces that are difficult to access or in dynamic production lines. In such cases, there is a growing need for cost-effective and user-friendly temperature sensing solutions to ensure consistent quality and process reliability.

One possible solution to this problem is the use of printed indicators for critical temperatures that contain thermochromic systems based on leuco dyes (Jenko, 2021; Pogorelc, 2023). They are screen-printed with thermochromic ink on self-adhesive labelling materials so that they can be easily applied to the object in question. These indicators undergo a colour transition from white to a strongly coloured state, with the final colour being determined by the type of leuco dye used once a certain critical temperature is reached (Seeboth, 2013; White, 1999). In one case, the colouration returns to white on cooling, making this type of indicator reversible. In the other case, the colouration remains even after cooling, providing the user with a visual record of the object's thermal history.

Earlier studies mostly focussed on reversible thermochromic printing inks. Kulčar et al. investigated the colouration behaviour as a function of temperature of binary mixtures of commercially available thermochromic printing inks (Kulčar, 2011). Two mixtures were analysed: one containing ink with similar colour transition temperatures and another with different transition temperatures. In the first case, a single-colour transition was observed at a temperature between the transition points of the individual thermochromic inks. In contrast, two separate and distinct colour transitions were observed in the mixture with different transition temperatures. Reversible thermochromic inks are usually microencapsulated to prevent unwanted contamination and ensure a reversible colour change. Irreversible thermochromic systems are designed for single use applications, i.e. for only one colour change, which requires a different formulation and composition. This raises an interesting question: How do irreversible thermochromic indicators behave when prepared with a mixture of two thermochromic inks, each with different transition temperatures? To investigate this, five different thermochromic indicators were prepared. Two of these were prepared for different transition temperatures and contained a single dye, while the remaining three were prepared by mixing the two dyes in different ratios. These indicators were then heated to specific temperatures, and several colour parameters were measured in the CIELAB colour space as a function of temperature (Kulčar, 2010; Panák, 2015). The results provided insights into the thermal behaviour of both single-dye and mixed-dye systems over a wider temperature range.

2. EXPERIMENTAL

Five different water-based thermochromic screen-printing inks were prepared. The mass fraction (%) of all components was kept constant for all inks produced, with the exception of the different content of the two dyes, blue and green. The five inks were prepared with different ratios of these two dyes, so that their cumulative weight in the ink was the same ratio. The ratio of the two dyes forming the dye component of the five inks is shown in Table 1. The critical temperature indicators were screen-printed using thermochromic ink with a screen-printing mesh of 61 μm diameter and a density of 64 threads/cm on self-adhesive polyester foil JAC SERIPOL Silver Matt (Avery Dennison, USA).

Table 1: Ratio of dyes in the dye component of the prepared inks (using mass fraction).

Indicator	Ratio of dyes in dye component	
	Blue dye (%)	Green dye (%)
100B–0G	100	0
75B–25G	75	25
50B–50G	50	50
25B–75G	25	75
0B–100G	0	100

The indicators were heated in a laboratory oven SP-55 EASY (Kambič, Slovenia) for 15 minutes at temperatures from 130 to 180 °C in steps of 5 °C and cooled to room temperature. The colouration was irreversible, i.e. no colour change was observed on cooling. A new label indicator was used for each temperature in the oven.

Several colour parameters of the indicators, including L^*, a^* and b^*, chroma and hue angle, were determined from reflectance measurements with the Datacolor Spectro 1050 spectrophotometer (Datacolor, Switzerland). The geometry used was di:8°, the radius of the integrating sphere was 152 mm and the radius of the sample aperture was 3 mm. The light source was a xenon lamp. Specular reflection was excluded. The spectra were measured between 400 and 700 nm with a step of 10 nm and processed using software from Datacolor applications. The 2° standard observer and illuminant D50 were used to calculate the colour parameters. Each sample was measured three times so that their average values were used. The colour differences between unheated samples and samples heated to a certain temperature were calculated using the simple colour difference ΔE^*_{ab} according to

Equation 1, where L^*_0, a^*_0 and b^*_0 are the values of the unheated indicators and the values L^*, a^* and b^* when heated to a certain temperature (Hunt, 2011).

$$\Delta E^*_{ab} = \sqrt{(L^*_0 - L^*)^2 + (a^*_0 - a^*)^2 + (b^*_0 - b^*)^2} \quad (1)$$

To better assess the results, we calculated the cumulative colour difference at a given temperature, $\Delta E_C(T)$, using Equation 2 (Panák, 2015). The L^*, a^* and b^* values of a sample i (where $i=1$ marks indicator heated to 130 °C, $i=2$ indicator heated to 135 °C and so on) were used to calculate the colour difference between samples heated to two adjacent temperatures. $\Delta E_C(T)$ is then determined as the sum of these differences until the sample is heated to the desired temperature $m(T)$.

$$\Delta E_C(T) = \sum_{i>1}^{m(T)} \sqrt{(L^*_i - L^*_{i-1})^2 + (a^*_i - a^*_{i-1})^2 + (b^*_i - b^*_{i-1})^2} \quad (2)$$

3. RESULTS WITH DISCUSSION

3.1 Colour coordinates in CIELAB colour space

Multiple colour parameters were measured for all indicators. As illustrated in Figure 1, the L^* parameter decreases significantly with increasing temperature, indicating a transition from white at temperatures below the critical value to dark colours at temperatures well above. Both single-dye indicators undergo this change within a narrow range of about 10 °C. For example, the blue-dye indicator (100B–0G) begins to show a decrease in L^* at 145 °C, while the green-dye indicator (0B–100G) does so at 160 °C. In contrast, mixed-dye systems show a more gradual and continuous decrease in L^* over a wider temperature range, suggesting that the mixed dyes influence the thermal response. Once the temperature reaches 165 °C or more, the L^* values of all samples converge to approximately 29 ± 3, indicating that they take on a dark almost achromatic appearance regardless of dye type or ratio.

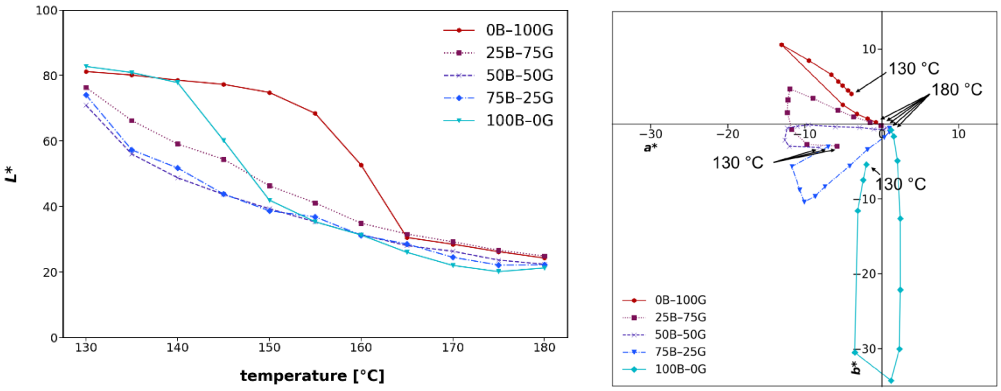


Figure 1: L* as a function of temperature (left) and a*, b* values (right).

The a^* and b^* values for all samples are shown in the a^*b^* diagram in Figure 1. For the green-dye indicator (0B–100G), heating to 130 °C results in a negative a^* value and a positive b^* value, indicating a slightly green hue. With further heating, a^* decreases sharply at 160 °C, corresponding to the onset of a strong green colouration, and then gradually decreases to zero as the indicator darkens. In comparison, the blue-dye indicator (100B–0G) has negative both a^* and b^* values at 130 °C, which corresponds to a blue hue. Above 150 °C, b^* decreases to -34, and a^* changes from negative to positive values. This change indicates the development of a strong blue colour, which becomes darker with further heating. For mixed-dye indicators, the ab values are more strongly grouped together at 130 °C, with both a^* and b^* values being negative. At this temperature, the b^* values are relatively consistent, while the a^* values show minor deviations that are not strongly correlated with the dye ratios. With further heating, the a^* minima shift to lower temperatures and show more gradual transitions compared to single-

dye indicators. Similarly, the *b** transitions are more gradual for mixed-dye indicators, but the *b** is more strongly influenced by the dye ratios. Indicators with a higher blue-dye content (75B–25G) maintain negative *b** values over the entire temperature range. In comparison, indicators with a higher green-dye content (25B–75G) show a transition to positive *b** values above 140 °C. An equal mixture (50B–50G) shows *b** values close to zero above 140 °C, reflecting an earlier onset of blue colouration compared to green one with the increasing temperature.

At the same time as the parameters *L**, *a** and *b**, the colour purity (chroma) and the hue angle were collected for all five indicators as a function of temperature (Figure 2).

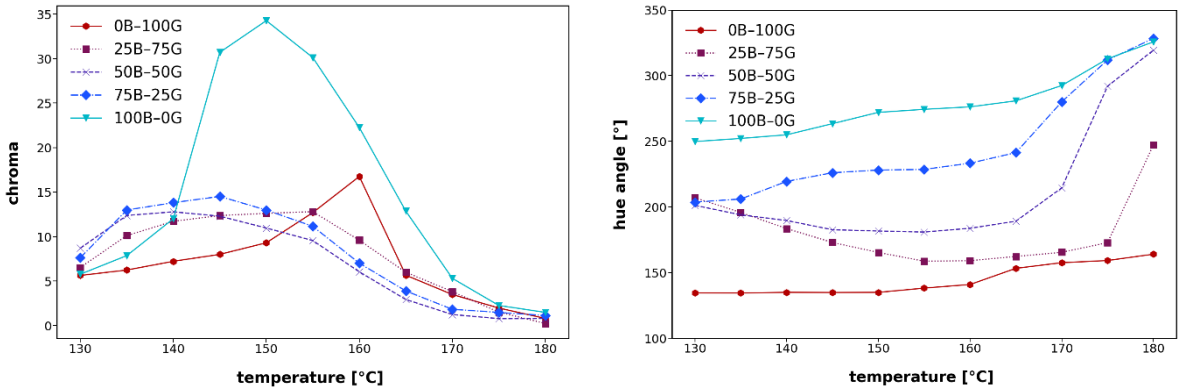


Figure 2: Chroma (left) and hue angle (right) as a function of temperature.

The most pronounced increase in chroma can be observed in sample 100B–0G around 150 °C, which can be attributed to the strong blue colouration. A similar, although weaker effect occurs with 0B–100G around 160 °C, reflecting its green hue. Indicators containing both dyes (25B–75G, 50B–50G, 75B–25G) show more moderate chroma values overall, suggesting that the chroma of the blue dye has been displaced by the less chromatic green dye.

The hue angle largely follows the colour distribution on the colour wheel. For sample 0B–100G, it remains relatively stable up to a temperature of about 160 °C, where a slight increase can be observed due to the green transition. The indicators 25B–75G and 50B–50G initially show a slight drop in the hue angle before it increases rapidly at higher temperatures (approx. 175 and 170 °C respectively). For sample 75B–25G, the hue angle increases steadily up to around 165 °C and then shows a sharper increase. Sample 100B–0G shows higher hue angle values at all temperatures, with significant shifts at 140 °C (its main hue transition) and again above 160 °C when it transitions to dark, almost achromatic colour.

3.2 Colour difference

An important parameter in the evaluation of temperature indicators is the colour difference as a function of temperature. Figure 3 shows the colour change compared to the initial, room-temperature colour (calculated with Equation 1) and the cumulative colour change (calculated with Equation 2).

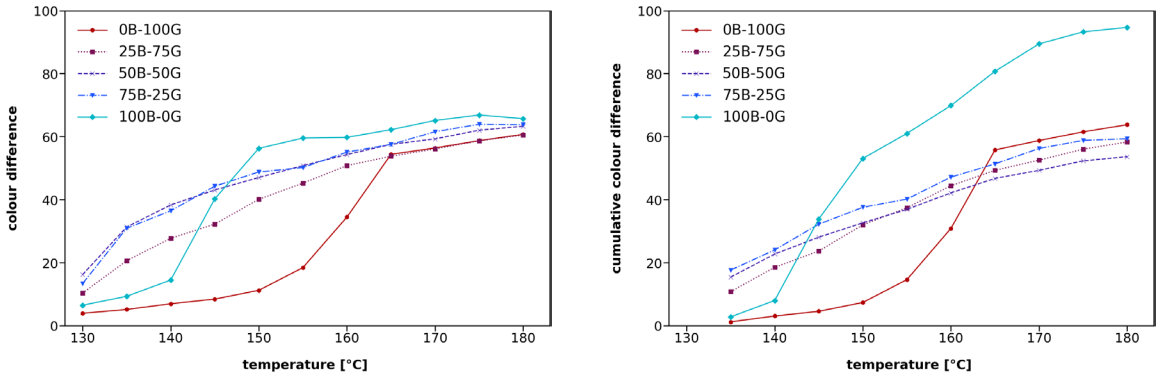


Figure 3: Colour difference between unheated and heated samples (left) and cumulative colour difference (right) as a function of temperature.

Single-dye indicators 0B–100G and 100B–0G show sharp colour transitions in the ranges 155–165 °C and 140–150 °C respectively, after which their colour remains relatively stable. Mixed-dye indicators (25B–75G, 50B–50G, 75B–25G) change colour at around 135 °C and continue their gradual – almost linear – change over a wider range. These results indicate that dye mixtures flatten and lengthen the colouration interval, while the dye ratio mainly influences the final perceived colour. The colour difference between unheated and to 180 °C heated samples is relatively similar for all indicators and varies by only about 5 units. For the single-dye indicators, the colour differences are 61 for 0B–100G and 66 for 100B–0G. In comparison, the colour differences for the mixed-dye indicators 25B–75G, 50B–50G, and 75B–25G are 61, 63 and 64 respectively.

The cumulative colour difference of the green single-dye indicator (0B–100G) shows only a slight difference in colour change compared to the initial, room-temperature colour. At 180 °C it reaches similar values at 64. In comparison, the blue single-dye indicator (100B–0G) shows the same strong colour transition when heated above 140 °C, and the cumulative colour difference then increases above 150 °C. This shows that the colour changes continuously from blue to dark, almost black, even when heated further. Mixed-dye samples show a continuous increase in cumulative colour difference as a function of temperature in a range of interest.

4. CONCLUSIONS

This study investigated the effect of combining leuco dyes to critical temperature indicators. Five different critical temperature indicators were prepared by screen-printing thermochromic inks on self-adhesive polyester foil. Their colour parameters were investigated in dependence of temperature. Two single-dye indicators, one containing a blue dye and the other a green dye, showed sharp colour changes within narrow temperature intervals between 140–150 and 155–165 °C, respectively. On the other hand, indicators with mixed dyes (ratios of green at 75%, 50%, and 25%) began changing colour when heated above 130 °C and transitioned continuously across the entire temperature range. The largest influence was on the trajectory of the observed colour change with predominant variation among inks in the b^* coordinate in the CIELAB space.

The findings of this research show that single-dye indicators are more suitable for industrial applications of critical temperature indicators where products must not exceed a certain temperature. Namely, no optimal blend was found that could replicate the sharp transitions of the single-dye indicators. Moreover, mixed-dye indicators did not even show any significant variance in measured colour difference as a function of temperature. Interestingly, colour transformation in the mixed-dye system starts at a lower temperature than expected from the single-dye indicators, suggesting that additional interactions between the compounds occur. The study further highlights the need for additional research to interpret those interactions and a better understanding of dye mixtures in irreversible thermochromic inks.

5. REFERENCES

Almubarak, A. A., 2017. “The Effects of Heat on Electronic Components.” Int. J. Eng. Res. Appl. 7 (5): 52–57.
Hunt, R. W. and Pointer, M. R. 2011. “Measuring Colour.” Chichester: John Wiley & Sons.
Jenko, K., Rozman, N., Pogorelc, E., Stražar, P., Kunaver, M. and Klanjšek Gunde, M. 2021. “Development of hydrophobic protection layer for high-temperature irreversible thermochromics.” In *Proceedings of the 2nd International Conference on Circular Packaging,* edited by Igor Karlovits, 171–176. Slovenj Gradec: Pulp and Paper Institute, Faculty of Polymer Technology.
Kulčar, R., Friškovec, M., Hauptman, N., Vesel, A. and Klanjšek Gunde, M. 2010. “Colorimetric properties of reversible thermochromic printing inks.” Dyes Pigm. 86: 271–277.
Kulčar, R., Friškovec, M., Klanjšek Gunde, M. and Knešaurek, N. 2011. “Dynamic colorimetric properties of mixed thermochromic printing inks.” Color. Technol. 127: 411–417.
Panák, O., Držková, M. and Kaplanová, M. 2015. “Insight into the evaluation of colour changes of leuco dye based thermochromic systems as a function of temperature.” Dyes Pigm. 120: 279–287.
Panayiotou, G. P., Bianchi, G., Georgiou, G., Aresti, L., Argyrou, M., Agathokleous, R., Tsamos, K. M., Tassou, S. A., Florides, G., Kalogirou, S. and Christodoulides, P. 2017. “Preliminary assessment of waste heat potential in major European industries.” Energy Procedia. 123: 335–345.
Pogorelc, E., Jenko, K. and Klanjšek Gunde, M. 2023. “Funkcionalne lastnosti temperaturnega indikatorja z ireverzibilno termokromno tiskarsko barvo.” Papir. 29: 38–41.
Tadini, C. C. and Gut, J. A. 2022, “The Importance of Heating Unit Operations in the Food Industry to Obtain Safe and High-Quality Products.” Front. Nutr. 9:853638.
Seeboth, A. and Lötzsch, D. 2013. “Thermochromic and Thermotropic Materials.” Boca Raton, FL: Taylor & Francis Group.
White, M. A. and LeBlanc, M. 1999. “Thermochromism in Commercial Products.” J. Chem. Ed. 76 (9): 1201–1205.

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ORAL PRESENTATION

ENVIRONMENTALLY FRIENDLY COATINGS AND THEIR EFFECT ON THERMOCHROMIC PRINTING INK FUNCTIONALITY

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Abstract: *Polymer waste poses a significant environmental challenge due to its non-biodegradable nature, leading to environmental pollution at the end of its lifecycle, meaning there is a pressing need to replace synthetic polymers with naturally derived ones. The introduction of circular economy practices is a solution to reduce waste materials by promoting waste reuse, particularly the agro-industrial waste. Protective coatings are crucial to enhance functionality, stability, and product lifespan. Biodegradable coatings are a promising alternative. Thermochromic printing inks, which change color based on temperature, are especially sensitive to UV degradation and thus require protective coatings for durability. The integration of thermochromic inks with protective coating made from sustainable materials offers an innovative solution for producing eco-friendly graphic products that are both interactive and durable. This approach reduces the industry's ecological footprint while delivering high-quality, functional products.*

Keywords: *Thermochromic priting ink, coating, natural products, sustainability.*

1. INTRODUCTION

The challenge of today, which affects practically every aspect of industrial progress, is the excessive waste production, especially polymer material waste. Such waste cannot be recycled indefinitely, whereas, during recycling process new issues occur, including issues with sorting, cleaning, separation processes, high transportation and electricity costs; etc. and most of it ends up in landfills (Okan et al., 2019). It is voluminous and non-biodegradable. The goal of every industry should be to avoid producing waste at the end of the production process. Waste as a high-value raw material, can be reused, reducing natural resource destruction. Recognizing waste as an input raw material can lower the economic cost of these materials. When less virgin resource is used and post-consumed materials can be recycled or reused from easily accessible materials, packaging materials are considered sustainable (Ibrahim et al., 2022). Industrial development in accordance with the circular economy is desirable and necessary. The food packaging industry is growing increasingly conscious of the development of intelligent and active biodegradable packaging (Bhargava et al., 2020) that achieves antioxidant, antimicrobial, and biocatalytic functions through the addition of bioactive components (Bastarrachea et al., 2015). Replacment of polymer based packaging solutions with paper based materials can be a promising sustainable alternative that reduces the environmental footprint. Certain drawbacks are expected in the terms of durability and strength of paper based materials, and thus by application of coatings, fiber reinforcement, lamination, and chemical treatment resistance to moisture, mechanical stress, and external factors can be used (Kunam et al., 2024). The coatings industry has been shifting toward using materials derived from renewable resources during the recent years and has significantly reduced VOC emissions over the past few decades, primarily by substituting solventbased coatings with waterbased coatings (Cunningham et al., 2019). The water-dispersive coating is free of volatile organic compounds that can cause a number of environmental issues and have a negative impact on people's health. In our case, the environmentally friendly bioactive coating is a water-dispersive (WD) coating enhanced with bioactive ingredients allantoin and ascorbic acid to improve the functionality of the coating. Ascorbic acid is a well-known antioxidant (Blokhina et al., 2003), and allantoin may also have antioxidant properties (Selamoglu et al., 2017). Antioxidants are molecules or compounds that donate electrons to free radicals in order to neutralize them. By neutralizing reactive oxygen species from both endogenous and exogenous sources, such as UV radiation, antioxidants added to coating work to stop photodegradation (Vukoje et al., 2024). Adding natural antioxidants could give these coatings functional qualities (Eça et al., 2014) such as enhanced physicochemical, mechanical, barrier, antioxidant, and antibacterial properties (Sultan et al., 2024). In addition to mechanical and chemical degradation,

thermochromic (TC) printing inks are particularly susceptible to UV-induced degradation. One of the primary goals of adding bioactive compounds was to reduce UV-induced degradation, since UV exposure is known to reduce the ink's thermochromic effect. Thermochromic printing inks are characterized by their ability to change color in response to temperature changes. Thermochromic printing inks have grown in significance for a variety of graphic art applications, including smart packaging, security printing, and marketing activities that aim to highlight a product's value or distinctiveness (Kulčar et al., 2010). Agro-industrial waste is ideal for paper production because it contains a significant amount of cellulose fibers. Non-wood lignocellulosic materials derived from citrus waste offer a viable substitute for traditional raw materials used to make paper and packaging (Vukoje et al., 2021). Since environmentally friendly coatings are a novel, eco friendly approach to current technology, it is necessary to observe the effects of these coatings in order to make improvements over time. Their development could eventually have a significant positive influence on the advancement of technological processes.

Due to the fact that there aren't many research papers on this specific subject, we attempted to apply the concepts we learned from the food packaging and coatings industry to the graphic industry by creating a environmentally friendly coating with added bioactive compounds for printing on paper. The graphic industry has recognized the waste issue, which can be resolved by a more thoughtful selection of materials that enter the process. This study will concentrate on preliminary tests of one step of the process, particularly regarding the use of environmentally friendly coatings and their impacts on the functionality of thermochromic printing inks and the thermochromic effect.

2. EXPERIMENTAL

2.1. Printing substrate and printing ink

For this research, a pressure sensitve label (PSL) based on citrus agro-industrial byproducts was used as a printing substrate. The upper layer of the label was produced with a 20% reduction in CO2 emissions (Avery Dennison, 2025). The label's composition includes 15% citrus fibers, 40% recycled paper, and 45% virgin wood pulp, ensuring high-quality natural paper.

The reversible thermochromic ink used is a commercially available leuco dye-based screen printing ink with an activation temperature (T_A) of 28°C. Before reaching the T_A, the TC print is coloured in orange. By heating up and reaching the T_A, the TC print changes its coloration to a neon yellow. This type of ink is also known as body heat activated because it changes color when exposed to human body temperature. Thermochromic inks with this activation temperature are commonly used in interactive packaging, temperature indicators on drinkware, novelty items, and security printing. Printing was carried out under laboratory conditions using a semi-automatic screen-printing device from Holzschurer KG, Wuppertal. A mesh with a density of 62 threads/cm was used for the printing process. The prints were produced in full tone.

2.2. Coating preparation

Weighing out 0.0440 g of ascorbic acid and adding distilled water until the total volume reached 25 mL produced the ascorbic acid solution, which had an initial concentration of 0.01 M. To make the allantoin solution, which had an initial concentration of 0.01 M, 0.0395 g of allantoin was weighed, and distilled water was added until the total volume reached 25 mL. Ascorbic acid and allantoin 0.01 M solutions were diluted to 0.08 mM for analysis in quartz cuvettes by mixing 20 µL of the bioactive component solution with 2480 µL of distilled water. To make the water-dispersive coating solution, 10 µL of pure water-dispersive coating was diluted with 100 mL of distilled water.

The commercially available water-dispersive coating was mixed with bioactive components L-ascorbic acid (Sigma-Aldrich, Merck, Germany), also referred to in the text as plainly ascorbic acid, and allantoin (Sigma-Aldrich, Merck, Germany) at a concentration of 0.25% to improve the performance of the coating.

A magnetic stirrer (IKA RCT basic IKAMAG® safety control, Germany) was used to mix the ascorbic acid and water-dispersive coating solution which was stirred for three hours at 400 rpm on a magnetic stirrer with periodically heating up to 50°C for 5 minutes every hour. The allantoin and water-dispersive coating solution was stirred for 10 minutes at 400 rpm on a magnetic stirrer without heating. The samples that had a pre-printed reversible thermochromic orange-neon yellow color were coated with a coater (RK K control coater, UK), a wire wound bar with

a 0.30 mm wire thread, producing a layer of 24 µm thick film. The uncoated and coated TC prints were exposed to UV radiation (Solarbox 1500e, CO.FO.ME.GRA, Italy) for 5, 10 and 15 hours at 50°C and 550 W/m^2.

2.3. UV-Vis spectroscopy

For the determination of UV apsorption potential, UV-Vis spectroscopy was used. The absorbance of pure water-dispersive coating solution and water-based solutions with bioactive components ascorbic acid and allantoin was measured using a UV-Vis spectrophotometer (Shimadzu, UV-1900 i, Japan) in the UV-Vis range of 190-1100 nm.

2.4. Color determination

Spectral reflectance was recorded using an Ocean Optics USB2000+ spectrometer equipped with a 30 mm wide integrating sphere, operating under an (8: di) measuring geometry. The printed samples were subjected to heating and cooling on a full-cover water block (EK Water Blocks, EKWB d.o.o., Slovenia). Measurements were taken at 1 nm intervals across the spectral range of 370–730 nm. Ocean Optics SpectraSuite software was utilized to compute the CIELAB values from the obtained reflectance data. The total color difference between printed PSL samples at 20°C and 40°C was determined using the CIEDE2000 formula (CIE Central Bureau, 2004).

3. RESULTS AND DISCUSSION

Figure 1. shows the absorption spectra of three different water-based solutions— WD coating (blue line), allantoin (orange line), and ascorbic acid (pink line)—in the UV-Vis region. The x-axis represents the wavelength in nanometers (nm), ranging from approximately 200 to 450 nm, while the y-axis indicates absorbance, showing how much light each substance absorbs at different wavelengths. WD coating exhibits strong absorption below 250 nm, suggesting high absorbance in the UV region. Allantoin shows a peak absorption between 200 and 250 nm, with a rapid decrease at higher wavelengths. Ascorbic acid has a distinct absorption maximum around 260 nm, which is characteristic of this compound. The absorption spectra suggest that ascorbic acid may contribute to UV radiation blocking when combined with WD coating. WD coating exhibits strong absorption below 250 nm, while ascorbic acid shows a distinct absorption peak around 260 nm, where the absorption of WD coating decreases. This indicates that their combination could enhance overall UV protection by covering a broader range of the UV spectrum.

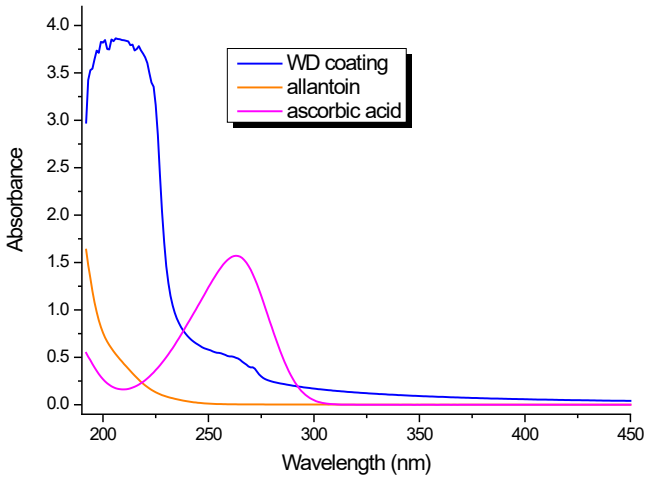


Figure 1. UV-Vis absorption spectra of water-based solutions - WD coating, allantoin, and ascorbic acid

Figure 2. shows the spectral reflectance curves of the unprinted PSL substrate and the thermochromic print, measured at two different temperatures, 20°C and 40°C. The Figure 2. illustrates how the reflectance properties of the thermochromic ink change with temperature, highlighting the ink's ability to undergo color shifts.

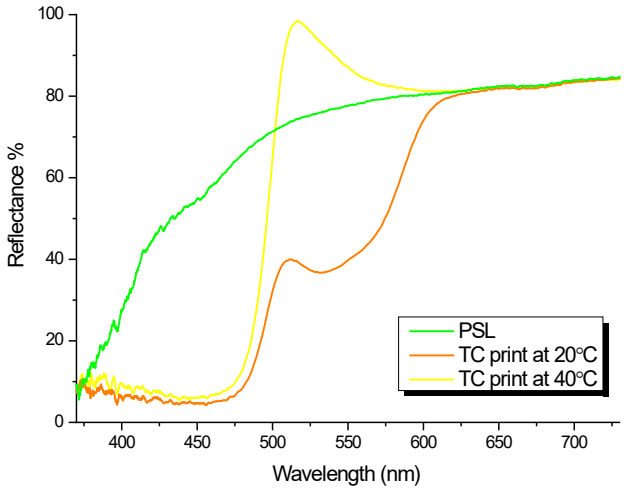


Figure 2. Spectral reflectance curve of the unprinted PSL substrate and the TC print, measured at two different temperatures

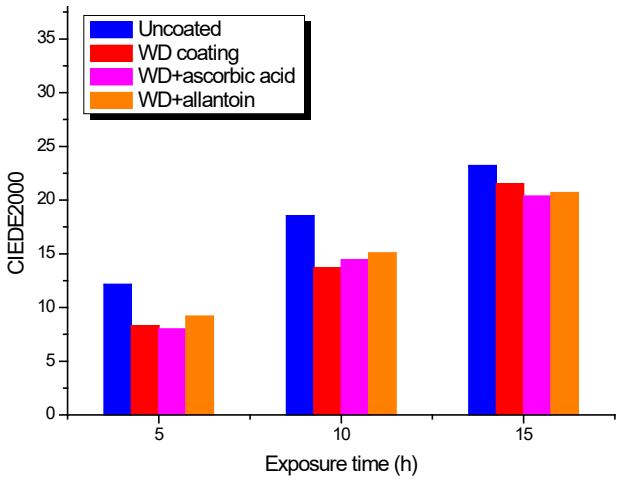


Figure 3. CIEDE2000 measured on TC prints with different solutions containing bioactive compounds in WD coatings at 20°C

The influence of different WD coatings with added bioactive compounds on the colour stability of thermochromic prints under UV exposure over time, with the sample colour observed at 20°C, is illustrated in Figure 3. The results indicate that coated samples exhibit lower colour differences (CIEDE2000) compared to the uncoated sample, suggesting that the applied coatings contribute to maintaining the thermochromic effect. At 5 hours of UV exposure, all coated samples show a reduced degree of colour change, highlighting their initial protective role. This trend continues at 10 hours, where the coatings still demonstrate their ability to slow down the degradation of the thermochromic effect. Even at 15 hours of exposure, coated samples maintain a slightly lower colour difference than the uncoated sample, demonstrating that coatings help extend the functionality of thermochromic prints.

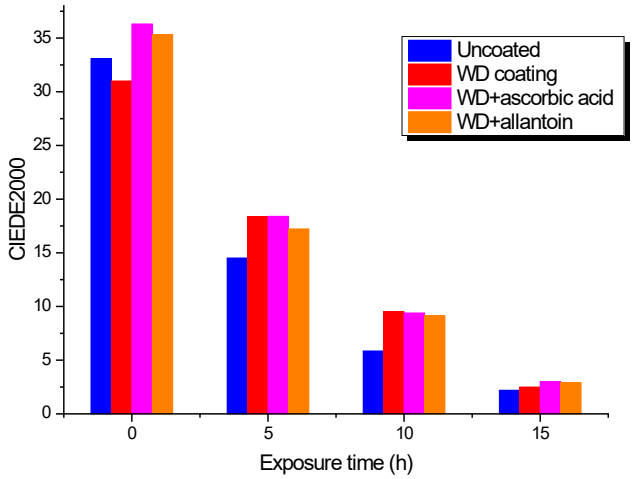


Figure 4. Total color contrast (TCC) between samples at 20°C and 40°C as a function of exposure time

The total color contrast (TCC) between samples at 20°C and 40°C is presented as a function of exposure time (Figure 4). A TC sample is considered effective if the TCC remains clearly visible. Comparing uncoated and coated samples, it is evident that coatings contribute to the prolonged functionality of thermochromic prints. Comparing the values of uncoated samples with those coated with various bioactive compounds reveals the protective effect of the coatings. The initial values (0 h) show that all coatings enhance the total color contrast compared to uncoated samples, indicating that coatings intensify the thermochromic effect. Dailliez et al. demonstrated that applying a smooth transparent layer to halftone prints darkens the print and enhances its color saturation. This effect occurs due to the lateral propagation of light within the coating during multiple reflections between the printed diffusing substrate and the coating–air interface (Dailliez et al., 2021). As exposure time increases, TCC values decrease for all samples, reflecting the gradual degradation of the thermochromic effect due to UV exposure. However, coated samples experience a significantly slower reduction in contrast than uncoated samples, confirming the protective function of coatings. After 5 hours of UV exposure, coated samples retain a higher color contrast than uncoated samples, emphasizing their effectiveness in slowing degradation. By 10 hours, the difference between coated and uncoated samples remains noticeable, although the overall contrast continues to decrease. After 15 hours of exposure, all samples exhibit very low TCC values, indicating substantial degradation of the thermochromic effect. However, coated samples still maintain slightly higher contrast values than the uncoated sample. This analysis demonstrates that coatings with added bioactive compounds not only enhance the initial thermochromic effect but also slow its degradation over time. These findings suggest that such coatings could be valuable for extending the longevity of thermochromic prints, offering potential applications in smart packaging, security printing, and interactive design.

4. CONCLUSION

The goal of our research was to incorporate bioactive compounds, ascorbic acid and allantoin, into commercially available water-dispersive coating to enhance overall UV protection by covering a broader range of the UV spectrum. The results indicate that one or more of the ingredients in commercially available water-dispersive coating, that we used as the base, may have an impact on the inhibition of the UV blocking effect of the bioactive compounds in our coating, since the exact composition of commercially available coatings is not entirely known. According to the results, we believe the initial idea is valid and promising. Future research will focus on developing initial coating formulation so that we can better regulate the interactions between the components. Our research group's objective is to develop and alter formulations to produce an environmentally friendly paper coating that maximizes the use of additional bioactive compounds. It is clear from the UV-Vis absorption spectra that the bioactive compounds exhibit a beneficial effect, — in other words, protection in the UV portion of the spectrum,

when analysed separately. The colorimetric analysis results also demonstrate the beneficial impact of bioactive compounds on the coating itself, as the coatings maintain and improve the thermochromic effect properties.

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6. REFERENCES

Avery Dennison. (2025). BT024 rCRUSH BARLEY FSC S2030-BG45WH FSC_EN.

Bastarrachea, L. J., Wong, D. E., Roman, M. J., Lin, Z., & Goddard, J. M. (2015). Active packaging coatings. In Coatings (Vol. 5, Issue 4, pp. 771–791). MDPI AG. https://doi.org/10.3390/coatings5040771

Bhargava, N., Sharanagat, V. S., Mor, R. S., & Kumar, K. (2020). Active and intelligent biodegradable packaging films using food and food waste-derived bioactive compounds: A review. In Trends in Food Science and Technology (Vol. 105, pp. 385–401). Elsevier Ltd. https://doi.org/10.1016/j.tifs.2020.09.015

Blokhina, O., Virolainen, E., & Fagerstedt, K. V. (2003). Antioxidants, oxidative damage and oxygen deprivation stress: A review. In Annals of Botany (Vol. 91, pp. 179–194). https://doi.org/10.1093/aob/mcf118

CIE Central Bureau. (2004). Colorimetry. International Commission on Illumination.

Cunningham, M. F., Campbell, J. D., Fu, Z., Bohling, J., Leroux, J. G., Mabee, W., & Robert, T. (2019). Future green chemistry and sustainability needs in polymeric coatings. In Green Chemistry (Vol. 21, Issue 18, pp. 4919–4926). Royal Society of Chemistry. https://doi.org/10.1039/c9gc02462j

Dailliez, F., Hébert, M., Blayo, A., Chagas, L., & Fournel, T. (2021). Impact of a transparent coating on the reflectance of a line halftone pattern. Coatings, 11(12). https://doi.org/10.3390/coatings11121465

Eça, K. S., Sartori, T., & Menegalli, F. C. (2014). Films and edible coatings containing antioxidants - a review. Brazilian Journal of Food Technology, 17(2), 98–112. https://doi.org/10.1590/bjft.2014.017

Ibrahim, I. D., Hamam, Y., Sadiku, E. R., Ndambuki, J. M., Kupolati, W. K., Jamiru, T., Eze, A. A., & Snyman, J. (2022). Need for Sustainable Packaging: An Overview. In Polymers (Vol. 14, Issue 20). MDPI. https://doi.org/10.3390/polym14204430

Kulčar, R., Friškovec, M., Hauptman, N., Vesel, A., & Gunde, M. K. (2010). Colorimetric properties of reversible thermochromic printing inks. Dyes and Pigments, 86(3), 271–277. https://doi.org/10.1016/j.dyepig.2010.01.014

Kunam, P. K., Ramakanth, D., Akhila, K., & Gaikwad, K. K. (2024). Bio-based materials for barrier coatings on paper packaging. Biomass Conversion and Biorefinery, 14(12), 12637–12652. https://doi.org/10.1007/s13399-022-03241-2

Okan, M., Aydin, H. M., & Barsbay, M. (2019). Current approaches to waste polymer utilization and minimization: a review. In Journal of Chemical Technology and Biotechnology (Vol. 94, Issue 1, pp. 8–21). John Wiley and Sons Ltd. https://doi.org/10.1002/jctb.5778

Selamoglu, Z., Dusgun, C., Akgul, H., & Fuat Gulhan, M. (2017). In-vitro Antioxidant Activities of the Ethanolic Extracts of Some Contained-Allantoin Plants. In Shaheed Beheshti University of Medical Sciences and Health Services Iranian Journal of Pharmaceutical Research.

Sultan, M., Taha, G., & Baseer, R. A. (2024). Active packaging coating films based on natural bioactive compounds. Egyptian Journal of Chemistry, 67(10), 223–244. https://doi.org/10.21608/EJCHEM.2024.260031.9139

Vukoje, M., Ivanda, K. I., Kulčar, R., & Dolovski, A. M. (2021). Spectroscopic stability studies of pressure sensitive labels facestock made from recycled post-consumer waste and agro-industrial by-products. Forests, 12(12). https://doi.org/10.3390/f12121703

Vukoje, M., Malenica, I., Lukavski, T., Kulčar, R., & Ivanda, K. I. (2024). Natural substances as protective agents against photodegradation. International Symposium on Graphic Engineering and Design. https://doi.org/10.24867/GRID-2024-p50

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POSTER PRESENTATION

THE VISUAL APPEARANCE OF PEARLESCENT PIGMENTS COATED WITH CELLULOSE NANOCRYSTAL (CNC) BINDER

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Abstract: *Pearlescent pigments are widely used in coatings, cosmetics, and packaging to achieve unique optical effects. This study investigates the visual appearance of pearlescent pigments coated with a cellulose nanocrystal (CNC) binder, focusing on how CNC affects their color and optical properties. In this study, three types of pearlescent pigments with different particle size but with the same color, form, type and pigment base were used. The coating was formulated in such a way that the pearlescent pigments were mixed with CNC binder in a ratio of 20:100. The paper was coated in two layers in machine direction. The color and optical properties, including color travel, flop index and print gloss, were analyzed using multi-angle spectrophotometry, gloss measurements and microscopy. The results show that the size of the pigments has an influence on color lightness and chrome, with the pigment with the smallest particle size achieving the highest values. The pigment with the largest particles achieved the highest values for the flop index and print gloss. These findings highlight CNC's potential as a sustainable binder for advanced pigment applications.*

Keywords: *Pearlescent pigments, cellulose nanocrystals (CNC), coating, print gloss, flop index.*

1. INTRODUCTION

The development of environmentally friendly and sustainable packaging materials is a major challenge for the packaging industry. With its excellent physical and chemical properties, including renewability, degradability, sound mechanical properties, and good biocompatibility, nanocellulose is promising for use in various applications *(Xu, 2024).* Cellulose nanomaterials (CNs) are of increasing interest due to their appealing inherent properties such as biodegradability, high surface area, light weight, chirality and the ability to form effective hydrogen bonds across the cellulose chains or within other polymeric matrices *(Tayeb, 2018).* All cellulosic materials with at least one dimension on the nanometric scale are referred to as nanocellulose (*Lengowsk, 2023).* Nanocellulose is a kind of cellulose-derived natural fiber at the molecular level, and can be obtained from lignocellulosic materials, marine animals, bacteria, and algae through extraction methods. Differences in extraction techniques and sources of cellulose fibers have significant influence on the characteristics of nanocellulose. Compared with ordinary cellulose, nanocellulose presents a variety of features, including a high Young's modulus, high crystallinity, high specific surface area, high tensile strength, and other special traits, suggesting promising prospects for application in the fields of papermaking, biomedicine, materials packaging, coating, etc. *(Xu, 2024).* Nanocellulose is a rod-like nanoparticle that can be categorized into three main groups based on its microphology, size and raw material source: **cellulose nanocrystals (CNCs), cellulose nanofibrils (CNFs)**, and **bacterial nanocellulose (BNC)** *(Hu, 2021).* CNCs, also known as "cellulose whiskers", "cellulose nano-whiskers" and "nanocrystalline cellulose", have structural dimensions in nanoscale width and length. The cellulose sources include bacterial cellulose, cotton, ramie, tunicate, soft wood and hard wood, etc. Although the sources of CNCs are different, the rod-like CNCs display a high surface area with a high amount of hydroxyl groups that give CNCs some extra natural properties, such as hyperfine structure, high transparency, high purity, high crystallinity, high strength and Young's modulus, and high reactivity. These properties differ greatly from those of the regular cellulosic fibers, which enables CNCs to extend more widespread applications *(Xie, 2018).* CNCs are mainly extracted from cellulosic materials through acid hydrolysis, in which the amorphous region dissociates, and then rod-like nanocrystals with strong acid resistance and high crystallinity will be formed. CNFs, as a type of nanocellulose, are obtained by a strong mechanical disintegration treatment owing to the complex structure of cellulose fibers. BNC, which is a term for nano-structured cellulose created by bacteria, is cultured in nutrient medium containing carbon sources. Although

these categories vary from each other, they are some-how connected in that many nanocellulose sources coexist in an extensive and overlapping material space *(Xu, 2024).*

Table 1: The types and characteristics of nanocellulose.

Types	Other Nomenclature	Micro-morphology	**Typical Sources**	**Average Size**	**Preparation Method**
Cellulose nanocrystals (CNCs)	Cellulose whiskers (CNWs), cellulose nanocrystalline (CNC), nanocrystalline cellulose (NCC)	Whiskers, rod-shaped	Plants (wood, cotton, hemp, flax, etc.)	Diameter: 50-70 nm Length: 100-250 nm	Acid hydrolysis
Cellulose nanofibrils (CNFs)	Micro-fibrillated cellulose (MFC), nano-fibrillated cellulose (NFC)	Twisted filamentous	Plants (wood, beet, cotton, hemp, flax, etc.)	Diameter: 5-60 nm Length: Several micrometers	Mechanical treatment
Bacterial nanocellulose (BNC)	Bacterial cellulose (BC), regenerated bacterial cellulose (RBC)	Gel-like, ribbon-like	Acetobacter, xylinum, pasteurii, etc.	Diameter: 20-100 nm Length: unfixed	Bacterial synthesis

The main differences between CNC and CNF are their dimension and crystallinity. CNFs consist of mixtures of amorphous and crystalline cellulose chains with length of up to several microns, while CNCs are highly crystalline with length typically less than 500 nm. Both materials have immense potential for various applications, and this review will focus on cellulose nanocrystals *(Grishkewich, 2017).* CNCs are spindle-like nanometer-scale materials with unique properties such as high strength, high specific surface area, high thermal stability, optical transparency, biodegradability, biocompatibility, and self-assembly capability *(Xu, 2021).*

Because nanocellulose is obtained from plant biomass, it is chemically compatible with paper and its application does not alter the paper's characteristics, reduce its biodegradability, or make it more dangerous to human health *(Lengowsk, 2023).*

2. EXPERIMENTAL

In this study, a commercially available cellulose nanocrystals "CNCs" (Table 2) as a binder (Manufacturer: Nanocrystacell) and three types of pearlescent pigments by Eckart (Germany) were used. All three pigments have the same color shade, the form, the same pigment base and differ only in their particle size (Table 3). Matte black paper with a grammage of 130 g/m^2 was used as a substrate (Manufacturer: Bringmann).

The coating formulation was based on pearlescent pigments mixed with cellulose nanocrystals (CNCs) at a ratio of 20:100. The paper was coated in machine direction using a K Control Coater / meter bar coating (wire diameter: 0.05 mm, wet film deposit: 4 µm). In the double-layer coating, the second layer was added after air drying the first layer. The samples were finally placed in standard conditions of 23 °C and 50% humidity for one day.

The MA-T12 handheld multi-spectrophotomer (X-Rite) was used to measure the lightness (L*) and chroma (C*) of pearlescent pigments coated with CNC binder (CIE D50 standard illumination) measured at 45as-15°, 45as15°, 45as25°, 45as45°, 45as75°, 45as110°.

The print gloss was measured at three different angles (20°, 60°, 85°) using Gloss Meter (Rhopoint IQ). Measurements conform to the ASTM D523 standard measurement protocol for specular gloss measurements. Gloss is

measured in gloss units (GU).

Table 2: Properties of cellulose nanocrystals (CNCs).

Parameter	Specification
Chemical name	$C_6O_5H_{10}$
Color	White-translucent
Form	Aqueous suspension, 2-5wt.% solids
Surface	Hydrophilic
Average size (Scherrer method, SEM)	10-15 nm wide,150-300 nm length
Crystallinity (XRD:Segal method)	90,3%
Initial decomposition temperature (DTGA in N2)	285 °C
Density	Aqueous gel: 1.04 g/cm^3
Lignin content	Negligible

Figure 1 shows SEM image of the cellulose nanocrystals (CNCs) and Table 3 shows the properties of the pearlescent pigments used in this study.

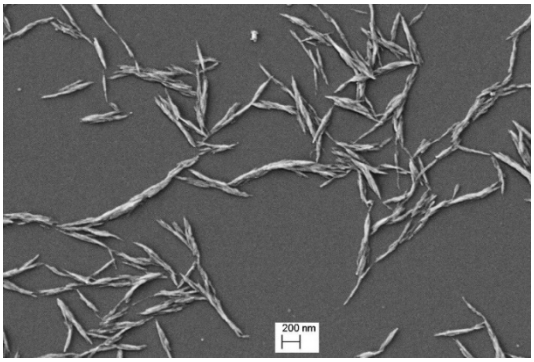


Figure 1: SEM image of the cellulose nanocrystals *(Nanocrystacell (2023).*

Table 3: Properties of the pearlescent pigments.

Properties	SYMIC A001 (Pigment P1)	SYMIC C001 (Pigment P2)	SYMIC E001 (Pigment P3)
Color shade	Interference silver	Interference silver	Interference silver
Form	Powder	Powder	Powder
Pigment type	Pearlescent pigment	Pearlescent pigment	Pearlescent pigment
Pigment base	Synthetic Mica	Synthetic Mica	Synthetic Mica
Particle size (μm)	1-15	10-40	20-150

3. RESULTS WITH DISCUSION

Lustre and hiding power of the pigments in the application system are two most important properties influenced by particle size distribution. A frequently used classification distinguishes five classes of the particle size distribution: **M** (1 to 15 μm), **F** (5 to 25 μm), **N** (10 to 50 μm), **S** (10 to 130 μm), and **L** (40 to 200 μm). As a rule, the larger the particles the better the lustre, the smaller the particles the better the hiding power. The large particles provide a large smooth surface and an undisturbed reflection of the incident light, resulting in an excellent gloss and high

brilliance. The smaller particles result in a less smooth surface, more edges and corners, greater scattering and reflection and therefore better opacity. *(Glausch, 1998).* As shown in Figure 2, the pigment particles differ in size, with the particle size for P1 ranging from 1 to 15 µm, for P2 from 10 to 40 µm, and for P3 from 20 to150 µm.

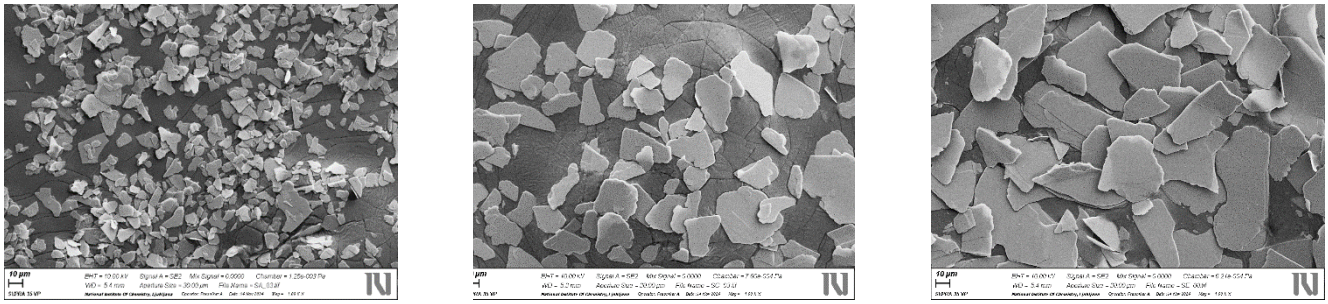


Figure 2: SEM images of P1, P2 and P3 particles (from left to right).

Characterising special effect pigments requires angle-dependent spectrophotometric testing. The color dynamics resulting from the combination of geometries and pigments can be illustrated by color changes (also known as color travel). Figure 3 shows color travel through lightness (L*) and chroma (C*) changes of P1, P2 and P3 pigments coated with CNC binder. The highest values of lightness (Figure 3, right) were observed at all three pigments at 45as-15° (P1: L*=125, P2: L*=107, P3: L*=119), meanwhile the smallest values of lightness at 45as110° (P1: L*=56, P2: L*=29, P3: L*=26). If we compare the lightness values for all three pigments, we see that the values for P1 are the highest. Color travel through chroma are shown in Figure 3 (left). All three pigments exhibit a similar overall trend, with a peak at the beginning, a significant dip in the middle, and a rise again towards the end. The chroma values are highest at 45as15° and 15as15°**,** indicating strong color intensity in these conditions.

The lowest chroma value appear at 45as75° for P3 (P3: C*=2.6). Pigment P3 demonstrates the most pronounced variation.

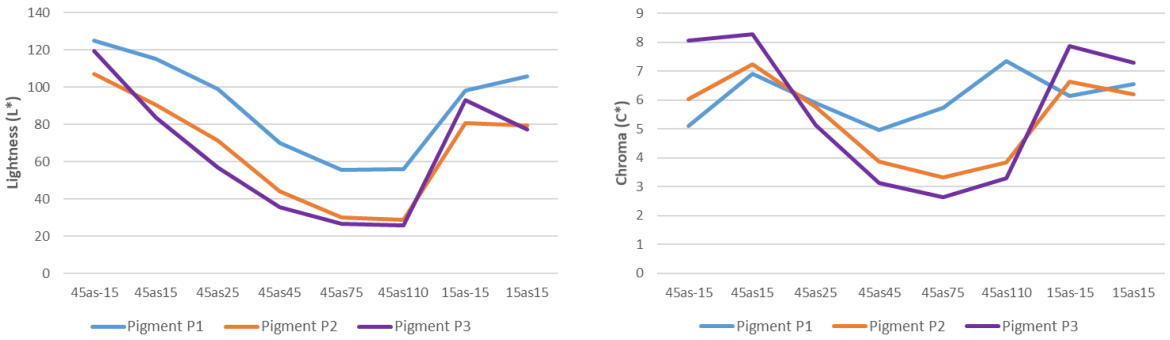


Figure 3: Color travel through lightness (L*) and chroma (C*) changes of P1, P2 and P3 pigments coated with CNC binder.

The flop (also known as Travel or Two-Tone) is probably the most commonly known optical property of effect pigments and is often simply called the metallic effect. This is understood as the alteration of the brightness as a function of observation angle. This change in brightness can easily be determined visually, observing the test panel on face and after that at oblique angles. In reality, the flop is evaluated by inspection at different angles, in some cases also a change in color can be found (color-flop). The color-flop can only be found at pearlescent pigments and in a few cases of advanced effect pigment technology. The observational angles are grouped into three categories: *"Face"* (near specular: 15º or 25º), *"Mid Specular"* (or diffuse: 45º), and *"Flop"* (far specular: 75º or 110º). An angle of 25º [=L*(25º)] has become accepted to describe the visual effect on face. Often angles closer to the reflected light ("nearer to the gloss") are used. If for example, measurements are taken at an angle of 15º [=L*(15º)], the accuracy of the measurement will be less as the measurement is "nearer the gloss". Other angles

used are 110º [=L*(110º)] and 70º, which measure the darker appearance on flop. Besides an intermediate angle around is common 45º [=L*(45º)]. From three color measurement values the flop index can be mathematically calculated. This allows pigments to be characterized and compared with each other. For the observed changes in intensity is given by the flop index. The flop index (FI) is the measurement of the change in reflectance of a metallic color as it is rotated through the range of viewing angles. A flop index of 0 indicates a solid color, while a very high flop metallic basecoat color may have a flop index of 15-17. The flop index (FI) is mathematically defined by the following formula:

$$FI = 2.69 \times \frac{(L^*15 - L^*110)^{1.11}}{(L^*45)^{0.86}}$$

Figure 4 (right) shows the calculated flop index (FI) of all three pigments coated with CNC binder. The flop index increased with the particle size, with pigment P3 having the largest particle size (20-150 µm). The lowest flop index was found for pigment P1, where the FI=6.4. The higher the value of FI, the greater the effect. In other words, the higher the flop index result (FI), the higher the change in reflectance of a metallic color as it is rotated through various viewing angles. If the colour of the print looks the same from all angles, then the value of FI would be 0. But if it changes substantially, a high value might come in at 15 plus *(Debeljak, 2010; Wißling, 2008)*

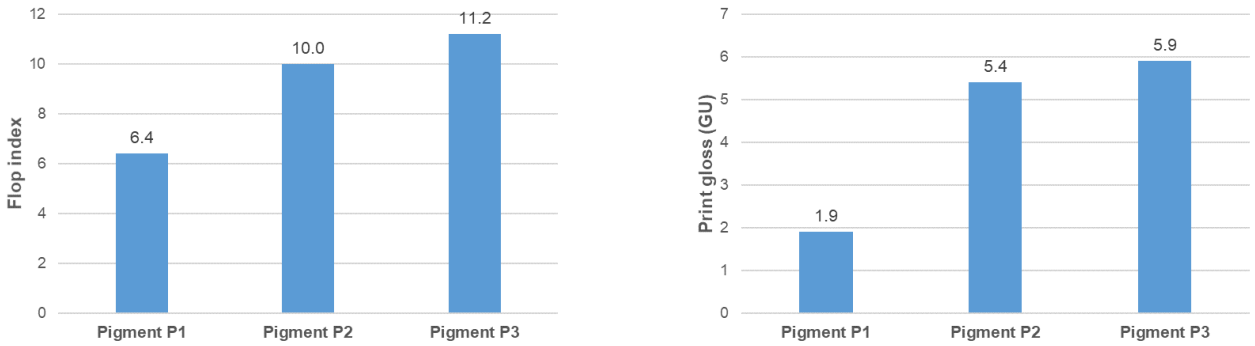


Figure 4: Flop index and print gloss of P1, P2 and P3 pigments coated with CNC binder.

Gloss is an important optical property assessing the print quality. The gloss perception describes the geometry-dependent properties of a surface. The visual appearance attribute called specular gloss describes the perceived luminance caused by specular reflection on the surface. A typical example for a surface with a high specular gloss is a mirror *(Kehren, 2013; Sharma 2022)*. As can be seen in Figure 4 (left), the print gloss increased with the particle size, as did the flop index. The pigment P3 coated with CNC binder achieved the highest print gloss (GU=5.9), followed by pigment P2 (GU=5.4) and the lowest pigment P1 (GU=1.9).

4. CONCLUSIONS

Cellulose nanocrystals (CNC) are used in various applications due to their exceptional mechanical properties, biodegradability, and optical characteristics. In coatings, CNCs serve as sustainable binders that enhance pigment stability and improve optical effects. The results demonstrate that pigment particle size significantly influences color lightness, chroma, flop index, and print gloss. Smaller pigment particles produced higher lightness and chroma values, while larger particles exhibited greater flop index and print gloss. These results suggest that CNC can be successfully used as a binder for coatings with effect pigments and represents a sustainable alternative to synthetic binders. The study highlights CNC's potential for applications in coatings, packaging, and printing, paving the way for further research into optimizing CNC formulations for tailored optical effects. Their versatility makes them a promising material for developing eco-friendly and high-performance products in numerous fields.

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6. REFERENCES

Debeljak, M. (2011) 'Obstojnost sistetičnih papirjev potiskanih s specialnimi tiskarskimi barvami', *PH diss*., University of Ljubljana, pp. 12-15.
Glausch, R. *et al.* (1998) 'Special Effect Pigments', Hannover: Vincentz, p. 31.
Grishkewich, N. *et al.* (2017) 'Recent advances in the application of cellulose nanocrystals', *Current Opinion in Colloid & Interface Science*, 29, pp. 32–45. Available at: https://doi.org/10.1016/j.cocis.2017.01.005.
Hu, F. *et al.* (2021) 'Cellulose nanofibrils (CNFs) produced by different mechanical methods to improve mechanical properties of recycled paper', *Carbohydrate Polymers*, 254, p. 117474. Available at: https://doi.org/10.1016/j.carbpol.2020.117474.
Kehren, K. (2013) 'Optical properties and Visual Appearance of Printed Special Effect Colors', *PH diss*., Technischen Universität Darmstadt, pp. 23-50.
Lengowski, E.C. *et al.* (2023) 'Nanocellulose Coating on Kraft Paper', *Coatings*, 13(10), pp. 1705–1705. Available at: https://doi.org/10.3390/coatings13101705.
Nanocrystacell (2023). Available at: https://www.nanocrystacell.eu/?lang=sl (Accessed: 18 February 2025).
Sharma, B. *et al.* (2022) 'Effect of cellulose nanocrystal incorporated acrylic copolymer resin on printing properties of waterborne inks', *Progress in Organic Coatings*, 167, p. 106842. Available at: https://doi.org/10.1016/j.porgcoat.2022.106842.
Tayeb, A. *et al.* (2018) 'Cellulose Nanomaterials—Binding Properties and Applications: A Review', *Molecules*, 23(10), p. 2684. Available at: https://doi.org/10.3390/molecules23102684.
Xie, S. *et al.* (2018) 'Applications of Cellulose Nanocrystals: A Review', *Engineered Science*, Volume 2 (June 2018)(34), pp. 4–16. Available at: https://www.espublisher.com/journals/articledetails/4 (Accessed: 18 February 2025).
Xu, C., Huang, C. and Huang, H. (2021) 'Recent advances in structural color display of cellulose nanocrystal materials', *Applied Materials Today*, 22, p. 100912. Available at: https://doi.org/10.1016/j.apmt.2020.100912.
Xu, Y. *et al.* (2024) 'Nanocellulose Composite Films in Food Packaging Materials: A Review', *Polymers*, 16(3), p. 423. Available at: https://doi.org/10.3390/polym16030423.
Wißling P. (2008). *Metallic Effect Pigments*, Fundamentals and Applications, Hannover: Vincentz Network, pp. 26-28.

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POSTER PRESENTATION

COLOUR STABILITY OF REVERSIBLE THERMOCHROMIC COMPOSITE

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Abstract: *Reversible thermochromic (TC) composites generally contain a leuco dye, a colour developer and a solvent. In such composites, the leuco dye can be in a coloured or colourless state. However, the colour stability of some TC composites is poor with certain compositions of substances and better with others. To gain an insight into this phenomenon, a TC composite consisting of the leuco dye crystal violet lactone (CVL), the developer benzyl 4-hydroxybenzoate (B4HB) and the solvent octadecan-1-ol (OD) was investigated. The stability of the colour was examined in the coloured state for the entire (ternary) composite and the binary composite containing only the dye and the developer. The freshly prepared samples and the samples aged for one month were analysed using FTIR and UV-VIS spectroscopy. The UV spectra showed some changes in the electronic transitions between the freshly prepared and the aged binary TC composite. For the ternary TC composite, the results after one month showed not only a colour change, but also a change in the characteristic peaks in the FTIR spectrum.*

Keywords: *reversible thermochromic composites, colour complex, colour stability, crystal violet lactone*

1. INTRODUCTION

TC composites generally contain three basic components: a leuco dye, a developer, and a solvent (White, 1999; Seeboth, 2008). The leuco dye can be in a colourless or coloured state, depending on the charge in the environment. The most commonly used colour developers are bisphenol A, gallates, phenols or weak acids. They are responsible for the reversible colour change and also for the colour intensity of the end product (TC composites). The third component is a weakly polar solvent, usually an alcohol or an ester. The solvents are responsible for the reversible temperature-dependent colour change of the TC composites. The melting point of the weakly polar solvent is the control point at which a colour change can be expected.

TC composites are usually prepared by melting the solvent and dissolving the dye and developer in the liquid solvent (Hajzeri, 2015). The liquid TC composite is generally colourless, but when it cools and solidifies, it becomes coloured. Normally, a TC composite contains the largest amount of solvent, followed by the developer, and the least amount of leuco dye. When the TC composite is heated above the melting point of the solvent, it liquefies so that the leuco dye and developer dissolve in it, and the composite becomes discoloured. When the TC composite cools below the melting point and solidifies, it becomes coloured.

This paper presents a study on the stability of TC composites made of developer and leuco dye with and without solvent. The structural and optical changes of such a TC composite over time were analysed while the samples were stored in a dry and dark place at room temperature for one month. The samples were analysed by Fourier-Transform Infrared Spectroscopy (FTIR) and ultraviolet-visible (UV-VIS) spectroscopy. Leuco-dye molecules are expected to undergo the strongest changes in the presence of coloured centres, i.e. the open lactone ring. The main aim of the research is to investigate the ability of the applied analytical method, FTIR or UV-VIS, to monitor such changes.

2. MATERIALS AND METHODS

2.1 Samples

Basic components were used for the preparation of TC composites: the leuco dye crystal violet lactone (CVL), the developer benzyl 4-hydroxybenzoate (B4HB) and the solvent octadecan-1-ol (OD). When CVL and B4HB are ground together with a mortar and pestle, a relatively strongly coloured powder is obtained. Even mixing the two components leads to charge transfer between B4HB and CVL, which opens the lactone ring of the dye. This effect does not occur if we mix the two powders without pressure. The colouring effect is strong after heating the powder mixture. When the CVL+B4HB+OD mixture is heated above the melting point of OD, OD liquefies so that CVL and B4HB can dissolve in it. In this work we have investigated how this colouring changes over time.
The effect of the heating temperature was observed by heating one part of the TC composite to 70 °C, which is well above the melting point of OD (58 °C). The second part was heated to 110 °C, which corresponds to the melting point of B4HB. The binary TC composite of B4HB and CVL was also prepared in two different ways. Firstly, the mixture was heated to 70 °C and the dye was mixed with the developer to form a coloured complex. Secondly, the mixture was prepared using a pestle and mortar, where only the physical contact of the powder particles was sufficient for colouration. The colour stability of the three-component TC composite of OD, B4HB and CVL was compared with the colour stability of the binary TC composite of B4HB and CVL. All samples prepared in this study are listed in Table 1. The samples were aged on the laboratory counter for one month at room conditions, protected from direct sunlight and dust. Fresh and aged samples were analysed using selected methods, which are described in detail in chapter 2.2. Four different samples were prepared with the basic components mentioned above. The samples were analysed fresh and aged for one month. A total of eight samples were analysed (Table 1):

- solvent + developer + dye (the solvent is melted during the preparation of the composite),
- solvent + developer + dye (the solvent and developer are melted during the preparation of the composite),
- developer + dye (thermal activation; heating),
- developer + dye (mechanical activation; using mortar and pestle).

Table 1: Description of laboratory-prepared samples, a total of 8 samples (4 fresh and 4 aged).

Sample	Basic components	Mass ratio of basic components	Preparation	Type of activation
4A	Solvent + developer + leuco dye	4 : 2 : 1	Heated to 70°C	Thermal
4B	Solvent + developer + leuco dye	4 : 2 : 1	Heated to 110°C	Thermal
5A	Developer + leuco dye	2 : 1	Heated to 70°C	Thermal
6T	Developer + leuco dye	2 : 1	Using mortar and pestle	Mechanical

2.2 Measurements

All samples were measured with the UV-VIS spectrometer and the ATR FTIR spectrometer. Samples 4A and 4B were additionally measured with the spectrometer i1. UV-VIS spectra were recorded using a Lambda 950 spectrometer (PerkinElmer) with an integrating sphere. Solid samples were ″scraped″ with a spatula to obtain a powder. All samples were prepared for transmittance measurement. For this purpose, the scraped powder was applied to a quartz slide and inserted into the inlet of the integrating sphere. The parameters were set using the UV WinLab programme: ordinate output (%T), measurement range 2500–250 nm and 5 nm step. The FTIR absorption spectra were recorded with a Tensor 27 FTIR spectrometer. The parameters were set using the Opus 8.5 programme: measuring range (500–4000 cm^{-1}), resolution (4 cm^{-1}) and number of scans (64). The 4A and 4B were measured at 12 locations with the spectrometer i1 and the average values were taken into account in the evaluation. The colour coordinates *L*, a*, b** were determined from the measured R spectra (D65, 2 °standard observer) using BabelColor PatchTool.

3. RESULTS WITH DISCUSSION

3.1 Visual representation

Figure 1 shows photos of fresh and aged samples. After one month, the colours of samples 5A and 6T fade. After a certain time, they become lighter (the effect is most obvious on the surface of the coloured powder of the aged sample 5A aged and the aged sample 6T).

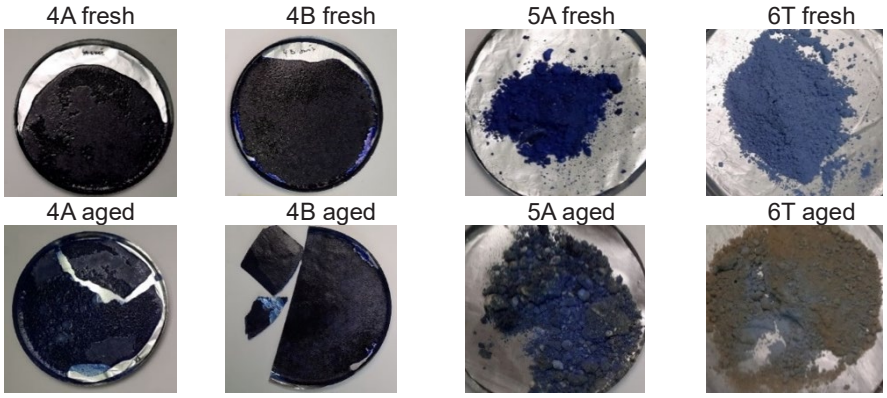


Figure 1: A visual representation of the difference between fresh and aged samples.

3.1 Spectrometer i1

Figure 2 shows the measurements with the i1 spectrometer. Each sample was measured at 12 different locations. Each point in the graph in Figure 2 represents a measurement on the *a*, b** diagram and *L** axis. The aged samples (4A and 4B) are less blue-coloured (the values on the *b** axis are higher) than the fresh samples (the values on the *b** axis are lower). A greater difference can be observed in sample 4B (the values on the *b** axis decrease visibly with ageing). For sample 4A, ageing has no significant influence on the colouration (the values on the *b** axis do not decrease significantly with ageing). The brightness does not differ significantly between the fresh and aged samples. The exception is sample 4A fresh, which has slightly higher values (which corresponds to the higher values on the *b** axis).

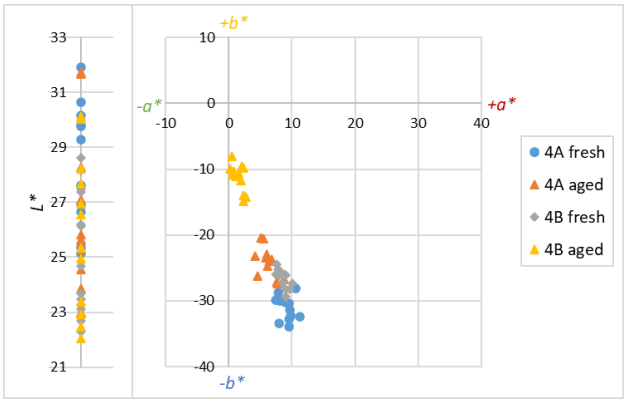


Figure 2: Measurement results of samples 4A fresh, 4A aged, 4B fresh and 4B aged with the i1 spectrometer.

3.2 UV-VIS spectra

Figure 3 and Table 2 show the important electronic transitions of all base components and prepared samples. We look at the changes in the electronic transitions in CVL. The electronic transitions in CVL indicate the formation of a coloured complex. CVL in the closed lactone ring form has an electronic transition at 410 nm (3.0 eV), and in the coloured state (when the lactone ring is open, we consider 4A, 4B, 5A as fresh) the electronic transition is shifted to 425 nm (2.9 eV). In the fresh sample 6T, we observe that the electronic transition is not significantly shifted (it

shifts by 5 nm), which means that only a small part of the CVL rings in the sample is open. This is also evident from the colour of fresh sample 6T, which is much brighter than fresh sample 5A (see Figure 1 and compare fresh sample 5A and fresh sample 6T). Both aged samples (5A and 6T) have the same electronic transition as CVL in the closed lactone ring form; at 410 nm (3.0 eV), which is consistent with the colour actually having faded. The colour change is also visible to the naked eye (see Figure 1, aged and fresh samples 5A and 6T).

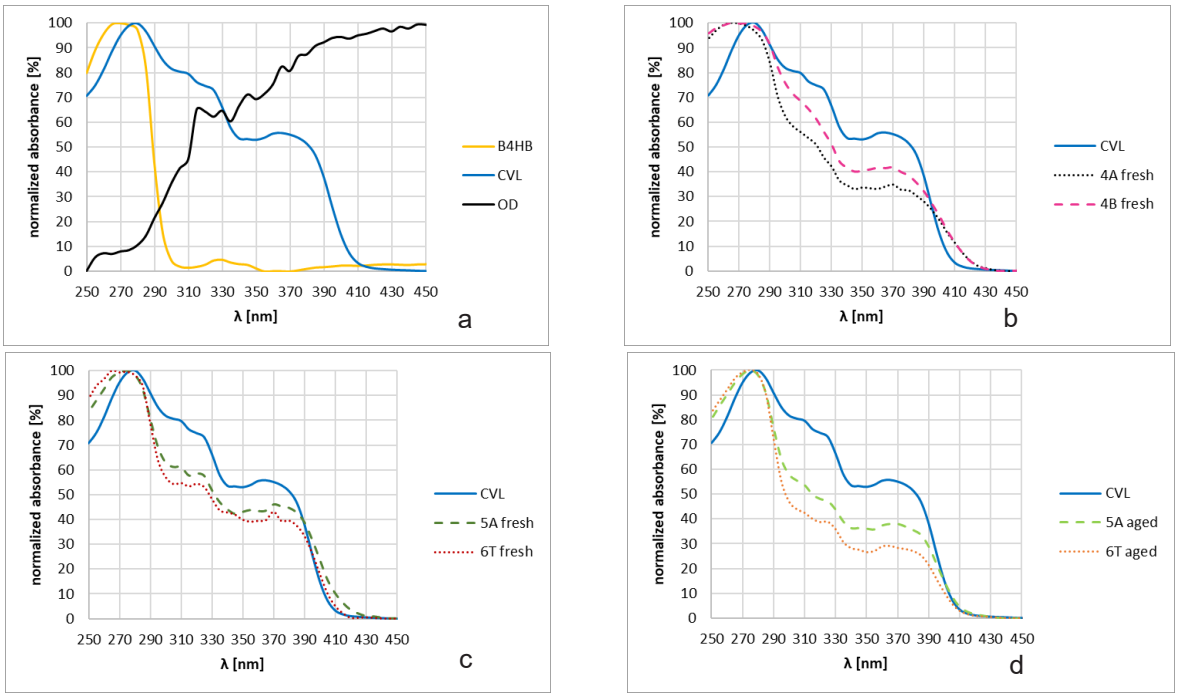


Figure 3: UV-VIS spectra of the measured samples: a – CVL, B4HB, OD; b – CVL 4A fresh, 4B fresh; c – 5A fresh, 6T fresh; d – CVL, 5A aged, 6T aged.

Table 2: The most important electronic transitions of the samples.

Sample	λ [nm]	E [eV]
CVL	410	3,03
B4HB	300	4,13
OD	/	/
4A, 4B, 5A fresh	425	2,92
6T fresh	415	2,99
5A, 6T aged	410	3,03

3.3 FTIR spectra

Hydrogen bonds are the most important bonds formed between alcohol molecules (e.g. in OD) (Colthup, 1990). This manifests itself in the form of stretching vibrations, in-plane and out-of-plane bending vibrations of the OH group. OD exhibit a very broad, strong absorption at 3302 cm^{-1}, which is due to the stretching of the O-H bond. The vibration of the O-H group at 3375 cm^{-1} is also observed in the B4HB spectrum, but this vibration is not present in the CVL spectrum. A strong C-H stretching vibration at 2917 cm^{-1} and a C-O stretching vibration at 1063 cm^{-1} are also observed in the OD spectrum. The most important vibrations in B4HB are the stretching vibration of the carbonyl group O-C=O at 1682 cm^{-1} and the C-O-C stretching vibration at 1272 cm^{-1}. The most important vibrations in

CVL are characteristic of the lactone ring. The spectrum shows the stretching vibration of the carbonyl group C=O at 1740 cm^{-1}. The stretching vibration of the C-C bond at 1608 cm^{-1} and the vibration of the aromatic ring (C=C) at 1511 cm^{-1} can also be recognised. Both vibrations are also observed in the B4HB spectrum. Therefore, these vibrations cannot be used to analyse the TC phenomena in the CVL and B4HB composite.
Figures 4a and 4b show the spectra of samples 4A and 4B (fresh and aged). It can be seen that the stretching vibration of the carbonyl group C=O at 1740 cm^{-1} is only weakly pronounced. It can also be seen that the spectra change after one month. Figures 4c and 4d show the spectra of samples 5A and 6T (fresh and aged). It can be seen that the stretching vibration of the carbonyl group C=O at 1740 cm^{-1} is clearly pronounced. It can also be seen that the spectra have not changed after one month.

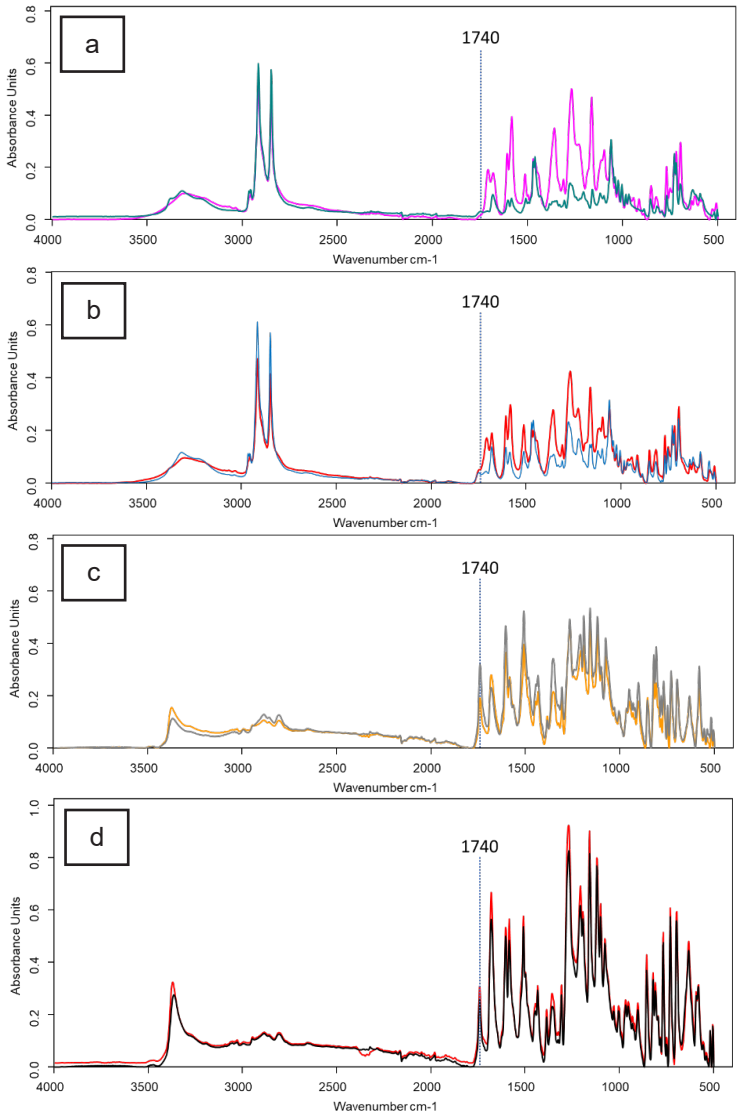


Figure 4: FTIR spectra of the measured samples: a – 4A fresh (pink) and 4A aged (turquoise), b – 4B fresh (red) and 4B aged (blue), c – 5A fresh (yellow) and 5A aged (grey), d – 6T fresh (red) and 6T aged (black).

4. CONCLUSIONS

Ternary TC composite with a mixture of OD+B4HB+CVL and binary TC composite with a mixture of B4HB+CVL were prepared. Fresh and aged samples were analysed by UV-Vis and FTIR spectroscopy as well as by colour analysis in CIELAB colour space. All samples measured had negative values on the *a** and *b** axes, which represent the blue-green colour. The aged samples are less blue-coloured than the fresh samples. The UV-VIS spectrometer was used to determine the changes in the electronic transitions of the base components based on

the measured transmittance values. The focus was on the change in the electronic transitions of CVL, as these indicate the formation of a colour complex. In all freshly prepared samples, the electronic transition of CVL in the composite shifted in comparison to the transition of pure CVL, which means that the lactone ring is open (coloured state). In aged samples of the binary TC composite (5A aged, 6T aged), the change in the electronic transition of CVL compared to pure CVL is small or does not occur at all. This means that most lactone rings are closed. This is consistent with visual observation; the aged samples fade/discolour with time. The FTIR analysis focussed on the valence vibration of the carbonyl group C=O at 1740 cm^{-1}, which is characteristic of the open lactone ring and is the most important vibration in the CVL spectrum. The spectra show that the vibration of the carbonyl group is clearly expressed in the binary TC composite and that the spectra have not changed after one month. In the ternary TC composite, on the other hand, the spectra change after one month and the vibration of the carbonyl group is only weakly expressed. These preliminary results show that the effect can be measured using UV-VIS and FTIR spectroscopy. To be sure when protonation or deprotonation occurs as a function of time, further UV-VIS and FTIR spectra are required at different ratios of the components and at different time intervals. Future work should focus on the investigating different ratios of components in TC composites and longer time intervals of ageing.

5. REFERENCES

Colthup, N., Daly, L., & Wiberley, S. (1990). Introduction to infrared and raman spectroscopy (3 ed.). San Diego: Academic press.

Friškovec, M., Kulčar, R. & Klanjšek Gunde, M. (2013). Light fastness and high-temperature stability of thermochromic printing ink. Coloration Technology, 129(3), 214–222. doi:10.1111/cote.12020

Hajzeri, M., Bašnec, K., Bele, M. & Klanjšek Gunde, M. (2015). Influence of developer on structural, optical and thermal properties of a benzofluoran-based thermochromic composite. Dyes and Pigments(113), 754–762. doi:10.1016/j.dyepig.2014.10.014

Seeboth, A. & Lötzsch, D. (2008). Thermochromic Phenomena in Polymers. Shawbury: Smithers Rapra Technology Limited.

White, M. & LeBlanc, M. (1999). Thermochromism in Commercial Products. Journal of Chemical Education, 76(9), 1201-1205. doi:10.1021/ED076P1201

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POSTER PRESENTATION

THE INFLUENCE OF THE METALLIC SUBSTRATE'S EMBOSSING PROCESS AND THE POSSIBILITY OF PRINTING WHITE ELECTROINK

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Abstract: *Printing white ink on silver metalized substrates is a general trend in label printing and cardboard packaging production. In the creation of smooth silver metalized substrates, printing companies can create various embossed structures, reducing metallic reflection while creating additional content. In this paper, embossing pre-processing was performed (with the Pantec Rhino S510 in-line printing unit installed in the OMET xFlex printing hybrid machine). This process generated two structures of printing substrate: factory gloss and grainy embossed foil (Vacuum Metal Silver-Lux Ultra WS). On printing the white mask, an HP Indigo WS 6800 electrophotographic printing machine was used. The experiment was carried out with different thicknesses of white ElectroInk ink (one, two, and three layers of white). The analysis of the new surface roughness was made with the MarSurf PS10 device and the determination of the hardness of the white coating was made with Elcometer 3092 device. Results show that the white ink adhesion is better with the factory metalized substrates (unembossed), while increased applications of white Elektronik ink will not change roughness notably. The optimal amount of white ElectroInk that could be used to print additional CMYK inks would be made with two layers.*

Keywords: *white ElectroInk, embossing of metalized substrates, surface roughness, coating hardness*

1. INTRODUCTION

Along with the dominant plastic and cardboard packaging (currently around 40% flexible and rigid plastic packaging and 35% shipping, food, and retail paper and cardboard packaging are printed), metal packaging is the third with a share of 10 - 15%. In the category of metal packaging, we primarily include metal boxes and cans for beverages, food, or cosmetics. However, in this category, we include labels and closures whose primary function is labeling and closure. Thus, with the application of varnishes and printing inks, the visual effect of the metalized surface will be maintained. Before printing, metalized surfaces can be treated. Mechanical and chemical processes are used. (Gotch, 2023.)

Metals that are successfully used are: *Pewter* (soft alloy with a low melting point and is easy to emboss work), *Gold* (excellent elasticity and flexibility and one of the most malleable metals for luxury goods), *Silver* (flexible, can be pressed into fragile silver foil, and can form complex patterns and designs), *Stainless steel* (high strength, excellent corrosion resistance, and can withstand more significant pressure and impact, and is not easily deformed, *Aluminum alloy* (good formability and lightweight characteristics), *Copper* (warm hues and malleability, suitable for metal embossing). Depending on the final application, the aluminum surface can be pre-treated using engraving (jewelry), etching (design complex patterns), and embossing (packaging, tools, and implements). Using gravers, rotary tools, and laser engravers, fine lines and depth are achieved on aluminum. This is also the main characteristic of engraving processing. Larger flat hollows and complex textures on aluminum are obtained using the etching methods tools, etching needles (selective application of acid-resistant materials), and etching acids. To get a clear three-dimensional effect of embossing, tools that can be used are Stylus, embossing presses, and rolling mills. Metal embossing is a technique in processing metal packaging and producing labels and closures. In doing so, two printing forms (male and female elements) are used, which, through their joint action, create complex

raised or recessed patterns, images, or text on metal surfaces. This technique primarily increases the aesthetic appearance of metal products and improves their functionality in various applications. (hlc-metalparts, 2025)
The preliminary research aims of this paper are to investigate in more detail the surface of the embossed and non-embossed self-adhesive metalized substrate before it is further processed in the CMYK and CMYK +W digital printing processes (Inkjet and EP).

2. THEORETICAL PART

2.1 Aluminum-Metalized Self-Adhesive Material

Aluminum-coated self-adhesive material is the predominant choice for creating labels with a metallic sheen. This type of material is primarily designed for beer labels, labels for sparkling wines and other wines, as well as luxury labels and declarations for cosmetic products and perfumes. The construction of aluminized label material comprises five layers: a surface metalized layer, a specially treated intermediate layer, a layer of permanent acrylic water-based adhesive, a silicone layer for facilitating the easy removal of the adhesive from the liner, and a backing liner made of supercalendered white paper (Fedrigoni VMS, 2025). Printing on this material is conducted exclusively on the top metalized surface, utilizing printing techniques compatible with solvent and UV-curing inks. Digital printing particularly employs ElectroInk and UV LED-cured inkjet inks (Landa, 1988). Designs typically feature stark contrasts in white and black inks; however, metallic hues of cyan, magenta, and yellow can be produced through the application of other process inks (Pierce, 1999).

2.2 Aluminum Metallized Layer

For reasons of practicality and reduced production costs, the outer layer is not composed of coated aluminum. Instead, a 12 µm thick polymer base, enhanced with a vacuum metalized aluminum layer measuring 40 nm, is utilized due to its significantly more favorable pricing. The vacuum metallization of materials involves a process known as Physical Vapor Deposition (PVD), where metal is deposited through vaporization at a rate of 10 m/s. This technique enables the production of coatings via the thermal evaporation of metals, allowing for application on various substrates. PVD is also employed in the creation of diverse graphic products, including the polymer rolls commonly used in the packaging industry (Rong, 2008; Forgacs, 2013). A crucial aspect of the PVD process is the thermal evaporation of the metal. The control of the vaporization process relies on several factors: the heat source applied, the characteristics of the material being evaporated (the evaporator), the boat or crucible from which it is released, the deposition method, the distribution from the evaporator, and the pressure or environment in which the process occurs. Figure 1 illustrates a schematic representation of the PVD process (Yam, 2009).

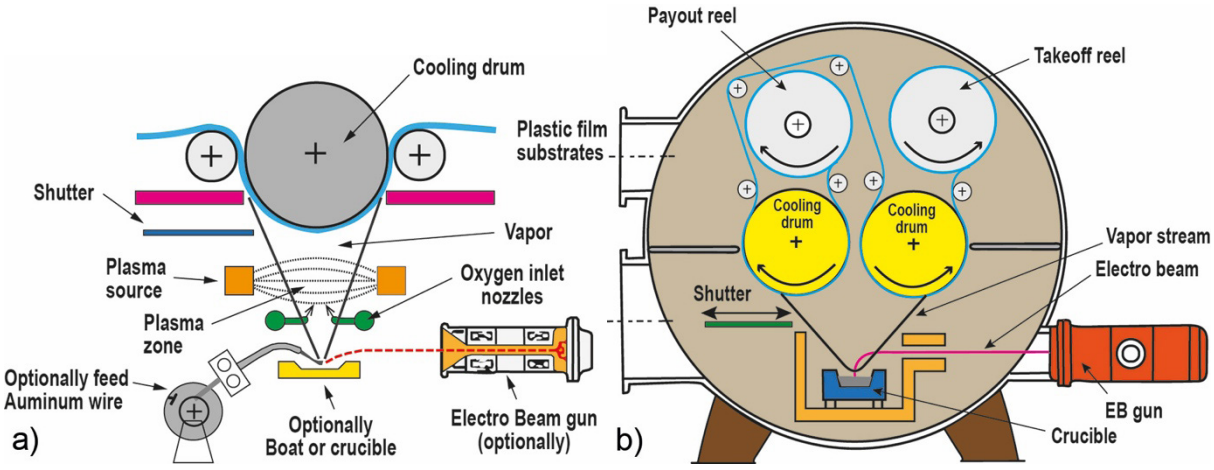


Figure 1: Schematic view of the aluminum oxide deposition process: a) reactive aluminum evaporation; b) Vacuum coating on roll materials on smaller machines.

To controllably deposit aluminum vapor onto plastic film substrates, additional aluminum wire and rod must be placed in a hot boat or crucible. Heat sources for melting include resistance, induction, and electron beam heaters. Optionally, a high-frequency electron beam can be directed onto the aluminum wire to enhance productivity. This radiation is generated by a precisely positioned electro-beam gun.

The liberated aluminum vapors then pass through oxygen inlet nozzles and enter a controlled zone influenced by two plasma sources. To ensure proper adhesion to the plastic film, the aluminum vapors must be cooled. Consequently, the pressure cylinder is continuously cooled. In the event of a potential stoppage in the roll transport, a shutter is activated to close off the distribution of aluminum vapors.

In vacuum metallizers, various factors, such as the selected geometry and the distance between the vaporizer source and the roll substrate, as well as the activation or deactivation of the cooling roller—which serves as an adjusting component for managing substrate temperature and coating speed—impact the properties of the final coating. In the case of a double-sided vacuum application, the system includes two cooled pressure cylinders. This enables one side of the substrate roll to be evaporated before it is turned over for evaporation on the other side. (Yam, 2009)

Heating caused by the resistance of electric current utilizes various reflective metals as heat sources. An effective resistance heating source consists of an electrical conductor with high electrical resistance, enabling it to reach the evaporation temperature with reasonable voltage levels. Refractory metals, such as tungsten, molybdenum, and tantalum, are also employed (these materials are chemically inert and possess higher melting points along with lower vapor pressures than aluminum), which is used as the evaporator. In practice, the most common configuration involves knitted refractory wires. Tantalum is particularly useful for depositing more complex shapes. Additionally, boron nitride, along with aluminum nitride, is utilized to shape materials into desired forms. Three-part boats made from boron nitride, aluminum nitride, and titanium diboride are also utilized. Typically, eleven such vessels are powered by a voltage of 20 V, which can be easily programmed to prevent rupture due to sudden current surges entering the cold boat or crucible.

Induction heating represents another type of heat source that can be utilized, although it is seldom used today due to challenges in control and diminishing economic viability. Nevertheless, it offers several advantages, including a consistent evaporation rate, stable maintenance of coating thickness uniformity, the capacity to use multiple evaporation sources, prevention of uncontrolled spraying, automatic regulation of the evaporation rate, ease of control, high aluminum purity, and extended boat lifespan. Additionally, it can refine more than 40 different types of metals.

One of the key advantages of electron beam heating is that it has no upper-temperature limit, enabling the evaporation of nearly any material. Currently, electron beam guns are utilized in metallization systems, available in both horizontal and vertical orientations. Horizontal electron beam sources create a beam that is reflected at 270° and directed onto a production roll with a width of 1000 mm. This design helps prevent vapor contamination and ensures a precise focus of the electron beam. In these systems, magnets are used to deflect the beam, allowing for optimal coverage of the boat that holds the vaporizer. Typical axial electron beam sources can generate a beam that, with proper deflection, can effectively cover the entire boat containing the vaporizer in nearly any configuration desired. When utilizing electron beam heating, it is crucial to ensure that secondary electrons do not strike the surrounding polymer material, as their thermal exposure can cause damage or destruction. While this heating method may be more expensive, it is also relatively straightforward to implement. The leading manufacturer of electron beam sources is VON ARDENNE GmbH, a German company that produces various configurations of these devices. Their products offer a maximum beam power ranging from 150 to 800 kW, with a turbomolecular pump capacity of 300 to 500 l/s in the cathode chamber, and X-ray leakage of less than 1 µSv/h (VON ARDENNE, 2025).

There are approximately 500 different types of metallizers available globally. These metalizing devices, when paired with roller coating machines, are capable of performing a diverse array of functions that extend beyond the requirements of the packaging industry. Additionally, this technology serves as the leading producer of aluminum-coated polymer films. (Lenk, et al. 1997)
The metalizing coating industry features a variety of in-line and offline configurations for roller coating machines. Regardless of the specific setup, the production process comprises four key steps: a) pre-coating (air removal), b) leading coating, c) aeration (air injection), and d) secondary coating. To enhance productivity, double-sided air-to-air coating machines have been introduced. These machines significantly improve equipment cost-efficiency while increasing production volume by 50%. This type of machinery is applicable in the packaging industry as well as in the coating of metal strips. (Johnson et al., 1998)

In addition to manufacturing embossing foils, the metallization process can also be utilized in creating gold-plated and silver-plated textiles such as bags, ties, curtains, towels, socks, scarves, slippers, tablecloths, lace, and stage costumes. Furthermore, the technique is applicable to ornamental items, including interior decorations, cosmetic packaging, christmas tree ornaments, nameplates, and baubles. It can also be employed in building materials like umbrellas, blinds, interior walls, and thermal insulation, as well as in the production of reflective metalized substrates used in traffic signs, license plates, mirrors, and capacitors.

3. EXPERIMENTAL PART

For the experiment, a printing form was made containing a white media wedge of 10 x 12 cm with patches ranging from 10 to 100% TV (10% TV step). The form was created in Adobe Illustrator version 2022 and saved in PDF X4 (format uploaded into the seven-color HP Indigo WS 6800 EP machine). For printing on the HP Indigo WS 6800, the special ElectroInk white color was activated. The printing substrate was a five-layer metalized foil Vacuum Metal Silver-Lux Ultra ws/SH6020 plus/WG80 produced by Fedrigoni company (table 1). In the RIP Esko HP SmartStream RIP Server (HP Indigo WS 6800), three variations of the white samples were made (sample 1 printed with one coat S1, simple with two coats S2, and simple for three coats S3). (HP Indigo, 2024)

Table 1: Characteristics of Self-Adhesive Film Vacuum Metal Silver-Lux Ultra WS /SH6020 plus/WG80

Front Label Layer	
Reference name	VACUUM METAL SILVER LUX ULTRA WS
Opće karakteristike	Metallised silver paper with high vacuum aluminium particles with high gloss grade and with an ULTRA WS treatment
Grammage ISO 536 (g/m^2)	103
Thickness ISO 534 (µm)	85
Adhesive layer	
Reference name	SH6020 PLUS
General characteristics	Permanent acrylic water based adhesive. Good adhesion to wet surfaces at low temperatures. Especially designed for glass containers, with excellent resistance to immersion in water/ice.
Tack (N) glass FTM-9	>12
Cohesion (h) 1kg FTM-8	>2
Labelling temperature (ºC)	>5°C
Usage temperature (ºC)	-10°C/+75°C
Support layer	
Reference name	WG80
General characteristics	Supercalendered glassine paper, white.
Grammage ISO 526 (g/m^2)	78
Thickness ISO 534 (µm)	67
Tensile strength ISO 1924 MD/CD (KN/m)	MD(KN/m) > 6,8 CD(KN/m) > 3,0

The first part of the experiment was based on direct white printing onto the foil's top metalized layer. In contrast, in the second part of the experiment, the metalized foil was first embossed on a Pantec Rhino S 510 unit (patterns were embossed with a mass of 80 tons to create a relief structure on the foil). (RHINO 510 S, 2025.) After that, a structured metalized aluminum self-adhesive foil was developed and re-printed with white ElectroInk (samples printed with one layer S4, samples with two layers S5, and samples with three layers S6). All the resulting sam-

ples of white ElectroInk ink were fixed to a 4 mm thick glass surface using a FINAT roller weighing (1 kg and a hardness of 70° Sh).

To determine the mechanical properties of the printed white ElectroInk layers, a MarSurf PS10 coating profile measuring device (Ra, Rp, and Rz profile) and an Elcometer 3092 Sclerometer coating hardness measuring device were used. (Roughness Tester, 2024; Elcometer 3092, 2024.) The results of the achieved profiles (without printed white ink layers and with printed white ink layers) were shown in a profile roughness diagram using the OriginPro 8.5 program. Using this digital printing method for small editions (CMYK + CMYKW), a dual-color metallic effect can be achieved alongside standard CMYK color reproduction on a white base. The chronological course of the experiment is shown in Figure 2.

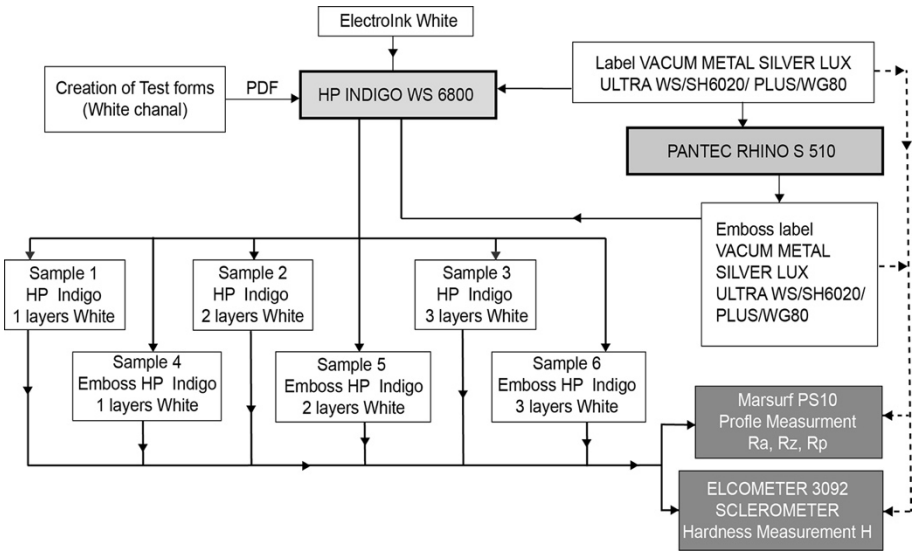


Figure 2: Schematic representation of the experiment.

4. RESULTS AND DISCUSSION

Three key parameters define surface roughness: Ra, which represents the arithmetic mean value of the profile; Rp, the absolute height of the profile irregularities; and Rz, which indicates the heights of the ten highest irregularities. Specifically, Rz is the sum of the mean height derived from the five tallest peaks and the five deepest valleys of the profile in relation to Ra and Rp, highlighting the extremes of surface roughness. Figures 3, 4, and 5 present graphical representations of the Ra, Rz, and Rp roughness parameters, as measured on white prints produced by HP Indigo, using both a smooth and an embossed metalized surface.

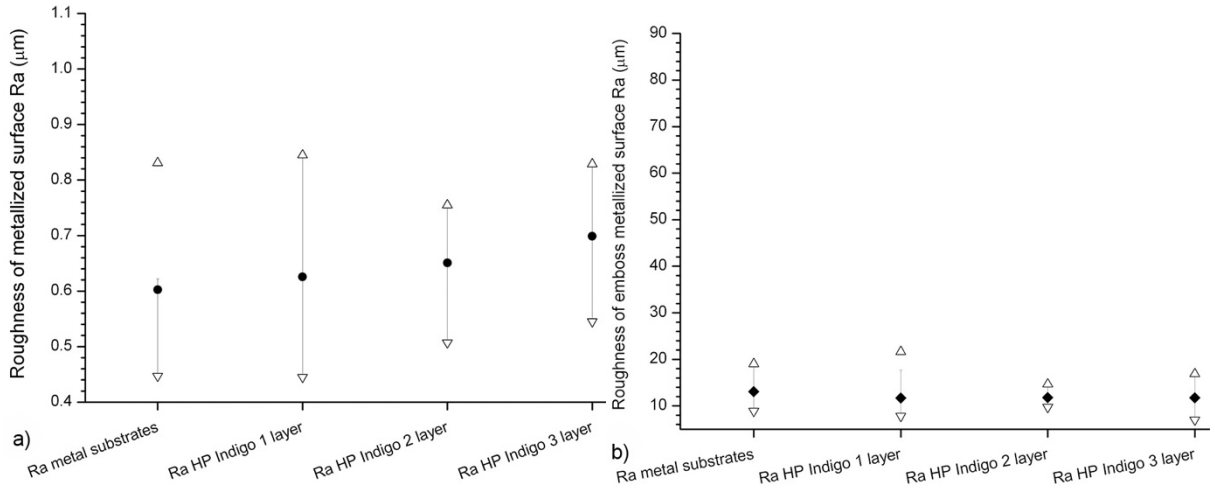


Figure 3: Roughness values of various white ink layers printed on the HP Indigo WS 6800 a) Ra of an original metalized substrate; b) Ra of an embossed metalized substrate.

Figure 3a displays a histogram illustrating the changes in the roughness of a factory metalized surface printed using an HP Indigo printing press. All results are derived from 10 measurements, with only the calculated mean values presented. The lowest roughness was observed on the original printing substrate (without printed white ink), recording a value of Ra = 0,6 µm. With the application of one layer of ElectroInk white ink, the surface roughness demonstrated a slight increase, with a change of $\Delta Ra_{sub._S1}$ = 0,02 compared to the original substrate.

The standard deviation ranged from 0,44 µm to 0,84 µm, indicating a rougher surface. The roughness increased further with two coats of ElectroInk white, resulting in a change of ΔRa_{S1_S2} = 0,04, with measurements fluctuating between 0,5 µm and 0,73 µm. After applying three layers of ElectroInk white ink, the roughness slightly increased compared to the two-layer application (ΔRa_{S2_S3} = 0,07 µm), with measurement results ranging from 0,55 µm to 0,82 µm. In summary, additional applications of HP Indigo white ink lead to a minor increase in the roughness of the printed white surface.

Figure 3b presents a histogram illustrating the roughness parameter Ra of three different layers of white ElectroInk ink printed on an embossed metalized substrate. The unprinted embossed substrate exhibits a high roughness (Ra_{emboss} = 13,04 µm), accompanied by a substantial statistical error in the measurement (ranging from 8,90 µm to 18,90 µm). The histogram clearly indicates that the application of a single layer of white ink reduces the roughness, suggesting that the ink has partially filled the depressions present on the embossed surface. Specifically, with one layer of ElectroInk white, the roughness decreased by ΔRa_{emboss_S4} = 1,53 µm compared to the clean substrate, while a significant statistical deviation persists (between 7,59 µm and 21,33 µm), highlighting the inhomogeneity of the resulting surface.

When two coats of ElectroInk are applied, the fluctuations in the roughness measurements diminish, indicating a more uniform application of the pasty electrophotographic white ink. The difference in roughness between the first and second layers of white ElektroInk is minimal, with an insignificant ΔRa_{S4_S5} = 0,01 µm. Furthermore, upon applying a third layer of white ElectroInk, there is a slight increase in roughness by ΔRa_{S4_S5} = 0,17 µm. The results from a more extensive set of measurements show the least variation, ranging between 6,70 µm and 16,74 µm. These findings suggest that increasing the application of ElectroInk does not significantly alter roughness, indicating that it does not further decrease despite the underlying grainy embossed surface.

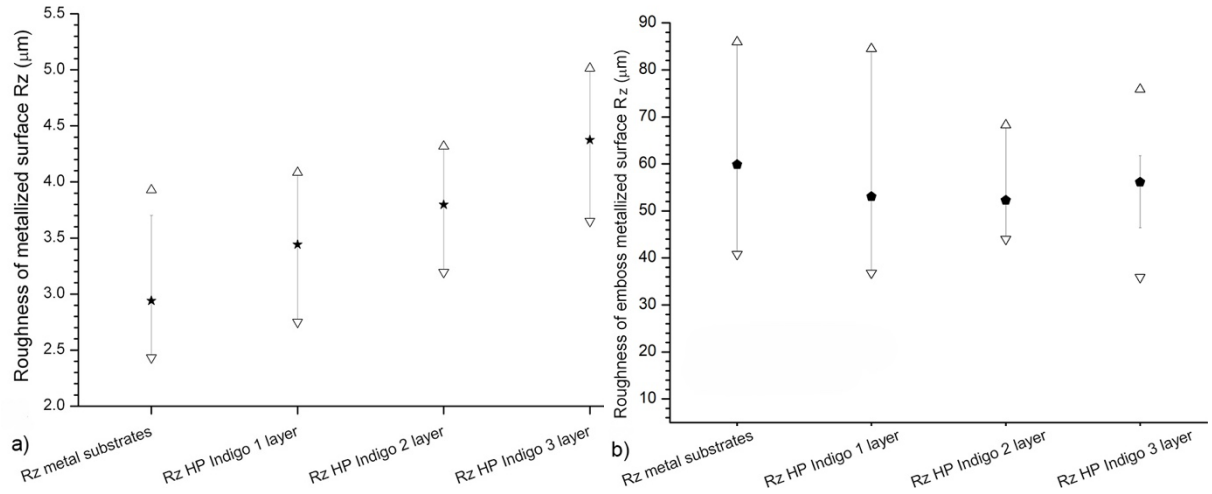


Figure 4: Roughness values of different layers of white colors printed on HP Indigo WS 6800 a) Rz of the original metalized substrate; b) Rz values of the embossed metalized substrate.

Figure 4a shows the histogram of Rz roughness parameters for three different layers of white Electroink. It is evident from the obtained measurement values that the deviations are more significant compared to the Ra measurements. It is also apparent that with the increase in ElectroInk application, there is a linear increase in the parameter Rz. The lowest value was measured with the original substrate and is $Rz_{sub\ =}$ 2,93 µm, with a standard deviation from 2,41 µm to 3,92 µm. By applying one layer of white ElectroInk, the roughness increases compared to the original substrate (ΔRz_{sub_S1} = 0,49 µm), and the results of 10 measurements oscillate between 2,73 µm and 4,06 µm. With two coats of white ElectroInk, the Rz parameter increases compared to the original substrate. This difference amounts to ΔRz_{S1_S2} = 0,85 µm. However, the measurement results oscillate less and range from 3,16 µm to 4,33 µm. Compared to the original substrate with three layers of white ElectroInk, the Rz parameter increases the most. This difference compared to the printing substrate amounts to ΔRz_{sub_S3} = 1,44 µm.

At the same time, the obtained roughness results oscillate between 3,65 µm and 4,95 µm. With the application of three layers of ElectroInk, large oscillations occur in the results, and the printed white surface has a significant roughness deviation.

Figure 4b presents a histogram detailing the Rz roughness parameters of various printed white colors on HP Indigo applied to an aluminized embossed metalized substrate. The measurements reveal that the unprinted embossed substrate (lacking a layer of white ink) exhibits the highest Rz value, which diminishes with the application of ElectroInk. Specifically, the pure embossed substrate has an Rz value of 59,92, with measured values ranging from 40,73 µm to 85,66 µm. The application of a single layer of white ElectroInk reduces both the roughness and the Rz parameter, decreasing by ΔRz_{embos_S4} = 6,76 µm compared to the unprinted substrate. However, this single ink layer introduces significant variability in the measurements, oscillating between 36,58 µm and 84,13 µm.

In contrast, after applying two layers of white ElectroInk, the roughness decreases slightly more (ΔRz_{S4_S5} = 0,64 µm), but the measurement results exhibit smaller oscillations, ranging from 44,23 µm to 68,21 µm. This indicates that two layers of printed white ElectroInk produce the most uniform surface. However, when three layers of white ElectroInk are applied, the roughness results show an increase compared to the two-layer application (ΔRz_{S5_S6} = 4,14 µm), alongside heightened measurement oscillations ranging from 36,38 µm to 75,86 µm. The addition of color to an already applied layer does not enhance the uniformity of the printed white surface; therefore, it appears that overprinting should be limited to a maximum of two layers of white ElectroInk for optimal results.

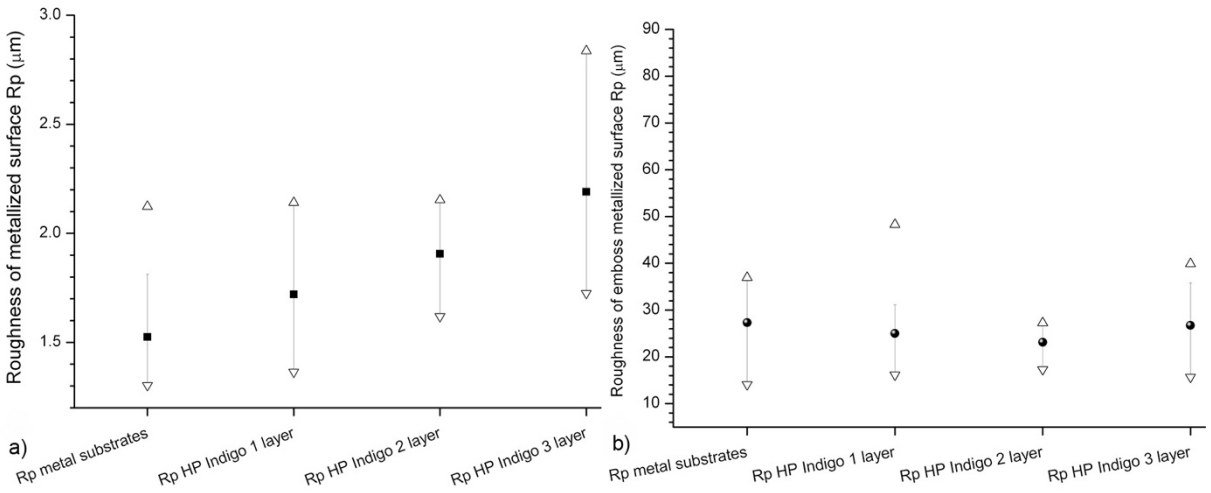


Figure 5: Roughness values of various layers of white ink printed on the HP Indigo WS 6800: a) Rp of the original metalized substrate; b) Rp value of the embossed metalized substrate.

Figure 5 presents a histogram of the roughness parameter Rp for the different printed layers of white ink. Notably, using the HP Indigo leads to an increase in the Rp parameter when compared to the original substrate. The Rp roughness of the original metalized substrate is measured at R_{sub} = 1,51 µm, exhibiting fluctuations within the range of 1,3 µm to 2,15 µm. In contrast to the unprinted substrate, the maximum depth of the profile rises with the initial application of ElectroInk, resulting in ΔRp_{sub_S1} = 0,20 µm. The measurements in this case vary between 1,36 µm and 2,13 µm. With the addition of a second layer of ElectroInk, there's a further increase in the Rp roughness; specifically, compared to the first layer of white ink, an increase of ΔRp_{S1_S2} = 0,18 µm is observed. The standard deviation for these measurements fluctuates between 1,62 µm and 2,15 µm, indicating that this surface was printed most uniformly, exhibiting the smallest variations in results. The highest Rp roughness was recorded after applying three layers of ElectroInk white ink, which increased by ΔRp_{S2_S3} = 0,27 µm in comparison to the two-layer application. This white print also demonstrated the largest measurement oscillations, ranging from 1,72 µm to 2,86 µm.

The Rp parameters of extreme roughness observed during the printing of various layers of white ElectroInk on an embossed metalized substrate are illustrated in Figure 5b. The histogram indicates that increasing the number of white color layers results in a slight reduction in profile depth. An exception occurs with prints that utilize a layer of pasty electrophotographic ink.

The unprinted embossed substrate exhibits the maximum profile value of Rp_{embos} = 27,43 µm, with measurements ranging from 14,13 µm to 36,80 µm. When a single layer of ElectroInk is applied, the profile depth decreases, measuring (ΔRp_{embos_S4} = 0,64 µm) relative to the original substrate. Samples with this configuration also show the greatest variability in measurements, spanning from 16,07 µm to 48,38 µm. In comparison, applying two layers of ElectroInk white results in a further reduction of the maximum profile depth by ΔRp_{S4_S5} = 1,97 µm. Notably, with this two-layer print, even the smallest oscillations in measurements are observed, ranging from 17,39 µm to 27,43 µm. When a third and final layer is added, the maximum depth shows a slight increase of ΔRp_{S5_S6} = 3,51 µm, accompanied by a narrower range of measurements (from 15,44 µm to 39,64 µm). This indicates that the third layer of ElectroInk does not effectively penetrate the embossed substrate but instead adheres to the surface areas.

In addition to the profile achieved, an essential parameter is the hardness of the coating. According to the ISO 4586-2 standard, the hardness of coatings and inks can be assessed using the Elcometer 3092 Sclerometer. The results of these measurements (table 2) are evaluated visually, with four possible descriptive ratings: 1 ink does not peel off; 2 partial ink peeling; 3 visible ink peeling; and 4 tearing of the imprint.

When applying a single layer of white ElectroInk on a factory-finished metalized surface, minimal damage occurs under low forces. The initial traces on the print become evident at a force of 7 N while tearing is observed at a force of 10 N. Therefore, it can be concluded that one layer of ink possesses a hardness rating of 7 N, corresponding to a hardness rating of 3. Both tested directions of applying pressure with the stylus yield no significant differences.

With two layers of white ElectroInk, a noticeable difference was observed depending on the direction of the stylus drawing. When two applications were made in the direction of printing (MD), a force of 0,5 N resulted in a visible line, indicating partial removal of the ink layer, while a force of 1 N led to significant ink removal. Increasing the force to 2 N caused the sample to tear. From these measurements, it can be concluded that the hardness of the two layers of white is 1 N, corresponding to a rating of 3. Conversely, when two layers of white were applied in the opposite direction of printing (CD), the ink remained intact even under a force of 20 N, resulting in a rating of 1.

Table 2: The hardness of different layers of white ink produced on the HP Indigo 6800 WS

Printed Elektroink white inks on an HP Indigo 6800 WS press							
	1 layer	2layer		1 layer	1 layer emboss	2 layer emboss	3 layer emboss
		Machine direction	Cross direction				
0.5 N	1	2	1	1	1	1	1
1 N	1	3	1	1	1	1	1
2 N	1	4	1	1	1	1	1
3 N	1	/	1	3	1	1	1
4 N	1	/	1	/	1	1	1
5 N	1	/	1	/	1	1	1
7 N	3	/	1	/	1	1	1
10 N	4	/	1	/	1	1	1
14 N	/	/	1	/	1	1	1
20 N	/	/	1	/	1	2	2
Ratings	1 ink does not peel off; 2 partial ink peeling; 3 visible ink peeling; 4 tearing imprint.						

The application of three layers of white ElectroInk results in visible ink removal when a force exceeding 3 N is applied. This force also determines the final hardness of the layer. Based on these tests, it is recommended to apply the ink in one or two layers, while carefully considering the direction of deformation (damage). In embossed samples produced through printing on the HP Indigo, an improved hardness of the white layer was observed. When printed with a single layer of ElectroInk white, the ink demonstrated stylus resistance against a force of up to 20 N, with no damage sustained to the ink layer. However, when multiple applications were utilized (two or three layers of white), applying a force of 20 N resulted in only partial removal of the ink layer, indicating a slight decrease in hardness.

5. CONCLUSION

In evaluating the roughness of white prints produced on HP Indigo, the differences observed were minimal. The deviation for white prints on a smooth surface was ΔRa=0,11, while for an embossed surface, it was ΔRa=0,18.

The analysis indicates that the optimal print quality for white ink on HP Indigo machines was achieved with two layers of white ink. Additionally, the printing direction has an impact on the hardness of the resulting white layer; specifically, the cross-direction exhibits better performance than the machine direction, with the coating demonstrating resistance to a force of 20 N.

It is noteworthy that altering the surface structure through the embossing process leads to variations in tone, particularly at higher surface coverage levels. In halftone printing, color changes are more pronounced, whereas full-tone variations remain minimal.

In the factory-processed metalized sample featuring two layers of white ElectroInk, a noticeable difference in hardness and varying printing directions was observed. In contrast, all other tested samples exhibited uniform hardness in the ink layer across both media directions. The highest level of hardness was recorded in the embossed sample with a single layer of white ink. Samples with two and three layers were only slightly behind in terms of coating hardness.

6. REFERENCES

Elcometer 3092, https://downloads.elcometer.com/PDFs/Datasheets/English/3092.pdf, Elcometer 3092, 9.2.2024." (last accessed on 9. 2. 2024).

Fedrigoni Vacuum Metal Silver, http://en.arconvert.it/products/WNE0368-es/print/?tipus%5B0%5D=, Vacuum Metal Silver LUX Ultra WS / SH6020 PLUS / WG80, (last accessed on 9. 2. 2024).

Forgacs P., (2013.) Theory of Ink Transfer in HP-Indigo Digital Press Machines. NIP29: The 29th International Conference on Digital Printing Technologies and Digital Fabrication 2013. Seattle, Society for Imaging Science and Technology, p.429

Gotch, E., The Future of Paper vs Plastic Packaging Markets to 2028, Smithers, Information Division, Olympus House, Cleeve Road, Leatherhead, KT22 7SA, UK, (2023)

hlc-metalparts, What Is Metal Embossing? Detailed Comprehensive Guide, https://www.hlc-metalparts.com/news/what-is-metal-embossing-77240679.html (last accessed on 23. 01. 2025).

HP Indigo WS 6800, https://h20195.www2.hp.com/v2/GetPDF.aspx/4AA7-9277ENW.pdf, HP Indigo WS 6800, (last accessed on 8. 2. 2024).

Johnson, C. A., Ruud, J. A., Bruce, R., & Wortman, D. (1998). Relationships between residual stress, microstructure and mechanical properties of electron beam–physical vapor deposition thermal barrier coatings. Surface and Coatings Technology, 108, p. 80-85.

Landa, B. (1988.), Toner for Use in Compositions for Developing Latent Electrostatic Images, Method of Making the Same, and Liquid Composition Using the Improved Toner. USA patent 4,794,651

Lenk, P., Helling, K., Obst, H., Wenzel, B., (1997) EB-Preheating Technology and Equipment for Thermal Barrier Coating. Proc. Conf. EB Melt. Ref. State of the Art, Reno 1997, p. 114

Pierce, R., (1999), The Printing Ink Manual, Kluwer Academic Publisher, Dordrecht. Netherlands, p. 186 - 194.

RHINO 510 S, https://graval.cl/wp-content/uploads/2019/12/RHINO-Product-brochure-20191001_EN.pdf (last accessed on 5. 2. 2025).

Rong X., (2008.) G7 Method for Indigo Press Calibration and Proofing, The 24th International Conference on Digital Printing Technologies and Digital Fabrication, Pittsburgh, Society for Imaging Science and Technology, p. 603

Roughness Tester, https://5.imimg.com/data5/AD/JL/MY-41879825/portable-roughness-tester.pdf, Portable Roughness Tester, (last accessed on 9. 2. 2024).

VON ARDENNE GmbH, EH800V electron beam guns https://vonardenne.cn/fileadmin/ user_upload/brochures/COMP_Ebeam/Ebeam_COMP_eng.pdf (last accessed on 27. 01. 2025).

Yam K. L., (2009.) Encyclopedia of Packaging technology (3. edition), p. 741.-750. John Wiley & Sons Inc. ISBN: 978-0-470-09704-6, Publisher.

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POSTER PRESENTATION

INFLUENCE OF GLYCEROL CONCENTRATION ON THE WETTING PROPERTIES OF THE METHYLCELLULOSE COATING

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Abstract: There are two main applications of coatings in graphic industry – primer on a printing substrate and an overprint coating for protection of the print or making some aesthetic feature. In this paper we focus on overprint coatings and aim to investigate wetting of the coatings prepared by mixing methylcellulose solution with glycerol applied onto different printing surfaces. For this research four coatings were prepared by altering weight ratio of glycerol in them. Measurements of the viscosity of coatings as well as contact angle on various surfaces were performed. Results of the investigation showed that adding glycerol will not significantly affect the viscosity of the methylcellulose solution and that the measured contact angles were high, with the lowest on coated paper. The glycerol amount does not significantly influence wetting, but relatively high contact angles of all samples indicate the need of wetting agents to apply them in graphic industry.

Keywords: *methyl cellulose, glycerol, coating, contact angle, wetting properties*

1. INTRODUCTION

Coating is a term which describes providing a layer of one substance on the other. In the graphic industry coatings are used in two different fields, as a primer or as an overprint varnish. The primer is set to enable a surface to have good printability, i.e. to enable proper ink transfer (Havenko et al., 2020; Morić* et al., 2019). On the other hand, overprint coating is used to enhance aesthetics of the print in terms of enhanced gloss of the surface or parts of the surface, to provide matte effect or to give protection of the ink film against mechanical or environmental deterioration. When applying an overprint coating there are some obstacles regarding transparency (Hébert et al., 2021) and by the fact that is applied on a homogeneous surface, i.e. clear printing substrate and/or ink film.

Methyl cellulose is the simplest cellulose derivative that offers wide variety of applications (Nasatto et al., 2015). It is often used as an adhesive in paper conservation (Borges et al., 2018). As materials used in conservation should not significantly influence basic material properties, it provides good basis for the application as an overprint coating. In the terms of cardboard packaging, the coating should be flexible not to crack under bending. Glycerol is often used as a plasticizer to various biobased materials used in packaging (Khotsaeng et al., 2023; Żołek-Tryznowska & Cichy, 2018) giving the film flexibility and therefore better properties.

Having in mind all above, the aim of this paper is to examine wetting of the coatings prepared by mixing methylcellulose solution with glycerol when applied on various printing surfaces.

2. EXPERIMENTAL

For this experiment four samples of the coatings were prepared by altering amount of added glycerol. First a solution of the methylcellulose was prepared by mixing 1 g of methylcellulose powder (purchased from Talas, New YOR, USA) in 100 mL of demineralized water. The solution was mixed with magnetic stirrer at 600 rpm at room temperature (22 °C) for 30 minutes. After mixing, the solution was left to settle down for 48 hours. After settling down, methylcellulose solution was used to prepare mixtures with glycerol in weight ratios of 10, 20 and 30 % (in accordance with Table 1).

After adding glycerol to methylcellulose solution samples were mixed for 10 minutes at 500 rpm and room temperature (22 °C). Before taking measurements, samples of coating were left to settle (some air bubbles was observed in solutions) for 24 hours.

Table 1: Composition of prepared coatings

Sample	Methyl cellulose solution (g)	Glycerol (g)	Total (g)
C0	50	0	50
C10	45	5	50
C20	40	10	50
C30	35	15	50

Measurements of the viscosity were performed to determine change of this significant property due to the composition of the coating. The measurements were conducted using Anton Paar RheolabQC. The unit is temperature controlled by external water bath. The sample of a coating was placed in the unit and left conditioning for 15 minutes to achieve defined temperature (22 °C). The test of viscosity was made by setting the shear rate of 1/200 s^{-1} and the value presented in results section was obtained after 10 minutes of the test procedure.

For the wetting properties testing three surfaces were used, a coated cardboard (Finesse gloss, UPM), uncoated cardboard (Tauro offset, Sappi) and full tone offset printed black ink (Novavit Supreme Bio, Flintgroup) on a coated cardboard. The contact angle measurements were performed by the use of Dataphysics' OCA30 device, applying the Sessile drop method with a drop of 1 µL and utilizing Young-Laplace fitting method. The obtained contact angle value was obtained four seconds after the initial liquid-solid contact.

3. RESULTS

The results of the viscosity measurements is presented in Figure 1. It can be seen that at defined shear rate (1/200 s^{-1}) and temperature, viscosity of the coatings changed significantly only for the sample C10 (w(glycerol) = 10%). Nevertheless, it can be observed that increasing the glycerol weight ratio will lead to slight increase of the viscosity.

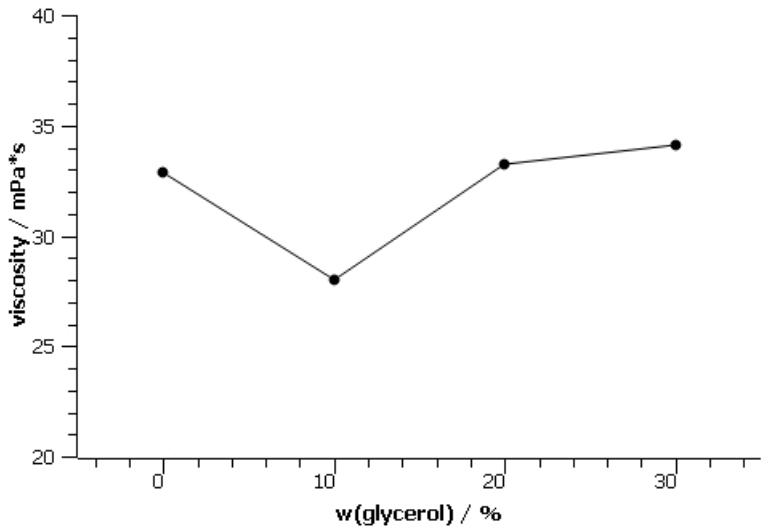


Figure 1: Viscosity of prepared coatings

Figure 2 presents results of the measured contact angles. Point in the graph represents average contact angle values and the error bars represent standard deviation. It can be observed that on coated cardboard and ink film (printed on coated cardboard) contact angle increases with the increase of the weight ratio of glycerol. On the other hand, applying coatings on the uncoated paper the contact angle will decrease. In addition, contact angles

are the highest on the uncoated cardboard and the lowest on the coated cardboard (except for C30 on coated cardboard).

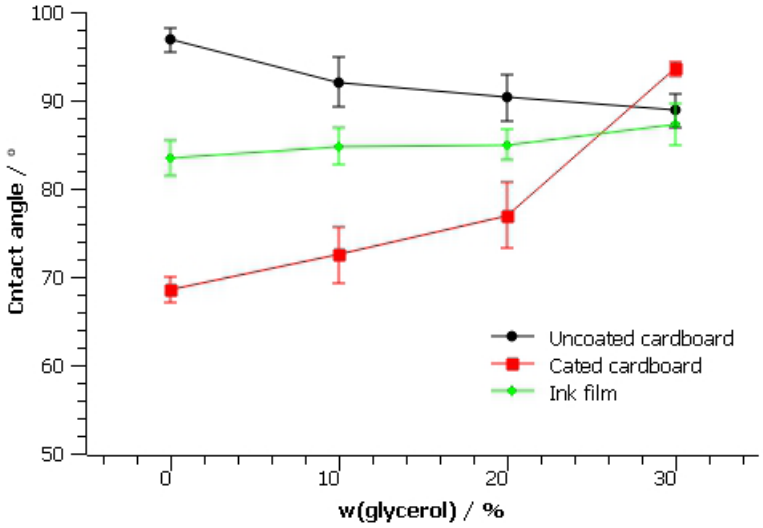


Figure 2: Contact angle of prepared coatings on different surfaces

The coating of the paper often includes various components, one of which could be polysaccharides (Li et al., 2020) leading to the better wetting with the methylcellulose coating, so adding glycerol will increase the contact angle. The smallest change of the contact angle due to the coating composition on ink film is probably consequence of its compact layer with no chemical interaction of coating with the dry ink film.

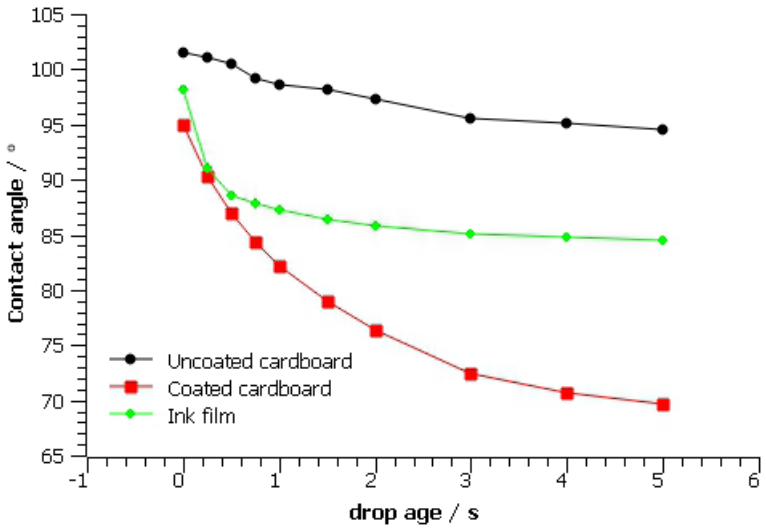


Figure 3: Dynamic contact angle of methylcellulose coating without glycerol

To determine application of a coating on the surface a bit further, dynamic contact angle of sample containing only methylcellulose was presented in Figure 3. These results are representative as all coating have similar behavior. It can be seen that on the ink film contact angle quickly stabilizes after approx. 0.5 s. The smallest change in time was obtained on the uncoated cardboard while the contact angle on coated cardboard stabilizes at 5 second with significant change from the initial contact (t = 0s).

The relatively stable contact angle on the uncoated cardboard could be the consequence of the parallel mechanisms of surface interaction and partial absorbance of the coating on the rough surface of the substrate.

4. CONCLUSIONS

The aim of this paper was to determine influence of adding glycerol to methylcellulose coating on wetting properties when applied onto various printing substrates. The results of the investigation showed that adding glycerol will not significantly change coating's viscosity. The contact angle is changing with the added glycerol, but the behaviour is more dependent on the substrate on which coating is applied.

To conclude, this research has shown that adding glycerol to methylcellulose coating will not significantly influence wetting properties, but as relatively high contact angles for all investigated coating-substrate combinations indicates the need of wetting agents for application of these coatings in the graphic industry.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Borges, I. da S., Casimiro, M. H., Macedo, M. F., & Sequeira, S. O. (2018). Adhesives used in paper conservation: Chemical stability and fungal bioreceptivity. Journal of Cultural Heritage, 34, 1–8. https://doi.org/10.1016/j.culher.2018.03.027

Havenko, S., Khadzhynova, S., Olejnik, K., Kibirkštis, E., & Vaitasius, K. (2020). Influence of Primers on the Optical Characteristics of Ink-Jet Imprints. Mechanika, 26(4), 360–364. https://doi.org/10.5755/j01.mech.26.4.24434

Hébert, M., Dailliez, F., & Simonot, L. (2021). Why a clear coating modifies halftone color prints. Electronic Imaging, Material Appearance 2021, 1311–1318. https://www.researchgate.net/publication/349516630

Khotsaeng, N., Simchuer, W., Imsombut, T., & Srihanam, P. (2023). Effect of Glycerol Concentrations on the Characteristics of Cellulose Films from Cattail (Typha angustifolia L.) Flowers. Polymers 2023, Vol. 15, Page 4535, 15(23), 4535. https://doi.org/10.3390/POLYM15234535

Li, Q., Wang, S., Jin, X., Huang, C., & Xiang, Z. (2020). The Application of Polysaccharides and Their Derivatives in Pigment, Barrier, and Functional Paper Coatings. Polymers 2020, Vol. 12, Page 1837, 12(8), 1837. https://doi.org/10.3390/POLYM12081837

Morić*, M., Majnarić, I., Pap, K., & Miloš, S. (2019). The influence of pre-treatment by priming on the CMY reproduction quality printed with ElectroInk. Tehnički Glasnik, 13(4), 305–310. https://doi.org/10.31803/TG-20191029125530

Nasatto, P. L., Pignon, F., Silveira, J. L. M., Duarte, M. E. R., Noseda, M. D., & Rinaudo, M. (2015). Methylcellulose, a Cellulose Derivative with Original Physical Properties and Extended Applications. Polymers 2015, Vol. 7, Pages 777-803, 7(5), 777–803. https://doi.org/10.3390/POLYM7050777

Żołek-Tryznowska, Z., & Cichy, Ł. (2018). Glycerol Derivatives As a Modern Plasticizers for Starch Films. 217–222. https://doi.org/10.24867/grid-2018-p27

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COMPUTER GENERATED GRAPHICS AND ANIMATION

ORAL PRESENTATION

FROM VIDEO TO CHARACTER ANIMATION FOR 3D THEATER PRODUCTION: A PILOT STUDY

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Abstract: *Bringing 3D characters to life has evolved significantly in digital animation. This pilot study explores the potential of Wonder Dynamics' Animation / Video to 3D Scene project type for creating 3D theater experiences. This tool converts live-action footage into editable computer-generated environments with synchronized character animations and camera setups. Using theatrical performances from the Tragic Talkers dataset as references, animations were generated and exported as Blender scenes for visual comparison with the original footage. Results show that while monologues had minor discrepancies, mainly in facial expressions and hand positioning, interaction scenes exhibited noticeable inaccuracies in hand positioning and character interactions. These findings highlight the platform's strengths and limitations in recreating theatrical motion and provide a foundation for future advancements in AI-driven digital theater production.*

Keywords: *3D characters, 3D theater, computer-generated settings, Wonder Dynamics, Animation / Video to 3D Scene*

1. INTRODUCTION

Artificial intelligence (AI) has changed the animation industry by automating animation processes and scene generation. Character animation has evolved significantly with AI-driven tools (Tang and Chen, 2024). One of the key challenges in AI-assisted animation is the generation of realistic character motion. Since character animation consists of a sequence of humanoid poses, AI must ensure both spatial and temporal smoothness to maintain realism (Sadat Mirzaei et al, 2020). 3D animation involves multiple steps where efficiency improvements are essential. However, despite AI's growing role in automating aspects of animation, studies focusing on its actual impact on production efficiency remain limited. Deep learning techniques allow creation of complex 3D models within limitations, while AI-driven tools streamline rigging and enable motion synthesis based on motion capture data (Chen et al, 2024). These advancements are important for animation production workflows with well-defined parameters. However, creative tasks still rely on human expertise, highlighting the current limitations of AI (Weingarten et al, 2020). Furthermore, the increasing use of AI also raises concerns regarding the balance between efficiency and artistic manner. The future of animation lies in the integration of human creativity and AI technology (Jia, 2024). Exploring the benefits and challenges of AI in animation helps clarify how technological advancements can support, rather than replace, artistic expression. Beyond animation, AI's role in motion tracking and automation can contribute to creative possibilities in virtual theater productions (Reynolds and Reason, 2012). The integration of AI-driven digital animation allows for interactions between virtual characters and live actors, expanding the creative possibilities of stage performances. The incorporation of multimedia components into theater creates a form of artistic expression that blends classical theatrical with modern digital aesthetics, redefining the nature of performance art in the digital era (Tonkoshkura, 2022). However, achieving performance authenticity is difficult, especially when it comes to capturing the hand movements, interpersonal interactions and micro expressions (Andreadis et al, 2010). Wonder Dynamics introduced a new type of project Animation / Video to 3D Scene which facilitates the creation of complete computer-generated (CG) scenes through a simplified workflow. This project type processes a sequence of shots within a scene and produces a synchronized animated sequence. The platform supports multi-cut videos and maintains spatial continuity of characters and camera positions. It enables the export of scene data, including motion capture, character animations, environment models, and camera tracking data, to software like Blender, Unreal Engine, and Maya (Wonder Studio, 2025). This study explores the feasibility of using Wonder Dynamics' Animation / Video to 3D Scene project type for

3D theater production, addressing questions of motion accuracy and character interaction. By examining the capabilities and limitations of this AI-based workflow, the research aims to contribute to ongoing discussions on AI's role in digital performance capture.

2. MATERIALS AND METHODS

The purpose of this study was to find video material that represents theater movements and use them as references for creating animations. The videos were provided by researchers from the Centre of Vision, Speech, and Signal Processing at the University of Surrey. The dataset "Tragic Talkers" represents the Romeo and Juliet drama captured with multi-camera setups and microphone arrays. It includes conventional acting scenarios, such as monologues, dialogues between two individuals (actor and actress), and dynamic interactions. The dataset includes 30 sequences captured from 22 distinct perspectives (Berghi et al, 2022). The videos feature multiple camera perspectives, including one-cut recordings that document monologues, dialogues, and interactions between Romeo and Juliet. For this study, these videos were used as references to generate animations that represent monologues, dialogues and interactions. The video files were uploaded in mp4 format to the Wonder Dynamics platform. The monologue videos had an average duration of 13.33 seconds, while the dialogue videos averaged 9.17 seconds. Monologues were used in their entirety as provided in the dataset, while interaction sequences were trimmed to focus on key moments. Animation / Video to 3D Scene project type's workflow is divided into four sections: Edit, Actor, Environment, and Export. The Edit section allows adjustments to imported videos, while the Actor section identifies actors within the frame and allows the user to assign digital characters to them. In this study, pre-rigged characters from the platform were used. In the Environment section, two options are currently available in the beta version: City Street and Empty Environment. The Empty Environment was selected for this study to allow additional customization. The Export section provides export options, including a complete 3D scene or individual elements like AI motion capture and camera tracking data. The execution of the project involved several steps, including: preparing the project, extracting video, detecting cuts, video preparation, tracking actors, tracking actors across cuts, capturing motion, camera tracking, cleaning up motion capture, hands motion capturing, hands motion cleanup and scene data preparation. Project type provided information about cameras, objects, ground, reflection, shadow catcher, ambient occlusion and lights. Blender scenes and Camera Tracking are exported from videos that represent actors' monologue, actor and actresses' conversation and their interactions. For this study, animations were created from recordings captured by cameras 1 and 21, as shown in Figure 1.

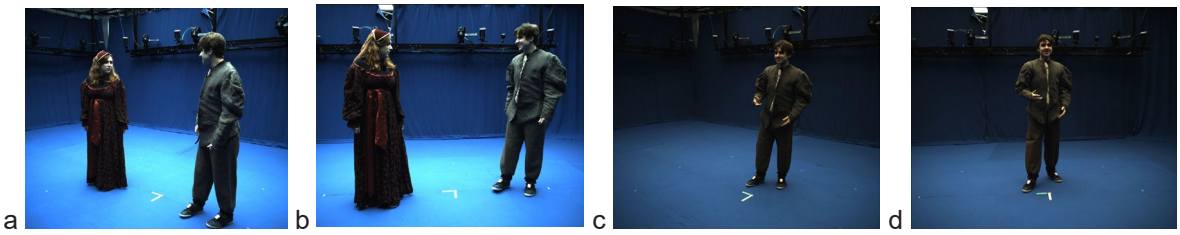


Figure 1: a) Interaction video captured with camera 1, b) Interaction video captured with camera 21, c) Male monologue captured with camera 1, d) Male monologue captured with camera 21

The animations were exported as Blender scenes (blend format) for comparison with the original videos. Blender version 3.4.1 was used to import and analyze the animations. Footages from the database were used to generate the animations and were played side by side to compare the results in 30 fps. Animations in blend format were created separately.

3. RESULTS AND DISCUSSION

Monologue recordings exhibited minimal movement, primarily involving facial expressions and limited hand gestures, while interaction scenes featured more dynamic movements. Monologues would be analysed first, followed by interactions.

In the recording titled “malemonologue1_t1 - cam1”, it was observed that the animated character fails to blink in sync with the reference video, as shown in Figure 2a and 2b, due to the fact that the actor’s eyes remain in shadow for most of the recording. Additionally, multiple instances were identified where the actor’s thumb penetrated through the index finger and other fingers. Furthermore, the actor’s left hand (the one closer to the camera) is clenched into a loose fist, whereas in the animation, the hand appears consistently outstretched (Figures 2c and 2d).

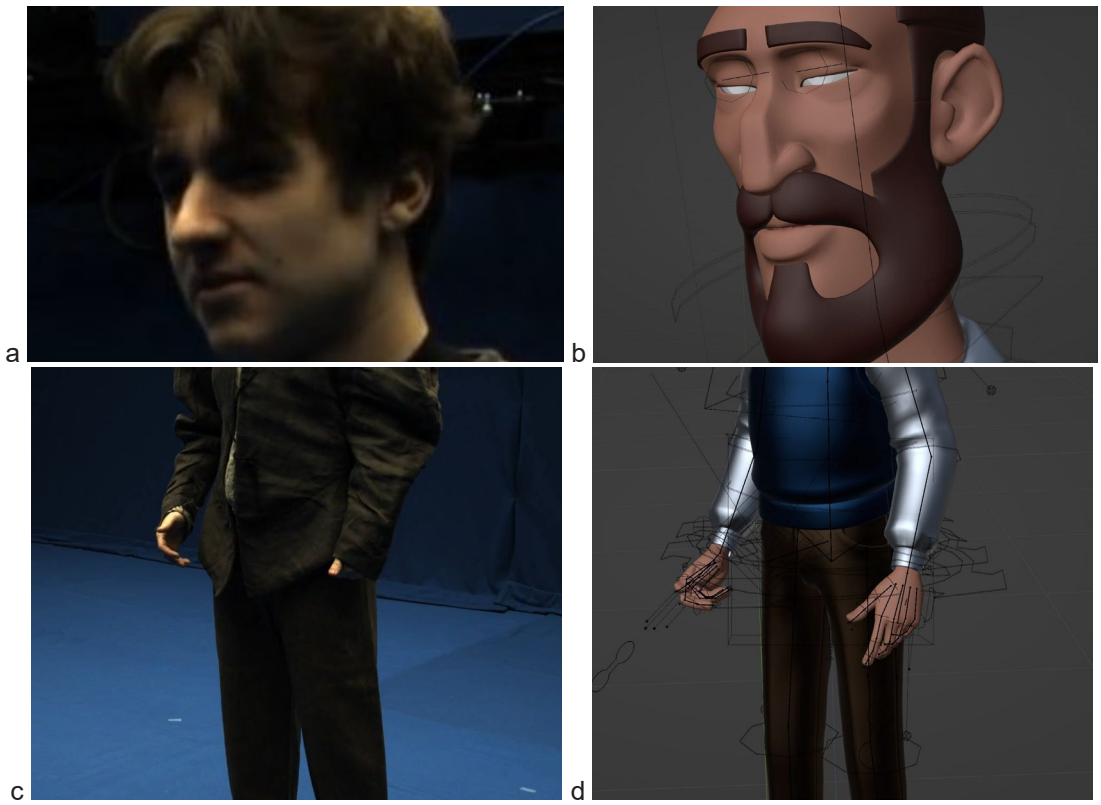


Figure 2: a) Animated character’s blinking detection inaccuracy, b) Animated character’s finger detection inaccuracy, c) Actor’s hand positioning, d) Animated character’s hand positioning

In the video titled “malemonologue1_t1 - cam21,” a different perspective of the same monologue and frame reveals that the animation inaccurately represents the left hand, as shown in Figures 3a and 3b. Moreover, the thumb's penetration into the other fingers is noticeable in the footage captured from this alternate angle. The video "malemonologue2_t1 - cam1" confirms the limitations in detecting finger movements. In the video, both the right and left palms are slightly clenched into fists, which is not the case in the animation.

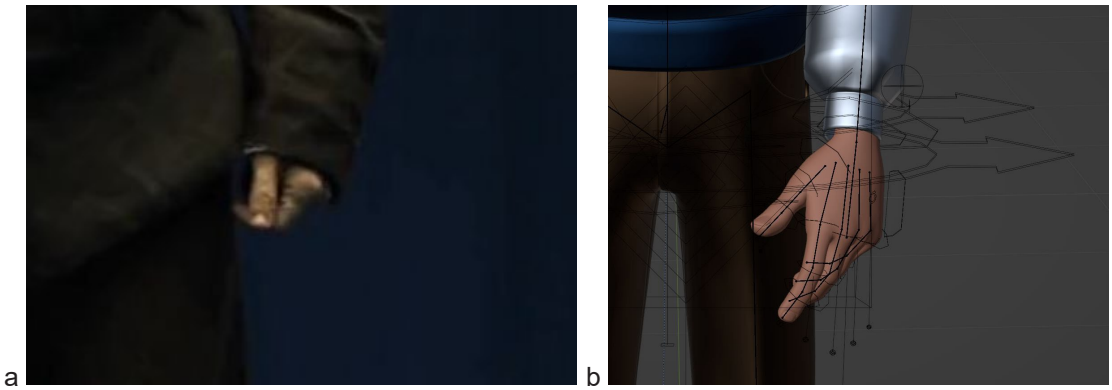


Figure 3: a) Actor’s hand positioning - camera 21 (front),
b) Animated character’s hand positioning - camera 21 (front)

Screenshots captured at the same frame of the video titled “interactive1_t1 - cam1” reveal discrepancies in hand positioning, as shown in Figures 4a and 4b. In the animation, the woman's fingers intersect with her other hand, and the intended positioning—where her hand rests over the man's—is not accurately maintained. In the video, the man firmly grasps the actress's hand with both hands, while her other hand naturally moves over his. Additionally, the woman's hand is positioned farther from the man's, making it seem as though he is not holding it. Throughout the animation, their hands do not make contact, as shown in Figures 4c and 4d. An animation created using the video “interactive1_t1 - cam21” as a reference confirms the claim.

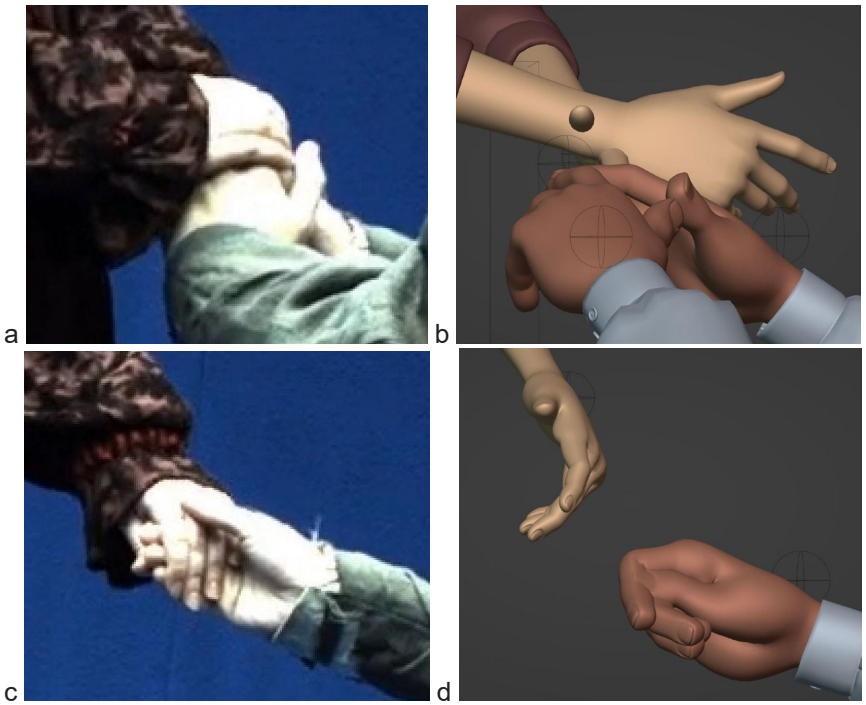


Figure 4: a) Hand placement during actor’s and actress’ interaction, b) Hand placement during animated character’s interaction, c) Holding hands - reference, d) Holding hands - result

In the video “interactive2_t1 - cam1”, the actor touches the actress's back, but in the animation, the model doesn’t make contact and simply continues moving, likely because the actress obstructed the view, as shown in Figures 5a and 5b. This interaction is further confirmed by the footage named "interactive2_t1 - cam21". Furthermore, in the video “interactive4_t1 - cam1”, the actors are depicted making physical contact in the video. However, in the animation, they are not positioned close enough to touch and simply pass by each other without making contact, as shown in Figures 5c and 5d.



Figure 5: a) Actor's hand placement, b) Animated character's hand placement
c) Proximity among actors - reference, d) Proximity among animated characters - result

4. CONCLUSIONS

The results indicate that the project type successfully generates synchronized animations from video footage but faces limitations when applied to the recreation of theatrical movements. While general body movement is properly detected, particularly in scenes without interactions, minor inconsistencies in finger positioning and facial expressions are noticeable. Interactions among actors posed the greatest challenge, especially when holding hands. Despite these challenges, Wonder Dynamics' Animation / Video to 3D Scene project type is considered a promising tool for generating animation out of video. However, achieving authentic performance representation in theatrical contexts still requires human intervention. This pilot study serves as initial research of the Animation / Video to 3D Scene project type and its potential applications in theater animation workflows. While the current research focuses on visual data, future studies will consider quantitative metrics to strengthen the analysis.

5. ACKNOWLEDGMENTS

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6. 5. REFERENCES

Andreadis, A., Hemery, A., Antonakakis, A., Gourdoglou, G., Mavridis, P., Christopoulos, D. and Karigiannis, J. 2010. “Real-Time Motion Capture Technology on a Live Theatrical Performance with Computer Generated Scenery.” Proceedings of the 14th Panhellenic Conference on Informatics 148-152.
Berghi, D., Volino, M. and Jackson, P. 2022. “Tragic Talkers: A Shakespearean Sound and Light-Field Dataset for Audio-Visual Machine Learning Research.” Proceedings of the 19th ACM SIGGRAPH European Conference on Visual Media Production 1-8.
Chen, Y., Wang, Y., Yu, T., and Pan, Y. 2024. “The Effect of AI on Animation Production Efficiency: An Empirical Investigation Through the Network Data Envelopment Analysis” Electronics 13 (24): 5001.
Jia, H. 2024. “The application and impact of artificial intelligence in the field of animation as well as the existing disadvantage.” Transactions on Computer Science and Intelligent Systems Research 5: 660-671.
Reynolds, D. and Reason, M. 2012. Kinesthetic Empathy in Creative and Cultural Practices. University of Chicago Press: Intellect Ltd.
Sadat Mirzaei, M., Meshgi, K., Frigo, E. and Nishida, T. 2020. “AnimGAN: A Spatiotemporally-Conditioned Generative Adversarial Network for Character Animation”
Tang, M. and Chen, Y. 2024. “AI and animated character design: efficiency, creativity, interactivity.” The Frontiers of Society, Science and Technology 6 (1)
Tonkoshkura, O. 2022. “Theatre in the Age of Digital Technologies.” ARTISTIC CULTURE. TOPICAL ISSUES 30-35.
Weingarten, E., Meyer, M., Ashkenazi, A. and Amir, O. 2020. “Human Experts Outperform Technology in Creative Markets.” She Ji: The Journal of Design, Economics, and Innovation 6 (3) 301-330.
Wonder Studio. 2025. Wonder Dynamics. URL: https://wonderdynamics.com/ (last accessed on 18. 01. 2025).

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ORAL PRESENTATION

VISUALIZATIONS IN COMPUTER GRAPHIC – A COLLABORATIVE BRIDGE BETWEEN MUSEUM AND HIGHER EDUCATION RESEARCH INSTITUTION

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Abstract: *Visualizations in computer graphics have transformed the landscape of cultural heritage preservation and interpretation. They serve as both a methodological tool and a communication bridge between museums and academic institutions. The aim of this paper is to present the importance of visualizations in computer graphics as a pivotal element in the communication strategies fostering cooperation between museums and higher education research institutions engaged in computer-aided planning and design. The study explores how visualizations in computer graphic facilitate non-invasive, accurate, repeatable, and controllable processes in cultural heritage conservation, documentation, presentation, and interpretation. Using the collaboration between the Provincial Museum Ptuj - Ormož and the Chair of Information and Graphic Arts Technology (Faculty of Textiles, Graphic Arts, and Design) as a case study, we present mutual motivations, the establishment of professional-scientific dialogues, multidisciplinary involvement, and the strategic dissemination of research outcomes through scientific platforms.*

Keywords: *museum, higher education institution, collaboration strategy, computer generated visualisation, cultural heritage.*

1. INTRODUCTION

Visualizations, ranging from 3D reconstructions and immersive virtual reality environments to interactive digital maps and augmented reality applications, have revolutionized the ways in which cultural artifacts and historical narratives are presented to both academic audiences and the general public (Vidrih, 2019; Perko, 2022). These technologies not only enhance the accessibility and engagement of cultural content but also provide innovative methodologies for research, education, and collaborative exploration.

The significance of visualizations in cultural heritage extends beyond mere representation. They serve as dynamic tools that enable the reconstruction of lost or damaged artifacts, the simulation of historical environments, and the detailed analysis of complex archaeological data. Through visual storytelling, museums and cultural institutions can create compelling narratives that bridge the gap between past and present, making history tangible and relatable. Moreover, visualizations foster inclusivity, allowing diverse audiences to interact with cultural heritage in meaningful ways, irrespective of geographical or physical limitations (Popadić, 2017; Selčan Božič, 2023).

The presented contribution examines communication framework developed over years of collaboration on cultural heritage research, focusing on computer graphics visualizations. Using the Provincial Museum Ptuj – Ormož (PMPO) and the Chair of Information and Graphic Arts Technology (KIGT) as a case study, it highlights unique communication models that optimize cooperation, enhance research impact, and support interdisciplinary engagement.

2. EXPERIMENTAL

In the experimental phase a structured communication strategy was designed and implemented to strengthen institutional collaboration and enhance the visibility and societal relevance of research outcomes. This strategy was directly aligned with the museum's documentation, presentation, and interpretation processes, which were conveyed through computer-generated visualizations. Five core components were identified and operationalized:

Mutual motivation, the establishment of a professional-scientific dialog: Interdisciplinary workshops and collaborative meetings were held regularly to establish a sustained professional-scientific dialogue among stakeholders. These sessions facilitated goal alignment, expectation clarification, and the cultivation of mutual trust, fostering an effective and cohesive collaborative environment.

Research tenders and inter-institutional support: Strategic actions were taken to identify relevant national opportunities. Joint proposals and institutional agreements were developed, providing financial support and reinforcing a foundation for long-term collaboration.

The introduction of multidisciplinarity and the involvement of students in the implementation work: Teams composed of professionals in museology, computer science, education, and environmental studies were formed. Students participated actively in implementation phases—including content design, AR development, and testing—thereby enhancing innovation and skill development.

The targeted planning of exhibition opportunities: Public exhibitions were planned in alignment with research milestones. These interactive showcases, integrating augmented reality components, served as engagement tools and evaluation opportunities, enabling feedback-driven refinement.

Academic dissemination: Research findings were disseminated through presentations at international conferences and publications in peer-reviewed journals. These efforts aimed to ensure academic rigor, promote knowledge exchange, and contribute to the broader research community.

3. RESULTS AND DISCUSSION

3.1 Mutual motivation and the establishment of a professional-scientific dialog

As a cultural institution with a focus on expanding the scope of the significance of cultural heritage, the museum is the starting point from which the research challenge arises (3D reconstructions, presentations of heritage objects, etc.). Research and higher education institutions, on the other hand, need challenges from practice, which include the work of researchers, educators (if the institution is pedagogically oriented), and students. This partnership is crucial for ensuring the scientific accuracy, authenticity, and educational value of visual content. Museums provide access to invaluable collections, curatorial expertise, and historical context, while research institutions contribute cutting-edge technological tools, methodological rigor, and interdisciplinary approaches.
In the 2018/19 school year, the collaboration between PMPO and KIGT began in the form of pedagogical-research work. The aim and purpose was to examine the starting points, references and literature about Panorama, the central part of Petoviona (an ancient Roman city located on the present-day site of Ptuj). Based on the list presented in Figure 1, 17 groups of students from the Master's degree program in Graphic and Interactive Communication created visualizations throughout the semester (Figure 1). On this basis, the PMPO representative was able to continue the study of the buildings, layout and appearance of the historical elements of the Roman city centre.

3.2 The search for research tenders and inter-institutional support

The cooperation between both institutions was based on the agreement of the representatives of both institutions in terms of working methods, enthusiasm for the work, technical agreements, work organization and the transparency of the transfer of information from the field of archaeology to visualizations in computer graphics and vice versa. Over the years of cooperation, the permanent representatives of the cooperation group have been two experts in the field of computer graphics and visualization and one archaeologist. The research team also temporarily included experts in geology, photogrammetry expert, a historian, a fashion and textile designer and an expert in color management. The search for research tenders took place at national level, whereupon we applied for the "Student innovative projects for social benefit" tender for 2019 and 2020 and successfully completed the

research work. In the following years, the collaboration was driven primarily by the goal of presenting the results at national and international exhibitions (which is described below).

	List
1	- schematic view of the city of Petovion from a bird's eye view (city area, river, streams, main road, streets, squares (that we know of)
2	- details of the environment and surroundings, landscape (trees, fences, walls, etc...)
3	- circumambulation sanctuary/dedicated to Jupiter
4	- smaller square 1
5	- smaller square 2
6	- street network
7	- domus without baths
8	- domus with baths
9	- commercial building/tabernae (Trajan's market), among which were also smaller simple sanctuaries (within the same building) 1
10	- simple sanctuary, inside a commercial building 1
11	- simple sanctuary, inside a commercial building 2
12	- smaller rectivis (vessels, jewelry)
13	- tools, utensils, other equipment 1
14	- tools, utensils, other equipment 2
15	- inhabitants, clothing 1
16	- inhabitants, clothing 2

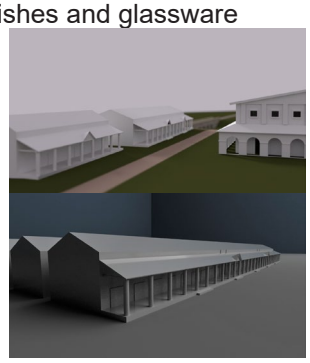
inventory of objects, artifacts and buildings intended for reconstruction



dishes and glassware



a circumambulating sanctuary dedicated to Jupiter



schematic representation of the city and commercial buildings



Roman costume

Figure 1: The list of objects, artifacts and buildings given by museum for reconstruction and first visualisations made by students.

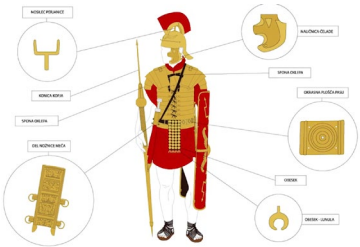
3.3 Student Involvement and Multidisciplinarity

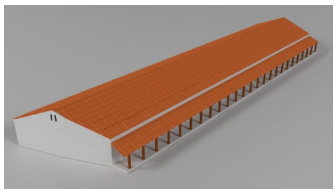
Involving students in research implementation enriched their academic experience and fostered the development of practical skills. Collaborative research offered students hands-on opportunities to apply theoretical knowledge in real-world contexts, enhancing their problem-solving abilities and professional competencies. Multidisciplinary approaches, integrating fields such as museology, archaeology, computer science, and graphic design, broadened the scope of research and created comprehensive educational environments. This diversity of perspectives encouraged innovative solutions and fostered a deeper understanding of complex cultural heritage issues. Students gained valuable experience working in interdisciplinary teams, preparing them for diverse career paths.

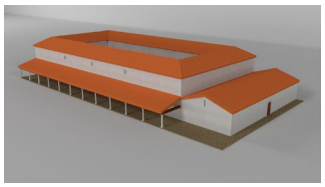
The presented research work involved students' participation of regular curricula of 1st and 2nd level study programmes and extracurricular performance work. On the basis of this experience, we were able to gain some insights into the advantages and disadvantages of involving students in the research methods mentioned. In a full-time study research, the number of students was larger, so that the amount of archaeological content to be worked on for reconstruction, interpretation and reproduction could be greater, but in this case the work results (in terms of motivation, diligence and willingness to learn) of student groups were very different, so that it was more difficult to bring the results to a common denominator. For a teacher and a professional staff member, supervising a larger number of students was also more demanding in terms of organization, time and pedagogical skills. When students were involved in extracurricular work, the work was more focused, the number of students involved was

smaller and the students were additionally supported by paid student work. We believe that at the beginning of the collaboration is optimal to carry out the research work with a larger number of students if possible and thus obtain a wider range of possible outcomes, and then narrow down the objectives of the research and work with a smaller number of more motivated students as part-time research. In the case of the collaboration between PMPO and KIGT and 3D Graphics Reconstruction of Petoviona research we initially involved students from the course of Advanced Computer Graphics and Visualizations course at the 2nd level of graphics studies (25 students), and we continued with the research work Student innovative projects for social benefit (Figure 2), in which, in addition to 6 students of Graphic design, students of Fashion and Textile Design and Geology (3 students) also participated. One Master's student subsequently obtained a Master's degree on this topic. Figure 3 present the visual and topological upgrades of the 3D objects that were previously modelled and textures.


Rome costume


Roman soldier


warehouse


Domus


Panorama, view 1


Panorama, view 2

Figure 2: Interdisciplinary research work results Student innovative projects for social benefit (Jerneja Sotlar, Maruša Možina, Ferdi Jajai, Špela Košir; mentors: Helena Gabrijelčič Tomc, Tanja Nuša Kočevar, Aleksandra Nestorović).


hill Panorama from a bird's eye view


view of the Panorama from the top of the hill


Domus with courtyard and atrium


Domus with private thermal baths and atrium courtyard

Figure 3: Results of Master thesis on the topic of 3D reconstruction of ancient city Poetovio (Jerneja Sotlar; mentors: Helena Gabrijelčič Tomc, Tanja Nuša Kočevar, Aleksandra Nestorović).

Regarding student involvement, we had excellent experiences in collaborating with extracurricular cooperation, which involves highly motivated students with the aim of enriching subject-specific competences. In this way, we and the institution collaborated on research into the graphic reconstruction of ancient mosaics (presented in Figures 5 and 6).

3.4 The targeted planning of exhibition opportunities

Exhibitions served as public-facing platforms to showcase the interdisciplinary outcomes of our collaborations. They offered opportunities to engage broader audiences, promoted cultural awareness, and demonstrated the practical applications of academic research in real-world settings. Exhibitions also helped in building public support, which were crucial for future funding opportunities.

The results of the mentored student research Student innovative projects for social benefit and the master's thesis were presented at the exhibition Osrčje Petovione in Ptuj, which is shown as a 360 exhibition in Figure 4.



Figure 4: Illustrations of a soldier and horse equipment made by students in the research work (PMPO, 2020).

The inter-museum and international exhibition Women's Stories presented the results of the graphic reconstruction of the mosaic with scenes of the abduction of Europa (Figure 5), which was also awarded the prestigious Valvasor award for museum achievements.

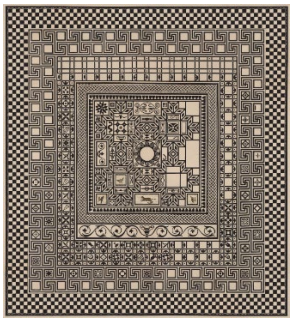


Figure 5: Animation with the graphical reconstruction of the mosaic with scenes of the abduction of Europa (authors of the reconstruction and animation: Gregor Oštir, Anže Mrak, mentors: Helena Gabrijelčič Tomc, Tanja Nuša Kočevar, Aleksandra Nestorović) (PMPO, 2022).

The exhibition as part of Museum night at the Regional Museum in Koper in June 2024 also hosted the results of the graphic reconstruction of Dionysus, Glory to Life, where we exhibited a reconstruction of a mosaic with animal emblems (Figure 6).



exhibition animated presentation



graphical reconstruction of the mosaic with animal emblems





reconstructed mosaic's animal emblems

Figure 6: Graphic reconstruction of a Roman mosaic with animal emblems (author of the reconstruction: Gregor Oštir; mentors: Helena Gabrijelčič Tomc, Tanja Nuša Kočevar, Aleksandra Nestorović).

3.5 Academic dissemination

Targeted planning of conferences and scientific journals for publishing research outcomes was a crucial component of the communication strategy. Disseminating research findings through reputable platforms not only enhanced academic recognition but also contributed to the broader scientific discourse on cultural heritage and digital technologies. Presenting at conferences provided opportunities for networking, knowledge exchange, and feedback from peers, which could inform and improve ongoing and future research. Publication in high-impact journal ensured that research findings reached a wide, international audience, increasing their visibility and impact. The results of the collaborative research have been published at 3 national conferences in the field of graphics and digital media and in one scientific impact factor (SCI) journal in the field of applied sciences (Oštir, 2024). In addition, we have also presented the results of our work in 3 professional articles in the field of archaeology.

4. CONCLUSIONS

This research underscores the impact of computer-generated visualizations in cultural heritage, demonstrating their role in enhancing interdisciplinary research and dissemination impacts. By integrating 2D and 3D reconstructions of objects of cultural heritage the collaboration between PMPO and KIGT optimized institutional partnerships, expanded research outreach, and fostered presentation and interpretation methodologies. The paper highlights key communication and collaboration focuses, including mutual motivation, student involvement, targeted exhibitions, and scholarly dissemination. The collaborative framework not only ensured the authenticity of digital heritage content but also enriched educational experiences of mentors and students. Through exhibitions and academic publications, the results reached wider audiences, reinforcing the significance of interdisciplinary cooperation in preserving and interpreting cultural artifacts. The study provides a replicable model for future research, demonstrating how harmony in cooperation and technological advancements can bridge the gap between archaeological research, education and public engagement.

5. REFERENCES

Oštir, G., Javoršek, D., Stergar, P., Kočevar, T. N., Nestorović, A., & Gabrijelčič Tomc, H. 2024. “Graphic Reconstruction of a Roman Mosaic with Scenes of the Abduction of Europa. ” Applied Sciences 14(9), 3931.
Perko, V. 2022. Družbena vloga (slovenskih) muzejev in kulturne dediščine. Muzeji in muzejska zakonodaja, SMD.
Pokrajinski muztej Ptuj - Ormož. Občasna razstava Osrčje Petovione. URL: https://pmpo.si/wp-content/themes/pmpo/virtual-gallery/Petoviona/index.html (last accessed on 5.3. 2024).
Pokrajinski muztej Ptuj - Ormož. 2022. Ženske zgodbe, medmuzejska razstava. URL: https://www.gorenjski-muzej.si/zenske-zgodbe-evropa-semitska-mati-evropejcev/ (last accessed on 5.3. 2024).
Popadić, M. M. 2017. The Origin and Legacy of the Concept of Musealit. URL: https://cyberleninka.ru/article/n/the-origin-and-legacy-of-the-concept-of-museality/viewer (last accessed on 2.12. 2024).
Selčan Božič, A. 2023. “StoryTeching—Immersing into the Past through the Digital Interpretation of Heritage. ” In MuseoEurope International Symposium; Koprivnik, V., Salecl, D., Eds.,168–169. Maribor Regional Museum: Maribor, Slovenia.
Vidrih Perko, V., Terčon, N., Bonin, F. 2019. Muzeji in njihova vloga v sodobni družbi, In Muzeji in njihova vloga v sodobni družbi : zbornik / XIX. zborovanje SMD, Verena Vidrih Perko, V., Terčon, N., Bonin, F. Eds., Slovensko muzejsko društvo.

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POSTER PRESENTATION

INTERPRETATION OF STOP-MOTION ANIMATION IN 3D COMPUTER TECHNIQUE

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Abstract: *Animating physical puppets and 3D animation have lots of differences, since they are two different animation techniques. However, some animation studios are recreating stop motion style in a 3D world. With this research we aimed to identify the best tools and techniques for achieving this aesthetic. The paper explores replicating the stop-motion style digitally using a 3D program, resulting in a short 3D animation. The theoretical section examines why are we as the audience attracted to the style of stop motion. Key stylistic features of stop-motion were analysed and applied in Blender, utilizing various tools and add-ons to achieve the desired effect. The animation was later edited in Adobe Premiere Pro. The results were evaluated by comparing traditional and digital techniques. Findings highlight the importance of interpolation, material creation, and render engine selection. During the making of the animation a useful Blender add-on was identified as particularly effective in simulating stop-motion within a 3D environment.*

Keywords: *stop motion, animation, 3D computer graphics, stylistic features*

1. INTRODUCTION

The development of technology over the years has introduced innovations in animation techniques, thereby also enhancing the production of traditional stop-motion animation. Although 3D animation dominates today, stop-motion animation has a unique charm that still captivates the audience.

This article describes the creation of an animation that attempts to replicate stop-motion style digitally. The objective was to explore the most effective ways to replicate this style using a 3D graphics program and to identify the tools that help us achieve that.

The anticipated result was a short 3D animation in the stop-motion style. We focused on understanding the differences between traditional and 3D stop-motion animation, particularly in terms of production methods, time requirements, and visual outcomes.

1.1 Stylistic features of stop motion

Stop-motion is a technique where objects are physically manipulated and photographed after each movement. This method, known as frame-by-frame animation, creates the illusion of motion when a sequence of frames is played (Gong, 2023).

A film is not merely an audio-visual experience (Langan, 2023). While textures in films cannot be physically touched - similarly to art pieces in galleries, where touching is typically prohibited - artists explore ways to evoke tactile sensations visually. Stop motion animations often incorporate materials from everyday life. Utilizing familiar textures brings the film closer to the audience, fostering a sense of connection as viewers can relate to the materials through prior experiences. By employing textures from daily life, filmmakers create an emotional resonance, enhancing relatability and engagement. (Minnan, 2020). This phenomenon, termed *haptic visuality*, refers to the process where the observation of specific textures triggers memories, allowing viewers to “feel” materials through visual perception and past experiences (Langan, 2023).

Stop-motion typically uses a frame rate of 12 frames per second. (Laybourne, 1998) The distinctive choppy movement resulting from a lower frame rate is one of the most recognizable stylistic features of stop-motion animation (Teh, 2023). Creators often seek to replicate this effect in digital animation to emulate the stop-motion style (Thill, 2023).

As mentioned, stop-motion animation inherently reflects the creator's touch. Puppets and models are manually crafted and moved, leaving behind visible fingerprints and sewn clothing. Everyday objects are often repurposed during filming. These imperfections are not flaws but rather expressions of real-world presence (Langan, 2023).

Finally, stop-motion animation evokes childhood memories of storytelling and playing with toys, giving viewers the feeling of nostalgia. It represents a dreamlike scenario where toys come to life. It is proven that as technology advances, the appreciation for handmade creations grows stronger. We tend to value objects crafted with significant effort and dedication.

2. EXPERIMENTAL

Our short animation is about a fox which comes into a living room, where different objects are placed. The fox, unfamiliar with its surroundings, begins to disrupt the setting. For 3D modelling and animating we used program Blender, which is free software for 3D graphics. After 3D modelling all the objects, we focused on different ways to achieve realistic look of the objects. Some of the materials were created using image-based textures and others were done manually. Two procedural materials were sourced from online repositories as this is also a way to achieve realistic material.

Special attention was given to simulating clay, which was the material used for the main character. We wanted to animate a material with transformative properties and focused on developing a realistic clay texture and movement.

Using UV mapping, we customized the fox character's surface with the function 'Smart UV Project'. This way we could apply fingerprint texture to simulate tactile imperfections, adding relief to enhance depth and reduce shine in certain areas.

2.1 Walk Cycle Animation

While adding bones to the character, we referenced a pre-existing wolf skeleton in Blender. Walk cycle animation relied on sketches of various walking phases, which guided the bone adjustments. Each step required positioning the fox in ten poses.

To create forward motion, we shifted the character along the Y-axis in each keyframe, ensuring consistent paw placement between frames. Constant interpolation was used for movement transitions. This approach mirrors traditional stop-motion, where the puppet is repositioned and photographed after each adjustment.

2.2 Keymesh Animation

The fox was animated using a combination of armature movement and the Keymesh plugin, developed by Pablo Dobarro and available on GitHub (GitHub). Keymesh allows frame-by-frame mesh deformation, akin to physically reshaping clay between shots. This technique closely resembles traditional stop-motion animation.

Armature animation alone led to artifacts (Figure 1a), which we corrected using Keymesh (Figure 1b). The combination of bones for basic motion and Keymesh for fine-tuning was effective.

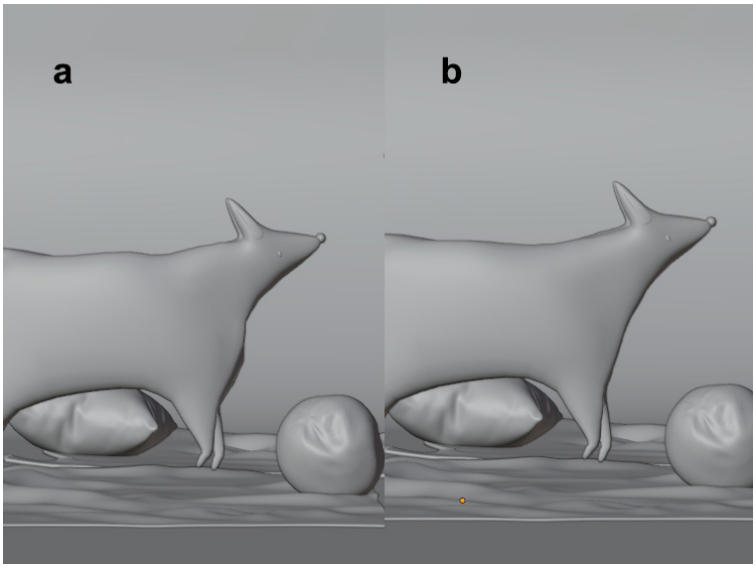


Figure 1: Artifacts on the character (a) and their reduction after using the plugin (b)

2.3 Animating other objects

Each object was animated according to the material from which it was made. We had to consider how each specific material would move in reality – fabric wrinkles softly, denim is stiffer, cardboard boxes flatten, etc.

Movements where objects only change location or rotation were animated by inserting keyframes in Object mode. When the fox jumps onto the cardboard boxes and flattens them, we again used the Keymesh plugin and flattened the box in each frame using the Grab tool in Sculpt mode. Similarly, we animated the wrinkling of fabric using the Cloth tool, which simulates the wrinkling or falling of textile.

For all the movements of the objects, which we carried out during this project, we used constant interpolation. Constant interpolation directly transitions from one keyframe to the next, without adding any intermediate frames or transitions. This type of interpolation is also the technique used to achieve the stop-motion animation style, as it functions in the same way as moving a puppet and taking a photograph after each movement. Since this interpolation results in very abrupt transitions from one pose to another, we had to ensure that we included enough keyframes for each movement to make it appear cohesive, yet still imperfect enough to resemble classic stop-motion animation.

The title animation was created in the style of claymation, also using Blender. We wanted the word “Fox” to appear as if the letters were gradually being shaped from clay. For this part of the animation, we exclusively used the Keymesh plugin. For each letter, we started with a subdivided cube, which we shaped using the Grab tool in Sculpt mode. With the plugin, we inserted new keyframes and slightly reshaped the letter in each frame, so that in the end, the word was fully formed. Figure 2 shows the clay title in the program.



Figure 2: Animating the title

2.4 Rendering and post-production

In our case Eevee rendered clay textures more convincingly, preserving details like fingerprints. In contrast, Cycles diminished these details, making fingerprints less visible even at high sample rates.

We exported our animation in image format. After exporting all the images, we imported them into Adobe Premiere Pro, as we first needed to convert them into a video. In the program, we set the animation speed to 12 frames per second. We set the duration of each imported image to 1, meaning each image lasted for one frame in the video. This gave us the final animation.

If we wanted to duplicate or extend the duration of any keyframe, we changed the image's duration to 2, with the Ripple Edit function enabled, which adjusts the duration of an individual frame without affecting the others.

3. RESULTS AND DISCUSSION

Our goal was to replicate stop-motion animation using digital tools. The clay title sequence and character (Figure 3) were particularly successful, achieving a convincing stop-motion aesthetic. Intentional imperfections added realism, reflecting changes typical of physical clay models.

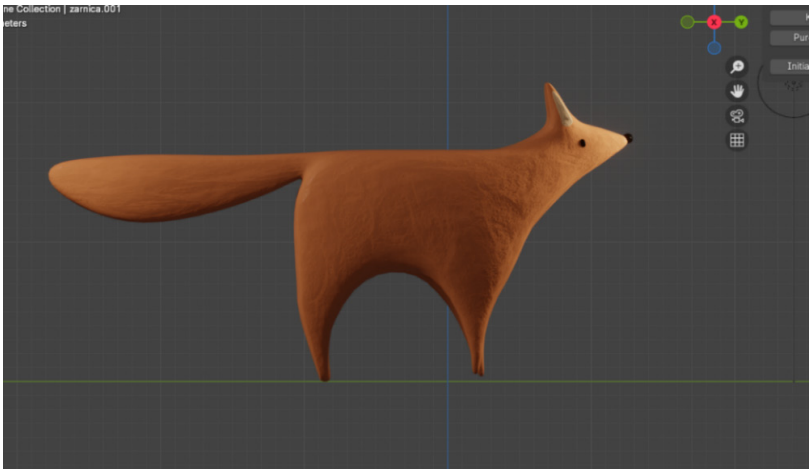


Figure 3: Clay material that was used in the final animation

Some other materials lack the charm of stop motion, making it more apparent that they were created in a 3D environment. The cardboard box was the least convincing due to texture visibility issues.

The movement successfully mimicked stop-motion's non-smooth flow. We avoided poses unachievable with real puppets, such as mid-air jumps. Instead, we split the jump into segments where the character always maintained ground contact.

Comparing traditional and digital stop-motion, traditional setups require fully prepared scenes and fixed lighting before shooting, as changes are difficult to implement later. In contrast, digital scenes allow continuous adjustments, saving time and enabling error correction even after rendering. 3D software also simplifies character manipulation, providing comprehensive viewing angles—an advantage over physically handling miniature models.

Throughout this project, we aimed to identify the tools and techniques that would best help us achieve the stop-motion animation style. Keymesh plugin proved highly effective, whether used alone (as in the title animation) or in combination with the skeleton rig. In this case, we used it to correct errors, ensuring that the character maintained its shape in all poses, or to add a clay-like effect.

We used the frame-by-frame technique, meaning that in each keyframe, we manually adjusted the position of the character or objects. This type of animation is more time-consuming than letting the program calculate the movements and add intermediate keyframes, but it allowed us to achieve the stop-motion style, as traditional stop-motion animation is also created frame by frame.

The key to achieving the recognizable, non-smooth movement of characters, as seen in stop-motion animation, is the use of constant interpolation. Of all the interpolation options in the program, this one most closely resembles the sequence of photographs that would be taken in traditional animation. We also considered to set the right number of frames per second, as too many frames would result in overly smooth movement, which would cause us to lose one of the key characteristics of stop-motion animation.

For exporting such an animation, it is suitable to export it in an image format, which does not export a video, but rather each keyframe separately. This way, we can also control the frames per second in post-production. If the movement appears too fast in some areas, we can duplicate keyframes.

4. CONCLUSIONS

During this research, we explored the most recognizable stylistic features of stop-motion animation. We aimed to replicate these characteristics and the style of such animation using a 3D animation software, while also identifying the best tools and techniques to achieve this.

In the experimental section, we gained a deeper understanding of Blender and the process of creating 3D animation within it. During production, we tested a combination of different animation techniques and analysed which one yielded the best results and why. Throughout the project, we engaged with the entire process of creating such an animation and observed the critical role post-production plays in achieving the desired outcome.

The final outcome aligned with our expectations. The project highlighted numerous advantages of digital animation production, including a faster and ultimately more cost-effective process (considering the costs of materials in traditional stop-motion animation).

However, each technique has unique merits, and both should be preserved to celebrate their distinct creative advantages. Computers and technology can successfully complement and enhance traditional stop-motion animation, but the digital realm should not entirely replace it.

5. REFERENCES

GitHub, URL: https://github.com/pablodp606/keymesh-addon/.
Gong, Y. The blend of reality and illusion – analysis of the artistic characteristics of stop-motion animation. URL: https://www.atlantis-press.com/proceedings/iclahd-22/125984403 (last accessed on 25. 1. 2024).
Langan, H. The appeal of stop motion in the digital age. URL: https://onshow.iadt.ie/wp-content/uploads/sites/6/2023/04/The-Appeal-of-Stop-Motion-in-the-Digital-Age.pdf (last accessed on 24.1.2024).
Laybourne, K.1998. The animation book: a complete guide to animated filmmaking--from flip-books to sound cartoons to 3- D animation. New York : Three Rivers Press.
Minnan, C., Yizhe, T. in Shenglu, a.X. Analysis of visual language for stop-motion animations. URL: https://www.e3s-conferences.org/articles/e3sconf/abs/2020/39/e3sconf_ewre2020_02104/e3sconf_ewre2020_02104.html> (last accessed on 17. 1. 2024).
Teh, S., Perumal, V. in Hamid, H.A. Investigating how frame rates in different styles of animation affect the psychology of the audience. URL: https://mmupress.com/index.php/ijcm/article/view/721 (last accessed on 24. 1. 2024).
Thill, S. An imperfect world: an interview with the directors of Flushed Away. URL: https://www.popmatters.com/an-imperfect-world-interview-with-sam-fell-and-david-bowers-directors-of-fl-2495740124.html (last accessed on 27.1.2024).

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POSTER PRESENTATION

WIDESPREAD VISUALIZATIONS WITH 3D TECHNOLOGIES

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Abstract: *The project explores maritime heritage and reflects on how to transform photographic material into a virtual spatial experience for the contemporary museum visitor. Today, museum presentations of artefacts and exhibits are enhanced by animations and simulations that complement the museum experience. On one hand, we explored the interiors and the companies that built and co-designed the ship's interiors. On the other hand, we aimed to draw attention to the rich art collection of General Navigation, which has been shaped by Slovenian artists. Among these, on Slovenian ships, we find the sculptural works of Stojan Batič, who, with his characteristic expression and signature style, furnished the Ljubljana, Bela Krajina, Ljutomer, Kras, Postojna, Portorož (I) and (II), and Trbovlje. While interpreting the photographic material, we experimented with surface treatments of the created objects, the choice of materials and colours, and tried to relate the realisations to the aesthetics of the 1950s and 1960s. At the outset, we had only black and white photographs as sources for modelling.*

Key-words: *Sculpture, virtual space, Slovenian ships, cultural heritage, art on ships.*

1. INTRODUCTION

The Maritime Museum Sergej Mašera Piran prepared the exhibition Slovenian Ships, 6 Ships of Splošna plovba in 2020. Splošna plovba also devoted considerable attention to the art used to decorate the interior spaces of its ships. The art collection was built through donations from the communities after which the ships were named and through public procurement by General Navigation. Formally and conceptually, the ship's godfathers intended for the artworks to interpret the traditions and history of the towns after which the ships were named. Alongside many artists who decorated Slovenian ships with their works - Avgust Černigoj, Lojze Spacal, Zvest Apollonio, and Zoran Mušič - we focused particularly on the artistic heritage of Stojan Batič (Žitko, 2020).

Stojan Batič (1925) had left a significant mark on his homeland with his sculptural works. He imprinted a wide variety of themes into clay. Initially figurative and marked by realism, his works later evolved into a distinctive authorial expression, almost scenographic in scale. The surfaces of his sculptures resemble branching scenes, carved close to the body, where various surface treatments unfold across the limited dimensions of the relief. Particularly striking is his use of surface as a compositional key - layering and sometimes using perspective. Despite the abstract appearance, Batič never neglected proportions or anatomical relationships in his depictions of individuals and groups (Čopič, 2000).

Batič contributed artworks to the ships Trbovlje (1960), Bela Krajina (1961), Ljubljana (II) (1964), Ljutomer (1965), Karst (1967), Postojna (1967), Portorož (I) (1968), and Portorož (II) (1986). In our research, we focused on Ljubljana (II) and Portorož (I). The motor ship Ljubljana (II), built at the Uljanik shipyard, was the fastest vessel in the fleet at the time. It measured 148.4 metres in length, 19.6 metres in width, and had a deadweight of 9,139 tonnes. In one of its salons, we find a sculptural relief Najada (1964), preserved in aluminium in the General Navigation collection (Žitko, 2020).

In the salon of the motor liner Portorož (I), we encounter Batič's Deklici (1968). The work depicts two female figures holding hands in a pronounced longitudinal composition. The surface is intricately decorated with the graffiti-like markings that the sculptor often integrated into his works. Also built in the Uljanik Pula shipyard, the motor liner Portorož (I) was 147.8 metres long, 20 metres wide, and had a deadweight of 11,230 tonnes (Žitko, 2020).



Figure 1: *Deklici* (1968), aluminium, 90 cm x 20 cm x 21 cm.

Photography plays a significant role in printmaking, especially with the introduction of silkscreen techniques in artistic expression and image reproduction. Transferring photographs to printing matrices expanded the colour palette for graphic communication, particularly in poster design, where office printers first enabled montage and collage layouts (Bernik, 1989).

In contemporary augmented and virtual spaces, photography becomes a tool for capturing and algorithmically adapting data into comprehensive visual „objects." Beyond its artistic value, photography serves as a document of the past, interpreting and explaining historical spaces in the context of time. Unsurprisingly, it is used in fields like ethnology and archaeology to build databases exploring heritage. Photography is also linked to restoration: modern software and technical tools help document restoration processes or objects. For example, Michelangelo's David was digitally scanned in Florence, enabling researchers to study the surface treatment of the Carrara marble (University of Florence, 2020; Madeline, 2021).

3D technologies have also been used for Batič's public monuments in Trbovlje, such as the Monument to the Revolution and the Orjuna Monument. The company 3Dpro specialises in virtual walkthroughs, 360-degree photography, mapping, and preparing point-cloud models (ZMT, 2022). 3D capture of sculptural forms is used for creating replicas or reconstructing missing parts. It's important to note that reproductions do not replace original artworks but serve as templates for educational or museum use. These techniques have largely replaced traditional copyists, reducing costs and making tactile materials more accessible - especially to the blind and visually impaired.

2. EXPERIMENTAL

Museum presentations of artefacts and exhibits are nowadays complemented by animations and various simulations that enhance the exhibition material. On one hand, this project explored ship interiors and the companies that built and co-designed them. On the other hand, we aimed to highlight the rich art collection of General Navigation, shaped by the contributions of Slovenian artists. Two works of art were recreated in the experiment. Deklici was captured using Polycam software. The relief was modelled through observation using Blender and Nomad Sculpt. The data, along with the artworks' dimensions, enabled us to establish a scale both for the furniture and for the recreation of the selected space.

The sculptural and relief templates, with their specific dimensions, served as a reference for scaling and interpreting the extended spaces, initially conveyed to us through photographic documentation of the interiors. Photography conveys various types of information - about space, time, and, not least, about people. If, in architectural representations, the human body is often used as a scale, in our case we chose to scale the space in relation to the artworks within it. Space is limitless, yet constrained by human intention and creativity, allowing objects to exist within it and be moved through it. In our case, what was once self-evident was transferred into the realm of imagination, because the photographic reference alone did not provide a complete representation or experience of the space. Space, therefore, was no longer a given, taken for granted (Muhovič, 2015).

The black and white photographs gave us a sense of depth through the use of grey tones. Using spatial cues such as overlapping and converging lines, we began to construct an imagined volume where the photograph failed to capture it. Our view was mediated by the photographer, but we used our own imagination to reconstruct the missing parts of the ship's interior. We aimed to offer the viewer a holistic experience of the chosen salon, including those walls and perspectives that were undocumented or lost from photographic archives. The frontal plane presented in the image had to be extended by its imagined mirror behind it, thus completing the spatial cross the photographer once occupied. His sensory experience was replaced and supplemented by our own, enriching the two-dimensional image with an impression of depth, spatiality, and the plasticity of objects (Butina, 1995).

While interpreting the grey photographic material, we experimented with the surface treatment of 3D objects, the selection of materials and colours, and aimed to relate our reconstructions to the aesthetics of the 1950s and 1960s. Initially, our only modelling sources were low-resolution black and white photographs, lacking any indication of scale. We determined colours based on those most frequently used in the mid-20th century, referencing catalogues and architectural monographs from that era. For furniture dimensions, we relied on standard measurements, researching the design solutions of companies such as Stol Kamnik and Meblo Nova Gorica. We were also aided by colour photographs from General Navigation's archives and the original 1964 plan of the ship Ljubljana, which provided scale and helped us reconstruct the unseen space behind the photographic lens.

A major focus of the creative process was capturing the sculptural object Deklici (1968) with Polycam software. The captured data was processed and scaled in 3D augmented space using Blender, and the sculpture was placed within the reconstructed interior. In the case of Najada (1964), we experimented with relief modelling in Blender and Nomad Sculpt. The photographic reproduction offered insight into the relief's shadows and sculptural drawing - its interplay of rough and smooth surfaces. We struggled to determine the true depth of the relief and to grasp the sculptor's impressions in the clay, which were cast in aluminium in the original. These challenges were addressed using comparable relief works by Batič that were available to us. Textures were rendered using a custom brush, allowing us to harmonise surface variations and build the best possible digital interpretation of the sculptor's composition. Both works were placed within reconstructed interiors, based on photographic references and ship plans.

While interpreting the grey material, we experimented with the surface treatment of 3D objects, the choice of material and colours, and tried to relate the realisations to the aesthetics of the 1950s and 1960s. At the beginning, we had only black and white photographs as modelling sources, which were of poor resolution and without scale. We tried to determine the colours based on those most commonly used in the 1950s and 1960s, which were available to us in the form of catalogues and architectural monographs. For the size of the furniture, we used standard measurements, researching the design solutions of the companies Stol Kamnik and Meblo Nova Gorica. We also used colour photographs of the Splošna Plovba and the original 1964 plan of the ship Ljubljana, which provided a scale with which we could construct the image behind the photographic lens.

A major focus of the creative process was the capture of the sculptural object *Deklice* (1968) with Polycam software. The captured data was further surface-processed with Blender and presented to scale in a 3D augmented space and the sculptural object was placed in the created interior. In Najada (1964), we experimentally undertook relief modelling in Blender and Nomad Sculpt, and we present the process in layers in Figure 3. The photographic reproduction of the work offered us a reading of the relief in the shadows and the sculptural drawing, the relationship of rough and smooth surfaces. We struggled to assess the depth of the relief structures and the sculptor‘s impressions in the clay, which in the original were cast in aluminium. The challenges of the depth structure of the relief were solved on the basis of other sculptor‘s solutions that were available to us. The textures were rendered with a created brush, which offered us the opportunity to coordinate the variety and build the best possible representation of the sculptor‘s composition. Both depictions were placed in interiors, which we depicted with examples of photographic images and ship plans.

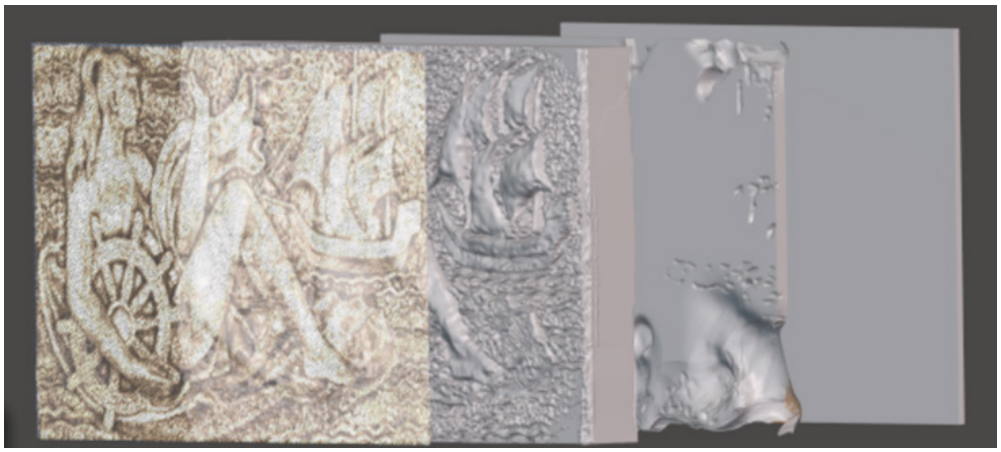


Figure 2: Relief created using Blender and Nomad Sculpt.

In rendering the interior, we used photographic material to determine light sources and reflections from smooth surfaces, which guided our choices of materials and textures. The original wooden floors were replaced with needlefelt carpet and linoleum, based on period accuracy. We also had to construct additional spatial boundaries to complete the room, further guided by the layout and orientation of objects in the ship's salon. This process allowed us to reconstruct a complete volume and spatial experience, into which the visitor - equipped with VR glasses - could be immersed. The spatial cross, once occupied by the photographer, was reconstructed as an interactive experience.

3. RESULTS WITH DISCUSSION

The results, presented in three different modelled spatial reconstructions, offer an expanded museum presentation based on the original content. The exhibition included short documentary films by Viba Film, noted for their strong artistic sensibility. This inspired us to also present the reconstructed spaces as video documentaries, where space could be experienced through time. Digital tools were used to ensure the content could be displayed and accessed online. Alongside the recreated sculptural works, we produced 3D models that make the ship's interiors accessible to the public, including virtual walkthroughs for the blind and visually impaired. This research is an effort to preserve and reinterpret the memory of our maritime heritage.



Figure 3: View of the expanded space in Blender with the Deklici statue.

The video animations and digital spaces form a dramaturgy of space, guided not by a photographer, but by the creator of the expanded environment. This designer incorporates light, texture, and object arrangement to shape the final experience. The musical background further enhances the visual impression of the virtual space, dictating its rhythm and tone. In one of our experiments, the animation ends with a visualisation of a degraded interior: furniture has been rearranged, and graffiti from urban settings covers the walls. In doing so, we drew a connection between private and public space, linking the history of these interiors with the eventual scrapping and abandonment of Slovenian ships.



Figure 4: View of Salon 1 and Blender view of the degraded graffiti area.

4. CONCLUSIONS

The Maritime Museum Sergej Mašera Piran prepared the exhibition Slovenian Ships, 6 Ships of General Navigation in 2020, which now includes a contribution we developed using black and white archival material. Our intention was to create an expanded spatial narrative through photographic sources and to share a simulation with those who never had the opportunity to experience the ship interiors firsthand. While we carefully considered the materials used in furnishing interior walls and furniture, our primary focus was on the artworks—now digitally rendered and made viewable from all directions, much like Batič's own approach when shaping his sculptures in evolving clay forms.

Most of the General Navigation ships are preserved only in reduced scale as physical models. Our aim was to offer a deeper glimpse into their interiors, allowing VR glasses to provide museum visitors with an enriched experience of industrial heritage and spatial design. One of our goals was also to make cultural heritage—often housed in private collections—more accessible, and to present it in the highest quality visual forms and digital templates. By digitising small sculptural works, we have extended the reach of Batič's oeuvre, which has predominantly been accessible only through his public monumental sculptures. Now, in a 360-degree virtual space, with options for zooming and interacting, selected works are available to researchers and admirers of Slovenian modernist figurative art alike.

5. REFERENCES:

Bernik, S. (1989), Plakat & znak, vodilni temi slovenskega sodobnega oblikovanja vidnih sporočil. Ljubljana: Sinteza
Čopič, Š. (2000), Javni spomeniki v slovenskem kiparstvu prve polovice 20. stoletja. Ljubljana: Moderna galerija
Madeleine, P, A. 2021. "3D printed replica of Michelangelo's statue of David presented at the Dubai World Expo, 3D Natives". (obtained by <https://www.3dnatives.com/en/3d-printed-replica-statue-of-david-dubai-world- expo- 051020216/> [24. 1. 2025]).
Muck, D., & Križanovskij, I. (2015). *3D-tisk.* 1. izd. Ljubljana: Pasadena.
Muhovič, J. (2015). *Leksikon likovne teorije: slovar likovno-teoretskih izrazov z ustreznicami iz angleške, nemške in francoske terminologije*. Celje: Celjska Mohorjeva družba.
Smyth, C. (2015). Functional design for 3D printing. Alaska: C. T. Smyth.
Stephen, H. (2018). 3D Printing for Artists, Designers and Makers. London: Bloomsbury Visual Arts.
University in Florence and the Hexagon group. 2020. "3D printed reproduction of Michelangelo's sculpture of David" (obtained by <https://www.theflorentine.net/2021/01/05/michelangelo-david-expo-dubai/> [20. 1. 2025]).
Žitko, D. (2020). Slovenske ladje: 6 ladji Splošne Plovbe. Piran: »Sergej Mašera« Piran.
Watson, F. (1982). The history of furniture. London: Obris

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