GLASILO SLOVENSKIH TEKSTILCEV • SLOVENE JOURNAL FOR TEXTILE AND CLOTHING TECHNOLOGY, DESIGN AND MARKETING

tekstilec

2/2024 • vol. 67 • 101–190
ISSN 0351-3386 (tiskano/printed)
ISSN 2350 - 3696 (elektronsko/online)
UDK 677 + 687 (05)

https://journals.uni-lj.si/tekstilec

tekstilec (ISSN: 0351-3386 tiskano, 2350-3696 elektronsko) je znanstvena revija, ki podaja temeljne in aplikativne znanstvene informacije v fizikalni, kemijski in tehnološki znanosti, vezani na tekstilno in oblačilno tehnologijo, oblikovanje in trženje tekstilij in oblačil. V prilogah so v slovenskem jeziku objavljeni strokovni članki in prispevki o novostih v tekstilni tehnologiji iz Slovenije in sveta, prispevki s področja oblikovanja tekstilij in oblačil, informacije o raziskovalnih projektih ipd.

tekstilec *(ISSN: 0351-3386 printed, 2350-3696 online) the scientific journal gives fundamental and applied scientific information in the physical, chemical and engineering sciences related to the textile and clothing industry, design and marketing. In the appendices written in Slovene language, are published technical and short articles about the textile-technology novelties from Slovenia and the world, articles on textile and clothing design, information about research projects etc.*

Dosegljivo na svetovnem spletu/*Available Online at*
https://journals.uni-lj.si/tekstilec

Tekstilec je indeksiran v naslednjih bazah/*Tekstilec is indexed in*
Emerging Sources Citation Index – ESCI (by Clarivate Analytics) za 2022: Journal Impact Factor (JIF): 0.7; Journal Citation Indicator (JCI): 0.25
Leiden University‘s Center for Science & Technology Studies: 2021: SNIP 0.777
SCOPUS/Elsevier za 2022: Q3, SJR 0.2, Cite Score 1.8, H Index 14
Ei Compendex
DOAJ
WTI Frankfurt/TEMA® Technology and Management/TOGA® Textile Database
World Textiles/EBSCO Information Services
Textile Technology Complete/EBSCO Information Services
Textile Technology Index/EBSCO Information Services
Chemical Abstracts/ACS
ULRICHWEB – global serials directory
LIBRARY OF THE TECHNICAL UNIVERSITY OF LODZ
dLIB
SICRIS: 1A3 (Z, A‘, A1/2); Scopus (d)

tekstilec

Ustanovitelja / *Founded by*

- Zveza inženirjev in tehnikov tekstilcev Slovenije / *Association of Slovene Textile Engineers and Technicians*
- Gospodarska zbornica Slovenije – Združenje za tekstilno, oblačilno in usnjarsko predelovalno industrijo / *Chamber of Commerce and Industry of Slovenia – Textiles, Clothing and Leather Processing Association*

Revijo sofinancirajo / *Journal is Financially Supported*

- Javna agencija za raziskovalno dejavnost Republike Slovenije / *Slovenian Research Agency*
- Univerza v Ljubljani, Naravoslovnotehniška fakulteta / *University of Ljubljana, Faculty of Natural Sciences and Engineering*
- Univerza v Mariboru, Fakulteta za strojništvo / *University of Maribor, Faculty for Mechanical Engineering*

Sponzor / *Sponsor*
Predilnica Litija, d. o. o.

Izdajatelj / *Publisher*
Univerza v Ljubljani, Naravoslovnotehniška fakulteta / *University of Ljubljana, Faculty of Natural Sciences and Engineering*

Revija Tekstilec izhaja pod okriljem Založbe Univerze v Ljubljani / *The journal Tekstilec is published by the University of Ljubljana Press*

Naslov uredništva / *Editorial Office Address:*
Uredništvo Tekstilec, Snežniška 5, SI–1000 Ljubljana
Tel. / *Tel.*: + 386 1 200 32 00, +386 1 200 32 24
Faks / *Fax*: + 386 1 200 32 70
E–pošta / *E–mail*: revija.tekstilec@ntf.uni-lj.si
Spletni naslov / *Internet page*: https://journals.uni-lj.si/tekstilec

Lektor za slovenščino / *Slovenian Language Editor* Milojka Mansoor
Lektor za angleščino / *English Language Editor*
Glen Champagne, Barbara Luštek Preskar

Oblikovanje platnice / *Design of the Cover* Tanja Nuša Kočevar
Oblikovanje / *Design* ENOOKI Kraft, Mitja Knapič s.p

Tisk / *Printed by* DEMAT d.o.o.

Revija Tekstilec izhaja šestkrat letno (štirje znanstveni zvezki in dve strokovni prilogi) / *Journal Tekstilec appears six times a year (four scietific issues and two proffessional supplements)*

Revija je pri Ministrstvu za kulturo vpisana v razvid medijev pod številko 583.
Letna naročnina za člane Društev inženirjev in tehnikov tekstilcev je vključena v članarino.
Letna naročnina za posameznike 38 € za
• študente 22 €
• za mala podjetja 90 € za velika podjetja 180 €
• za tujino 110 €

Cena posamezne številke 10 €

Na podlagi Zakona o davku na dodano vrednost sodi revija Tekstilec med proizvode, od katerih se obračunava DDV po stopnji 5 %.

Imetnik računa / *Account holder*:
Univerza v Ljubljani,
Naravoslovnotehniska fakulteta,
Askerceva 12, 1000 Ljubljana, SI-Slovenija

Transakcijski račun / *Bank Account:*
SI56 01100–6030708186, Banka Slovenije,
Slovenska 35, 1000 Ljubljana, SI-Slovenija
SWIFT / *SWIFT Code*: BSLJSI2X

SCIENTIFIC ARTICLES/
Znanstveni članki

Md. Nahid-Ull-Islam, Shah Md. Maruf Hasan, Md. Kamrul Hassan Chowdhury, Md Shahidul Islam Sakib, Sabbir Ahamed, Md. Abu Sayeed, Mahmuda Akter
Department of Apparel Engineering, Bangladesh University of Textiles, Tejgaon, Dhaka-1208, Bangladesh

Sustainable Approaches of Ozone Wash and Laser Fading Over Conventional Denim Wash

Trajnostni pristopi pranja z ozonom in laserskega bledenja v primerjavi z navadnim pranjem jeansa

Original scientific article/*Izvirni znanstveni članek*
Received/*Prispelo* 1-2024 • Accepted/*Sprejeto* 4-2024

Corresponding author/*Korespondenčna avtorica:*
Mahmuda Akter
E-mail: mahmuda.akter.mitu88@gmail.com
ORCID: 0000-0001-6730-3960

Abstract

Sustainability is highly valued in the contemporary process of washing denim. The apparel business, specifically the denim washing sector, faces significant sustainability concerns, mostly due to its contribution to water contamination and chemical waste. This study employed a range of strategies to highlight the issue of sustainability in apparel washing. This study examined the sustainability of different denim wash techniques, including ozone wash and ozone wash with laser fading, in comparison with conventional methods. Its aim was to establish the credibility of these techniques as sustainable practices by demonstrating their efficacy across various denim wash categories using environmental impact measurement (EIM) software. Environmental impact measurement evaluates the ecological consequences of apparel across four key areas: water usage, chemical usage, energy consumption during production and the impact on labour. It was observed that the methods mentioned above necessitate minimal usage of water and chemicals, resulting in reduced waste and pollution. This study included a comprehensive assessment of various aspects of apparel washing, and concluded that ozone washing and ozone wash with laser fading are advantageous methods for adopting sustainable washing.
Keywords: denim, sustainability, ozone wash, laser fading, environmental impact measurement (EIM) software

Izvleček

V sodobnem tehnološkem procesu pranja jeansa je trajnostni pristop zelo pomemben. Zaradi onesnaženosti vode in nastajanja kemičnih odpadkov je treba razmisliti, kako ravnati z oblačili, predvsem z vidika pranja jeansa. Ta študija je osvetlila vrsto strategij, povezanih z vprašanji trajnosti pranja oblačil. Proučevana sta bila postopka pranja jeansa z ozonom in z laserskim bledenjem ter primerjana z ustaljenimi metodami. Namen je bil proučiti ustreznost teh postopkov z vidika trajnostnih praks, tj. s prikazom učinkovitosti postopkov na različnih stopnjah pranja jeansa s pomočjo programske opreme za presojo vplivov na okolje. Ta omogoča oceno ekoloških posledic oblačil na štirih ključnih področjih: porabe vode, kemikalij in energije med proizvodnjo ter vpliva na delo. Ugotovljeno je bilo, da ozonsko pranje in lasersko bledenje jeansa zahtevata minimalno porabo vode in kemikalij, pri čemer nastane malo

odpadkov in je onesnaževanje okolja majhno. Ugotovljeno je bilo, da sta pranje z ozonom in pranje z laserskim bledenjem ugodni metodi z vidika trajnosti pranja. V članku je podana tudi celovita ocena različnih postopkov pranja oblačil.
Ključne besede: denim, trajnost, pranje z ozonom, lasersko bledenje, programska oprema za presojo vplivov na okolje

1 Introduction

The terms 'green products', 'pro-environment behaviours' and 'environmentally friendly' are frequently linked to the sustainability concept in 'products', and are more closely related to environmental aspects of sustainability (such as air and water pollution) than to social aspects (such as worker rights, gender equality, and exploitation). The European Green Deal does not address the social dimensions of sustainability and instead mandates that "companies making 'green claims' should substantiate these against a standard methodology to assess their impact on the environment" [1]. The fashion sector was accountable for 93 billion cubic meters of water consumption and 3.30 million tonnes of CO_2 emissions (10% of annual global carbon emissions). In 2018, the sector consumed 79 billion cubic meters of water and released 1.72 million tonnes of CO_2. Furthermore, the dyeing and cleaning of fabric produces around 20% of wastewater, while 87% of the fibre used in clothes is burned or dumped in a landfill. Only 20% of garments are gathered for recycling or reuse [2]. Bangladesh's garment industry accounts for the majority of its export revenue, and because it uses a great deal of chemicals and water, the textile and apparel washing sector is one of the main producers of industrial waste [3]. The production of textiles generates trash and other pollutants because they contain oil, grease, caustic soda, Glauber salt, ammonia, sulphur dioxide, lead and heavy metals [4]. Due to its beauty and user comfort, washing is regarded as one of the most popular finishing techniques [5]. The process of making denim involves numerous steps, from the beginning to the end product. Textile mill effluent, which includes denim garment washing plant effluent, is a source of high-water quality parameters, such as chemical oxygen demand (COD), biochemical oxygen demand (BOD), total dissolved solids (TDS) and total suspended solids (TSS). It also contains both organic and inorganic compounds that are not within the standard range [6].

These components regulate variables such as TSS, dissolved oxygen (DO), BOD, COD, TDS, and potential of Hydrogen (pH) [7]. Such effluent will become more toxic when combined with freshwater, increasing the risk of skin conditions, including dermatitis, liver damage and kidney cancer [8, 9]. A method was used to create silver nanoparticles in denim materials by reducing silver nitrate at the cellulose chain in the presence of alkali media such as glucose or starch. The treated fabric was analysed using SEM, Raman spectroscopy and colorimetric tests. Nano silver particles of 30–40 nm were successfully produced on the fabric, reducing the denim colour. The fabric showed antibacterial properties against *E. coli* and *S. aureus*, but glucose reduced the antibacterial effect [10]. Researchers studied laser fading on denim fabric and found that the process poses challenges to traditional methods. The study showed that laser fading retains fabric qualities with minimal colour change and can even improve properties such as rip strength and shrinkage. The CO_2 laser is the most viable option due to its unique interaction properties, efficiency in converting energy and cost-effectiveness compared to other lasers [11]. Another study explored a textile design process that combines laser engraving with foil lamination to enhance the appearance of denim fabric. Experimental findings show that changes in characteristics are linked to the liquefied and vaporised surfaces of laminated foil, as well as the development of cracks, wrinkles and pores on the fibre surface with increased laser energy. The study also reveals the potential to create patterns and reflective looks on denim fabric by combining foil lamination with laser engraving, with lower resolutions allowing for indistinct patterns using small laser beam dots [12]. A study focused on improving the tactile comfort and low-stress mechanical qualities of denim materials through various factors such as raw materials, mix ratio, weaving parameters and washing processes. The study found a strong correlation between perceived tactile comfort and low-stress mechanical properties, particularly in biaxial and multiaxial movements. Stone cleaning was identified as the most effective technique for enhancing tactile comfort, while enzyme washing had a minor impact. Adjusting weaving parameters and increasing the proportion of viscose in polyester/viscose blend weft yarns were recommended for enhancing fabric qualities [13]. A study used ozone treatment on denim fabric samples to analyse the impact on appearance and physical properties. The study included testing bagging resistance, force at break, shrinkage, spectroscopic testing, rubbing fastness evaluation, and the Fourier transform-infrared analysis of treated and untreated denim fabrics. The Taguchi design was used to assess input parameters. Results showed ozone treatment increased whiteness values, altered physical and mechanical characteristics, decreased force at break by 30.11%, increased shrinkage by 15.15% and reduced bagging resistance by 40.17% [14]. Cotton textiles were treated with an environmentally friendly wash using nanobubble technology to make them water-repellent. The findings obtained demonstrate that cotton samples treated with nanobubble technology, nontoxic and environmentally acceptable finishing chemicals, and short-chain fluoropolymers have high washing durability and water repellent characteristics [15]. The researchers conducted an experiment using microassays to investigate the abrasive activity of cellulase and back staining. Their goal was to propose model microassays that assess the denim-washing performance and indigo deposition on garment pocketing fabric [16]. There was an investigation into one-step amylase, cellulose or laccase treatment for a more hygienic denim manufacturing process. It was determined that there was no significant difference in the colour produced from the samples treated with the three enzymes compared to the bio-desized garment treated with cellulose or laccase and cellulase/laccase [17]. A carbon dioxide (CO_2) laser was utilized to treat denim fabrics for colour fading, and was deemed a clean method of treating denim fabric. If processing conditions are well managed, they found that the colour fading effect caused by a CO_2 laser in denim fabrics is more successful than traditional cellulase treatment [18].

Denim processing involves the treatment of denim fabric to obtain desired effects such as softness, a faded appearance or a distressed look. This treatment procedure is known as washing. This process commonly entails employing several methods, such as stone washing, enzyme washing or acid washing, to modify the texture, colour and look of the fabric. An emerging concept known as 'sustainable apparel wash' aims to lessen the impact that the garment wash procedure has on the environment. Reducing trash, using eco-friendly chemicals and detergents, and utilizing less energy and water are all examples of sustainable clothes washing techniques. There are several eco-friendly denim washing methods available, including enzyme washing, laser washing, ozone washing and e-Flow (nanobubble technology) washing. Without the use of harsh chemicals, denim fabric may be softened and decoloured with ozone, a potent oxidant. To fade denim jeans, its oxidizing qualities are employed in place of enzymes, pumice stones or hypochlorite bleaching techniques. A distance accelerates oxygen in the direction of a high voltage point. This part involves applying a high voltage to oxygen, which causes the diatomic molecules to disintegrate into single atoms and then reassemble to produce ozone (Figure 1). Instead of having two oxygen molecules, some of the recombined molecules had three. The device therefore generates a powerful new chemical ozone. Ozone denim wash generates a great deal less effluent, and can cut energy and water usage by up to 70% [19, 20].

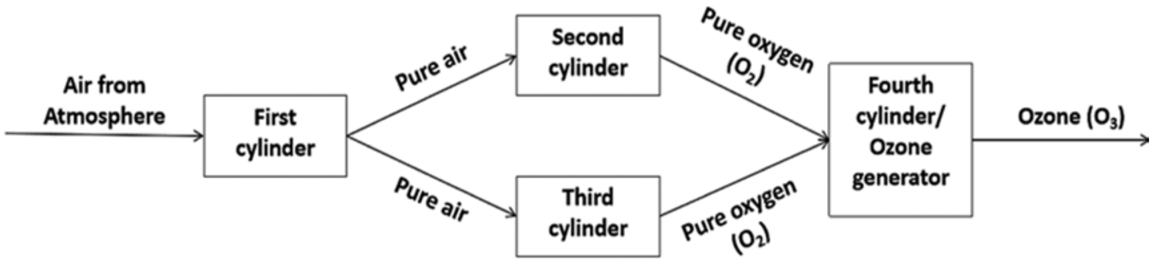


Figure 1: Corona display method for ozone fading

Using a laser may create a faded effect on denim [21], which is an alternative to more conventional methods. The use of a laser beam showed ample advantages over conventional techniques for treating denim fabric, including reduced water use, flexibility in gas production and environmental friendliness in terms of chemical consumption. The material is subjected to intense heating inside a very tiny region within the concentrated zone. The laser energy is absorbed as heat, and the substance rapidly warms up, causing melting as the phase shift from solid to liquid occurs. Some of the molten liquid attempts to move, propelled by the liquid's surface tension. The remaining liquid rapidly warms up, boils and expels vapor as another phase shift from liquid to gas occurs. Figure 2 shows the mechanism of laser fading on apparel.

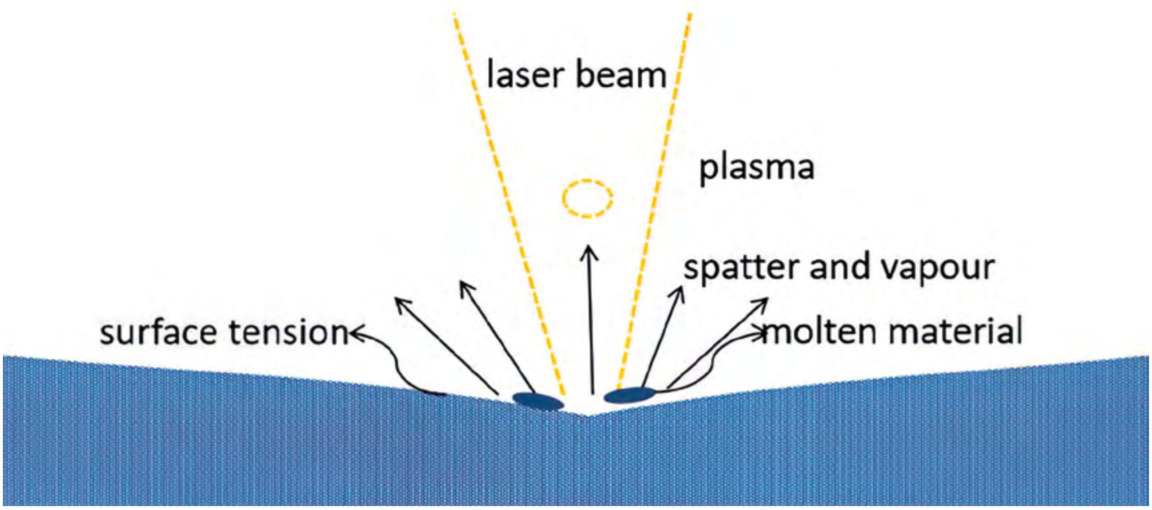


Figure 2: Mechanism of laser fading

The EIM (Environmental Impact Measurement) software V2.0 (Figure 3) was used to conduct an analytical comparison of several sustainable techniques. It categorizes the impacts of garment washing processes into four categories: worker health, chemicals, water consumption and energy consumption. It also allows the user to analyse and compare in a variety of ways [22].

It is a self-accrediting tool made to enhance the environmental performance of the production process as it relates to jeans finishing. The EIM tenets include:

i. Universal
ii. Simple
iii. Clear
iv. Economically viable
v. Aligned with industry evolution
vi. Aligned with industry sustainable criteria.

Four areas are used by EIM to evaluate environmental effects: labour impact, chemical impact, water and energy requirements, and other factors. Three EIM software steps:

1. Quantification for each of the categories
2. Setting a benchmark for each of the categories
3. Classify the processes and scoring for each category.

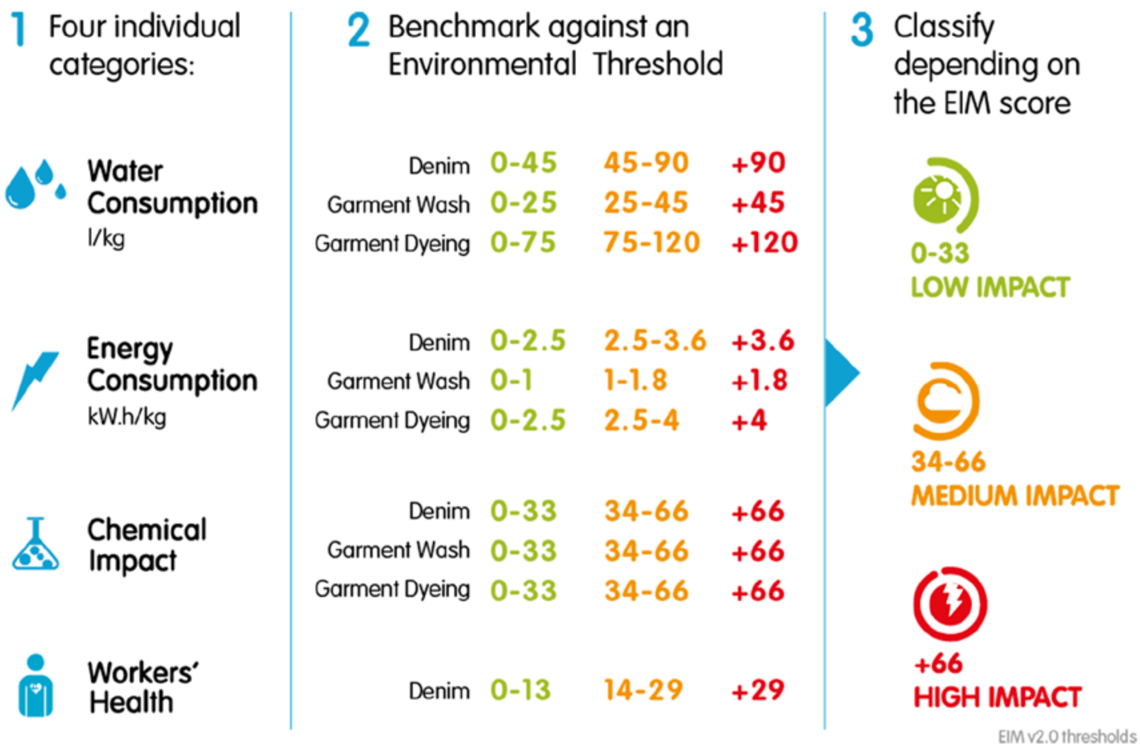


Figure 3: EIM Software V2.0 [23, 24]

The measurement of the impact of garment washing methods is categorized into four groups, which serve as benchmarks against the environmental thresholds of denim, garment wash and garment dyeing. The recommended EIM score for low impact is between 0 and 33; between 34 and 66 for medium impact; and greater than 66 for high impact. EIM facilitates an understanding of how apparel manufacturers, retailers and brands follow industry norms. Consequently, being able to set and track both short- and long-term goals and direct activities toward a final decrease in environmental impact [23, 24]. The industry has defined EIM software as a method for comparing environmental effect data at the wash level.

The aim of this study was to compare the sustainability of conventional washing, ozone washing and laser fading of denim using EIM software. The overall EIM scores suggest that both ozone washing and laser fading are regarded as sustainable. During our study, we found that ozone washing and laser fading resulted in reduced water usage and process time compared to conventional washing methods. Additionally, in the case of ozone wash, the effluent treatment plant (ETP) value demonstrates superior performance compared with conventional washing methods. Ozone washing results in a significant reduction in both chemical consumption and energy consumption compared to conventional washing methods. Similarly, laser fading results in a reduction in chemical consumption compared to conventional washing.

2 Materials and methods

2.1 Materials

The denim fabric was collected from a renowned denim factory in Bangladesh. The general structure of fabric was 3/1 warp-faced twill with an average mass per surface area of 400 g/m^2.

Table 1 summarizes the chemicals used for washing denim. Garment washing was divided into two categories: a wet process and a dry process. The dry process of washing necessitates the use of tools to visualize the result, while the wet process necessitates the use of chemicals to perform activities. Novalase LT 40 (alpha amylase derivative enzyme) was used as a desizing agent in this study, along with Novastone Neutral MR Enzyme (strong buffer neutral cellulase enzyme), calcium hypochlorite as a bleaching agent, sodium metabisulfite as a neutralizer, potassium permanganate for PP spray) and Deterpal F33 Powder as a cleaning agent (dispersing agent that improves the blue/white contrast, appearance and cleaning of the jeans). Base OT concentrate (highly concentrated softener for natural and synthetic fibres) was used to soften jeans.

Table 1: Chemicals used for washing

Process	Chemical
Desizing	Novalase LT 40
Enzyme	Novastone neutral MR
Bleaching	Calcium hypochlorite
Neutralizing	Sodium metabisulfite
PP spray	Potassium permanganate
Cleaning	Soda ash
	Deterpal F33 powder
Softening	Base OT concentrate

Washing methods

There are primarily two different types of denim washing methods available:

i. Conventional denim wash
ii. Sustainable denim wash

Although there are some newly invented denim washing methods, this study dealt with the ozone wash and sustainable wash with laser fading.

Conventional washing

Conventional denim washing consists of both dry and wet processes, which are primarily carried out by manual and front-loading washing machines, respectively. It was carried out by a Tonello G1 130 industrial washing machine for this study.

Ozone washing

For this method, an additional machine was used known as a Jeanologia G2 Cube from the manufacturer Jeanologia, which consists of four chambers and was specifically manufactured for ozone washing.

For the most part, this technique uses four-cylinder engines. First, pure oxygen is isolated after purified air is gathered from the surrounding air and placed in a cylinder. The ozone generator receives pure oxygen from the oxygen cylinder. Oxygen travels at a high voltage site at a fast speed. In this part, oxygen is exposed to high voltage, which causes the diatomic molecules to break apart into single atoms and then come back together to produce ozone. Three oxygen molecules instead of two were present in some of the recombined molecules. Thus, the device generates a powerful new chemical ozone. To get the desired yellowish fading effect on denim, 10% ozone is applied for the first 10 seconds, followed by 20% ozone for the next 10 seconds. The maximum ozone concentration used is 40%.

Laser fading

For this method, an additional machine was used known as a Jeanologia Compact HR laser fading machine. It was designed for maximum production versatility, accuracy and cost efficiency.

Process of denim washing for different methods

In conventional denim washing, a large amount of water and chemicals are used, contaminating the water with solid particles and chemical components [14]. On the other hand, it has been shown that ozone washing and laser fading consume less water and chemicals than traditional wash due to the removal of several processes in the whole washing process [25]. Ozone washing eliminates the desizing procedure. Similarly, laser fading eliminates the desizing, PP spray, and multiple drain and rinse stages.

Table 2 indicates the operations of conventional washing, ozone washing and laser fading on denim. While ozone washing requires 22 operations to complete the process of replacing the desizing stages and laser fading requires 17 operations to finish the corresponding wash, conventional denim washing requires 23 operations to complete the entire task, from whiskering and sanding to tumble drying. Laser fading eliminates the whiskering and sanding processes by replacing the dry washing with the ozone washing operation.

Table 2: Operations of conventional washing, ozone washing and laser fading on denim

Process stage number	Name of operation		
	Conventional washing	Ozone washing	Ozone washing with laser fading
1	Whisker & sanding (dry)	Whisker & sanding (dry)	Tag (dry)
2	Tag (dry)	Tag (Dry)	Ozone fading (wet)
3	Desizing (wet)	Ozone fading (Wet)	Stone-enzyme (wet)
4	Drain and rinse (wet)	Stone-enzyme (wet)	Drain and rinse (wet)
5	Stone-enzyme (Wet)	Drain and rinse (Wet)	Stone remove (Dry)
6	Drain and rinse (Wet)	Stone remove (Dry)	Rinse and drain (Wet)
7	Stone remove (Dry)	Rinse and drain (Wet)	Denim bleach (Wet)
8	Rinse and drain (Wet)	Denim bleach (Wet)	Drain and rinse (Wet)
9	Denim bleach (Wet)	Drain and rinse (Wet)	Neutralization (Wet)
10	Drain and rinse (Wet)	Neutralization (Wet)	Drain and rinse (Wet)
11	Neutralization (Wet)	Drain and rinse (Wet)	Cleaning (Wet)
12	Drain and rinse (Wet)	Hydro extraction (Wet)	Drain and rinse (Wet)
13	Hydro extraction (Wet)	Tumbler drying (Wet)	Softening (cationic softener)
14	Tumbler drying (Wet)	PP spray (Dry)	Drain (Wet)
15	PP spray (Dry)	Neutralization (Wet)	Hydro extraction (Wet)
16	Neutralization (Wet)	Drain and rinse (Wet)	Tumbler drying (Wet)
17	Drain and rinse (Wet)	Cleaning (Wet)	Whisker & sanding with laser (Dry)
18	Cleaning (Wet)	Drain and rinse (Wet)	
19	Drain and rinse (Wet)	Softening (cationic softener)	
20	Softening (cationic softener)	Drain (Wet)	
21	Drain (Wet)	Hydro extraction (Wet)	
22	Hydro extraction (Wet)	Tumbler drying (Wet)	
23	Tumbler drying (Wet)		

Software

The EIM V2.0 software was used to make a comparison analysis of washing procedures in order to evaluate their sustainability.

Table 3 shows the EIM software results, which include the process name, time, EIM score and other information. The ranges for the EIM score are 0-33, 33-66, and +66, while the associated categories are low impact, medium impact and high impact. Water, energy, chemical impact and worker impact are all separately categorized in the EIM score. The software compares the outcomes of each category to a preset environmental threshold. After classifying each category independently, it rates the procedure's overall impact as low, medium, or high. Colour coding is used to present the results in an easy-to-understand manner.

Table 3: EIM software result display

EIM Environmental impact					
Process name: conventional				**Threshold: EIM V2.0 – denim**	
EIM Score:		Water	Energy	Chemical Impact	Worker Impact
74		84.00	2.54	100	100
Low impact	0–33	0–45	0–2.5	0–33	0–13
Medium impact	33–66	45–90	2.5–3.6	33–66	13–29
High impact	+66	+90	+3.6	+66	+29

2.2 Methods

Testing ensures that items fulfil prescribed quality requirements. It enables producers to discover any problems or issues in the manufacturing process, allowing them to be addressed before a product is distributed to the market. Table 4 shows the different tests of fabric and the standard method that were used to measure those properties in this research work. All these tests were carried out at a well-known laboratory. The pH was measured using the ISO 3071:2020 standard, while grams per square meter (GSM) were determined using the EN 12127:1997 standard. To test for colour fastness against rubbing, washing and water, the ISO 105-X12:2016, ISO 105-C06:2010 and ISO 105-E01:2013 standards were used. While seam slippage was done using the IS0 13936-2:2004 standard, tear force and seam force were tested using the IS0 13937-1:2000 and ISO 13935-2:2014 standards. All tests that were done for the research were performed using the instruments shown in the table below.

Table 4: Test methods

Test name	Standard	Instruments
pH	ISO 3071:2020	Glass electrode, pH meter
GSM	EN 12127:1997	GSM cutter, Weighing Balance
Colour fastness to rubbing	ISO 105-X12:2016	Rubbing finger size: 16 mm dia.; Track length: 104.0 mm; Weight: 9.0N
Colour fastness to washing	ISO 105-C06:2010	Gyrowash
Colour fastness to water	ISO 105-E01:2013	Perspiration tester
Tear force	IS0 13937-1:2000	Elma tear testing machine (pendulum method)
Seam force	ISO 13935-2: 2014	Constant rate of elongation (CRE) machine (grab method)
Seam slippage	IS0 13936-2:2004	CRE machine

3 Results and discussion

3.1 Sustainability of ozone washing compared to conventional washing

This study assessed the effects of ozone washing and compared them with conventional washing. Table 5 summarizes the comparison between conventional and ozone washing in terms of water consumption, carbon footprint and processing time. The data in Table 5 indicates that for every piece of garment, ozone washing requires 14.80 litres less water than conventional washing, which is 44.04% more efficient than conventional washing because of the ozone techniques applied in this research. Ozone washing produces 0.5 kg less CO_2 per garment than conventional washing. It was also determined that ozone washing requires almost 12 minutes less time than conventional washing. All these results indicate that the water consumption, carbon footprint and processing time of denim washing are all improved through ozone washing.

Table 5: Comparison of conventional and ozone washing in terms of water consumption, carbon footprint and process time

Parameters	Method	
	Conventional	Ozone
Water consumption	33.60 (L/garment)	18.80 (litre/garment)
Carbon footprint	0.42 (kg CO_2/garment)	0.37 (kg CO_2/garment)
Process time	5h 0′ 44s per garment	4h 48′ 59s per garment

Table 6 presents a comparison of the effluent treatment plant (ETP) values of conventional washing and ozone washing. The table clearly shows that the temperature required for ozone washing is 4 °C lower than the conventional method of 39 °C. In conventional washing, the BOD and COD levels will be roughly 43 mg/L and 115 mg/L, respectively, but those figures are reduced to nearly 22 mg/L and 80 mg/L, respectively, in ozone washing, demonstrating that ozone treatment is critical for the river and canal environment. The ozone technique produces a TSS value of only 13 mg/L, while the conventional method produces a value of 75 mg/L, which is nearly one sixth of the conventional method. As the ozone (oxidant) dose is increased, carbon-carbon single bonds are attacked and broken, resulting in a loss of COD, BOD, and TSS.

Table 6: Comparison of ETP value for conventional and ozone washing

Parameters	Conventional wash at 39 °C (mg/L)	Ozone wash at 35 °C (mg/L)
DO	7.5	6.146
BOD	43	22
COD	115	80
TDS	1746	1584
TSS	75	13

Figure 4 shows the efficiency of ozone washing for different parameters of ETP. The values of these parameters, such as DO, BOD, COD, TDS and TSS, are 18.05%, 48.83%, 30.43%, 9.27%, and 82.66%, respectively. The efficiencies of these parameters also show that washing with ozone is better than traditional washing. Measures of free, non-compound oxygen found in water and other liquids are called DO and BOD. The metric in question holds significant value when evaluating the quality of water due to its impact on aquatic species. At 82.66%, ozone washing has the highest efficiency in terms of TSS, with nearly 48.83% for BOD. A research article provides similar findings [25]. The particles in water that a filter may catch are called TSS. It contributes significantly to the physical and visual deterioration of the sediment, and is a useful indication of other contaminants, especially nutrients and metals transported on the surfaces of suspended sediment.

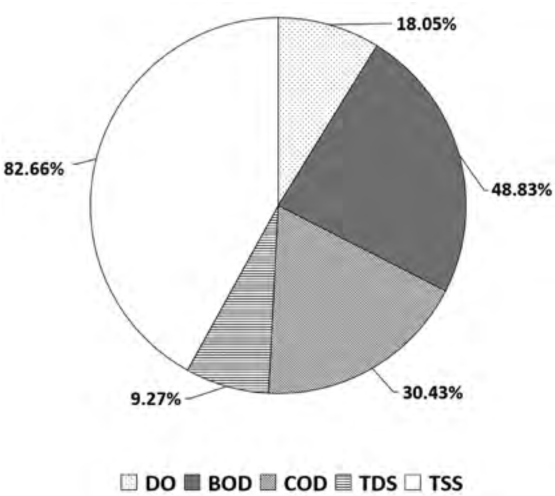


Figure 4: Efficiency of ozone washing for ETP

Table 7 shows a comparison of chemical consumption with conventional washing and ozone washing. Desizing is an additional step that is required in traditional washing; however, it is not necessary in ozone washing. Thus, the desizing agents employed in washing can be preserved with ozone washing. Compared to traditional washing, ozone washing also reduces the need for bleaching, enzymes, neutralizing, cleaning and softening agents. When processing a single garment in ozone washing, about 2.4 g of enzyme, 2.4 g of bleaching agent, 2.4 g of neutralizing agent, 24 g of potassium permanganate, 7.2 g of neutralizing agent and 0.8 g of softener less are used. Sustainable ozone washing is about 82.14% more efficient than standard washing because it uses 73.6 g less chemicals per piece of clothing.

Table 7: Comparison of chemical per garment consumption with conventional washing and ozone washing

Process	Chemical	Conventional	Ozone
Desizing	Novalase LT 40	4g	-
Enzyme	Novastone neutral MR	4g	1.6g
Bleaching	Calcium hypochlorite	6.4g	4g
Neutralizing	Sodium metabisulfite	4g	1.6g
PP spray	Potassium permanganate	40g	16g
Neutralizing	Sodium metabisulfite	12g	4.8g
Cleaning	Hydrogen peroxide	8g	3.2g
	Soda ash	4g	1.6g
	Deterpal F33 Powder	4g	1.6g
Softening	Base OT conc.	3.2g	2.4g
Total		89.6g	16g

Table 8 presents a comparison of energy consumption between conventional washing machines and ozone washing machines. The machines used in the traditional method, the Tonello G1 130 machine, use 18.5 kwh of power per hour, whereas the Jeanologia G2 machine, used in the ozone process, requires 9 kwh. The most recent Jeanologia G2 system uses half as much energy per batch and nearly half the time. In comparison to the Jeanologia G2, which consumes 9.5 kwh less electricity, the Tonello G1 130 consumes 51.35% more energy per machine. Because the ozone process uses less energy and time, labour and utility costs may be minimized.

Table 8: Comparison of energy consumption between conventional washing and ozone washing machines

Machine	Energy consumption (kWh)
Tonello G1 130	18.5
Jeanologia G2	9

Table 9 shows a comparison of the EIM score for water and energy with conventional and ozone washing, whiles Table 10 shows the standard parameters of the EIM score for conventional washing and ozone washing, which provide an opportunity to compare the EIM score with standards. It is feasible to make sustainability measurable throughout the production process by using the EIM score. Compared with traditional washing, ozone washing has a minimal environmental effect in terms of water and energy consumption. In ozone washing, the impact factor for water is 43, which correlates with the low impact EIM score (0–45), while the EIM score for energy is 2.54, which falls in the medium range (2.5–3.5). Both EIM scores indicate the sustainability of ozone washing compared with conventional washing.

Table 9: Comparison of EIM score for water and energy (conventional washing and ozone washing)

Category	EIM Score	
	Conventional	Ozone
Water	84.00	43.00
Energy	2.54	2.12

Table 10 presents the standard parameters of EIM scores, which provide information about the benchmark values for water consumption, energy consumption and worker impact. This study compared the above scores for ozone washing and laser fading with standard EIM scores.

Table 10: Standard parameters of EIM score

Impact	EIM score		
	Water	Energy	Worker impact
Low	0–45	0–2.5	0–13
Medium	45–90	2.5–3.5	13–29
High	+90	+3.6	+29

Sustainability of laser fading compared to conventional washing

A laser is used to burn the wash into the jeans as it passes over them. The wash effects look fantastic and the process is rather fast. With the help of this water-free technology, denim may achieve the desired 'worn-in' or 'distressed' effect.

Table 11 summarizes a comparison of water consumption with conventional washing and laser fading. The latter uses 18.00 litres less water for each outfit. Sustainable washing with laser fading produces 30 g more CO_2 per item than regular washing. This is mostly due to the use of a Jeanologia Compact HR, which has a higher carbon footprint due to laser burning. Although the entire laser system is enclosed in a tight container, the impact of the CO_2 footprint on the environment is minimized. It also demonstrates that washing with a laser takes nearly two hours less time than traditional washing. Because laser fading needs less energy and time, it can minimize shipping lead time, which is directly tied to cheaper labour and power costs. These findings are also supported by another article [26].

Table 11: Comparison of water consumption (conventional washing and laser fading)

Parameters	Method	
	Conventional	Laser
Water consumption (L/garment)	33.60	15.60
Carbon footprint (kg CO_2/garment)	0.42	0.45
Process time (s/garment)	18,044	11,760

Table 12 shows a comparison of EIM scores between conventional washing and laser fading. According to the information in Table 12 and Table 10, traditional washing has an EIM score of 84 for water consumption, which indicates that its environmental impact is moderately high. In contrast, laser fading, with a score of 39, shows that its environmental impact is relatively low, meaning that water consumption is reduced. In terms of energy consumption, conventional methods score 2.54, while laser fading has a score of 2.12. However, worker impact is extremely low, falling short of the threshold by nine, indicating that fewer workers are required to perform laser fading.

Table 12: Comparison of EIM scores between conventional washing and laser fading

Category	EIM score	
	Conventional	Laser
Water	84.00	39.00
Energy	2.54	2.12
Worker impact	100	9

Total EIM score

Sustainability in the manufacturing process may be quantified by using the EIM score. The environmental effects that are relevant to industrial washing are evaluated by the EIM score, which offers an equivalent and reliable assessment method.

Table 13 summarizes the total EIM score of conventional washing, ozone washing and laser fading. The EIM score is determined based on worker impact, chemical impact, energy consumption and water consumption. The overall EIM score for conventional washing is 74, while the scores for ozone washing and laser fading are 66 and 46, respectively. Both washing methods offer a moderate environmental impact, with minimal water, energy, chemical and worker impacts, while they identify as sustainable. It is evident that laser fading has the lowest score out of the three methods, suggesting its superiority over the other two approaches in terms of sustainability.

Table 13: Total EIM score of conventional washing, ozone washing and laser fading

Conventional	Ozone	Laser
74	66	46
Low impact	0–33	
Medium impact	33–66	
High impact	+66	

Comparison of product quality

Product quality is defined as how well a product meets client demands, serves its purpose and adheres to industry norms. In this study, when evaluating product quality, we illustrated the various washing impacts while taking consumer preferences into account**.**

Figure 5 shows samples before and after washing, along with the significance of the changes in viewpoint and look. Figure (a) shows sample before ozone washing and laser fading. Figure (b) shows the sample's modifications following ozone treatment; following washing, a notable visual change was observed. The sample's appearance changed as a result of multiple wet and dry processes carried out both before and after the ozone step. A laser was used in place of the dry process in Figure **(c)** for laser fading, and the accuracy of the laser allows for more exact and accurate results. Compared to traditional washing, which uses more water and chemicals, both sustainable washing methods produce a decent change after washing.

(a) (b) (c)

Figure 5: Denim: a) before washing, b) ozone washed and c) laser faded

Table 14 shows the product quality parameters of denim fabric after ozone and laser fading through various tests. It is shown that overall both goods demonstrated good durability qualities, while all test parameter values were within the acceptable ranges. Numerous tests were conducted and compared to standard values, including pH, GSM, colour fastness to rubbing, washing, water, tear force, tensile force, seam force and seam slippage. pH is an important number that indicates a solution's chemical makeup. The availability of nutrients, biological processes, microbial activity and chemical behaviour are all regulated by pH. Although this wash employed a great deal of chemicals and neutralizing agents to neutralize them, the pH values for both washing methods were determined to be within the standard range. The results showed that the product from ozone washing had higher values than the product from the laser fading, especially in GSM. The GSM value for denim after ozone washing was 439.1, while the GSM value for denim after the laser fading was 423.8. There was a slight increase in the GSM values for both washing methods because of shrinkage after washing, which did not actually affect the quality of the product. The term 'colour fastness to rubbing' describes a yarn-dyed fabric's ability to maintain its original colour in the face of outside interference. Grade 5 is the best, while Grade 1 is the poorest in terms of colour fastness to rubbing. Grade 4 shows that the colour fastness to rubbing of denim fabric is better than other fabrics. In the colour fastness to washing test, a textile's colour changes, while any colour stains on adjacent fabric are evaluated. A score of 4 indicates superior performance in terms of preventing colour stains on adjacent fabric. The ability of textile colours to withstand submersion in water is determined by their colour-fastness. The table's value is in the normal range and indicates improved performance. The fabric was torn using a tearing tester's falling pendulum, and the readings were recorded using the Elmendorf tester scale. The results are presented in the Table 14, where it is evident that denim fabric that has been laser faded and treated with ozone produces both warp and weft-way tear force values that are slightly higher than the minimum value and provide better performance. After ozone washing and laser fading, the seam force of the denim fabric was measured using a CRE machine (grab method). The inseam seam forces for laser fading and ozone washing were 266.9 N and 264.4 N, respectively, while both will function properly and not drop below the minimal number. Seam forces for the seat, back rise and front of both ozone-washed and laser-faded samples are within a good range and preserve the seam strength, while seam forces for the side seam were 295.5 N and 293.0 N. While an acceptable range of inseam slippage was determined for both the laser-faded sample and the ozone-washed sample, the side seam exhibited a 2 mm seam slippage, which falls within the maximum range of 6 mm. As a result, the seam was situated appropriately. This finding is supported by several previously released publications [14, 25, 27].

Table 14: Product quality parameters of denim after ozone washing and laser fading through various tests

Tests	Standard	Ozone wash	Laser fading
pH	4.0–7.5	5.4	5.9
Mass per unit area (g/m^2)	415	1	423.8
Colour fastness to rubbing	3–4	4	4
Colour fastness to washing	3–4	4	4
Colour fastness to water	3–4	4	4
Tear force (N)	Min. 30 (warp way)	46.8	45.8
	Min. 24 (weft way)	26.7	26.6
Seam force (N)	Min. 260	266.9 (inseam)	264.4 (inseam)
		295.5 (side seam)	293.0 (side seam)
		459.4 (seat)	457.9 (seat)
		355.0 (back rise)	353.9 (back rise)
		276.3 (front rise)	275.0 (front rise)
Seam slippage (mm)	Max. 6	0 (inseam)	0 (inseam)
		2 (side seam)	2 (side seam)

4 Conclusion

According to the study's findings, ozone and laser-based denim washing are the most eco-friendly and straightforward of sustainable techniques. The latter was appropriate because of its high energy and water efficiency. It could also lead to lower costs and increased production capacity. While the use of laser fading raises concerns regarding the carbon footprint and energy consumption, the combination of ozone washing with laser fading provides enhanced sustainability in various categories, including water consumption, chemical impact, and worker health. Among the observed sustainable washing methods, all these testing parameters indicate that ozone washing is sustainable in terms of water and energy consumption, showing overall 44.04% and 51.35% efficiency, respectively. Laser fading is sustainable in terms of water consumption (53.57%), time (34.66%) and worker impact (91%), while energy consumption and the carbon footprint remain issues. A major obstacle to conducting this study was the use of EIM software. The software gave a score of 100 (high impact) for the chemical impact of each washing method. Thus, proper insight into the chemical impact was not obtained. This study did not provide a further comprehensive analysis of other sustainable methods, such as e-flow washing and enzymatic washing. More research is required for the aforementioned methods.

Conflicts of Interest: The authors hereby declare that there were no potential conflicts of interest concerning the research, authorship and/or publication of this article.

Funding: The authors received no financial support for the research, authorship and/or publication of this article.

References

1. GONÇALVES, A., SILVA, C. Looking for sustainability scoring in apparel: a review on environmental footprint, social impacts and transparency. *Energies,* 2021, **14**(11), 1–33, doi: 10.3390/en14113032.
2. NIINIMÄKI, K., PETERS, G., DAHLBO, H., PERRY, P., RISSANEN, T., GWILT, A. The environmental price of fast fashion. *Nature Reviews Earth & Environment*, 2020, **1**(4), 189–200, doi: 10.1038/s43017-020-0039-9.
3. AKTER, M.M.K., HAQ, U.N., ISLAM, M.M., UDDIN, M. Textile-apparel manufacturing and material waste management in the circular economy: a conceptual model to achieve sustainable development goal (SDG) 12 for Bangladesh. *Cleaner Environmental Systems*, 2022, **4**, 1–12, doi: 10.1016/j.cesys.2022.100070.
4. MUTHUKUMARANA, T.T., KARUNATHILAKE, H.P., PUNCHIHEWA, H.K.G., MANTHILAKE, M.M.I.D., HEWAGE, K. Life cycle environmental impacts of the apparel industry in Sri Lanka: analysis of the energy sources. *Journal of Cleaner Production*, 2018, **172**, 1346–1357, doi: 10.1016/j.jclepro.2017.10.261.
5. MONDAL, M.I.H., KHAN, M.M.R. Characterization and process optimization of indigo dyed cotton denim garments by enzymatic wash. *Fashion and Textiles*, 2014, **1**, 1–12, doi: 10.1186/s40691-014-0019-0.
6. KABIR, S.M.F., CHAKRABORTY, S., HOQUE, S.A., MATHUR, K. Sustainability assessment of cotton-based textile wet processing. *Clean Technologies*, 2019, **1**(1), 232–246, doi: 10.3390/cleantechnol1010016.
7. HAQUE, N. Mapping prospects and challenges of managing sludge from effluent treatment in Bangladesh. *Journal of Cleaner Production*, 2020, **259**, 1–8, doi: 10.1016/j.jclepro.2020.120898.
8. DADI, D., STELLMACHER, T., SENBETA, F., PASSEL, S.V., AZADI, H. Environmental and health impacts of effluents from textile industries in Ethiopia: the case of Gelan and Dukem, Oromia Regional State. *Environmental Monitoring Assessment*, 2016, **189**, 1–30, doi: 10.1007/s10661-016-5694-4.
9. KUMAR, P., GUNASUNDARI, E. Sustainable wet processing - an alternative source for detoxifying supply chain in textiles. In *Detox Fashion.* Edited by Subramanian Senthilkannan Muthu. Singapore : Springer, 2018, 37–60, doi: 10.1007/978-981-10-4876-0_2.
10. SADEGHIANMARYAN, A., MONTAZER, M., HARIFI, T. One step synthesis of silver nanoparticles and discoloration of blue cotton denim garment in alkali media. *Journal of Polymer Research*, 2013, **20**, 1–10, doi: 10.1007/s10965-013-0189-2.
11. ORTIZ-MORALES, M., POTERASU, M., ACOSTA-ORTIZ, S.E., COMPEAN, I., HERNANDEZ-ALVARADO, M.R. A comparison between characteristics of various laser-based

denim fading processes. *Optics Lasers in Engineering*, 2003, **39**(1), 15–24, doi: 10.1016/S0143-8166(02)00073-8.
12. JIANG, S., YUAN, G., HUANG, J., PENG, Q., LIU, Y. The effect of laser engraving on aluminum foil-laminated denim fabric. *Textile Research Journal*, 2016, **86**(9), 919–932, doi: 10.1177/0040517515599738.
13. UREN, N., OKUR, A. Analysis and improvement of tactile comfort and low-stress mechanical properties of denim fabrics. *Textile Research Journal*, 2019, **89**(23–24), 4842–4857, doi: 10.1177/0040517519840634.
14. BEN FRAJ, A., JAOUACHI, B. Effects of ozone treatment on denim garment properties. *Coloration Technology*, 2021, **137**(6), 678–688, doi: 10.1111/cote.12568.
15. ZOUARI, A., MANICH, A., MARTI, M., GARGOUBI, S., BOUDOKHANE, C. Nanobubble technology for a water-repellent treatment on cotton fabrics: a comparative study. *ChemEngineering*, 2023, **7**(3), 1–16, doi: 10.3390/chemengineering7030047.
16. SINITSYN, A.P., GUSAKOV, A.V., GRISHUTIN, S.G., SINITSYNA, O.A., ANKUDIMOVA, N.V. Application of microassays for investigation of cellulase abrasive activity and backstaining. *Journal of Biotechnology*, 2001, **89**(2–3), 233–238, doi: 10.1016/S0168-1656(01)00306-6.
17. MARYAN, A.S., MONTAZER, M. A cleaner production of denim garment using one step treatment with amylase/cellulase/laccase. *Journal of Cleaner Production*, 2013, **57**, 320–326, doi: 10.1016/j.jclepro.2013.05.041.
18. KAN, C-W. CO_2 laser treatment as a clean process for treating denim fabric. *Journal of Cleaner Production*, 2014, **66**, 624–631, doi: 10.1016/j.jclepro.2013.11.054.
19. GARCIA, B. Reduced water washing of denim garments. In *Denim: Manufacture, Finishing and Applications*. Edited by Roshan Paul. Woodhead Publishing, 2015, 405–423, doi: 10.1016/B978-0-85709-843-6.00013-5.
20. ISLAM, M., PERRY, P., GILL, S. Mapping environmentally sustainable practices in textiles, apparel and fashion industries: a systematic literature review. *Journal of Fashion Marketing Management*, 2020, **25**(2), 331–353, doi: 10.1108/JFMM-07-2020-0130.
21. ONDOGAN, Z., PAMUK, O., ÖNDOĞAN, E., OZGUNEY, A. Improving the appearance of all textile products from clothing to home textile using laser technology. *Optics & Laser Technology*, 2005, **37**(8), 631–637, doi: 10.1016/j.optlastec.2004.10.001.
22. KHALIL, E. Nano bubble technology: a new way to sustainable jeans finishing. In *56th Convention of Institution of Engineers, Bangladesh (IEB)*, 2016, doi: 10.6084/m9.figshare.4578373.v1.
23. Water is over: air is the future [online]. Jeanologia [accessed 23 November 2023]. Available on World Wide Web: <https://www.jeanologia.com/eflow-k-lab/>.
24. Improve your ecological footprint [online]. Jeanologia [accessed 23 November 2023]. Available on World Wide Web: <https://www.jeanologia.com/eim/>.
25. SARKER, U.K., KAWSER, M.D.N., RAHIM, A., Al PARVEZ, A., SHAHID, Md.I. Superiority of sustainable ozone wash over conventional denim washing technique. *International Journal of Current Engineering and Technology* [Internet]. 2021, **11**(05), 516–621, doi: 10.14741/ijcet/v.11.5.4.
26. NAYAK, R., GEORGE, M., JAJPURA, L., KHANDUAL, A., PANWAR, T. Laser and ozone applications for circularity journey in denim manufacturing – a developing country perspective. *Current Opinion in Green and Sustainable Chemistry*, 2022, **38**, 1–7, doi: 10.1016/j.cogsc.2022.100680.
27. NIZAM, E., ISLAM, M., TANVIR, M., HOSSAIN, M., MIA, B., ISLAM, A. Effects of O_3 treatment on different composition % (cotton, polyester, elastane) of denim fabrication (GSM 295, 327, 340, 343,357, 360, 413) after random O_3 wash. *Journal of Textile Science and Engineering*, 2023, **9**, 215–223, doi: 10.4236/jtst.2023.94014.

Wassie Mengie, Kura Alemayehu Beyene, Getaneh Alamir Eshetie
Ethiopian Institute of Textile and Fashion Technology, Bahir Dar University, Bahir Dar, P.O. Box 1037, Ethiopia

Modelling Surface Roughness of 3/1 Twill Fabric Using Weft Yarn Count and Weft Thread Density

Modeliranje površinske hrapavosti tkanine v vezavi keper 3/1 na podlagi dolžinske mase votka in gostote niti v smeri votka

Original Scientific Article*/Izvirni znanstveni članek*
Received/*Prispelo* 10-2023 • Accepted/*Sprejeto* 4-2024

Corresponding author/*Korespondenčni avtor:*
Wassie Mengie
E-mail: wassie215@gmail.com
ORCID: 0000-0001-6715-8839

Abstract

The surface roughness of fabric is one of the fabric properties that is used to evaluate the sensorial comfort of clothes. However, its objective evaluation requires sophisticated and expensive testing instruments and skilled testing expertise. Developing a predictive model is therefore an alternative approach to overcome such limitations. This study investigated a regression model to predict the surface roughness of 3/1 twill fabric using weft yarn count and weft thread density. Nine samples were produced by varying the weft yarn count and weft thread density at three different levels, while their surface roughness was determined using a Kawabata instrument (KES-FB4) under standard testing conditions. A two-factor predictive model equation was developed using design expert software. Based on the results and findings, the effects of count and density on the roughness of 3/1 twill fabric were found to be statistically significant for the developed model at a confidence interval of 95%. The model was tested by correlating the measured and predicted surface roughness values of 100% cotton 3/1 twill fabric. The results of the model test indicate a significant correlation (R^2 = 0.9644) between the measured and predicted surface roughness values of 3/1 twill fabric, with a 95% confidence interval.

Model validation was performed, and the study showed that the measured and predicted values of the surface roughness of 3/1 twill fabric have a 0.828 coefficient of determination (R^2). This indicates that the surface roughness of 3/1 twill fabric can be predicted well by weft yarn count and weft thread density. This model can be thus used in textile industries and by research institutes for predicting the surface roughness of 3/1 twill fabrics in the new product development process.

Keywords: surface roughness, 3/1 twill weave, weft yarn count, weft thread density, predictive model

Izvleček

Površinska hrapavost tkanine je ena od lastnosti tkanine, ki se uporablja za oceno čutnega udobja oblačil. Objektivno vrednotenje čutne udobnosti zahteva sofisticirano in drago laboratorijsko opremo in ustrezno usposobljenost za izvedbo ekspertize. Razvoj napovednega modela je alternativni pristop za premagovanje omenjenih omejitev.

V tej študiji je bil raziskan regresijski model za napovedovanje površinske hrapavosti tkanine v vezavi keper 3/1, ki temelji na dolžinski masi votkovnih niti in gostoti niti v smeri votka. Izdelanih je bilo devet vzorcev, pri katerih so spreminjali dolžinsko maso votka in gostoto votkovnih niti na treh različnih ravneh, pri čemer je bila površinska hrapavost tkanin določena z instrumentom Kawabata (KES-FB4) v standardnih razmerah preizkušanja. S pomočjo programske opreme Design Expert je bila razvita enačba dvofaktorskega napovednega modela. Na podlagi rezultatov je bilo ugotovljeno, da je vpliv dolžinske mase votka in gostote votkovnih niti na hrapavost tkanine v vezavi keper 3/1 pri razvitem modelu statistično značilen pri 95-odstotnem intervalu zaupanja. Model je bil preverjen s pomočjo korelacije izmerjenih in predvidenih vrednosti površinske hrapavosti 100-odstotne bombažne tkanine v vezavi keper 3/1, pri čemer je bila ugotovljena visoka korelacija (r^2 = 0,9644) med izmerjenimi in predvidenimi vrednostmi. Izvedena je bila validacija modela, ki je pokazala, da imajo izmerjene in predvidene vrednosti površinske hrapavosti tkanine v vezavi keper 3/1 koeficient validacije (R^2) 0,828. To kaže, da je s podatki o dolžinski masi votka in gostoti votkovnih niti mogoče dobro napovedati površinsko hrapavost tkanine v vezavi keper 3/1. Zato je model primeren za napovedovanje površinske hrapavosti tkanin v vezavi keper pri razvoju novih izdelkov v tekstilni industriji in na raziskovalnih inštitutih.

Ključne besede: površinska hrapavost, vezava keper 3/1, dolžinska masa votkovnih niti, gostota votkovnih niti, napovedni model

1 Introduction

A consumer's sensations and experiences are used to assess fabric comfort, which is a full physiological, psychological and physical assessment of a fabric and its surroundings [1–3]. The sensorial comfort of clothing has a great impact on customer choice and satisfaction. The sensorial comfort of clothing is determined by the sense of touch of fabric properties, such as surface state, weight, thickness, shear, compression, bending and tactile factors [4]. The surface roughness of textile fabric is one of the most important fabric parameters influencing fabric handle and customer preferences because of its effect on wellbeing, and the performance and efficiency of garments [5, 6]. Surface roughness is a tactile fabric property that is an important part of skin sensorial wear comfort, which describes the mechanical contact sensations caused by a textile on the skin [7, 8]. Surface roughness and other low-stress mechanical properties include softness, drapeability and the comfort of cloth in relation to the handle properties thereof [8]. The surface of woven fabrics is not flat and smooth because fabrics are produced through the interlacement of warp and weft yarns with irregularities. Thus, due to the interlacement of warp and weft yarns and the inherent non-uniform structure of spun yarns, the geometrical roughness of a fabric is, to a certain extent, considerable [9].

Therefore, evaluating the surface roughness of clothing is important for both manufacturers and wearers. The surface roughness of the fabric can be assessed subjectively or using an objective measurement system with different testing equipment, such as the Kawabata evaluation system, FAST and other tough senor instruments [10–13]. The subjective evaluation of fabric handle requires a highly skilled person, while the results vary from person to person and over time. However, it is simple and can be applied anywhere, without any limitation. Due to a lack of quantitative descriptions and poor data comparability, the application of the subjective assessment of fabric handle is limited [14]. Such limitations result in the development of highly sophisticated and accurate instruments to quantify fabric handle properties. The objective measurement of fabric handle properties was started by Peirce. Many researchers subsequently investigated the development of instruments for the objective measurement of fabric handle properties [15, 16]. The Kawabata Evaluation

System (KES-F) and Fabric Assurance by Simple Testing (FAST) system were the two commonly used instruments for determining the handle properties of fabric [17, 18].

As described above, the hand feeling of the fabric is a combined effect of several characteristics. Among these, surface roughness is the basic and critical factor for clothing [17]. The surface roughness of fabric can be quantified using a surface profile system called surface height variation (SHV), applying two methods: contact/mechanical or non-contact methods. This study focused on the evaluation of surface roughness using the contact or mechanical method [17]. It is known that determining the surface roughness of fabric requires well-organized laboratories, including skilled experts, different consumable materials, expensive testing machines (like KES and FAST) and other facilities, such as air conditioning systems. Because of the large investment and running cost for determining the surface roughness of fabric using expensive instruments, clothing industries cannot test surface roughness and other related fabric properties. Today, however, researchers investigate other means, such as mathematical modelling, statistical tools and computer applications to predict fabric properties based on constructional and material parameters [18, 19]. Taieb, Mshali [20] used an artificial neuro network (ANN) to predict fabric drapability based on fabric formability resulting from the FAST system. Other researchers [21] predicted the bending rigidity and shear stiffness of fabric based on a three-dimensional model. Similarly, the water absorption properties of polyurethane and acrylic binder-treated polyester fabric were predicted using an adaptive neuro-fuzzy inference system (ANFIS) and artificial neural network (ANN) methods [22]. Researchers also developed predictive models for the surface roughness of fabrics and other materials. For example, the surface roughness of free-hand grinding was predicted using a regression modal based on the parameters of machine vision [19], while the surface roughness of woven fabric was modelled based on weave structure and weft density [23]. A regression model was developed to predict the surface roughness of woven bed sheet fabric based on weft count and weft thread density [24]. The development of predictive models for the evaluation of the surface roughness of fabric helps to avoid existing trial and error in the product development process. To develop a predictive model, all factors affecting the surface roughness of a fabric should be investigated and analysed. There are a number of factors that influence the surface roughness of woven fabric. They are mainly fibre type [25], fibre properties (fineness, length and strength) [26], yarn properties and fabric properties [27, 28]. Fabrics made of fibres with high bending rigidity and tensile resilience (such as linen) show low shear rigidity, while shear hysteresis is stiffer and demonstrates a higher surface roughness. On the other hand, fabrics made from fibres with low bending rigidity, such as 100% cotton and cotton/viscose, have a soft and smooth surface [29]. Fibre properties, such as fineness, length and bending stiffness, affect the surface properties of fabric. Coarser fibres have a higher bending rigidity, while the yarns and fabrics made of such types of fibres are stiffer and have a harsh feeling. The surface friction of yarn and fabric are affected by the length and length uniformity of the constituent fibres. For example, 100% cotton fabric and hairiness on the fabric surface, which is mainly influenced by fibre length and length uniformity, plays an important role in terms of the surface roughness of fabric [30]. Yarn properties, such as twist level, bulkiness, uniformity and flexibility/stiffness, affect the surface roughness of fabrics. Fabrics made of high twisted and stiffer yarns have a higher bending rigidity, which results in the higher surface friction of fabrics. Yarn with higher unevenness and a larger number of irregularities increase the surface friction of fabrics made from such types of yarns. Fabric properties are the cumulative effect of fibre type, fibre properties, yarn properties and fabric constructional parameters. Thus, any factor that affects the hairiness, tensile, bending, shearing, compression and thickness of the fabric affects fabric surface roughness.

Researchers have found that the surface roughness of woven fabric decreases in the warp, weft, and diagonal direction when the weft yarn density increases [31, 32]. However, many researchers have not studied which type of regression model equation has better a predictive and evaluation ability when quantifying this property spatially for 3/1 twill fabric, or and how to evaluate and identify the accuracy, reliability and rationality of the model equations. Hence, it is intended to develop a linear equation based on weft yarn count and weft thread density for studying the surface roughness of 3/1 twill fabric. This study focused on the development of a novel predicted regression model for the surface roughness of 3/1 twill fabric based on the weft yarn count and weft thread density.

2 Materials and methods

Cotton woven fabrics with different weft yarn count and weft thread density were used to determine surface roughness. Fabrics were made of 100% cotton ring spun warp yarn and open end (OE) rotor-spun weft yarn, while the detailed fibre properties used to produce weft yarns were evaluated using USTER HVI 1000, as shown in Table 1: Cotton fibre properties.

Table 1: Cotton fibre properties

Fibre	Cotton
Spinning consistency index, SCI	106.7
Moisture content (%)	4.85
Micronaire index (-)	4.735
Maturity (-)	0.87
Upper half mean length, UHML (mm)	28.42
Short fibre (%)	9.45
Strength (g/tex)	22.38
Elongation (%)	6.86

Nine 3/1 twill woven fabrics were produced at the Kombolcha Textile Share Company (KTSC) by varying the weft yarn count and weft thread density, as shown in Table 2, while other fabric constructional parameters, such as warp density, warp count, tension, speed, RH% and machine speed (rpm) remained unchanged for all samples (see Table 2). The weft yarn count and weft thread density (only for the model test) were determined according to the ISO 2060:1994(R2019) and ISO 7211-2 standards, [33, 34] respectively, under standard atmospheric testing conditions.

Table 2: Sample fabric construction parameters (3/1 twill fabric)

Fabric sample no.	Warp thread density (cm^{-1})	Warp yarn count (tex)	Weft thread density (cm^{-1})	Weft yarn count (tex)
S1	24	30	18	20
S2	24	30	18	30
S3	24	30	18	42
S4	24	30	22	20
S5	24	30	22	30
S6	24	30	22	42
S7	24	30	26	20
S8	24	30	26	30
S9	24	30	26	42

Combined pretreatment was conducted for all samples using 3% sodium hydroxide, 4% hydrogen peroxide, 2% sodium silicate, 0.5% wetting agent and 0.5 ethylenediaminetetraacetic acid (EDTA) on the weight of fabric with a liquor ratio of 1:20. The sample fabrics were dried using a hot air oven at 50 °C for 15 minutes. After the pretreatment process, the surface roughness mean deviation (SMD) of the fabrics was determined using the Kawabata evaluation system under standard atmospheric conditions.

The Kawabata evaluation system (KES-FB4) can simultaneously measure a fabric's geometrical roughness and the coefficient of friction (µm) using a sensing element comprising a metallic rod equipped in its free end with a thin U-shaped wire. The sensor touched the surface of the fabric under a constant normal force and the vertical movement of the sensor due to the fabric surface roughness that proportionally transformed to an electrical signal [9, 24, 32].

The experimental condition was determined by three-level factorials using the Design Expert @11 software. This means that each independent factor, i.e. the weft yarn count (tex) and weft thread density (picks/cm), changed at three different values, as shown in Table 2. The experiment had nine non-centre and four centre points, and a total of 13 runs with five numbers of replications, as shown in the Table. 3.

Table 3: Experimental design with two factors and three levels

Fabric sample code	Run	Factor 1	Factor 2	Response SMD (μm)
		A: weft yarn count (tex)	B: weft thread density (cm^{-1})	
S2	1	20	22	1.69
S5	2	30	22	2.01
S8	3	42	22	2.85
S1	4	20	18	1.81
S6	5	30	26	1.94
S5	6	30	22	2.01
S4	7	30	18	2.50
S7	8	42	18	3.45
S5	9	30	22	2.01
S5	10	30	22	2.01
S9	11	42	26	2.00
S5	12	30	22	2.01
S3	13	20	26	1.56

A predictive model for the surface roughness of 3/1 twill fabric was developed in terms of actual and coded units by a design expert. To arrive at the actual equation, each term in the coded equation was replaced with its coding formula (equation 1).

$$X_{coded} = \frac{X_{actual} - \bar{X}}{(X_{High} - X_{Low})/2} \quad (1)$$

where X_{coded} represents the coded values of surface roughness, X_{actual} represents the actual surface roughness, $\bar{X}$ represents the mean values of a surface roughness, X_{High} represents the maximum values of surface roughness and X_{Low} represents the minimum value of surface roughness.

The surface roughness of 3/1 twill fabric was predicted based on a general two-factor predictive model (equation 2), while the model was validated using the actual measured and predicted values of the surface roughness of 3/1 twill fabric.

$$SMD = \beta_0 + \beta_1 x + \beta_2 y + \beta_3 x \times y \quad (2)$$

where *SMD* represents the surface roughness (μm), *x* represents weft yarn count (tex), and *y* represents weft thread density (cm^{-1}).

3 Results and discussion

3.1 Development of a predictive model for the surface roughness of 3/1 twill fabric

A predictive model for the surface roughness of 100% cotton 3/1 twill pretreated fabric was developed using the measured surface roughness values of nine samples, which were measured using a KES-FB4 instrument. An equation for the surface roughness (equation 3) was developed based on two independent variables or factors (weft yarn count and weft thread density) with three different levels of each. This equation should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor and the intercept is not at the centre of the design space.

$$SMD = -1.85024 + 0.201288x + 0.112974y - 0.00689xy \quad (2)$$

where *SMD* represents the surface roughness (μm), *x* represents weft yarn count (tex), and *y* represents weft thread density (cm^{-1}).

The effect of the two factors – weft thread density and weft yarn count – on the surface roughness of 3/1 twill fabric is described in Table 3. As is evident from Table 3, three samples (S2, S5 and S8) have the same fabric constructional parameters, except the weft yarn count. S2, S5 and S8 were produced from 20 tex, 30 tex and 42 tex weft yarns, respectively, and the measured surface roughness values of these samples were 1.69 µm, 2.01 µm and 2.85 µm, respectively. S2 had the lowest surface roughness, while S8 had the highest surface roughness. This difference occurs only due to weft yarn count. A finer weft count has a lower yarn diameter, while the up-and-down movement of the surface sensor in the KES-FB4 instrument is lower. Since an electrical signal occurred due to the vertical reciprocating movement of the sensor, proportionally converted to the surface roughness values of the fabric, the lower vertical movement of the fabric results in lower surface roughness values. Similarly, fabrics made from coarser weft yarn count have a higher amplitude in the reciprocating movement of the sensor, which results in a higher surface roughness value.

Sample fabrics S1, S2 and S3 were produced with 18 cm^{-1}, 22 cm^{-1} and 26 cm^{-1}, respectively, by maintaining other fabric constructional parameters constant. The measured surface roughness values of these sample fabrics were 1.81 µm, 1.69 µm and 1.56 **µm** for S1, S2 and S3, respectively. This result shows that the values of surface roughness decrease as the weft thread density increases. When a fabric is constructed with dense weft thread density, the amplitude of the vertical reciprocating movement of the measuring sensor in the KES-FB4 instrument is low, which results in a low surface roughness value for the fabric.

Table 4 shows the measured and predicted surface roughness values of 3/1 twill fabrics constructed with different weft thread density and weft yarn count. The result shows that weft thread density has a negative correlation and weft yarn count has a positive correlation with the predicted and measured surface roughness values of 3/1 twill fabric.

3.2 Model validity test

To check the validity of the developed model, it was necessary to determine the correlation between the surface roughness of the samples determined using a Kawabata instrument (KES-FB4) and the predicted surface roughness values of the same samples (Table 4). As is evident from Figure 1, the coefficient of determination (R^2) between measured and predicted surface roughness values is 0.96443 at a 95% confidence level. This shows that the predicted and measured surface roughness of 3/1 twill fabric have a strong positive relationship.

Table 4: Measured (SMD) and estimated (SMD) values for model validity for 3/1 twill fabrics

Sample code	Warp density (cm^{-1})	Warp count (tex)	Weft density (cm^{-1})	Weft count (tex)	Measured (SMD)	Estimated (SMD)
S1	24	30	18	20	1.81	1.67
S2	24	30	22	20	1.69	1.60
S3	24	30	26	20	1.65	1.52
S4	24	30	18	30	2.5	2.52
S5	24	30	22	30	2.01	2.14
S6	24	30	26	30	1.94	1.76
S7	24	30	18	42	3.45	3.36
S8	24	30	22	42	2.85	2.68
S9	24	30	26	42	2.00	2.01

In addition, mean comparison was performed at a 95% confidence level to analyse whether there is significant difference between the measured and predicted surface roughness values of 3/1 twill fabric. As is evident from Table 5, the p-value for comparison of means using two sample T-tests is 0.807 at a 95% confidence level, which is much higher than a 0.05 level of significance. That means the predicted and measured surface roughness (SMD) values had no significant difference at a 95% confidence level.

Table 5: Mean comparison for measured and predicted surface roughness values using a two-samples T-test

Properties	Measured SMD	Estimated SMD	Difference	Hypothesized difference
Mean	2.211	2.14	0.071	0
Variance	0.367	0.373		
Observations	9	9		

Degree of freedom = 16; t-stat = 0.248; $P(T \le t)$ two-tail = 0.807; t-critical two-tail = 2.12

Thus, predicting the surface roughness of 3/1 twill fabric using a regression model has a significant impact on the product development process of textile industries and researchers, while it can also help to avoid the purchase of expensive testing instruments, and reduce material destruction during testing and product delivery time.

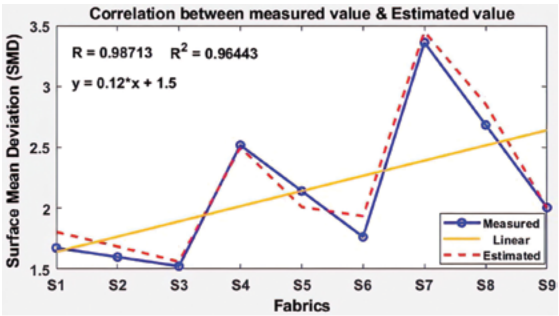


Figure 1: Correlation between SMD values measured using a KES-FB4 instrument and SMD values calculated using a model equation

3.3 Model test

To test the efficiency of the developed model, other three 3/1 twill fabrics were used. The constructions of those fabrics are shown in Table 6. The surface roughness of the three 3/1 twill half-bleached fabrics were determined using a Kawabata instrument (KES-FB4) and predicted using a predictive model.

Table 6: Samples for model test

Sample code	Weave type	Warp density (cm^{-1})	Warp count (tex)	Weft density (cm^{-1})	Weft count (tex)	Measured SMD (μm)	Calculated SMD (μm)
ST_1	Twill 3/1	39	21	22	21	1.59	1.70
ST_2	Twill 3/1	42	29	24	29	2.05	1.92
ST_3	Twill 3/1	38	31	19	31	2.30	2.49

As is evident from Figure 2, the predicted and measured surface roughness value of 3/1 twill fabric have a strong positive relation, while their coefficient of determination (R^2) is 0.8281 at a 95% confidence level.

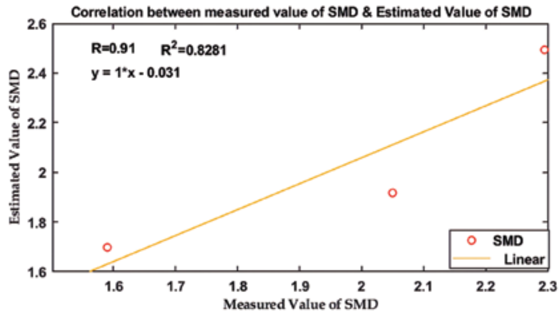


Figure 2: Correlation between SMD values measured using a KES-FB4 instrument and SMD values calculated using a model equation for model testing fabrics

4 Conclusion

This study investigated a regression model for predicting the surface roughness of 3/1 twill fabric based on the weft yarn count and weft thread density. This model was developed based on the surface roughness of the samples measured using a KES-FB4 instrument, while the weft density and weft linear density and the efficiency of the developed model were also verified using the measured and predicted surface roughness values of three 3/1 twill fabrics with different weft counts and weft density. The measured and predicted surface roughness values of 3/1 twill fabric have a strong positive correlation with a 0.828 coefficient of determination(R^2) at a 95% confidence level. Thus, the model can be used in textile industries and research institutes to predict the surface roughness of 3/1 twill fabric in new product development process.

Acknowledgments

This research was completed with the help of the Kombolcha Textile Share Company located in Kombolcha, Ethiopia. The author would like express his heartfelt gratitude to the management and staff members of the Kombolcha Textile Share Company for their efforts and cooperation.

References

1. AKGÜL, E., KIZILKAYA AYDOĞAN, E., SINANOĞLU, C. Investigation of different denim fabrics with fabric touch tester and sensory evaluation. *Journal of Natural Fibers,* 2022, **19**(13), 5551-5565, doi: 10.1080/15440478.2021.1881687.
2. SAVILLE, B. *Physical testing of textiles.* Cambridge : Woodhead Publishing, 1999.
3. WANG, H., MAHAR, T.J., HALL, R. Prediction of the handle characteristics of lightweight next-to-skin knitted fabrics using a fabric extraction technique. *The Journal of The Textile Institute,* 2012, **103**(7), 691–697, doi: 10.1080/00405000.2011.602230.
4. ZOUHAIER, R., MOHAMED, H., AYDA, B., NAJEH, M., SADOK, R. Surface roughness evaluation of treated woven fabric by using a textile surface tester. *Research Journal of Textile and Apparel,* 2013, **17**(2), 51–60, doi: 10.1108/RJTA-17-02-2013-B008.
5. CLASSEN, E. 3 - Comfort testing of textiles. In *Advanced characterization and testing of textiles.* Edited by Patricia Dolez, Olivier Vermeersch and Valério Izquierdo. Woodhead Publishing, 2018, 59–69, doi: 10.1016/B978-0-08-100453-1.00004-0.
6. WAN, T., STYLIOS, G.K. Effects of coating process on the surface roughness of coated fabrics. *The Journal of The Textile Institute,* 2017, **108**(5), 712–719, doi: 10.1080/00405000.2016.1180951.
7. MATSUDAIRA, M. Fabric handle and its basic mechanical properties. *Journal of Textile Engineering*, 2006, **52**(1), 1–8, doi: 10.4188/jte.52.1.
8. MILITKÝ, J.Í., MAZAL, M. Image analysis method of surface roughness evaluation. *International Journal of Clothing Science and Technology,* 2007, **19**(3/4), 186–193, doi: 10.1108/09556220710741650.
9. VASSILIADIS, S.G., PROVATIDIS, C.G. Structural characterization of textile fabrics using surface roughness data. *International Journal of Clothing Science and Technology*, 2004, **16**(5), 445–457, doi: 10.1108/09556220410554633.
10. PHOOPHAT, P., KUMPHAI, P., SUWONSICHON, S., BOONYARIT, J., PLANGMON, C., CHOLLAKUP, R. Application of Kawabata evaluation system for the tactile properties of woven silk fabrics in textile industry. *IOP Conference Series: Materials Science and Engineering,* 2020, **773**(1), 1–6, doi: 10.1088/1757-899X/773/1/012035.
11. SISODIA, N., PARMAR, M., JAIN, S. Effect of pretreatment on the smoothness behaviour of cotton fabric. *Fibres & Textiles in Eastern Europe,* 2019, **5**(137), 47–52.
12. TIAN, Y., SUN, Y., DU, Z., ZHENG, D., ZOU, H., LIU, Z, LIU, G., PAN, X. Tactile evaluation of down jacket fabric by the comprehensive handle evaluation system for fabrics and yarns. *Textile Research Journal,* 2020, **91**(11–12), 1227–1238, doi: 10.1177/0040517520977207.
13. BEYENE, K.A., GEBEYEHU, E.K., ADAMU, B.F. The effects of pretreatment on the surface roughness of plain-woven fabric by the Kawabata Evaluation System. *Textile Research Journal,* 2022, **93**(9-10), 2149–2157, doi: 10.1177/00405175221139322.
14. 1MAHAR, T.J., WANG, H., POSTLE, R. A review of fabric tactile properties and their subjective assessment for next-to-skin knitted fabrics. *The Journal of The Textile Institute,* 2013, **104**(6), 572–589, doi: 10.1080/00405000.2013.774947.
15. MATUSIAK, M., BAJZIK, V. Surface characteristics of seersucker woven fabrics. *Autex Research Journal*, 2021, **21**(3), 284–292, doi: 10.2478/aut-2019-0079.
16. McGREGOR, B.A., NAEBE, M., WANG, H., TESTER, D., ROWE, J. Relationships between wearer assessment and the instrumental measurement of the handle and prickle of knitted wool fabrics. *Textile Research Journal,* 2014, **85**(11), 1140–1152, doi: 10.1177/0040517514551460.
17. MOONEGHI, S.A., SAHARKHIZ, S., VARKIANI, S.M.H. Surface roughness evaluation of textile fabrics: a literature review. *Journal of Engineered Fibers and Fabrics*, 2014, **9**(2), 1–18, doi: 10.1177/155892501400900201.

18. THAMIZHMANII, S., SAPARUDIN, S., HASAN, S. Analyses of surface roughness by turning process using Taguchi method. *Journal of Achievements in Materials and Manufacturing Engineering,* 2007, **20**(1–2), 503–506.
19. JOSHI, K., PATIL, B. Prediction of surface roughness by machine vision using principal components based regression analysis. *Procedia Computer Science*, 2020, **167**, 382–391, doi: 10.1016/j.procs.2020.03.242.
20. TAIEB, A.H., MSHALI, S., SAKLI, F. Predicting fabric drapability property by using an artificial neural network. *Journal of Engineered Fibers and Fabrics*, 2018, **13**(3), 1–7, doi: 10.1177/155892501801300310.
21. YU, Z., ZHONG, Y., GONG, R.H., XIE, H. Predicting the bending rigidity and shearing stiffness of fabric based on three-dimensional drape model. *The Journal of The Textile Institute,* 2022, **113**(9), 1767–1774, doi: 10.1080/00405000.2021.1947638.
22. SARKAR, J., PROTTOY, Z.H., BARI, M.T., Al FARUQUE, M.A. Comparison of ANFIS and ANN modeling for predicting the water absorption behavior of polyurethane treated polyester fabric. *Heliyon*, 2021, **7**(9), 1–9, doi: 10.1016/j.heliyon.2021.e08000.
23. EZAZSHAHABI, N., LATIFI, M., MADANIPOUR, K. Modelling of surface roughness based on geometrical parameters of woven fabrics. *Indian Journal of Fibre & Textile Research*, 2017, **42**, 43–50.
24. BEYENE, K.A., SAMPATH, V. Modeling surface roughness for prediction and evaluation of bedsheet woven fabric. In *International Conference Proceedings CTA – 2019, EiTEX, BDU, Ethiopia*, 42–48.
25. SALMAN, M., IFTIKHAR, F., KHAN, M.Q., HUSSAIN, T., AHMED, N., FAZAL, M.Z., JAVED, Z.,NAEEM, M.S. Development and characterization of knitted fabrics for better sensorial comfort properties in sportswear by using grey rational analysis. *Journal of Natural Fibers*, 2022, **19**(14), 8514–8528, doi: 10.1080/15440478.2021.1964138.
26. ATALIE, D., ROTICH, G.K. Impact of cotton parameters on sensorial comfort of woven fabrics. *Research Journal of Textile and Apparel,* 2020, **24**(3), 281–302, doi: 10.1108/RJTA-01-2020-0004.
27. HOSSEINI RAVANDI, S.A., VALIZADEH, M. 2 - Properties of fibers and fabrics that contribute to human comfort. In I*mproving comfort in clothing*. Edited by Guowen Song. Woodhead Publishing, 2011, 61–78, doi: 10.1533/9780857090645.1.61.
28. BEYENE, K.A., KUMELACHEW, D.M. An investigation of the effects of weave types on surface roughness of woven fabric. *Textile Research Journal,* 2021, **92**(13–14), 2276–2284, doi: 10.1177/00405175211010683.
29. KAMALHA, E., ZENG, Y., MWASIAGI, J.I., KYATUHEIRE, S. The comfort dimension; a review of perception in clothing. *Journal of Sensory Studies*, 2013, **28**(6), 423–444, doi: 10.1111/joss.12070.
30. BECERIR, B., AKGUN, M., ALPAY, H.R. Effect of some yarn properties on surface roughness and friction behavior of woven structures. *Textile Research Journal,* 2015, **86**(9), 975–989, doi: 10.1177/0040517515606354.
31. AKGUN, M. Assessment of the effect of fabric constructional parameters on surface roughness of wool fabrics. *The Journal of The Textile Institute,* 2015, **106**(8), 845–852, doi: 10.1080/00405000.2014.948730.
32. KAWABATA, S., NIWA, M. Objective measurement of fabric mechanical property and quality. *International Journal of Clothing Science and Technology*, 1991, **3**(1), 7–18, doi: 10.1108/eb002968.
33. ISO 2060. Textiles – yarn from packages – determination of linear density (mass per unit length) by the skein method. Geneva : International Organization for Standardization, 1994, 1–13.
34. ISO 7211-2. Textiles – woven fabrics – construction – methods of analysis. Part 2: determination of number of threads per unit length. Geneva : International Organization for Standardization, 1984, 1–6.

Amit Chakrabortty, Siyam Quddus Khan
Ahsanullah University of Science and Technology, Department of Textile Engineering, 141–142, Love Road, Tejgaon, Industrial Area, Dhaka-1208, Bangladesh

Investigating Carded Yarn Quality through Cross-Doubling in the Draw frame: A Comprehensive Analysis

Raziskovanje kakovosti mikane preje z združevanjem pramenov več mikalnikov na raztezalu: celovita analiza

Original scientific article/*Izvirni znanstveni članek*
Received/*Prispelo* 3-2024 • Accepted/*Sprejeto* 4-2024

Corresponding author/*Korespondenčni avtor:*
Amit Chakrabortty
E-mail: amit.te@aust.edu
ORCID: 0000-0002-8592-3757

Abstract

A carding machine's performance has an impact on the quality of the carded sliver, which in turn affects the quality of the carded yarn produced. Several factors can influence a machine's efficiency, resulting in fluctuations in the slivers generated over time. To achieve consistent and reproducible quality levels, slivers from all carding machines must be blended homogeneously. This blending process is vital for achieving homogeneity in the final product and maintaining a high quality standard. This can be achieved by cross-doubling. In this technique, carded slivers are arranged into categories of good, medium and low quality based on the nep removal efficiency of the carding machine behind the breaker draw frame. This is a specific type of doubling process. The focus of this research was the effectiveness of the aforementioned practice. Three carding machines were selected out of seven based on the quality level of the produced carded sliver, which was measured by nep removal efficiency. Yarn samples of 29.5 tex were produced from the slivers of the individual carding machines and by cross-doubling them at the breaker draw frame. Samples were collected at each stage of processing and tested. The results showed that cross-doubling significantly reduced variation in the imperfection level and yarn strength, but had very little effect on the mass variation level of the strands. Furthermore, the categorization of the four samples for selection was carried out using the Analytic Hierarchy Process method. This study will provide a guideline for new spinners to enhance yarn quality through cross-doubling on a draw frame machine.
Keywords: cross-doubling, nep removal efficiency, imperfection level, AHP

Izvleček

Delovanje mikalnika vpliva na kakovost mikanega pramena, kar posledično vpliva na kakovost izdelane mikane preje. Več dejavnikov lahko vpliva na učinkovitost stroja, ki lahko povzročijo nihanja v pramenu. Za doseganje konsistentnosti in ponovljivosti lastnosti je treba pramene z vseh mikalnikov homogenizirati z mešanjem oz. združevanjem pramenov z različnih mikalnikov. Postopek združevanja pramenov je ključnega pomena za doseganje homogenosti končnega izdelka in ohranjanje kakovosti. To je mogoče doseči z združevanjem mikalniških *pramenov pred prvim raztezanjem. Na podlagi učinkovitosti odstranjevanja nopkov na mikalniku je treba pri tem postopku mikane pramene za raztezalom razvrstiti po kakovosti v kategorije dobri, srednji in slabi. To je poseben postopek združevanja pred prvim raztezanjem, katerega učinkovitost je bila proučena v tej raziskavi. Izmed sedmih mikalnikov smo na podlagi količine nopkov v izdelanih mikanih pramenih izbrali tri mikalnike. Iz pramenov istega mikalnika, kot tudi z združevanjem pramenov vseh treh mikalnikov na raztezalniku (prvo raztezanje), so bili izdelani vzorci prej dolžinske mase 29,5 tex. Na vsaki stopnji izdelave so bili zbrani vzorci tudi analizirani. Pokazalo se je, da je združevanje pramenov s treh mikalnikov bistveno zmanjšalo nihanja v stopnji nepopolnosti in trdnosti preje, minimalno pa je združevanje vplivalo na nihanje mase pramenov. Kategorizacija štirih vzorcev za izbor je bila izvedena z analitičnim hierarhičnim procesom. Ta raziskava podaja smernice za izboljšanje kakovosti preje, če izberemo združevanje pramenov iz več mikalnikov na raztezalniku v novih predilnicah.*

Ključne besede: združevanje mikalniških pramenov, učinkovitost odstranjevanja nopkov, stopnja nepopolnosti, AHP

1 Introduction

Carding is considered the heart of spinning. This is because it is the first machine in the yarn manufacturing process sequence that opens, cleans, orients and processes fibres individually [1]. This results in the improved quality of end products, which cannot be matched by any other machine. For combed yarn, there is the further process of combing, which contributes to improved quality. For carded yarn, however, carding is the last machine that performs individual fibre opening and cleaning. For this reason, the quality of the carded sliver directly translates into the quality of short staple spun yarn. The performance of a machine is significantly affected by other machines and by fibre parameters, such as gauge settings, wire sharpness, roller rpm, material throughput rate, presence of autoleveller, the sliver fineness and orientation of previous materials, etc. While processing fibres in a spinning factory, multiple of carding machines are used to meet production demands. Although similar machine parameters are maintained between different machines, the quality of the output sliver obtained is not always the same. This can be attributed to variation in the fineness of the fibre web, gauge variations (because these are very narrow settings, slight variation may cause different results), the sharpness of the card clothing, machine condition, etc. This variation in carded sliver eventually results in variation in the produced yarn, which is very undesirable. The performance of a carding machine is determined by nep removal efficiency. Nep removal efficiency shows the ratio of the incoming neps count of the card mat to the resulting card sliver. This generally, enables a better evaluation of actual card performance. Ideally, both, absolute nep levels and removal efficiency should be monitored for card performance [2]. Nep removal efficiency can be calculated using the following equation 1.

$$\mathrm{NRE} = \frac{\mathrm{Neps\ in} - \mathrm{Nep\ \ out}}{\mathrm{Neps\ in}} \times 100\% \quad (1)$$

where NRE represents nep removal efficiency, Neps in represents feed batt and Neps out represents the card sliver.

Today, the consistent level of quality is a prerequisite, together with high quality for all customers. Hence, necessary means are required to minimize this variation.

In 2019, Gulhane, S. et al. investigated the correlation between carding performance, particularly nep removal efficiency, and yarn quality. The research demonstrated the significant influence of nep removal efficiency on yarn quality while highlighting the critical role that carding parameters, settings and machine settings play in the manufacture of slivers. The research included a comprehensive assessment of literature, and investigated the reasons why nep removal efficiency varies between carding machines [2].

In 2013, Jabbar, A. et al. investigated the impact of draw frame doubling on the properties of ring-spun yarn and discovered that yarn tenacity, elongation and hairiness increase by increasing draw frame doubling up to a certain level before decreasing with further doubling [3]. In 2011, Das et al. studied how varying cylinder and doffer speeds affect fibre orientation in carded slivers. Increased cylinder speed and decreased doffer speed led to higher anisotropy, particularly forward. Using a mathematical model, we identified a strong correlation when comparing our fibre orientation results with previous studies [4]. In 2009, Ishtiaque S. M. et al. studied the influence of carding parameters and draw frame speed on fibre axial distribution in ring-spun yarn. Their study focused on critical process variables: card draft, coiler diameter and draw frame delivery speed. The findings indicated a consistent decrease in trailing, leading and total hooks, along with their impacts on ring-spun yarn, with increased draw frame delivery speed and coiler diameter in the carding machine [5]. In 2008, Ishtiaque, S. M. et al. explored the effects of draw frame speed and preparatory processes on ring-spun yarn properties. Increasing draw frame speed and card coiler diameter led to higher tenacity and breaking elongation, along with reduced mass variation (CVm%), total imperfections, hairiness and long thin faults in the yarn [6]. In 2005, Ishtiaque, S.M. et al. conducted a study on fibre openness and its effects on roving drafting force and yarn quality. Increased fibre openness correlated with reduced roving drafting force and significantly influenced parameters such as nep count, short fibre content, mass irregularity, total imperfections and yarn tenacity across various processing stages [7]. Although different experimental work has been conducted on doubling, the effectiveness of cross-doubling in the spinning industry requires additional investigation, particularly with regard to the quality of carded slivers. Cross-doubling is a specific type of doubling method that strategically arranges carded slivers based on a carding machine's performance, particularly in terms of the efficiency of nep removal behind the breaker draw frame. This controlled approach aims to combine variations in carded slivers into a single draw sliver. Subsequently, these drawn slivers undergo further doubling with other breaker drawn slivers, ultimately yielding a final product of consistent quality. A clear set of instructions for achieving optimal quality through cross-doubling is currently unavailable, particularly when a carding machine's performance is hindered by delayed or inadequate grinding. Different improvements to machines and processes were proposed and put into practice. The most economic and practically viable solution was to introduce cross-doubling. Thus, the objective of this study was to analyse how cross-doubling effects the consistency of quality in produced slivers and thus its impact on yarn.

2 Materials and Methods

2.1 Materials

In this experiment, Cameroon cotton fibre was used as a raw material, while the properties of the fibre were measured using a High-Volume Instrument (HVI) in accordance with the ISO 2403, and ASTM 1445, 1447, 1448, 2812 and 5867 test methods [8]. The resulting fibre properties are described in Table 1.

Table 1: Properties of raw material

Fibre properties	Values
Fibre fineness (tex)	0.17
Fibre length (mm)	28.4
Short fibre content (%)	9.2
Elongation (%)	5.96
Spinning consistency index (SCI)	126
Strength (cN/tex))	2.92

2.2 Methods

Working plan

A schematic diagram for the experimental investigation is shown in Figure 1, and the research was carried out in accordance with this specified plan. In accordance with the research strategy, four samples were prepared under different conditions and then tested using various types of quality control equipment. Applying the cross-doubling technique, Sample D was made from a combination of good, medium and low-quality slivers obtained from samples A, B, and C based on the nep removal efficiency of the carding machine.

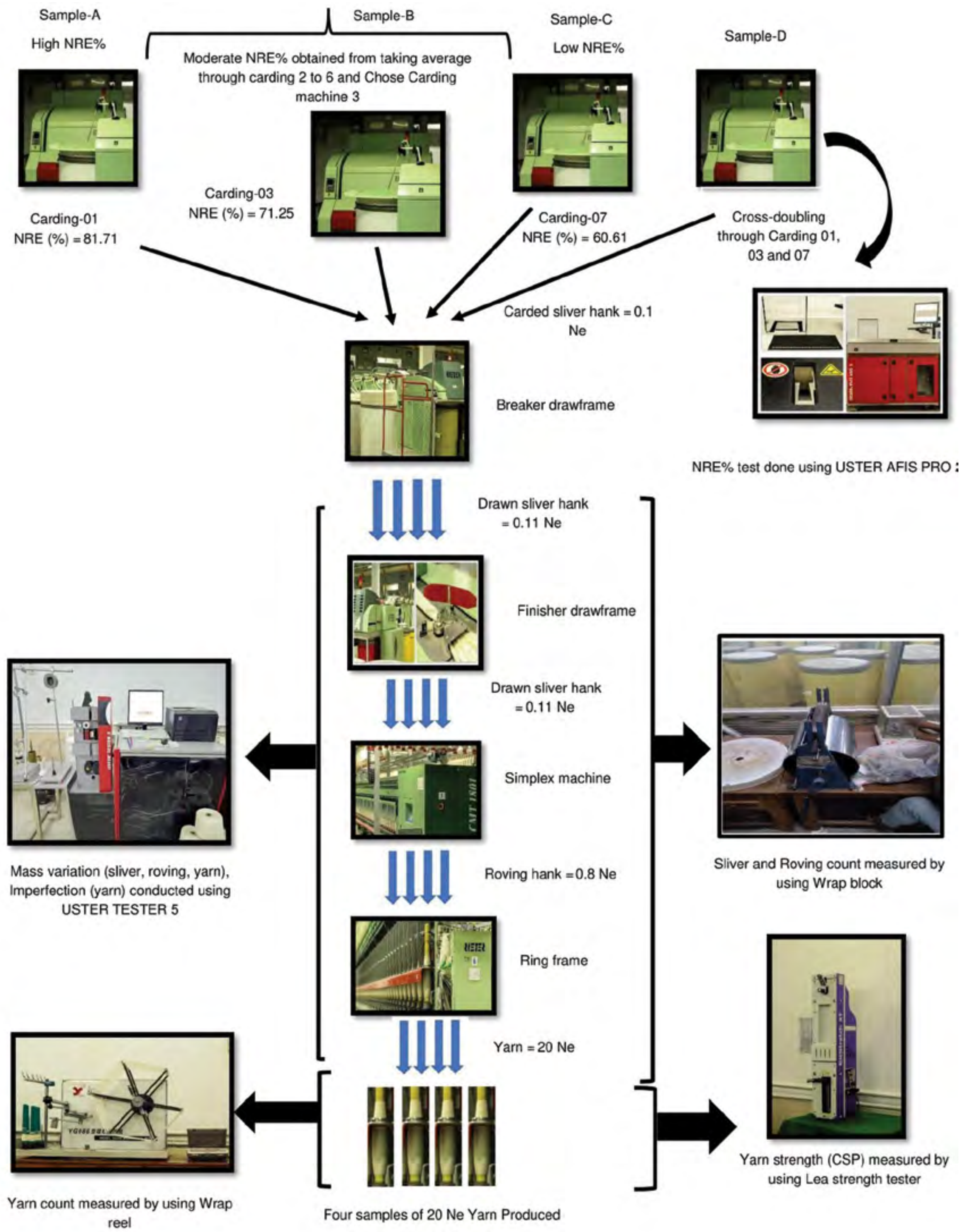


Figure 1: Process flow chart of research plan

Working procedure

Three carding machines (Rieter C70) were chosen from seven based on their nep removal efficiency using USTER® AFIS PRO-2. The selection of machines was influenced by the availability of floor space. The three machines were then referred to as samples A, B and sample according to their nep removal efficiency values. Sample A was prepared using a carding machine with a higher nep removal efficiency. Sample B was made by incorporating the average values from carding machines 2 through 6, and was then aligned with carding machine 3. Sample C was made from a carding machine that exhibited a lower nep removal efficiency. Meanwhile, sample D was prepared by combining samples A, B and C. A sample matrix are shown in Table 2. Six cans of card slivers were produced for all three samples and fed to breaker and finisher draw frames, while six cans of finisher drawn sliver were prepared. These finisher drawn slivers were then fed to a roving frame that produced eight rovings. Sample D was produced through the homogenous mixing of carded slivers at the breaker draw frame. From that point, eight ring cops were produced by repeating a similar process that was carried out for samples A, B and C. Evenness and AFIS tests were carried out at each processing stages for samples A, B, C and D using an Uster Evenness Tester and USTER AFIS PRO-2. Yarn samples from varied conditions were subjected to testing using an Evenness Tester-6, Wrap Reel, Lea Strength Tester and Digital Balance. The testing methods are outlined in Table 3. The test results were analysed to observe the effect of cross-doubling on the quality of produced yarn. During testing, a standard temperature (20 °C ± 2 °C) and RH% (65% ± 2%) were maintained in the testing lab. Various machine parameters used in the preparation of samples are presented in Table 4.

Table 2: Sample matrix

Carding machine	Nep content in card matt	Nep content in carded sliver	NRE [a)] (%)	Sample
Card-1	453	83	81.71	A
Card-2	405	110	72.83	-
Card-3	420	121	71.25	B
Card-4	425	105	75.29	-
Card-5	435	141	67.58	-
Card-6	467	145	68.95	-
Card-7	487	191	60.61	C
Combination of samples A, B and C				D

[a)] Nep removal efficiency.

Table 3: Sample observation test method

Parameters	Test method	Reference
Fibre nep content	ASTM D 5866	[9]
Sliver or roving evenness	ASTM D1425-D1425M	[9]
Yarn count	ASTM D 1907	[10]
Yarn evenness, imperfections, hairiness	ASTM D1425M-14	[11]
Count strength product (CSP) [a)]	ASTM D1578	[11]

[a)] Expressed as a product of breaking load in pounds of a lea of yarn and its English count (Ne); 109.73 m (120 yd) skein made on a 1,372 m (1.5 yd) girth reel is used in the cotton count system and is called a lea; tex = 590.5/Ne.

Table 4: Specifications of various machines

Machine name	Parameters	Values
Carding	Cylinder speed (Hz)	14.17
	Taker-in speed (Hz)	23.98
	Cylinder to flat (Gauge, Thou, inch [a)])	0.012, 0.011, 0.010, 0.010, 0.010
	Sliver fineness (tex)	5905
Draw frame (breaker and finisher)	No. of doublings	6 (breaker), 8 (finisher)
	Draft	6.6 (breaker), 8.8 (finisher)
	Delivery speed (m/min)	700 (breaker), 600 (finisher)
	Sliver fineness (tex)	5368
Simplex	Flyer speed (Hz)	16.33
	Draft	7.27
	Roving twist (m^{-1})	41.3
	Roving hank tex)	738
Ring frame	Ring diameter (mm)	40
	Roller gauge (mm)	43 (front zone) × 70 (back zone)
	Spindle gauge (mm)	70
	Spindle speed (Hz)	258.33
	Yarn twist (m^{-1})	616
	Yarn fineness (tex)	29.5

[a)] 1 inch = 2.54 cm

Statistical analysis for sample categorization

In this experiment, analytic hierarchy process (AHP) statistical tools were used. The AHP, introduced by Saaty, is a powerful tool that allows decision makers (DMs) to easily choose the best alternatives [12]. This statistical tool would aid in categorizing the four samples according to their weight. Satty simulated random pairwise comparisons with matrices of varying sizes and computed consistency indices, and derived an average consistency index for random judgments in each matrix size.

Information regarding compatibility and consistency for judgment matrices of varying sizes is presented in Table 5. Table 6 shows how the relationship between consistency and compatibility changes as the number of items increases. The consistency ratio, measured as the ratio of the consistency index to the average consistency index for random comparisons in a matrix of the same size, is generally regarded as satisfactory when it is less than 10%. Consistency index and consistency ratio are also determined using equations 2 and 3 [12].

$$CI = \frac{\lambda_{max}}{n-1} \tag{2}$$

where CI represents the consistency index, λ_{max} represents the consistency vector and n represents the number of elements.

$$CR = \frac{CI}{RI} \tag{3}$$

where CR represents the consistency ratio, CI represents the consistency index and RI represents the random consistency index.

Table 5: Pairwise comparison scale used in the analytic hierarchy process [12]

Importance/ preference level	Verbal definition
1	Equal importance of both elements
3	Moderate significance of one element
5	Strong importance of one element.
7	Significant importance of one element.
9	Extreme importance of one element over
2, 4, 6, 8	Intermediate values

Table 6: Relationship between consistency and compatibility [12]

Dimension of matrix	3	4	5	6	7
Consistency ratio	0.05	0.08	0.10	0.10	0.10

Steps involved in AHC

The statistical analysis was carried out using the flowchart shown in Figure 2. Initially, it is imperative to establish goals and criteria, as indicated in Figure 2. Following this, a pairwise matrix should be constructed for the criteria, and the consistency ratio should be assessed for reliability.

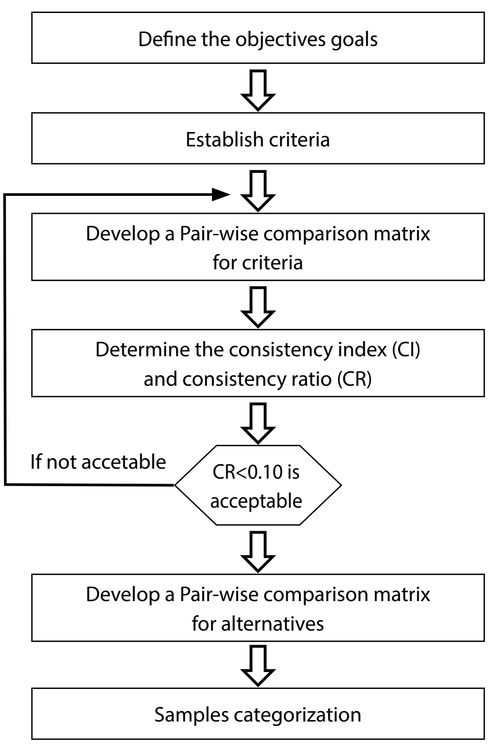


Figure 2: Process flowchart of AHP method

Develop a model for problem analysis

The problem depicted in Figure 3 was analysed using the model that follows. The step-by-step description of the working procedure involved in statistical analysis is outlined below. Various criteria were formulated using the Satty scale described in Table 6, applying the AHP method and incorporating feedback from industrial experts, as shown in Table 7.

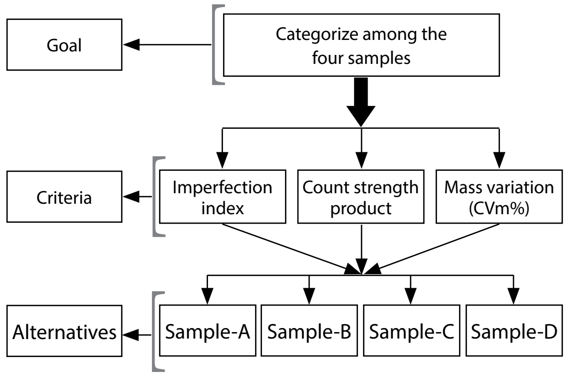


Figure 3: Statistical model for problem analysis

Table 7: Pair-wise matrix

Criteria	Imperfection index (IPI)	Count strength product (CSP)	Mass variation (CVm%)
Imperfection index (IPI)	1	3	5
Count strength product (CSP) [a)]	0.33	1	2
Mass variation (CVm%)	0.2	0.5	1

3 Results and discussion

3.1 Graphical representation

Comparison of the CVm% of different breaker and finisher draw frame

The bar diagram shown in Figures 4 and 5 represent the mass variation (CVm%) of different samples of breaker and finisher drawn slivers. Based on this diagram, it can be concluded that there was no notable variation between samples A, B, C and D for breaker and finisher drawn slivers. Finisher drawn slivers, however, demonstrated lower mass variation mass variation (CVm%) than breaker drawn slivers. This occurred the finisher draw frame machine was equipped with an autoleveller. Sample A, with a higher nep removal efficiency for both finisher and breaker, exhibited a lower mass variation. The mass variation of slivers obtained from different draw frames was enhanced through the successful elimination of neps. This achievement was made possible through the successful carding operation performed by carding machine. The evaluation of samples A, B and C resulted in an average mass variation for the finisher and breaker drawn slivers that was explained by an analysis of sample D. Particularly for sample D, the average mass variation obtained by blending samples A, B and C is clearly attributable to the critical role of cross-doubling.

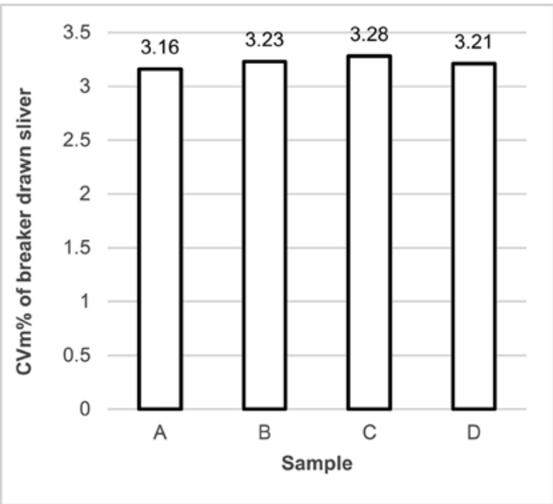


Figure 4: Mass variation of different breaker drawn slivers

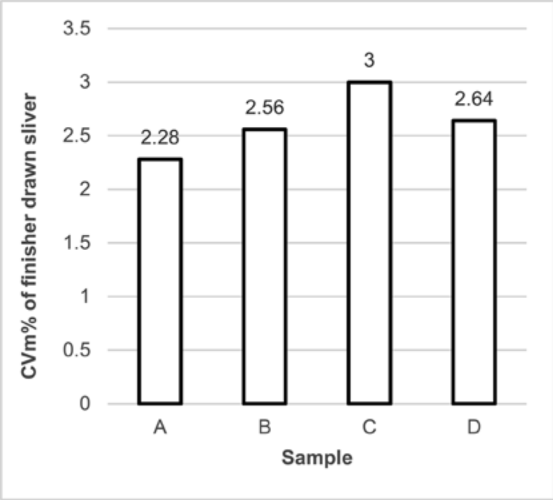


Figure 5: Mass variation of different finisher drawn slivers

Comparison of the CV_m% of different rovings and yarns

The bar diagrams in Figures 6 and 7 depict the mass variation (CV_m%) between various samples of rovings and yarns. For roving and yarn, a higher mass variation was observed compared to the back process (carding, draw frame). This was the result of the introduction of a higher draft in the ring frame machine and the simplex machine, respectively. Samples A, B and C displayed a consistent trend for both roving and yarn, reflecting the observations made in the breaker and finisher draw frames. The average mass variation (CV_m%) for roving and yarn in Samples A, B and C was 4.8 and 11.49, respectively, which closely matched the value derived for Sample D through cross-doubling. Sample D, which is the result of cross-doubling, is a combination of carded slivers representing samples A, B and C. The results obtained indicate that cross-doubling has minimal impact on mass variation (CV_m%), not only in slivers but also in yarn. The minimal impact occurred because of the presence of an autoleveller in the finisher draw frame.

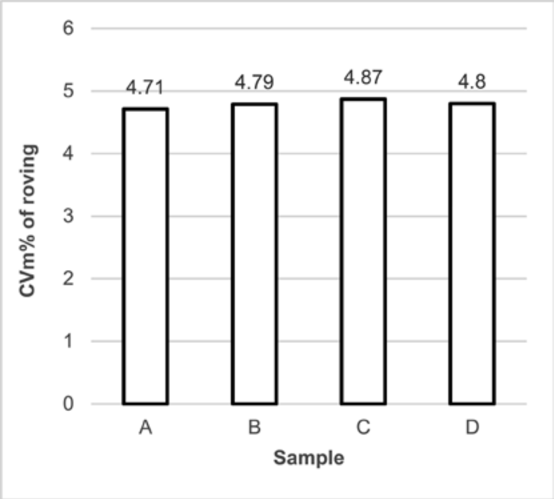


Figure 6: Mass variation of different rovings

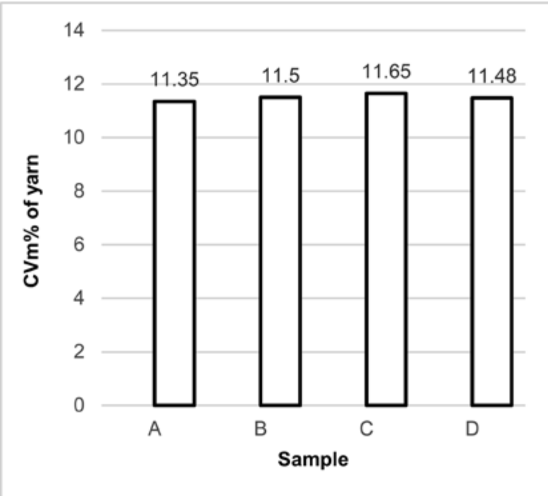


Figure 7: Mass variation of different yarns

Comparison of the IPI of different yarns

The imperfection index (IPI) is the total number of thin places (-50%), thick places (+50%) and neps (+200%) per 1 km of yarn [13]. It is evident from Figure 8 that samples A, B and C have a low, moderate and high imperfection Index (IPI). Their average value of 113.6 closely aligns with the values observed for sample D (113.3). The efficient removal of neps during the carding process by the carding machine has a major impact on the imperfection values in yarns. When the nep removal efficiency (NRE) is high, the carding action is ascribed to the cylinder and flat wires' sharpness, as well as the proper surface speed in both carding machine components. Sample A exhibited lower imperfections due to its higher NRE. This was achieved through the effective carding action between the cylinder and flat, which successfully eliminated neps from the fibre sample. The positive impact of this action was reflected in the reduced imperfections of the yarn. Sample D exhibited an average IPI, as it is the results of the combination of sample A (with minimal nep content, yielding lower IPI) and sample B and C (with moderate and higher nep content, resulting in moderate and higher IPI). The average IPI in sample D derived from the cross-doubling of the other samples. This particular approach had a significant impact on the imperfection values of the yarns. Enhanced yarn quality in sample C will achieved through the effective grinding action between the cylinder and flat of the carding machine.

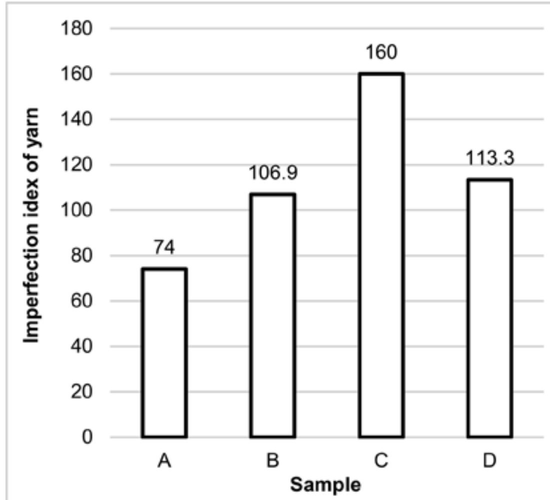


Figure 8: IPI of different yarns

Comparison of the count strength product (CSP) of different yarns

CSP is the abbreviation for count strength product, where lea (i.e. 120 yards or 109.72 m length of a yarn) breaking load is expressed in pounds or 4.482 N, and yarn fineness in English count (Ne) (in tex = 590.5/Ne) [11]. Figure 9 shows that the highest CSP values were observed in Sample A, produced from slivers obtained from carding machine 1. Subsequently, Sample B, produced from sliver obtained from carding machine 3, and Sample C, produced from slivers obtained from carding machine 7, followed in descending order of CSP values. Three samples were produced using the same ring frame machine. However, the differences in nep levels within the fibre samples were the result of the unique carding actions performed by the carding machine. The higher nep content in sample C resulted in more weak points in the yarn, contributing to a lower CSP value. Additionally, the lower nep content in sample A reduced the number of weak points in the yarn, resulting in an increased CSP value. The yarn produced from sample D demonstrated a higher strength than samples B and C. This outcome was attained through the simple technique of cross-doubling.

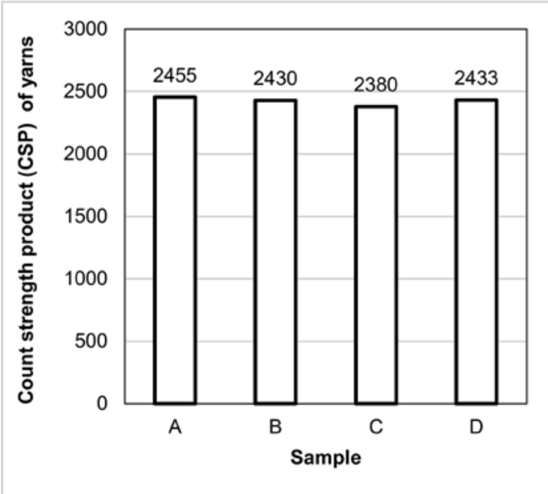


Figure 9: CSP of different yarns

3.2 Statistical analysis through AHPA

Three criteria were selected based on the feedback of industry professionals. The weights of the criteria were determined using Excel. First, the consistency ratio and consistency index were computed. The consistency ratio was the calculated and is shown in Table 8.

Table 8: Calculation of the consistency index and ratio

Criteria`s	Imperfection index (IPI) Count strength product (CSP) Mass variation (CVm%)
Average consistency vector, λ_{max}	3.026
Consistency index, $CI = \frac{\lambda_{max} - n}{n-1}$	0.013
Consistency ratio = $\frac{\text{Concistency index}}{\text{Random concistency index}}$	0.022
Consistency ratio check	If CR, 0.022 < 0.1, (acceptable)

The value of the random consistency index for element 03 is 0.58 [12]. Weights were assigned to each alternative based on the lowest imperfection index (IPI), highest count strength product (CSP) and lowest mass variation values, taking into account the weights of criteria. The ultimate performance score was the calculated and is presented in Table 9.

According to statistical analysis, the options are in the sequence A > D >B> C (see Table 10).

Table 9: Calculation of weights for various alternatives

Criteria weight	0.611	0.247	0.142
Alternatives	Imperfection Index (IPI)	Count strength product (CSP)	Mass variation (CVm %)
Sample-A	74	2,455	11.35
Sample-B	130	2,430	11.50
Sample-C	160	2,380	11.65
Sample-D	113.3	2,433	11.48

Table 10: Weights of various alternatives

Criteria for alternatives	Criteria weight	Performance score
Sample-A	1.00	1
Sample-B	0.73	3
Sample-C	0.66	4
Sample-D	0.78	2

4 Conclusion

Today, the consistent quality of yarn is a pre-requisite for any customer and spinner. To achieve these different practices, specialized equipment is incorporated into processes by spinners. Among these, cross-doubling is a very simple practice that involves no additional cost. While studying its effectiveness, it was observed that by using this practice, the variation in the imperfection level and strength of the yarn caused by the carding machines can be effectively maintained at a certain level, although the minimization in mass variation observed was negligible. The weights of criteria were determined through expert opinions, taking into account crucial yarn quality parameters, such as imperfection level, strength and mass variation. The performance scores achieved by samples A, B, C and D were 1, 3, 4 and 2, respectively. Sample D, which is the result of combing samples A, B and C, is deemed more appropriate for producing high-quality yarn than samples B and C, based on the statistical results. Sample A scores first in this regard. Yarn quality parameters for sample D, including imperfection level and mass variation, were 12.84% and 29.18% lower, respectively, than samples B and C, while the yarn strength for sample D was 0.12% and 2.17% higher than that of samples B and C. Using a simple cross-doubling approach resulted in high-quality yarn, with no consideration given to the associated costs in carding machine grinding. It can thus be deemed an effective practice for obtaining a consistent quality level and should be applied in production.

References

1. LAWRENCE, CA. *Fundamentals of spun yarn technology*. Boca Raton : CRC Press, 2003.
2. GULHANE, S., PATIL V., KOLTE, P., GUPTA, J. Impact of card neps removal efficiency on yarn quality. *Journal of the Textile Association,* 2019, March – April, 432–434.
3. JABBAR, A., HUSSAIN, T., MOQEET, A. Impact of carding parameters and draw frame doubling on the properties of ring spun yarn. *Journal of Engineered Fibers and Fabrics*, 2013, **8**(2), doi: 10.1177/155892501300800209.
4. DAS, D., ISHTIAQUE, S.M., DIXIT, P. Influence of carding and drawing processes on orientation of fibers in slivers. *The Journal of the Textile Institute*, 2012, **103**(6), 676–686, doi: 10.1080/00405000.2011.598667.
5. ISHTIAQUE, S.M., MUKHOPADHYAY, A., KUMAR, A. Impact of carding parameters and draw frame speed on fibre axial distribution in ring-spun yarn. *Indian Journal of Fibre & Textile Research*, 2009, **34**(3), 231–238.
6. ISHTIAQUE, S.M., MUKHOPADHYAY, A., KUMAR, A. Influence of draw frame speed and its preparatory on ring-yarn properties. *The Journal of The Textile Institute*, 2008, **99**(6), 533–538, doi: 10.1080/00405000701679632.
7. ISHTIAQUE, S.M., SALHOTRA, K.R., DAS, A., SUKHADEV, N.S. Study on fibre openness – its impact on roving drafting force and yarn quality. *Indian Journal of Fibre & Textile Research*, 2005, **30**(1), 26–31.
8. Uster textile laboratory testing. Full range of services [online]. USTER [accessed 12.04.2024]. Available on World Wide Web: <https://www.uster.com/fileadmin/user_upload/Downloads/2_ValueAddesServices/Laboratory_Systems/Uster_textile_laboratory_testing_services_062019.pdf>.
9. Laboratory testing services [online]. USTER [accessed 29.12.2023]. Available on World Wide Web: <https://www.uster.com/laboratory-testing-services/>.
10. Standard test method for linear density of yarn (yarn number) by the skein method [online]. ASTM [accessed 29.12.2023]. Available on World Wide Web: <https://cdn.standards.iteh.ai/samples/17742/1a5a198fdda948b081a775d1d0a3ffbc/ASTM-D1907-97.pdf>.
11. HOSSEN, J., SAHA, S.K. Influence of blending method and blending ratio on ring-spun yarn quality – a MANOVA approach. *Tekstilec*, 2023, **66**(3), 227–239, doi: 10.14502/tekstilec.66.2023023.
12. SAATY, T.L. *Decision making with dependence and feedback: the analytic network process*. Pittsburgh : RWS Publications, 1996.
13. CHAKRABORTTY, A., HOSSAIN, A., GHOSH, J. Study on the effect of air suction pressure on the quality of compact yarn by changing the frequency of inverter. *Tekstil ve Mühendis*, 2020, **27**(119), 154–158, doi:10.7216/1300759920202711903.

Mst. Murshida Khatun[1,2]
[1]Daffodil International University, Textile Engineering Department, Ashulia, Dhaka, Bangladesh
[2]Bangladesh University of Engineering & Technology, Dhaka, Bangladesh

Life Cycle Assessment of Jeans Production Using Organic and Conventional Cotton

Analiza življenjskega cikla izdelave kavbojk iz organskega in konvencionalnega bombaža

Original scientific article/*Izvirni znanstveni članek*
Received/*Prispelo* 9-2023 • Accepted/*Sprejeto* 4-2024

Corresponding author/*Korespondenčna avtorica:*
Mst. Murshida Khatun
E-mail: murshida@daffodilvarsity.edu.bd
ORCID: 0000-0001-6073-0193

Abstract

Because of concerns about environmental impacts and the growing demand for denim jeans, the textile sector must implement innovative strategies to improve sustainability. The present study investigated the advantages of using organic cotton rather than conventional cotton. A life cycle assessment approach was used to investigate the environmental effects of a pair of jeans in four distinct scenarios due to the excessive use of natural resources in the manufacturing of cotton, which is a necessary raw material for textiles. The other possibilities were selected based on a product's type of cotton, manufacturing technique and geographical location. The ReCiPe midpoint (H) approach was used to analyse the environmental impact categories of fossil resource scarcity (FRS), terrestrial ecotoxicity (TE), terrestrial acidification (TA) and global warming (GW). Considering only raw materials, organic cotton has achieved remarkable improvements in four impact categories –FRS (-24.34%), GW (-19.83%), TA (-11.31%) and TE (-36.45%) – relative to conventional cotton. When considering the entire life cycle of denim jeans, life cycle assessment results indicated that Scenario 2 had the lowest environmental impacts.

Compared to conventional cotton, however, organic cotton has less of an environmental impact throughout the cotton-growing phase. Moreover, the use of an air-jet loom and ring spinning uses in Scenarios 3 and 4 results in the consumption of more energy. Thus, the best result for reducing environmental impacts derives from the use of organic cotton with conventional weaving and open-end spinning. Using organic cotton as a raw material during the production process greatly improves the life cycle of a pair of jeans.
Keywords: conventional cotton, organic cotton, life cycle assessment, environmental impact

Izvleček

Zaradi naraščajočega povpraševanja po tkaninah denim za kavbojke je nujno uvajanje inovativnih strategij za izboljšanje trajnostnih pristopov. Ta raziskava se osredinja na prednosti uporabe organskega bombaža pred konvencionalnim bombažem. Zaradi prekomerne rabe naravnih virov pri pridelavi bombaža, ki so nujna surovina za tekstilije, so bili v analizi življenjskega ciklusa za raziskavo vpliva izdelave kavbojk na okolje uporabljeni štirje *različni scenariji. Drugi dejavniki so bili izbrani glede na vrsto bombaža, postopek pridelave in geografsko območje. Za analizo pomanjkanja fosilnih virov, ekotoksičnosti zemljine, zakisavanja tal in globalnega segrevanja je bila uporabljena metoda ReCiPe Midpint (H). Če upoštevamo le surovino, ima organski bombaž izjemno prednost pred konvencionalnim v štirih kategorijah vpliva: pomanjkanja fosilnih virov -24,34 %, globalnega segrevanja -19,83 %, zakisavanja tal -11,31 % in toksičnosti zemljine -36,4 5 %. Pri upoštevanju celotnega življenjskega cikla tkanine denim za jeans so rezultati pokazali, da ima scenarij 2 (vključuje konvencionalni bombaž) najmanjše okoljske vplive, čeprav je vpliv gojenja organskega bombaža na okolje manjši kot pri konvencionalnem bombažu. Scenarija 3 in 4 vključujeta uporabo statev z zračnim curkom in prstansko predenje, ki pomenita veliko porabo energije. Zato bodo najboljši rezultati pri zmanjševanju vplivov na okolje doseženi z uporabo organskega bombaža, rotorskim predenjem in konvencionalnim postopkom tkanja. Uporaba organskega bombaža kot surovine med proizvodnim procesom močno vpliva na nadaljnji boljši življenjski cikel kavbojk.*

Ključne besede: konvencionalna bombažna vlakna, organska bombažna vlakna, ocena življenjskega cikla, vpliv na okolje

1 Introduction

There is a wealth of research available on the internet about LCA. Water consumption, toxicity, eutrophication and greenhouse gas emissions are only a few of the negative environmental impacts of cotton [1]. Since cotton is naturally cultivated rather than manufactured, it is typically seen as an environmentally negative fibre. However, the agricultural phase requires many resources that have an impact on the environment, such as electricity, water and chemicals. Consumers across the world frequently wear trousers, a type of denim clothing that is incredibly adaptable. According to a study by Haque et al. [2], denim jeans are one of the most popular textile articles of clothing and one of the world's greatest success stories. Denim trousers are quite popular across all generations, according to Devare et al. [3]; younger generations currently believe them to be the most in-demand outfit. Denim has numerous environmental impacts, ranging from cotton farming to manufacturing to end-of-life disposal, including water consumption and contamination, destruction of large-scale ecosystems and transportation pollution [4]. Denim will endure for a very long time, according to Periyasamy et al. [5]. In today's world, denim is a fabric that can be used for everything, not just clothing. Cotton jeans with huge market demand have a great potential negative impact on the environment, especially in terms of climate change and water depletion [6]. Agriculture, raw material processing, transportation, consumer use and final disposal are the five stages that make up the life cycle of a pair of denim trousers. The complete life cycle of a product may be interpreted using LCA, which is a useful technique. Following the creation of the international LCA approach, it has been extensively used in the textile industry as a decision-support method for assessing the environmental implications of goods and services, according to the International Organization for Standardization ISO 14040:2006 [7] and ISO 14044:2006 standards [8]. The modelling of the effects that denim trousers have on the environment is also presented in this article. Two different approaches are used to analyse impacts. One is the quantitative computation of the carbon footprint caused by the life cycle of denim trousers. Software-based analysis of environmental impacts is an additional analysis. Software is widely available to evaluate the environmental impacts of denim jeans. There are several life cycle impact assessment (LCIA) methodologies that are widely used. The names of the methodologies are CML, Cumulative Energy Demand, Eco-Indicator 99, Ecological Scarcity Method 2006, ILCD 2011, USEtox, ReCiPe, etc. The ReCiPe method provides harmonised characterization factors at midpoint and endpoint levels. The ReCiPe [9] assessment model comprises eighteen sets of midpoint levels and standardised models from characterization and classification. These midpoint indicators have a direct link to endpoint impact categories. The life cycle impact assessment (LCIA) approach in this research work was the ReCiPe 2016 midpoint (H). openLCA, SimaPro, GaBi, etc. are available to illustrate the environmental impacts of denim jeans. openLCA 2.0.2 was chosen from the above software. The reason is that it is free of charge, user-friendly and provides full control over the whole life cycle analysis of a product. In addition, there are many databases available that can be used in openLCA software. A full system model for any product can be developed. SimaPro and GaBi also provide access to databases, but these options are very expensive. The results can also be saved in a spreadsheet. This saves a lot of time and makes the analysis more dynamic.

Literature review

Previous life cycle assessment (LCA) studies have linked the use of various resources in cotton production to significant environmental impacts. Rana et al. [10] studied the full cotton life cycle, from the farming stage to final disposal. Water, energy and chemicals are the key inputs for natural cotton production, as stated by Van der Gun [11]. The manufacturing industry has become much more resource-intensive. Cotton is the most important natural fibre used in the textile industry worldwide. The environmental impacts of cotton production are multifaceted and readily apparent [12]. Seren et al. [13] used the LCA technique to investigate consumer behaviour and the use of organic cotton in denim manufacturing. Amicarelli et al. [14] studied life cycle assessment as a means of combating the take-make-waste model of textile production. As a result, the main environmental impact-producing stages are those connected to agricultural and consumer usage in the life cycle of denim jeans. The distribution process has been found to have a minimal environmental impact. Piccoli et al. [15] studied a Brazilian natural fibre across its whole production cycle. They concluded that a textile item always has an impact on society and the environment. The agricultural phase is the first in this life cycle and is followed by the disposal phase. Connecting the many actors in the supply chain is essential for ensuring the long-term viability of a product. The environmental impact of denim jeans was analysed and addressed in this article. A study by Huang et al. [16] examined the environmental impact of producing raw materials such as Chinese-grown cotton. The fundamental argument here is that in the next few years, greenhouse gas emissions can be reduced by making more efficient use of power and fertiliser in the cotton farming sector. In this research, a model was developed to determine the environmental impact of cotton production. The results are useful in formulating a new carbon emissions policy for China's long-term economic development. Determining the Energy Balance and Greenhouse Gas Emissions of Cotton Cultivation in Turkey: A Case Study from the Bismil District of Diyarbakr Province is the topic of Baran et al.'s [17] research. It was found that during the agricultural phase, greenhouse gas emissions totalled 6,482.36 kgCO_2-eqha-1. Of that amount, 47.94% (3,107.60 kgCO_2-eqha-1) was the result of electricity consumption [18]. In their study of two Vietnamese fashion companies' denim production, Nayak et al. [19] showed how laser and ozone technology contribute to circular economies and sustainable production. The environmental impact of the denim jeans washing businesses in Bangladesh was measured by Shamsuzzaman et al. [20] through an analysis of wastewater. The research highlighted the importance of all process participants paying close attention to reducing the carbon footprint of the washing facility. According to research by Yen et al. [21], cotton jeans may have a significant adverse impact on environmental sustainability. Denim fabric production was studied for its environmental impact in terms of global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), water consumption and cumulative energy demand (CED) [22]. This evaluation took into account the impacts of climate change (CCP), acidification (AP), water depletion (WD) and agricultural land occupation (ALO). The study revealed that for cotton products, the majority of CCP impact (56.52%) is created by consumer usage, and this derives primarily from energy consumption during clothing care (51.63%) [23]. According to the findings, the amount of virtual carbon embedded in the worldwide denim trade climbed from 14.8 Mt CO_2e to 16.0 Mt CO_2e between 2001 and 2018, while the amount of virtual water consumed decreased from 5.6 Tm^3 to 4.7 Tm^3 (billion m^3). Most greenhouse gases and water are used in the manufacturing of denim fabric and cottons, respectively [24]. From this research, we learned that LCA is most frequently employed in comparative studies, the vast majority of which evaluate different brands of denim trousers. Denim jean manufacturing faces difficulties due to a lack of natural gas, say Islam et al. [25]. According to Rahman et al. [26], energy sources represent a constraint on denim jean production for any country. Furthermore, there has been no investigation of the impacts of denim manufacturing processes on the environment. This study investigated how the production of denim jeans affects the environment. The findings of this study will inform those with a stake in the denim industry about the gravity of the impacts caused by the manufacturing process, empowering them to take the precautions necessary to keep carbon emissions to a minimum.

2 Materials and methods

2.1 Scenarios

Four scenarios were used to assess the impacts of cotton agriculture, both conventional and organic, in various regions. The construction of scenarios was based on the type of cotton. Scenarios one (S1) and two (S2) used conventional cotton, while scenarios three (S3) and four (S4) used organic cotton. Cotton production is the primary source of greenhouse gas emissions that harm the environment. Organic cotton was identified in S3 and S4 to find more sustainable solutions. Determining how much conventional and organic cotton farming contributes to the environmental impacts of a pair of jeans was the study's primary objective.

Denim jeans made from both conventional and organic cottons were the source material used in this study. The key phases in the creation of denim jeans were the cultivation of cotton, the spinning of yarn, the bleaching and dyeing process, and the weaving and consumer usage phase. Just eight nations produced 97% of the world's organic cotton in 2020–2021: India (38%), Kazakhstan (4%), Tajikistan (4%), Turkey (24%), China (10%), Tanzania (6%), Kyrgyzstan (9%), Tanzania (6%) and the US (2%). Three percent comes from the remaining thirteen nations that produce organic cotton [27]. Thus, the information about organic cotton from India and other countries is considered in this study. The Table 1 contains the details of the scenarios.

Table 1: Summary of scenarios

Scenario	Raw material	Cotton cultivation zone
S1	Conventional cotton (CO_{conv})	Seed-cotton production, conventional | seed-cotton | Cutoff, U - IN-GJ
S2	Conventional cotton (CO_{conv})	Seed-cotton production, conventional | seed-cotton | Cutoff, U
S3	Organic cotton (CO_{org})	Seed-cotton production, organic | seed-cotton, organic | Cutoff, U - IN
S4	Organic cotton (CO_{org})	Seed-cotton production, organic | seed-cotton, organic | Cutoff, U

2.2 Environmental impact assessment using LCA

In this study, the LCA approach was used to determine the environmental impacts of defined scenarios for a pair of jeans. LCA was carried in accordance with the ISO 14040 [7] and ISO 14044 standards [8]. According to the ISO standards, goal and scope, LCI, LCIA and interpretation are the steps of an LCA study. The aforementioned steps are detailed below:

Goal and scope

The aim of the life cycle assessment (LCA) study was to ascertain the environmental impacts of an average-size pair of jeans by examining the use of conventional and organic cotton in the four key stages of production. The research made use of data from a literature review and the Ecoinvent database V 3.8 (cut-off). Cotton farming, raw material processing (spinning or yarn production, bleaching and dyeing, weaving and jeans production), transportation, consumer usage and disposal are the five phases of the denim jeans life cycle. Assessing the product from the agricultural phases to the ultimate disposal phase involves using a cradle-to-grave system boundary approach. Figure 1 illustrates the system's foreground processes and boundaries.

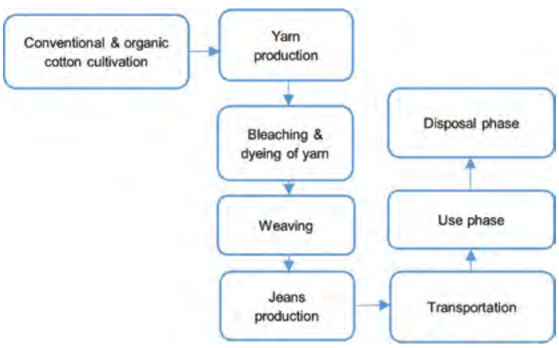


Figure 1: System boundary diagram

2.3 *Life cycle inventory analysis and assumptions*

The LCA technique requires a significant amount of data from primary or secondary sources. The secondary data used in this investigation came from the Ecoinvent V 3.8 (cut-off) database and was process-specific. Establishing the system's boundaries involved the phases of cotton cultivation, raw material processing, transportation, consumer use and waste. The subsections below provide a thorough explanation of the assumptions and data used for the five phases.

a) Cotton cultivation

This stage involved accounting for the process of growing cotton. This statistic took into account both conventional and organic cotton. This figure did not consider the ginning process. The Ecoinvent V 3.8 (cut-off) database was the source of the data. This database compiles standard data for both India and the rest of the world. Data on organic cotton is gathered for India and the rest of the world in the same manner as data on conventional cotton. In this case, traditional cotton farming in India was considered the baseline or reference scenario. Besides the reference, there were the other three scenarios.

b) Raw material processing phase

The raw material processing phase comprised the following processes: spinning yarn, bleaching and dyeing yarn, weaving fabric and jeans production with a washing process. Since the information was not present in the Ecoinvent V 3.8 (cut-off) database, the impact calculation in this case did not account for the production of jeans with a washing process.

c) Transportation

All raw material transportations were excluded in the calculation because, due to the variation of raw material, transportation impacts will not change. According to ISO 14040 [7], we excluded capital goods (land, buildings and machinery) and intermediate packaging, assuming a 1% cut.

d) Consumer use phase

The upkeep of clothing appears to have minimal and negligible impacts on the environment, but as everyone on the planet participates in the process, there are major environmental impacts [28]. A pair of jeans only requires one textile production step, but constant maintenance is required during the usage phase. The assumption is that the consumer use phase will not change, despite changes in raw materials. The consumer use phase was thus considered same for all four scenarios in this study.

e) End of life

When a piece of clothing is no longer functional, there are a few things that can be done with it. The environmentally friendly waste treatment hierarchy is as follows: landfill, incineration, recycling and reuse [29, 30]. Nevertheless, these alternatives were excluded from the purview of this study since reuse and recycling in the textile industry are not yet at an acceptable level. The EPA's 2019 statistics on textile waste indicate that 66% of textile was disposed of in landfills and 19% was incinerated [31]. These factors led to the examination of landfill techniques as an end of life in this study. The disposal phase was thus not considered in this study. Textile phase and process were included in this study, while data sources are given in Table 2.

Table 2: Textile phase and processes with data source used in the study

SL No	Phases	Process	Source of Data
1.	Agricultural phase	Farming and ginning	Ecoinvent V 3.8
2.	Raw material processing phase	Yarn production	Collected data from a textile company Ecoinvent V 3.8
		Yarn dyeing	Collected data from a textile company Ecoinvent V 3.8
		Fabric production with sizing	Collected data from a textile company Ecoinvent V 3.8
		Denim jeans production with washing	Not included in the calculation due to unavailability of data
3.	Transportation phase	Product-carrying vehicles truck (by road), cargo ship (by sea)	Not included in the calculation
4.	Consumer usage phase	Machine washing and drying	Collected data from a textile company Ecoinvent V 3.8
5.	Disposal phase	Landfill	Not considered in the calculation
		Incineration	

Life cycle impact assessment

Employing the life cycle assessment (LCA) approach, the environmental impacts of using conventional and organic cotton as raw material and the raw material's cultivation zone were examined for sustainable jeans. Life cycle assessment was conducted from cradle to grave using openLCA 2.0.2 software while adhering to ISO 14040/44 principles [7]. The LCA approach, which has been widely used in earlier LCA studies on the textile sector, was the ReCiPe midpoint (H). With this method, four distinct environmental impact potentials were investigated: fossil source scarcity (FSS), terrestrial acidification (TA), terrestrial ecotoxicity (TE) and global environmental effects. These categories were chosen based on uniformity with the environmental concerns and the target of the study according to literature.

3 Results and discussion

Four scenarios using the life cycle assessment (LCA) approach evaluated the specific environmental implications of a pair of jeans made with conventional and organic cotton in different agricultural zones. Figure 2 provide the environmental implications for a pair of jeans, respectively. Figure 2 shows that jeans made with organic cotton instead of regular cotton have much better results in tests for fossil resource scarcity (0–25%), global warming (0–26.16%), terrestrial acidification (0–21.53%) and terrestrial ecotoxicity (0–38.55%).

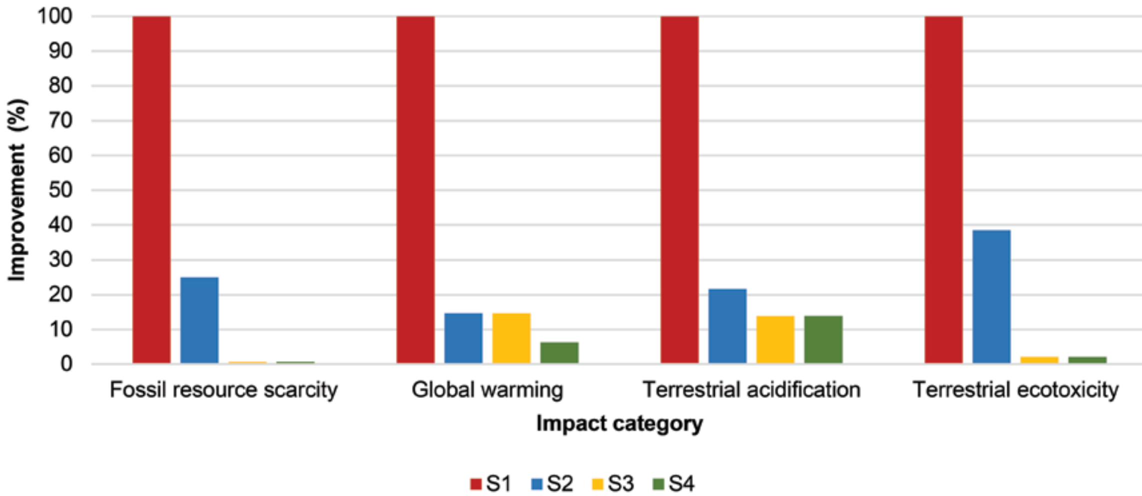


*Figure 2: Reduction compared to ref. case of environmental impacts of all tested scenarios for a pair of jeans (*S: S1, was the reference scenario; the reference scenario was accepted as 100%)*

For each scenario, the contribution of jean production phases to selected environmental impact categories throughout their life cycle is given in Figure 3.

The global warming potential per pair of jeans was 33.21 kg CO_2 equivalent (eq.). in the reference scenario (Table 2, S1). For the calculation in S1, conventional cotton cultivated in India was considered. The usage phase was the same for all four scenarios. The open-end spinning process and conventional weaving process in India were used in scenario 1. In S2, conventional cotton cultivated for the rest of the world, open-end spinning and conventional weaving data for the rest of the world were considered. Here, global warming potential decreased to 21 kg CO_2 eq. The main reason for decreasing carbon emissions was the technology and machinery used in the process involved in making denim jeans. Technology and machines are responsible for the consumption of diesel and the emission of carbon footprints. In S3, organic cotton cultivated in India, the ring spinning process and air jet weaving used in India were considered. Here, global warming potential was 27.2 kg CO_2 eq. In S3, the ring spinning process consumes more energy than open-end spinning, which emits more greenhouse gases compared to S1. The use of organic cotton is another reason. The less fertiliser used, the smaller the carbon footprint. In S4, organic cotton cultivated in the rest of the world, the ring spinning process and air jet weaving in the rest of the world were considered for the calculation. Here, global warming potential was 24.76 kg CO_2 eq. which is a decrease from S1. The main reason for the decreased carbon footprint is the use of organic cotton instead of conventional cotton. Restricting the use of fertilizers and pesticides in the production of organic cotton reduced the global warming impact. When the global warming potential was analysed in the life cycle stages in the reference scenario, the highest impact was in the weaving phase, responsible for 15.33 kg CO_2 eq. In S2, the weaving phase was responsible for 11.22 kg CO_2 eq. In S3, S4 and S5, the yarn production process and weaving process created a larger carbon footprint than other processes. The usage and disposal phases were the same for all scenarios.

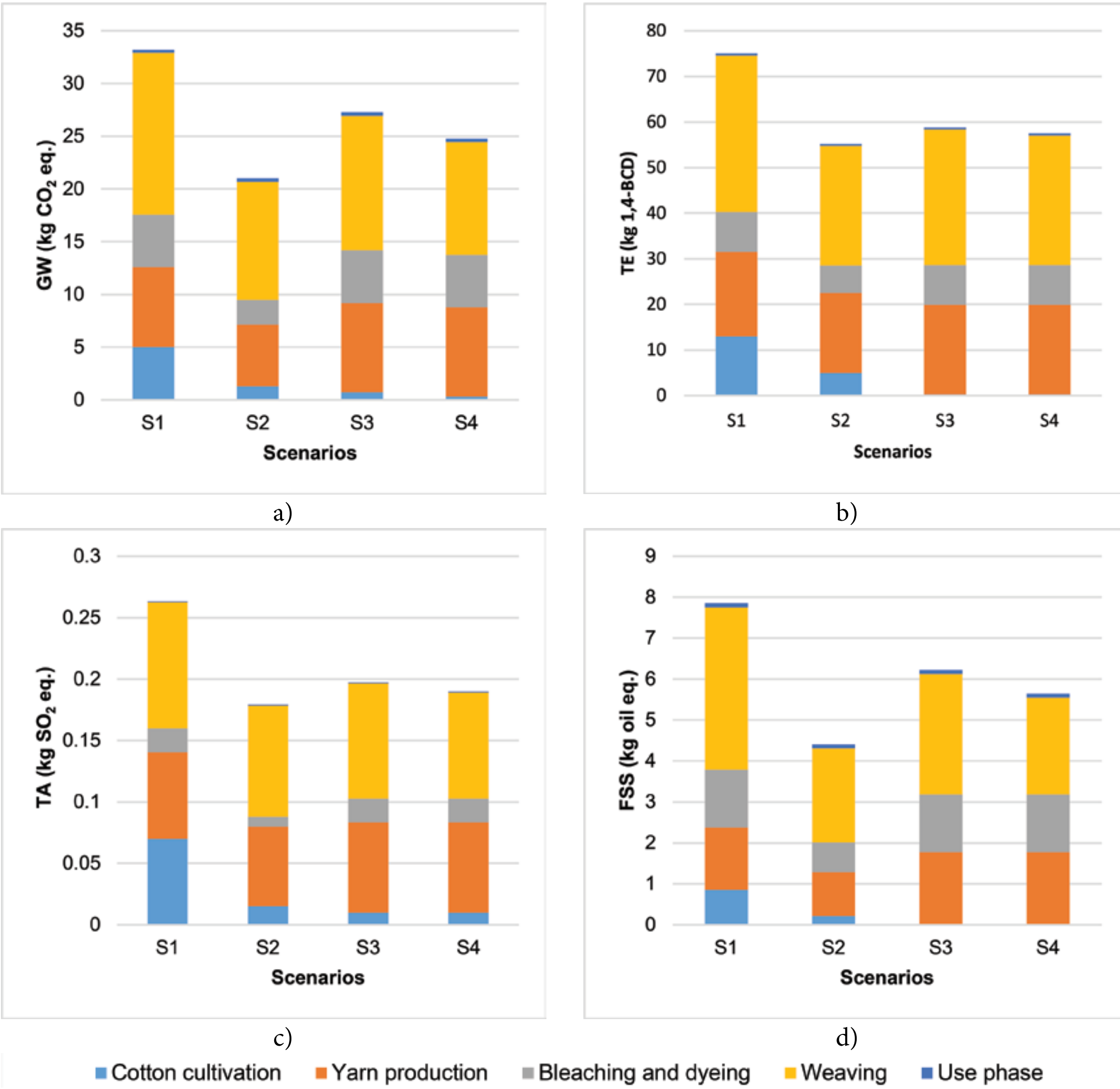


Figure 3: Contribution of jeans production phases to environmental impact categories

In the reference scenario (S1), the calculation for the terrestrial acidification (TA) of a pair of jeans resulted in 0.26 kg SO_2 eq. The TA value was decreased to 0.17 kg SO_2 eq. The cotton cultivation stage is the primary reason for the decrease in value. At this stage, we analysed the cotton cultivation data in a global context. In S3, S4 and S5, the TA value was 0.19 kg SO_2 eq., a decrease in that value relative to S1. The main reason for the decreased value was the cultivation of organic cotton. Moreover, in the weaving phase, the TA was slightly lower than in S1. These findings demonstrate the value of shifting to organic cotton over conventional cotton. La Rosa et al. [30] showed that organic cotton has an 80% lower TA than conventional cotton.

The reference scenario's terrestrial ecotoxicity (TE) value was 75.04 kg 1,4-DCB eq. S2 revealed an improvement by decreasing the value to 55.19 kg 1,4-DCB eq. in the cotton cultivation and weaving phases. Using fewer chemicals and energy resources, particularly diesel, reduces terrestrial ecotoxicity. S3, which was investigated for the use of organic cotton, showed a significant improvement in the cotton cultivation phase because environmental pollution is caused by wastewater, air pollution and agricultural fertiliser [34]. In S4 calculations, organic cotton was used. Differences from the reference scenario were primarily in the yarn production and weaving phases. The change in spinning and weaving methods in S3 and S4 was the reason for the difference. The adoption of ring spinning and air jet loom machines increased fuel consumption, resulting in an increase in terrestrial ecotoxicity.

Fossil sources represent a finite resource that is being rapidly depleting. Finite resources, such as oil, coal and natural gas, have limited availability. S1's fossil fuel scarcity was 7.85 kg of oil eq. The value in S2 decreased to 4.41 kg oil eq. The main reasons for the decreased value from S1 are cotton cultivation, bleaching and dyeing, and the weaving phase. Using data from India, the reference S1 was calculated. Calculating S2 involved analysing the data in a global context. Over a long period of time, using more machinery consumes more energy. In a global context, using modern machines with less fuel consumption helps to alleviate the fossil fuel scarcity problem. In S3 and S4, the values were 5.64 and 6.23 kg oil eq., respectively. In S3 and S4, the cotton cultivation phase showed a remarkable improvement. Because the use of fossil resources in the organic cotton cultivation phase is near zero, organic cotton cultivation requires very little fertiliser production, transport and use. Air jet looms in S3 and S4 used fossil resources more for weaving purposes. Using organic cotton instead of conventional cotton can lead to improvements compared to S1. Conventional weaving highlights another improvement over an air jet loom.

Effect of raw materials

The effect of raw materials is the primary factor causing environmental impacts. Therefore, it was crucial to investigate how using different fibres impacts the environment. More research was carried out to answer to this question. Six natural fibres – conventional cotton, organic cotton, flax, jute, hemp and kenaf – were the basis for this inquiry. Specific field activity data was collected from the Ecoinvent database V 3.8 (cut-off) for these six natural fibres. Since the investigation focused on natural raw materials, it was assumed that the value of the other phases of jeans remains constant. For the global warming potential calculation, only field activity during the agricultural phase was considered. Machinery and fixed overhead were excluded from the calculation, since machinery and fixed overhead provide services over several years, and their impacts per kg of plant is very low. The findings indicated that conventional cotton had the highest global warming potential during field activity compared to other fibres; the value was 1.31 kg CO_2 eq. Organic cotton had a lower value than the conventional cotton, with a value of 0.31 kg CO_2 eq. Kenaf had the least significant impact, generating 0.09 kg of CO_2 eq. However, it will be difficult to meet demand. In addition, more research is required to determine whether kenaf is suitable for producing jeans.

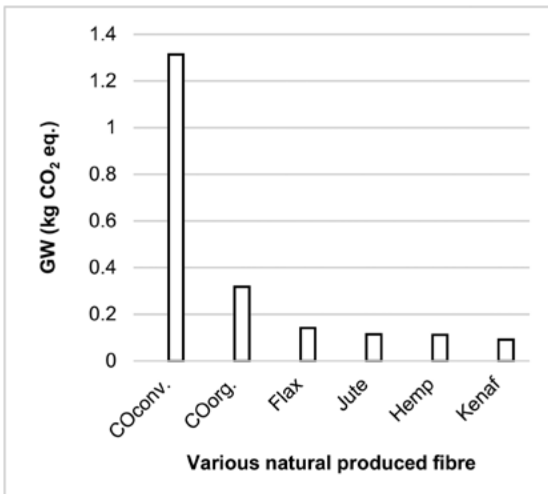


Figure 4: Global warming effect for 1 kg of various natural produced fibres of field activity during the agricultural phase

4 Conclusion

This research work investigated the environmental effects of switching to organic cotton from conventional cotton by conducting life cycle assessments (LCAs) and modelling the cotton cultivation, yarn production, bleaching and dyeing, and weaving phases of a pair of jeans. The study selected the ReCiPe midpoint (H) approach to evaluate environmental impacts. Additionally, the results showed that the type of fibre used had a major effect on the production of sustainable products when a pair of jeans made with organic cotton was compared to those made with other natural fibres.

The hot spots of a pair of jeans differed based on the environmental impacts studied, including GW, TE, TA and FFS, according to the LCA results produced using the reference scenario. Regarding global warming potential, S2 showed the greatest improvement. S3 and S4 also demonstrated improvements with use with organic cotton. In terms of TA, S2 improved most. In addition, the use of organic cotton resulted in a notable improvement in the cotton cultivation stage in S3 and S4. In terms of TE, S2 exhibited the greatest improvement and the lowest value (55.19 kg 1,4-BCD eq.). In this instance, S3, S4 and the cotton cultivation phase also showed a significant improvement. Regarding FRS, S2 recorded the lowest value, of 4.41 kg of oil eq. For the cotton cultivation period, the FRS value in S3 and S4 was almost zero. These results demonstrated how important raw material selection is to the whole life cycle of a pair of jeans. Numerous stakeholders found value in the study's findings. In order to reduce the environmental impact of the industry's goods, cotton, the most popular natural fibre, was evaluated across several environmental impact categories. It not only enumerated the benefits of organic cotton for the environment but also examined in detail the environmental impact of a pair of jeans at every phase of its lifecycle, from cotton cultivation to end of life/disposal phase (which is assumed to be consistent across all scenarios). Findings suggest that switching to more environmentally friendly cotton options and modifying technologies weaving, bleaching, dyeing processes in and yarn production, can decrease the environmental impact of jeans. Consequently, the study's scope can be expanded to encompass additional sustainable raw material alternatives, including repurposed cotton. Investigations tailored to a particular nation can also determine the raw material processing phase and usage phase.

References

1. ZHENGGUI, Zhang, HUANG, Jing, YAO, Yuan, PETERS, Gregory, MacDONALD, Ben, LA ROSA, Angela Daniela, WANG, Zhanbiao, SCHERER, Laura. Environmental impacts of cotton and opportunities for improvement. *Nature Reviews Earth & Environment,* 2023, **4**, 703–715, doi: 10.1038/s43017-023-00476-z.
2. HAQUE, M. Comparative study between slasher or sheet denim and rope denim. *Journal of Fashion Technology & Textile Engineering*, 2022, **11**(3), 1–8, doi: 10. 4172/ 2329-9568.1000248.
3. DEVARE, M.D., TURUKMANE, R.N., GULHANE, S.S., PATIL, L.M. Effect of yarn stretch in sizing on loom performance. *International Journal of Textile Engineering and Processes*, 2016, **2**(4), 19–23.
4. GEERTSMA, R.D., NEGENBORN, R.R., VISSER, K., HOPMAN, J.J. Design and control of hybrid power and propulsion systems for smart ships: a review of developments. *Applied Energy*, 2017, **194**, 30–54, doi: 10.1016/j.apenergy.2017.02.060.
5. PERIYASAMY, A.P., WIENER, J., MILITKY, J. Life-cycle assessment of denim. In *Sustainability in denim*. Edited by Subramanian Senthilkannan Muthu. Elsevier, 2017, 83–110, doi: 10.1016/B978-0-08-102043-2.00004-6.
6. LUO, Y., WU, X., DING, X. Carbon and water footprints assessment of cotton jeans using the method based on modularity: a full life cycle perspective. *Journal of Cleaner Production*, 2022, **332**, 1–15, doi: 10.1016/j.jclepro.2021.130042.
7. ISO 14040:2006 Environmental management – life cycle assessment – principles and framework. Geneva : International Organization for Standardization, 2006, 1–20.

8. ISO 14044:2006 Environmental management – life cycle assessment – requirements and guidelines. Geneva : International Organization for Standardization, 2006, 1–46.
9. HUIJBREGTS, M.A.J., STEINMANN, Z.J.N., ELSHOUT, P.M.F., STAM, G., VERONES, F., VIEIRA, M.D.M., HOLLANDER, A., ZIJP, M., van ZELM R., *ReCiPe 2016. A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization. RIVM Report 2016-0104*. Available on World Wide Web: <https://www.rivm.nl/bibliotheek/rapporten/2016-0104.pdf>.
10. RANA, S., KARUNAMOORTHY, S., PARVEEN, S., FANGUEIRO, R. Life cycle assessment of cotton textiles and clothing. In *Handbook of Life Cycle Assessment (LCA) of textiles and clothing*. Edited by Subramanian Senthilkannan Muthu. Woodhead Publishing, 2015, 195–216, doi: 10.1016/B978-0-08-100169-1.00009-5.
11. GUN van der, Jac. *Groundwater and Global Change: Trends, Opportunities and Challenges. The United Nations World Water Development Report*. Paris : UNESCO, 2012.
12. CHAPAGAIN, A.K., HOEKSTRA, A.Y., SAVENIJE, H.H., GAUTAM, R. The water footprint of cotton consumption: an assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. *Ecological Economics*, 2006, **60**(1), 186–203, doi: 10.1016/j.ecolecon.2005.11.027.
13. ŞENER FIDAN, F., KIZILKAYA AYDOĞAN, E., UZAL, N. The impact of organic cotton use and consumer habits in the sustainability of jean production using the LCA approach. *Environmental Science and Pollution Research,* 2023, **30**(4), 8853–8867, doi: 10.1007/s11356-022-22872-6.
14. AMICARELLI, V., BUX, C., SPINELLI, M.P., LAGIOIA, G. Life cycle assessment to tackle the take-make-waste paradigm in the textiles production. *Waste Management,* 2022, **151**, 10–27, doi: 10.1016/j.wasman.2022.07.032.
15. PICOLI, J.F., GUIMARÃES, T.C., COLERATO, M.P. Life cycle assessment of textile fibres in Brazil: a literature review. In *Progress on Life Cycle Assessment in Textiles and Clothing. Textile Science and Clothing Technology.* Edited by Subramanian Senthilkannan Muthu. Singapore : Springer, 49–82, doi: 10.1007/978-981-19-9634-4_3.
16. HUANG, W., WU, F., HAN, W., LI, Q., HAN, Y., WANG, G., FENG, L., LI, X., YANG, B., LEI, Y., FAN, Z., XIONG, S., XIN, M., LI, Y., WANG, Z. Carbon footprint of cotton production in China: composition, spatiotemporal changes and driving factors. *Science of the Total Environment*, 2022, **821**, 1–11, doi: 10.1016/j.scitotenv.2022.153407.
17. BARAN, M.F., GÖKDOĞAN, O., BAYHAN, Y. Determination of energy balance and greenhouse gas emissions (GHG) of cotton cultivation in Turkey: a case study from Bismil district of Diyarbakır province. *Tekirdağ Ziraat Fakültesi Dergisi*, 2021, **18**(2), 322–332, doi: 10.33462/jotaf.795179.
18. SAINI, Phreny. *Implementation of clean development mechanism in textile industry-denims. Doctoral dissertation*. School of Petroleum Management, 2021.
19. NAYAK, R., GEORGE, M., JAJPURA, L., KHANDUAL, A., PANWAR, T. Laser and ozone applications for circularity journey in denim manufacturing – a developing country perspective. *Current Opinion in Green and Sustainable Chemistry,* 2022, **38**, 1–7, doi: 10.1016/j.cogsc.2022.100680.
20. SHAMSUZZAMAN, M., KASHEM, M.A., SAYEM, A.S.M., KHAN, A.M., SHAMSUDDIN, S.M., ISLAM, M.M. Quantifying environmental sustainability of denim garments washing factories through effluent analysis: a case study in Bangladesh. *Journal of Cleaner Production*, 2021, **290**, 1–13, doi: 10.1016/j.jclepro.2020.125740.
21. LUO, Y., WU, X., DING, X. Carbon and water footprints assessment of cotton jeans using the method based on modularity: a full life cycle perspective. *Journal of Cleaner Production*, 2022, **332**, 1–15, doi: 10.1016/j.jclepro.2021.130042.

22. FIDAN, F.Ş., AYDOĞAN, E.K., UZAL, N. An integrated life cycle assessment approach for denim fabric production using recycled cotton fibers and combined heat and power plant. *Journal of Cleaner Production*, 2021, **287**, 1–15, doi: 10.1016/j.jclepro.2020.125439.
23. MOAZZEM, S., CROSSIN, E., DAVER, F., WANG, L. Assessing environmental impact reduction opportunities through life cycle assessment of apparel products. *Sustainable Production and Consumption*, 2021, **28**, 663–674, doi: 10.1016/j.spc.2021.06.015.
24. ZHAO, M., ZHOU, Y., MENG, J., ZHENG, H., CAI, Y., SHAN, Y., YANG, Z. Virtual carbon and water flows embodied in global fashion trade – a case study of denim products. *Journal of Cleaner Production*, 2021, **303**, 1–12, doi: 10.1016/j.jclepro.2021.127080.
25. ISLAM, M.M., KHAN, A.M., ISLAM, M.M. Textile industries in Bangladesh and challenges of growth. *Research Journal of Engineering Sciences*, 2013, **2**(2), 31–37.
26. RAHMAN, M., TAMIN, M., RAHMAN, L. Analysis of natural gas consumption by the industrial sector of Bangladesh. *Journal of Chemical Engineering*, 2012, **27**(1), 1–7.
27. Organic cotton market report 2022 [online]. Textile Exchange [accessed 26.4.2024]. Available on World Wide Web: <https://textileexchange.org/app/uploads/2022/10/Textile-Exchange_OCMR_2022.pdf>.
28. LAITALA, K., KLEPP, I.G., HENRY, B. Does use matter? Comparison of environmental impacts of clothing based on fiber type. *Sustainability*, 2018, **10**(7), 1–25, doi: 10.3390/su10072524.
29. DAHLBO, H., AALTO, K., ESKELINEN, H., SALMENPERÄ, H. Increasing textile circulation – consequences and requirements. *Sustainable Production and Consumption*, 2017, **9**, 44–57, doi: 10.1016/j.spc.2016.06.005.
30. SANDIN, G., PETERS, G.M. Environmental impact of textile reuse and recycling – a review. *Journal of Cleaner Production*, 2018, **184**, 353–365, doi: 10.1016/j.jclepro.2018.02.266.
31. PATWARY, Sarif Ullah. *An investigation of the substitution rate and environmental impact associated with secondhand clothing consumption in the United States*. Kansas State University ProQuest Dissertations Publishing, 2020.
32. WERNET, G., BAUER, C., STEUBING, B., REINHARD, J., MORENO-RUIZ, E., WEIDEMA, B. The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, 2016, **21**, 1218–1230, doi: 10.1007/s11367-016-1087-8.
33. LA ROSA, A.D., GRAMMATIKOS, S.A. Comparative life cycle assessment of cotton and other natural fibers for textile applications. *Fibers*, 2019, **7**(12), 1–8, doi: 10.3390/fib7120101.
34. Life cycle assessment of cotton cultivation systems: better cotton, conventional cotton and organic cotton [online]. Thinkstep [accessed 26.4.2024]. Available on World Wide Web: < https://laudesfoundation.org/en/resources/4332environmentallcareportjune19.pdf>.

Ivana Salopek Čubrić,[1] Alenka Pavko Čuden,[2] Goran Čubrić,[1] Vesna Marija Potočić Matković[1]
[1] University of Zagreb Faculty of Textile Technology, Prilaz baruna Filipovića 28a, Zagreb, Croatia
[2] University of Ljubljana Faculty of Natural Sciences and Engineering, Aškerčeva cesta 12, Ljubljana, Slovenia

The Comfort of Knitted Materials for Sportswear: A Focus on Air and Water Vapour Permeability

Udobnost pletiv za športna oblačila s poudarkom na zračni prepustnosti in prepustnosti vodne pare

Original scientific article/*Izvirni znanstveni članek*
Received/*Prispelo* 3-2024 • Accepted/*Sprejeto* 5-2024

Corresponding author/*Korespondenčna avtorica:*
Vesna Marija Potočić Matković
E-mail: marija.potocic@ttf.unizg.hr
ORCID: 0000-0002-2907-7306

Abstract

Factors such as the growing popularity of sports, changing lifestyles and the increasing number of sporting events contribute significantly to the popularity of sports textiles. Sports textiles play an important role in the performance of athletes, as they need to provide freedom of movement and comfort to the wearer during activity. In this paper, seven conventional and high-performance polyamide and polyester yarns were selected for the development of knitted fabrics for sportswear. The fabrics were manufactured as single jersey and double jersey structures, both with and without incorporated elastane yarn. The fabrics manufactured were tested for mass per unit area, fabric thickness, fabric density, porosity, air permeability and water vapour permeability. The results of the study indicate that the air permeability of all four fabric groups shows a strong correlation with the measured porosity. The average water vapour permeability of single jersey fabrics is significantly higher than that of double jersey fabrics, and the addition of elastane leads to a further reduction. The correlation between the water vapour permeability and the thickness of single jersey, elastane-plated single jersey and double jersey fabrics is negative.
Keywords: yarn, fabric, knitwear, air permeability, water vapour permeability, sportswear, mechanical functionalisation

Izvleček

Dejavniki, kot so naraščajoča priljubljenost športa, spreminjajoči se življenjski slog in vse večje število športnih dogodkov, pomembno pripomorejo k priljubljenosti športnih tekstilij. Športne tekstilije igrajo pomembno vlogo pri športnih uspehih, saj morajo zagotavljati svobodo gibanja in udobje med športno dejavnostjo. V raziskavi je bilo pri razvoju pletiv za športna oblačila izbranih sedem konvencionalnih in visokozmogljivih poliamidnih in poliestrskih prej. Iz njih so bila izdelana enofonturna in dvofonturna pletiva z vpletenim elastanom in brez njega. Preskušane so bile naslednje lastnosti pletiv: površinska masa, debelina, površinska gostota, poroznost, zračna prepustnost in prepustnost vodne pare. Rezultati študije kažejo, da je zračna prepustnost vseh štirih skupin pletiv močno odvisna od izmerjene poroznosti. Povprečna prepustnost vodne pare enofonturnih pletiv je bistveno večja kot pri dvofonturnih

pletivih, dodatek elastana pa vodi k zmanjšanju prepustnosti vodne pare. Korelacija med prepustnostjo vodne pare in debelino enofonturnih pletiv, enofonturnih pletiv z elastanom in dvofonturnih pletiv je negativna.
Ključne besede: preja, pletivo, pletena oblačila, zračna prepustnost, prepustnost vodne pare, športna oblačila, mehanska funkcionalizacija

1 Introduction

Sports textiles play an important role in the performance and comfort of athletes, both in recreational and competitive sports. Sportswear must therefore offer improved functionality. Its purpose is to allow the wearer freedom of movement and provide comfort or protection during activity. The design of functional sportswear varies for different sports and also depends on the weather conditions, the type of sport and physical activity required for a particular sport, as well as the intensity of the exercise and activity. The increasing demand for knitted sportswear is primarily due to its moisture transport ability, crease resistance, easy breathability, softness, comfort stretch, power stretch, durability, etc. [1–3].

Factors such as the growing popularity of sport, changes in lifestyle and eating habits and the increasing number of sporting events are contributing significantly to the growing popularity of sports textiles [4]. The reasons for buying sportswear can be categorised into three groups: firstly, to actively participate in sport, secondly, to wear sportswear for fashion reasons and thirdly, to wear for leisure and comfort [5].

The contemporary knitted sportswear market is experiencing a robust growth trajectory driven by a combination of technological advances, changing consumer preferences and an increased focus on performance and style. Consumers are looking for versatile garments that transfer effortlessly from the gym to everyday life, driving demand for fashionable and functional knitted sportswear [2, 6].

A key factor in the growth of today's sports textiles market is the emergence of eco-friendly sportswear. The use of recycled fibres helps to reduce the environmental impact of sportswear production, as fewer virgin raw materials are required.

With the increasing production and use of functional knitted fabrics for sportswear, the continuous research and analysis of their functional properties is of great importance for their further development. So far, only a small amount of research has focused on investigating the properties and applicability of recycled synthetic fibres compared to virgin and high-performance fibres in sportswear. A systematic comparison of non-elasticised and elasticised, single and double knitted structures made from conventional, functionalised and recycled synthetic fibres has not yet been presented.

Hatamlou et al. [7] investigated the dynamic liquid transport properties, capillary transfer property, drying rate and water absorption capacity of knitted fabrics produced from 100% polyester and 100% recycled polyester yarns. It was found that the recycled polyester fabric provides better results than virgin polyester fabric in terms of absorption rate, wettability, drying rate and capillarity [7]. Claussen et al. [8] investigated preferences and perceived differences between sports T-shirts made from virgin polyester, mechanically recycled polyester and mechanically recycled polyester-containing ocean plastics. The responses to the wear trial questionnaires showed that participants struggled to perceive a difference between the different types of polyester T-shirts [8]. The characterisation of recycled polyester, virgin polyester and polyester/polyamide blend knitted fabrics was carried out by Choi & Kim [9]. Moisture regain and moisture permeability were the best in recycled polyester/polyamide blend knitted fabric. However, the wickability of mechanically recycled polyester knitted fabric was better than other recycled polyester knitted fabrics [9]. Souza et al [10] developed and evaluated eight functional plain single jersey knitted fabrics for various comfort-related properties in terms of thermal control, air and water vapour permeability, wickability, coefficient of kinetic friction and antimicrobial efficiency. On the one hand, fabrics made from looser and finer yarns show higher air permeability than dense yarns. On the other hand, the higher water vapour permeability of some fabrics can be attributed to the lower mass per unit area. Fabrics with higher density and special cross-sectional shapes of the fibres used showed low indexes of water vapour transmission rate [10]. Daukantiene & Vadeike [11] investigated the air permeability of knitted fabrics with different elastane yarn content and their seams. The results show that the air permeability of the investigated knitted fabrics depends not only on their structural parameters but also on the type of seams [11].

The aim of the present study was to investigate the comfort properties of knitted fabrics made from conventional and functionalised polyamide and polyester yarns, focusing on the analysis of air permeability and water vapour permeability. The study compared the properties of single and double knitted fabrics, both without incorporated elastane and with plated elastane. We included a yarn made from recycled fibres in the study alongside functionalised yarns with antibacterial, water-management and thermal functionalised properties, and a yarn made from hollow fibres.

1.1 Knitted sportswear

One of the most important features of contemporary knitted sportswear is the emphasis on breathability and moisture-wicking properties. Knitted fabrics, which are often made from synthetic fibres or blends with natural fibres, are characterised by the fact that they allow air circulation and efficiently manage sweat. This helps keep athletes cool and dry during intense physical activity, contributing to greater comfort and performance.

An ongoing collaboration between the sports and technology industries encompasses a wide range of applications utilising cutting-edge materials and technologies to drive innovation and efficiency in the world of sport [3].

1.2 Fibres and structures used in knitted sportswear

Early sportswear was dominated by fabrics of natural origin. With the development of synthetic fibres, sportswear was produced mostly using knitting technologies [12]. Fibres used for sports and functional clothing are multidimensional and require a number of properties. The parameters that influence performance are fibre fineness, fibre shape, molecular structure and the addition of finishes. The most important factor that fibres/filaments contribute to wearing comfort is moisture and heat balance, which leads to a suitable microclimate next to the skin [13].

Polyester is the most commonly used fibre for sportswear and activewear. Other synthetic fibres suitable for activewear are polyamide, polypropylene, polyacrylonitrile and elastane. Synthetic fibres can be modified, i.e. by producing hollow fibres and fibres with an irregular cross-section, or optimally blended with natural fibres to improve their thermophysiological and sensory properties [4, 14].

Polyester has outstanding dimensional stability and is pleasantly soft to the touch. Due to its low moisture absorption, ease of care and low cost, it is the most commonly used fibre in activewear base fabrics. High tenacity and good durability also make it the first choice for high-stress outdoor use. Polyester is the ideal clothing for wet and humid environments. By producing hollow fibres, air is trapped in the fibre and insulates the body heat. This keeps the body warm in cold weather. Another method of insulation is to use crimped polyester. The crimp helps to keep the warm air inside [14, 15].

The use of polyamide for sportswear fabrics offers many advantages. Polyamide is very light and is therefore perfect for high-intensity workouts and sporting activities. Its high elasticity enables full freedom of movement, allowing athletes to perform without restriction. Polyamide fabrics are moisture-wicking, they transport sweat away from the body and keep the athlete cool and dry. Sportswear made of polyamide is easy to wash, dries particularly quickly and retains its shape well.

Another advantage of polyamide sportswear is its durability, tear and abrasion resistance. Polyamide fabrics are also crease-resistant, rot-proof and seawater-resistant [16–18].

Elastane fibres were an important driving force in the development of high-performance sportswear. A small amount of elastane added to a fabric allows the garment to return to its original shape after each stretch. Traditionally, elastane is used in the manufacture of knitwear, as the structure of the interlinking loops already has a certain amount of stretch and is therefore a perfect vehicle for a stretch yarn. The fabric stretches and contracts in accordance with the body's muscle movement, which helps to improve muscle recovery while reducing muscle fatigue during active sports through support provided by the garment. Elastane can be incorporated directly into a fabric structure that is predominantly made of another type of fibre. In this case, it is hidden within the fabric structure and provides the desired fit and comfort [13, 16].

In addition to their stretchability and elasticity compared to woven fabrics, knitted fabrics are preferred for sportswear because of the possible transfer of body vapours to the next textile layer. They also act as a second skin, allowing the body to move without compromising function/performance [14, 19, 20]. Different structures have different effects on the properties and performance of fabrics, especially in supporting the thermoregulation of the human body. The knitted fabrics used in everyday sportswear generally have a simple structure, such as single and rib structures and mesh in weft knitting, while the double structure is predominant in warp knitting [21, 22].

When manufactured as elastic continuous fabrics on single jersey circular knitting machines, weft structures, such as plain single jersey, fleece, terry, various piqués or other single structures, are created by plaiting the elastic yarns on the technical back of a fabric construction. All double-knit structures, including plain double jersey, can be produced with elastane yarns using lay-in, knit-in or plaiting techniques. Rib fabrics made on rib circular knitting machines are typically used for trimmings or close-fitting garments. Elastane yarns are most commonly incorporated into the construction by using lay-in carriers [23].

1.3 Thermo-physiological comfort

Thermophysiological comfort is directly related to the role of textiles as a barrier between the human body and the environment. It is also related to the transport properties of clothing and the way that clothing helps to maintain the heat balance of the body during various levels of activity [24, 25]. Thermophysiological comfort can be estimated by the overall moisture management capacity and breathability of a garment, and is essential for an athlete's well-being without compromising performance and effectiveness. For activewear fabrics, the geometry, packing density and structure of the component fibres must be carefully considered to allow heat and moisture to dissipate effectively. Sportswear designers are experimenting with different fibre cross-sectional shapes, shape factors and specific surfaces, yarn variables such as twist, linear density, structure and packing coefficient, and fabric variables such as loop length and porosity. They also use different knit structures such as plated and elasticised fabrics, as well as those produced using bio-mimetic concepts to design sportswear for performance sports [26].

1.3.1 Porosity

It is well known that the porosity of fabrics affects the physical and thermal properties and end use of fabrics, especially knitted fabrics. The porosity of fabrics can give us an indication of thermal resistance, air permeability and water vapour resistance. Heat, liquid sweat and water vapour must be dissipated from the body to the environment. Water vapour moves mainly through the pores of the fabric, diffusing in the air from one side of the fabric to the other. The porosity of the fabric depends on the pore size, volume and distribution of the pores. These factors are in turn influenced by the parameters of the fabric construction, e.g. the yarn thickness, the fabric structure, the machine settings and the finishing process [27, 28].

The porosity of knitted fabrics can be assessed using various methods. One of these is to analyse the physical properties of knitted fabrics, such as air permeability, using standard test methods. Image processing methods using specialised software can also be used to determine porosity [29]. Porosity can also be determined theoretically by geometric modelling, which focuses on defining the loop shape and the geometric parameters of the knitted structures [29].

Guidoin defined porosity mathematically as the ratio of the void space within the boundaries of a solid material to the total volume occupied by this material, including the voids [30]. Jakšić and Jakšić's method is based on the selective squeezing out of liquid from the pores of wet fabrics by air pressure. The porosity parameters, such as the hydraulic diameter of the pores, the distribution of the pores, the open area for the liquid flow and the number of hydraulic pores, can be estimated. The parameters are estimated based on the measurement of air volume velocity through wet and dry samples as a function of air pressure [31].

1.3.2 Air permeability

The air permeability of a fabric is a measure of how well it allows air to pass through. It is the rate of air flow passing vertically through a known area under a prescribed air pressure difference between the two surfaces of a material, and is defined as the volume of air in millilitres that passes through 100 mm^2 of the material in one second at a pressure difference of 10 mm water column [25, 32].

Air permeability influences drying performance, as it helps to channel air through the fabric. The exchange of air between the clothing and the outside environment controls the thermal insulation and water vapour resistance of a fabric. When air is channelled through the fabric, there is a greater chance that the fabric will dry faster. In addition, the athlete's body releases heat and sweat during physical activity. The sweat is absorbed by the fabric, which becomes wet as a result. In this state of wetness, the air permeability of the fabric must be sufficient for effective vapour transport. If the air permeability of the fabric is insufficient, the sweat condenses on the skin, which reduces the drying performance of the fabric. High air permeability is therefore desirable in sportswear [33–36].

1.3.3 Water vapour permeability

The water vapour permeability of textiles is generally understood to be the ability of a permeable fabric to transmit water vapour through the textile structure, and is usually expressed in units [gm^{-2}/day^{-1}]. Various methods can be used to measure water vapour permeability [37].

The ability of clothing to transport water vapour away from the body is an important determinant of physiological comfort. During intense physical activity, sweating occurs to evaporate heat from the skin. If the clothing is not breathable, moisture builds up in the clothing and on the skin, making the body hotter. The amount of perspiration produced depends greatly on the level of activity. Clothing that may be comfortable during low activity may not wick away enough water vapour during high activity. However, when activity decreases, frostbite can occur as the clothing is now damp and the body's heat production has been reduced [25, 36, 38]. In addition, trapped moisture can heat up under hot conditions and lead to fatigue or reduced performance. Excessive moisture can also cause the garment to become heavy, increase the friction of the material and damage the skin through chafing. Moisture management is therefore one of the most important performance criteria in today's apparel industry [14, 39].

2 Experimental

2.1 Materials

2.1.1 Yarn selection

Seven conventional and high-performance polyamide and polyester yarns with a linear density of 150–190 dtex were selected for the development of fabrics for sportswear: conventional polyamide, recycled polyamide, antibacterial polyamide, water-management polyamide, thermal polyamide, conventional polyester and polyester yarn made from hollow fibres. Details of the properties of the individual yarns can be found in Table 1.

Table 1. Yarn details

Designation	Yarn material composition	Yarn specifics	Yarn linear density (dtex)
Y1	Polyamide 6 (100% PA 6)	conventional	180
Y2	Polyester (100% PES)	conventional	180
Y3	Polyamide 6.6 (100% PA 6.6)	recycled	180
Y4	Polyamide 6.6 (100% PA 6.6)	antibacterial	180
Y5	Polyamide 6.6 (100% PA 6.6)	water management	150
Y6	Polyamide 6.6 (100% PA 6.6)	thermal	170
Y7	Polyester (100% PES)	hollow fibre	190
YEA	Elastane (100% EL)	elastane	44

2.1.2 Fabric preparation

Two series of single jersey samples with and without incorporated elastane yarn were produced on a single-cylinder circular knitting machine (Lonati, Italy) in gauge E17 (Figure 1). Two series of double jersey samples were produced on a double-cylinder circular knitting machine (Mayer and Cie, Germany) in gauge E17, with and without incorporated elastane yarn (Figure 2). The yarn tension was set to approximately 3 cN. The fabric samples were knitted from yarns that were comparable in terms of linear density and raw material composition on a similar type of knitting machine.

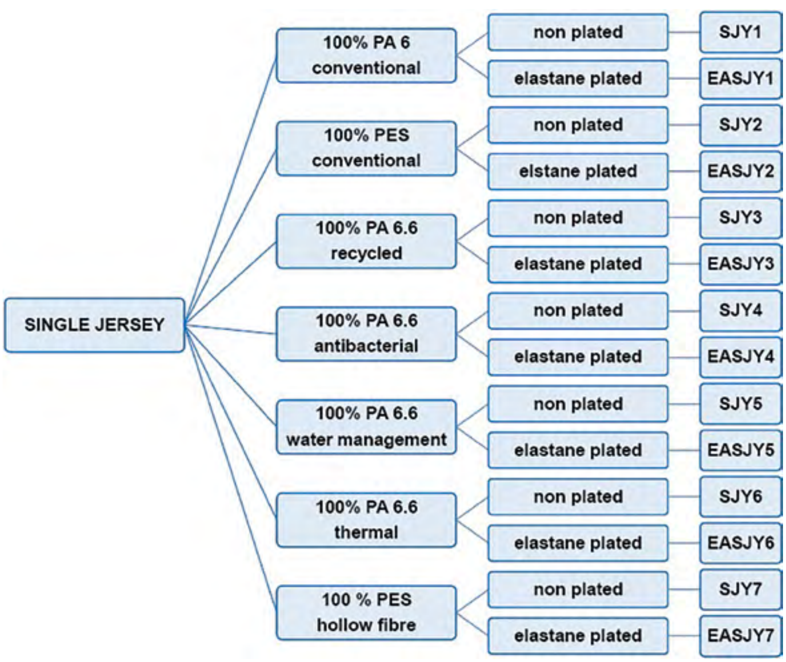


Figure 1: Single jersey sample designations

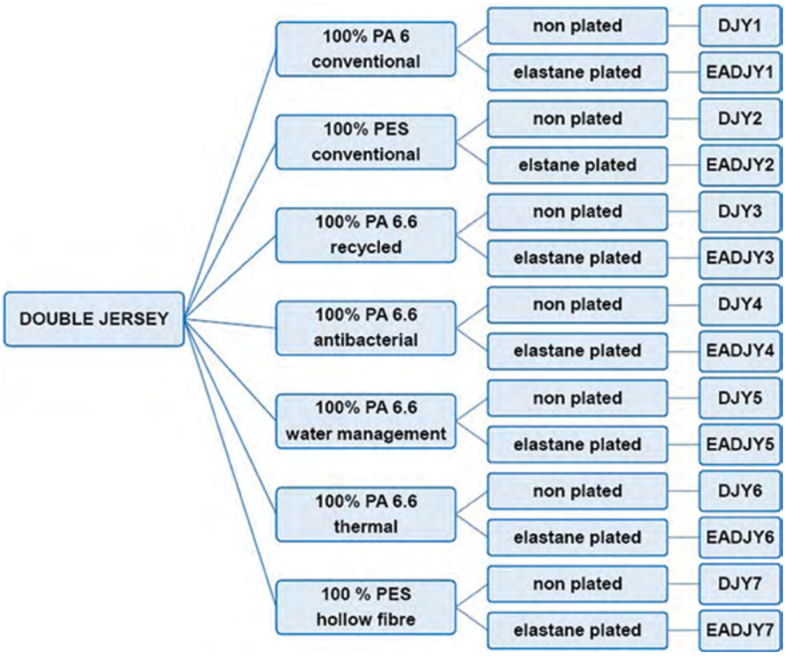


Figure 2: Double jersey sample designations

2.2 Methods of measurement

The manufactured knitted samples were tested for mass per unit area, fabric thickness, fabric area density, porosity, air permeability and water vapour permeability.

The mass per unit area of the materials was measured in accordance with the ISO 3801 standard [40], method 5. The fabric thickness was determined in accordance with EN ISO 5084: 1996 [41] using the DM 2000 Wolf thickness meter.

The number of loops/cm^2 was determined by counting the number of loops per unit length, vertically and horizontally, in accordance with EN 14971:2006 [42].

The porosity was determined by image analysis using an electronic microscope (Dino-Lite, Taiwan) to take images at 50x magnification, and the ImageJ software for image analysis [43]. An image of knitted fabric with clearly visible pores, taken on a white or illuminated background, was opened using the ImageJ software. Images should be converted from RGB to 8-bit type. The pore surface can be precisely adjusted using the Adjust Threshold function, if necessary. The software calculates the percentage of pore surface. Only vertical pores were visible in the fabric and could be measured using this method, as can be seen in the picture of double jersey DJY7 fabric (Figure 3).

Air permeability was measured using an Air Tronic air permeability tester (Mesdan, Italy) as the velocity of air flow in l/min passing vertically through the knitted samples. The test area was 20 cm^2, the pressure drop was set to 100 Pa and the measurement volume was 10 litres in accordance with EN ISO 9237:1995 [44.

The water vapour permeability was measured using a PCE - MA 100 instrument equipped with a selectively permeable membrane placed between the water cup and the specimen. The temperature of the instrument was set to 41°C and the drying time to 15 minutes. Each specimen was weighed before and after heating, and the results were used to calculate the water vapour permeability following the guidelines given in the ISO 15496 standard [45].

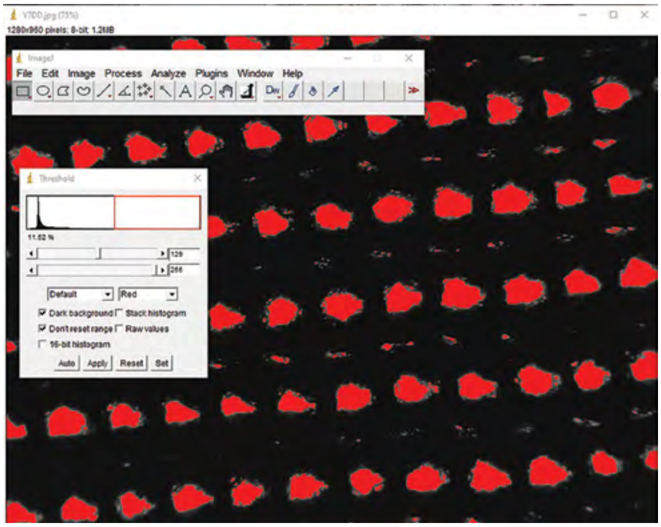


Figure 3: Double jersey sample image analysis in ImageJ software

3 Results and discussion

3.1 Knitted fabric structural parameters

The results of the measured structural parameters of the knitted fabric are shown in Table 2.

Table 2: Knitted fabric structural parameters

Designation	Mass per unit area (g/m^2)	Thickness (mm)	Density (loops/cm^2)
SJY1	111.61	0.800	180
SJY2	73.42	0.465	154
SJY3	109.02	0.646	143
SJY4	110.81	0.664	132
SJY5	105.45	0.669	168
SJY6	95.44	0.705	143
SJY7	118.86	0.725	154
EASJY1	242.54	1.044	187
EASJY2	143.48	0.696	168
EASJY3	197.85	1.016	168
EASJY4	190.88	1.020	176
EASJY5	185.07	1.006	204
EASJY6	184.29	0.988	204
EASJY7	166.48	0.958	176
DJY1	168.00	0.977	374
DJY2	146.00	0.841	260
DJY3	172.00	0.931	352
DJY4	168.00	0.933	320
DJY5	183.00	0.970	352
DJY6	161.00	0.947	352
DJY7	158.00	0.964	308
EADJY1	253.78	1.030	396
EADJY2	253.29	0.952	336
EADJY3	275.28	1.016	396
EADJY4	266.44	0.979	380
EADJY5	279.11	1.004	462
EADJY6	267.22	1.016	484
EADJY7	243.25	0.988	440

As expected, single jersey fabrics have the lowest measured mass per unit area among the fabrics tested, at an average of 103.5 g/m^2 (Table 2). The thickness of the fabrics is correspondingly low at an average of 0.668 mm. The average number of knitted loops is 153 loops/cm^2. By adding elastane yarn to the knitted structure, the fabric shrinks, the mass per unit area increases to 187.2 g/m^2, the thickness increases to 0.961 mm and the average number of knitted loops increases to 183 loops/cm^2.

The average mass per unit area of double jersey fabrics is 165.1 g/cm^2 and the thickness is 0.938 mm (Table 2). The number of knitted loops per cm^2 is significantly higher for double jersey fabrics than for single jersey fabrics with or without elastane, at average of 331 loops/cm^2. The average mass per unit area, the thickness and the number of knitted loops still increase with the addition of elastane yarn (mass per unit area 262.6 g/m^2, thickness 0.998 mm and number of knitted loops to 413 loop/cm^2) (Table 2).

3.2 Porosity

To facilitate the discussion of the results of the main properties on which this paper focuses (i.e. air and water vapour permeability), the fabrics were also tested for their porosity. The results are shown in Table 3.

Table 3. Porosity

Designation	Porosity (%)	Designation	Porosity (%)
SJY1	6.2	DJY1	5.2
SJY2	21.4	DJY2	18.5
SJY3	13.4	DJY3	5.4
SJY4	7.6	DJY4	9.6
SJY5	6.2	DJY5	5.8
SJY6	13.3	DJY6	8.2
SJY7	14.6	DJY7	11.5
EASJY1	3.5	EADJY1	3.6
EASJY2	6.4	EADJY2	9.3
EASJY3	1.1	EADJY3	0.3
EASJY4	2.3	EADJY4	1.1
EASJY5	0.5	EADJY5	3.7
EASJY6	1.0	EADJY6	0.7
EASJY7	2.7	EADJY7	6.1

As shown in Table 3, the porosity of the materials produced ranges from 0.5–21.4 %. The porosity of all produced fabrics decreases significantly with the addition of elastane. A comparison of the porosity of single jersey and double jersey fabrics shows that the porosity of most double jersey fabrics is slightly lower than that of single jersey fabrics. The only exception is the pair of knitted fabrics SJY4 and DJY4, where the porosity of the double jersey structure is slightly higher. The porosity results are analysed in more detail in sections 4.3. and 4.4.

The difference in porosity between two fabrics, single jersey SJY2, and double jersey DJY5 is shown in Figure 4.

3.3 Air permeability

The results of the air permeability of the tested knitted fabrics are shown in Table 4. The correlation of the air permeability with the structural parameters of the knitted fabric and the porosity is shown in Table 5.

Table 4: Air permeability

Designation	Air permeability (l/min)	Designation	Air permeability (l/min)
SJY1	138.56	DJY1	169.88
SJY2	265.15	DJY2	240.58
SJY3	149.08	DJY3	149.14
SJY4	139.96	DJY4	187.44
SJY5	152.12	DJY5	128.12
SJY6	159.18	DJY6	174.66
SJY7	157.10	DJY7	231.16
EASJY1	43.72	EADJY1	64.20
EASJY2	62.92	EADJY2	126.78
EASJY3	35.26	EADJY3	28.20
EASJY4	35.24	EADJY4	37.98
EASJY5	32.14	EADJY5	30.06
EASJY6	38.86	EADJY6	34.26
EASJY7	45.18	EADJY7	69.80

Under the test conditions of a test area of 20 cm^2, a pressure of 100 Pa and a measurement volume of 10 litres, the average air permeability for single jersey fabrics was as high as 165.9 l/min (Table 4).

For single jersey knitted fabrics, there is a strong negative correlation between the air permeability and the mass per unit area ($r = -0.8958$) and the thickness ($r = -0.8743$). The porosity and air permeability of single jersey fabrics show a strong positive correlation ($r = 0.8301$), as seen in Table 4. The average measured porosity of single jersey fabrics is 11.8% and is therefore the highest porosity of the four fabric groups (Table 3).

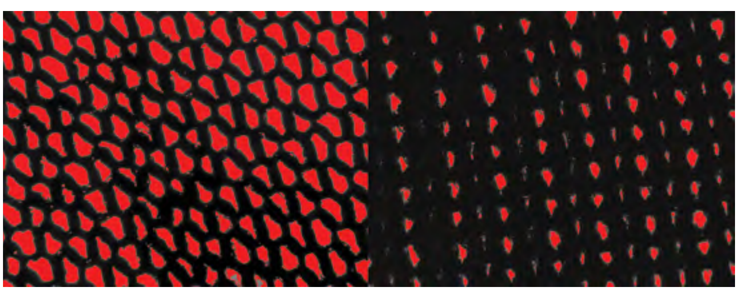


Figure 4: The difference in porosity between SJY2, and DJY5 in ImageJ software

Regarding the influence of the yarns used on the air permeability property, the results showed that the use of standard PES yarn increased the air permeability in all observed knitted structures. This was also evident when using PES hollow yarn. Regarding the use of recycled yarn, the results showed that the air permeability decreases in most cases when using recycled yarn (more specifically in EASJ, DJ and EADJ). Regarding the use of functional PA yarns compared to standard PA yarns, no clear change was seen in the observed knitted structures. This was expected, as the functional yarns are designed to perform better for a specific property (in this case, water vapour and thermal management).

Table 5. Correlation of air permeability with the knitted fabric structural parameters and porosity

Air permeability	Yarn count	Mass per unit area	Thickness	Horizontal density	Vertical density	Density	Porosity
SJ	0.1154	-0.8958	-0.8743	-0.3155	0.1844	-0.0171	0.8301
EASJ	0.4485	-0.5019	-0.8961	0.0471	-0.4734	-0.4683	0.9454
DJ	0.7076	-0.9242	-0.5699	-0.5175	-0.8223	-0.8313	0.8796
EADJ	0.4185	-0.7081	-0.6763	0.7245	-0.7902	-0.6400	0.9147

The addition of elastane yarn to the knitted structure drastically reduces air permeability by 75% to 41.9 l/min (Table 4). Elastane-plated single jersey fabrics show a strong negative correlation of air permeability with fabric thickness (r = -0.896) and a medium negative correlation with mass per unit area (r = -0.5019) and the number of knitted loops (r = -0.4683). As expected, the porosity of the elastane-plated single jersey fabric and the air permeability of the fabrics show a strong positive correlation (r = 0.9454), as seen in Table 5. The addition of elastane yarn in a single jersey structure reduces the average porosity from 11.8% to 2.5% (Table 3).

Under the test conditions described, double jersey fabrics show higher air permeability than single jersey fabrics. The air pressure under the conditions prescribed by the norm strongly stretches the fabric, which favours the greater air permeability of the stretchable double jersey fabric. The average air permeability for double jersey fabrics was up to 183.0 l/min (Table 4). Double jersey fabrics show a strong negative correlation with the mass per unit area (r = -0.9242) and the number of knitted loops (r = -0.8313), as well as an average negative correlation with the fabric thickness (r = -0.5699). The correlation between the air permeability and porosity of double jersey fabrics is r = 0.8796 (Table 5). The average measured porosity of double jersey fabrics is 9.2% (Table 3) and is therefore lower than the porosity of single jersey fabrics. This is due to the double structure of double jersey fabrics and the measurement limitation of the software used for vertical pores in the fabric.

With the elastane plating in a double jersey structure, the air permeability is reduced by 69% and is now 55.9 l/min (Table 4). Elastane-plated double jersey fabrics show a negative correlation with mass per unit area (r = -0.7081), the number of knitted loops (r = -0.6400) and the fabric thickness (r = -0.6763). The correlation between the air permeability and porosity of elastane-plated double jersey fabrics is strong (r = 0.9147), as seen in Table 5. The addition of elastane yarn in a double jersey structure reduces the average porosity from 9.2% to 3.5% (Table 3).

Within all four groups of knitted fabrics, it was statistically confirmed that the mass per unit area and the thickness of the fabric have a strong negative effect on the speed of the airflow, while the porosity of the knitted fabric has a strong positive effect on the speed of the airflow, which should be taken into account when designing the fabric.

A comparison of the data between the four groups of samples shows that double jersey fabrics allow a greater air flow through the fabric than single jersey, although the mass per unit area and the thickness of the fabrics in this group of samples are significantly higher. This is probably due to the measuring method using an Air Tronic device, in which the double structure of the knitted fabric opens up under air pressure. The mass per unit area and the thickness of elastane-plated single and double jersey fabrics are higher than in the other two fabric groups, and the porosity is lower, so that the air permeability is drastically reduced.

For this reason, sportswear that would ensure high air permeability and thus the comfort of athletes in competitive sports should be made from single jersey or double jersey knitwear without the addition of elastane. An exception is made for sports that also require pressure to be exerted on the muscles, such as competitive swimming. In the case of leisure sportswear or fashionable sportswear, the fit of the clothing can also be more important than greater air permeability, which is why materials with elastane are chosen.

3.4 Water vapour permeability

The results of the measured water vapour permeability of knitted fabrics are shown in Table 6. The correlation of the water vapour permeability with the knitted fabric structural parameters and the porosity is shown in Table 7.

In terms of water vapour permeability, the tested single jersey fabrics show a very strong negative correlation with the fabric thickness (r = -0.8276) and a strong negative correlation with the mass per unit area (r = -0.7038), as seen in Table 7. The horizontal and vertical density do not play a significant role for the produced group of fabrics and the observed property.

Table 6: Water vapour permeability

Designation	Water vapour permeability (g/m^2h)	Designation	Water vapour permeability (g/m^2h)
SJY1	314.37	**DJY1**	140.27
SJY2	374.10	**DJY2**	215.87
SJY3	335.74	**DJY3**	125.73
SJY4	348.95	**DJY4**	135.87
SJY5	314.36	**DJY5**	132.80
SJY6	311.85	**DJY6**	158.00
SJY7	292.36	**DJY7**	101.33
EASJY1	266.49	**EADJY1**	120.60
EASJY2	342.66	**EADJY2**	159.60
EASJY3	275.35	**EADJY3**	111.40
EASJY4	306.49	**EADJY4**	90.80
EASJY5	283.80	**EADJY5**	98.80
EASJY6	270.15	**EADJY6**	102.80
EASJY7	266.49	**EADJY7**	93.60

The results indicate that the addition of elastane yarns to the structure of the single jersey fabric causes a reduction in water vapour permeability from 8% to 18%. Regarding the correlation between the parameters of the fabric group with elastane and the water vapour permeability, there is a very strong negative correlation with the fabric thickness (r = -0.8138), as seen in Table 7. As with the single jersey structures without elastane, there is a negative correlation with the fabric mass per unit area (r = -0.6121). The porosity is positively correlated with the water vapour permeability (r = 0.6867), as seen in Table 7.

Table 7: Correlation of water vapour permeability with knitted fabric structural parameters and porosity

Water vapour permeability	Yarn count	Mass per unit area	Thickness	Density horizontal	Density vertical	Density	Porosity
SJ	0.0935	-0.7038	-0.8276	-0.3240	-0.3044	-0.3410	0.4316
EASJ	0.0325	-0.6121	-0.8138	0.2502	-0.5648	-0.4416	0.6867
DJ	-0.0813	-0.5926	-0.8344	-0.6018	-0.4420	-0.5461	0.6593
EADJ	0.1526	-0.2774	-0.4162	0.8367	-0.8591	-0.6705	0.6513

The water vapour permeability of double jersey fabrics is in the range of 101–215 g/m^2h. Compared to single jersey fabrics, it decreases significantly, by up to 65%. The correlation coefficients show that the water vapour permeability for this fabric group is strongly negatively correlated with the fabric thickness (r = -0.8344), followed by the mass per unit area. Porosity has a positive influence on water vapour permeability in this material group (r = 0.6593), as seen in Table 7.

The results indicate that the addition of elastane yarns to the structure of double jersey fabrics causes an even greater decrease in water vapour permeability than in single jersey fabrics. The decrease is between 7% and 34%. In this group of fabrics, the loop density is more negatively correlated with water vapour permeability than other fabric properties ($r = -0.8591$). Porosity has a positive influence on the water vapour permeability of double jersey fabrics with elastane ($r = 0.6513$), as seen in Table 7.

Regarding the influence of yarn type on water vapour permeability, the results show that the use of recycled polyamide yarn contributes to an increase in water vapour permeability in SJ and EASJ knitted fabrics. Regarding the functional yarns used, the use of yarn with water management capabilities has been shown to have a similar effect on the observed property as the use of yarns with thermal management. However, the use of the same yarn leads to an increase in the water vapour permeability compared to the hollow yarn. In this case, the yarn with water management is therefore preferable for the production of sportswear.

4 Conclusion

The results of this study show that the air permeability of all four fabric groups, e.g. single jersey, elastane-plated single jersey, double jersey and elastane-plated double jersey, correlates strongly with the measured porosity of the fabrics. It should be kept in mind that the measured porosity is only an approximation of the actual porosity. The air permeability of knitted fabrics is negatively correlated with the mass per unit area of the fabric, especially for fabrics without elastane, and with the thickness of the fabric. Elastane contributes only slightly to the mass of the unit area of the fabric but reduces the porosity considerably, meaning this behaviour is consistent with the expected result of adding elastane to the structure. The average air permeability of single jersey fabrics decreases from 165.88 l/min to 41.90 l/min with the addition of elastane. The average air permeability of double jersey fabrics decreases from 183.00 l/min to 55.90 l/min with the addition of elastane.

The water vapour permeability of single jersey, elastane-plated single jersey and double jersey fabrics is mainly negatively correlated with the thickness of the fabric. In the case of elastane-plated double jersey fabrics, however, there is a correlation with the fabric density. The average water vapour permeability of single jersey fabrics is significantly higher than that of double jersey fabrics. The addition of elastane to single jersey fabrics reduces the water vapour permeability from 327.39 g/m^{2}h to 287.35 g/m^{2}h, while it reduces the water vapour permeability of double jersey fabrics from 144.27 g/m^{2}h to 111.09 g/m^{2}h. Regarding the functional yarns used, it was shown that the use of yarns with increased water management capabilities has a greater potential for the transfer of water vapour than the hollow yarns, similar to the yarns with thermal management.

Acknowledgment: This work was fully supported by the Croatian Science Foundation under the project IP-2020-02-5041 Textile Materials for Enhanced Comfort in Sports – TEMPO.

References

1. BARTELS, V.T. Physiological comfort of sportswear. In: *Textiles in sport*. Edited by R. Shishoo. Cambridge : Woodhead Publishing, 2005, 176–203, doi: 10.1533/9781845690885.3.177.
2. Performance knited fabrics market analysis [online]. Fact.MR [accessed 3.1.2024]. Available on World Wide Web: <https://www.factmr.com/report/performance-knitted-fabrics-market>.
3. Sports textiles market report, global forecast from 2023 to 2031 [online]. Dataintelo [accessed 5.1.2024]. Available on World Wide Web: <https://dataintelo.com/report/global-sports-textiles-market/.

4. SHISHOO, R. Introduction. In *Textiles in sport*. Edited by R. Shishoo. Cambridge : Woodhead Publishing, 2005, 1–11.
5. DHANAPALA, S. An overview of the sportswear market. In *Materials and technology for sportswear and performance apparel*. Edited by Steven George Hayes and Praburaj Venkatraman. Boca Raton : CRC Press, 2016, 1–22.
6. Sportech textiles market analysis report 2023-2027 [online]. Technavio [accessed 5.1.2024]. Available on World Wide Web: <https://www.technavio.com/report/sportech-textiles-market-industry-analysis>.
7. HATAMLOU, M., ÖZGÜNEY, A. T., ÖZDIL, N., MENGÜÇ, S.G. Performance of recycled PET and conventional PES fibers in case of watertransport properties. *Industria Textila*. 2020, **71**(6), 538-544, doi: 10.35530/IT.071.06.1691.
8. CLAUSSEN, L., LLOYD, A., RUIZ, D., HAVENITH, G. Recycled versus virgin polyester sportswear – can a difference be perceived in actual use? *International Journal of Fashion Design, Technology and Education*, 2024 [in press], doi: 10.1080/17543266.2023.224742.
9. CHOI, Y. J., KIM, S.H. Characterization of recycled polyethylene terephthalates and polyethylene terephthalate – nylon6 blend knitted fabrics. *Textile Research Journal*, 2015, **85**(4), 337–345, doi:10.1177/0040517514547207.
10. SOUZA, J. M., SAMPAIO, S., SILVA, W.C., de LIMA, S.G., ZILLE, A., FANGUEIRO, R. Characterization of functional single jersey knitted fabrics using non-conventional yarns for sportswear. *Textile Research Journal*, 2018, **88**(3), 275–292, doi: 10.1177/0040517516677226.
11. DAUKANTIENE, V., VADEIKE, G. Evaluation of the air permeability of elastic knitted fabrics and their assemblies. *International Journal of Clothing Science and Technology*, 2018, **30**(6), 839–853, doi: 10.1108/IJCST-02-2018-0021.
12. SABIR, T., WOOD. J. Fabrics for performance clothing. In *Materials and Technology for Sportswear and Performance Apparel*. Edited by Steven George Hayes and Praburaj Venkatraman. Boca Raton : CRC Press, 2016, 87–102.
13. VENKATRAMAN, P. Fibres for sportswear. In *Materials and technology for sportswear and performance apparel.* Edited by Steven George Hayes and Praburaj Venkatraman. Boca Raton : CRC Press, 2016, 23–52.
14. HARLIN, A., JUSSILA, K., ILEN, E. Sports textiles and comfort aspects. In *High performance technical textiles*. Edited by Roshan Paul. Hoboken : Wiley, 2019, doi: 10.1002/9781119325062.ch3.
15. 7 things you need to know about polyester [online]. ISPO [accessed 3.2.2024]. Available on World Wide Web: <https://www.ispo.com/en/products/7-things-you-need-know-about-polyester>.
16. HALLETT, C., JOHNSTON, A. *Fabric for fashion: the complete guide*. London : Laurence King, 2014, 192–196.
17. The benefits of sportswear nylon fabrics [online]. Yitai Knitting [accessed 15.1.2024]. Available on World Wide Web: <https://www.yitaifabrics.com/news/the-benefits-of-sportswear-nylon-fabrics.html>.
18. MILITKÝ, J., VENKATARAMAN, M., MISHRA, R. The chemistry, manufacture, and tensile behavior of polyamide fibers. In *Handbook of properties of textile and technical fibres*. Edited by Anthony R. Bunsell. Cambridge : Woodhead Publishing, 2018, 367–420, doi: 10.1016/B978-0-08-101272-7.00012-2.
19. KEJKAR, V., DHORE, R. Active sportswear fabrics. *Trends in Textile Engineering & Fashion Technology*, 2019, **5**(2), 603–608, doi: 10.31031/tteft.2019.05.000606.
20. GILL, S., PRENDERGAST, J. Garment fit and consumer perception of sportswear. In *Materials and technology for sportswear and performance apparel.* Edited by Steven George Hayes and Praburaj Venkatraman. Boca Raton : CRC Press, 2016, 245–260.
21. VENKATRAMAN, P. Fabric properties and their characteristics. In *Materials and technology for sportswear and performance apparel.* Edited

by Steven George Hayes and Praburaj Venkatraman. Boca Raton : CRC Press, 2016, 53–86.

22. Development of functional knitted sportswear fabric [online]. Shaoxing Liuyi Textile [accessed 10.1.2024]. Available on World Wide Web: <https://www.lymeshfabric.com/news/development-of-functional-knitted-sportswear-fabric/>.
23. HU, J., LU, J. Recent developments in elastic fibers and yarns for sportswear. In *Textiles for sportswear*. Edited by Roshan Shishoo. Cambridge : Elsevier, 2015, 53–76, doi: 10.1016/B978-1-78242-229-7.00003-5.
24. ANGELOVA, R.A. *Textiles and human thermophysiological comfort in the indoor environment*. Boca Raton : CRC Press, 2015, 3–10.
25. SAVILLE, B.P. *Physical testing of textiles*. Cambridge : Woodhead Publishing, 1999, 209–243.
26. AHMAD, F., AKHTAR, K.S., ANAM, W. MUSHTAQ, B., RASHEED, A., AHMAD, S., AZAM, F., NAWAB, Y. Recent developments in materials and manufacturing techniques used for sports textiles. *International Journal of Polymer Science*, 2023, **2023**, 1–20, doi: 10.1155/2023/2021622.
27. RAMRATAN, KUMAR, R., SOOD, S. A study on porosity related aspects of cotton knitted fabric with single jersey structure for improved comfort application for garment. *Journal of Textile Engineering & Fashion Technology*, 2020, **6**(5), 199–204, doi: 10.15406/jteft.2020.06.00251.
28. MEZARCIÖZ, S., OĞULATA, R.T. Modelling of porosity in knitted fabrics. *Journal of Fashion Technology & Textile Engineering*, 2015, **1,** 1–3, doi: 10.4172/2329-9568.S1-005.
29. ABDOLMALEKI, S., JEDDI ALI, A.A., AMANI, M. Estimation on the 3D porosity of plain knitted fabric under uniaxial extension. *Fibers and Polymers*, 2012, **13**(4), p. 535–541, doi: 10.1007/s12221-012-0535-8.
30. 30. GUIDOIN, R., KING, M., MARCEAUAT, D., CARDOU, A. Textile arterial prostheses: Is water permeability equivalent to porosity? *Journal of Biomedical Materials Research*, 1987, **21**(1), 65–87, doi: 10.1002/jbm.820210111.
31. JAKŠIĆ, D., JAKŠIĆ, N. Assessment of porosity of flat textile fabrics. *Textile Research Journal*, 2007, **77**(2), 105–110, doi: 10.1177/0040517506065892.
32. ONOFREI, E., ROCHA, A.M., CATARINO, A. The influence of knitted fabrics' structure on the thermal and moisture management properties. *Journal of Engineered Fibers and Fabrics*, 2011, **6**(4), 1–13, doi: 10.1177/155892501100600403.
33. BOUSKILL, L., HAVENITH, G., KUKLANE, K., PARSONS, K., WITHEY, W. Relationship between clothing ventilation and thermal insulation. *AIHA Journal*, 2002, **63**(3), 262–268, doi: 10.1080/15428110208984712.
34. NAYAK, R., KANESALINGAM, S., HOUSHYAR, S., WANG, L., PADHYE, R., VIJAYAN, A. Evaluation of thermal, moisture management and sensorial comfort properties of superabsorbent polyacrylate fabrics for the next-to-skin layer in firefighters' protective clothing. *Textile Research Journal*, 2017, **88**(9), 1077–1088, doi: 10.1177/0040517517697640.
35. NASRIN, S., MANDAL, S., ISLAM, M.D.M., PETROVA, A., AGNEW, R.J., BOORADY, L.M. Factors affecting the sweat-drying performance of active sportswear – a review. *Textiles*, 2023, **3**(3), 319–338, doi: 10.3390/textiles3030022.
36. BIVAINYTĖ, A., MIKUČIONIENĖ, D. Investigation on the air and water vapour permeability of double-layered weft knitted fabrics. *Fibres & Textiles in Eastern Europe*, 2011, **19**(3), 69–73.
37. HAVLOVA, M. Air permeability, water vapour permeability and selected structural parameters of woven fabrics. *Vlákna a Textil*, 2020, **27**(1), 12–18.
38. Fabrics for sportswear [online]. Fabric blog [accessed 9.1.2024]. Available on World Wide Web: <https://blog.fabricuk.com/974-2/>.
39. BRENDLEY, K.W., STEEB, R. *Military applications of microelectromechanical systems*. Santa Monica : National Defence Research Institute, 1993, 66 p.
40. ISO 3801:1977 Textiles – Woven fabrics – Determination of mass per unit length and mass per

unit area. Geneva : The International Organization for Standardization, 1977, 1–4.

41. ISO 5084:1996 Textiles – Determination of thickness of textiles and textile products. Geneva : The International Organization for Standardization, 1996, 1–5.
42. EN 14971:2006 Textiles – Knitted fabrics – Determination of number of stitches per unit length and unit area. Geneva : International Organization for Standardization, 2006, 1–12.
43. Dino-lite digital microscope [online]. Dino-Lite [accessed 9.2.2024]. Available on World Wide Web: <https://www.dino-lite.com/index.php>.
44. EN ISO 9237:1995 Textiles – Determination of the permeability of fabrics to air. Geneva : International Organization for Standardization 1995, 1–5.
45. ISO 15496:2018 Textiles: Measurement of water vapour permeability of textiles for the purpose of quality control. Geneva : International Organization for Standardization, 2018, 1–13.

R.A.H.S. Ranawaka,[1] S.D.M.W. Kularatne,[1] E.A.S.K. Fernando1, S.N. Niles,[1] T.S.S. Jayawardane,[1] R.K.P.S. Ranaweera[2]
[1] Department of Textile and Apparel Engineering, University of Moratuwa, Moratuwa, Sri Lanka
[2] Department of Mechanical Engineering, University of Moratuwa, Moratuwa, Sri Lanka

Developing a Medical Garment for Upper-Body Posture-Related Issues

Razvoj medicinskega oblačila za izboljšanje drže zgornjega dela telesa

Original scientific article/*Izvirni znanstveni članek*
Received/*Prispelo* 2-2024 • Accepted/*Sprejeto* 5-2024

Corresponding author/*Korespondenčni avtor:*
Nilhan Niles
E-mail: nilhan.niles@gmail.com
ORCID: 0000-0002-1161-0889

Abstract

The increase in incorrect posture in the daily lifestyle of many individuals has led to numerous issues. Of these, lower back pain is recognized as the most common posture-related medical condition. Existing effective solutions for posture-related issues are complex to use, and are diverse in nature, ranging from the identification of the problem to the correction of posture. In this research, an attempt was made to provide an effective solution in the form of a short sleeve undershirt with carefully designed extensible structures matching the required reinforcement for different segments of the spine. The additional functionality of the proposed garment was verified through proper scientific testing using sEMG. The correction mechanism utilizes a combination of sensory tension applied to the wearer and the reinforcement of the spine with a specially made backbone structure attached to a custom-made garment. Woven narrow bands and warp knitted fabrics were used in the garment. The backbone structure is strategically placed on the garment to control the specific muscles related to correct postural balance. It was found that the garment reduces the activation of certain back muscles and promotes voluntary posture correction.
Keywords: posture modification, posture correction, posture measurement orthosis garment, narrow bands with predefined elasticity

Izvleček

Zaradi sodobnega načina življenja ima vse več posameznikov probleme z nepravilno držo. Bolečina v spodnjem delu hrbta je dokazano najpogostejša težava, ki je povezana z neustrezno držo. Obstoječe rešitve za opozarjanje in popravljaje drže učinkovito odpravljajo težave nepravilne drže, a je njihova uporaba zapletena. V tej raziskavi je bila za učinkovitejšo rešitev problema poskusno izdelana spodnja majica s kratkimi rokavi in skrbno oblikovanimi raztegljivimi strukturami, ki ustrezajo zahtevanim ojačitvam posameznih delov hrbtenice. Funkcionalnost predlaganega oblačila je bila preverjena z znanstvenim testiranjem z uporabo površinske elektromiografije, sEMG. Zaznavanje in prilagajanje napetosti v hrbtenici omogoča korekcijski mehanizem v hrbtenični strukturi, izdelani

po meri uporabnika, ki je vgrajena v oblačilo. Oblačilo je bilo izdelano iz snutkovnega pletiva in tkanih ozkih trakov. Hrbtenična struktura je bila v oblačilo strateško nameščena tako, da lahko nadzira specifične mišice, povezane s pravilnim ravnotežjem, tj. uravnavanjem drže. Ugotovljeno je bilo, da oblačilo zmanjša aktivacijo določenih hrbtnih mišic in spodbuja prostovoljno popravljanje drže.
Ključne besede: sprememba drže, korekcija drže, oblačilo za merjenje in korekcijo drže, ozki trakovi z načrtovano elastičnostjo

1 Introduction

In today's context, people live busy lives. As a result, many aspects of good health, including good body posture, tend to be neglected. Due to a sedentary and complicated lifestyle, much time is spent in unhealthy postures [1]. This results in soreness and pain in the lower back, the misalignment of the spine or knees, poor blood circulation, fatigue and forward head posture. These are some of the most common musculoskeletal disorders (MSDs) affecting people today [2]. Furthermore, these primary effects can lead to secondary effects such as bad mood, headaches and ineffective breathing [3]. Having good posture is advantageous as it eases lower back pain, decreases stress on ligaments, and prevents backache and muscular pain, while indirect benefits include a good appearance and confident posture.

Non-specific musculoskeletal disorders (MSDs) represent one of the most common disorders affecting people in industrialized countries. For instance, a Chinese survey revealed that MSDs involved the neck (25.16%), shoulders (17.17%) and upper back (13.29%) [4]. Factors that contribute to the risk of developing back pain include high a body mass index (BMI), a low level of exercise and weak back strength [5]. Biomechanical factors include non-neutral static posture, frequent bending and twisting, as well as whole-body vibration [5]. Any work situation requiring the repetitive bending of joints and/or twisting for long periods, or sustained bending therefore leads to the risk of back pain [6]. Factors such as low social support in the workplace and low job satisfaction are among the psychosocial factors causing lower back pain [7]. These factors are the most powerful predictor of progression to chronicity [7]. Furthermore, various studies have estimated that neck and shoulder pain affect approximately 42.33% of the working population annually [4]. This is common today because of the increased use of computers and improvements in the manufacturing processes, resulting in faster speeds and shorter work cycles [5]. It is thus evident that unhealthy posture is a major contributor to many common upper-body musculoskeletal disorders.

Postural control is defined as the control of the body's position in space for the purposes of balance and orientation [8]. The focus of this research was the correction of upper-body posture. Correcting upper-body posture therefore involves maintaining the optimum shape of the spine so that the spine, muscles and ligaments are not overstressed. Various posture modification techniques have been developed in the recent past, with posture-related issues becoming more common. Some of the most popular methods are surgical treatments, specific training/exercises, orthoses, wearable electronic devices and soft material structures [9].

Surgical methods are used to correct permanent posture deformities and relieve pain, and is only used for clinical treatment. Studies show that the primary aim of exercise therapy is to strengthen back muscles, increase the spinal flexibility of the patient and improve kyphotic deformity, but is typically insufficient for improving posture [10, [11]. An orthosis is a brace, splint or other artificial external device to support the limbs or spine, or to prevent or assist relative movement. These are usually recommended for patients who suffer from severe spinal diseases. Although orthoses are generally effective in modifying posture, they can cause other health issues. Moreover, some researchers have emphasized that problems such as bulkiness, device discomfort, limited body movements and attracting unwanted attention may lead to reduced wearer acceptability [12]. Perhaps the best way to correct posture is to improve awareness of the current body posture. Wearable solutions use sensors to detect the body posture and make the wearer aware when posture begins to slip. This technique is relatively new, yet has been effective. One of the shortcomings of using wearable electronic devices is that products remain very expensive because the technology is till emerging [13].

Clothes may restrict body movement. At the same time, clothing pressure occurs between the body surface and clothes. When elastic bands have been stretched in an extensible textile material such as stretch fabrics, they tend to return to their original shape. This exerts clothing pressure on body muscles. The intensity of clothing pressure can be used to correct body shapes and to solve health issues. [14].

In this research, the goal was to develop a textile-based solution for upper-body posture-related issues, with a primary focus on lower back pain (LBP), and to provide scientific proof for the effectiveness of the product. The target group was office workers with sedentary lifestyles. The proposed product can be categorized as a soft-material structure, and is therefore targeted for non-clinical treatment. The product is a tight-fitting short sleeve undergarment with elastic bands strategically placed on the back of the garment to reinforce the spinal column and to apply a sensory tension on the wearer when the posture slips from its ideal position.

A survey of the market indicates that various posture modification products have been developed. However, there is a lack of academic research in this area to question the effectiveness of prior work. The ALIGNMED Posture Shirt, Intelliskin Posture Shirt and TruPosture smart shirt are some examples of commercially available products. The ALIGNMED Posture Shirt is a product based on the correction of posture by providing mechanical support for the spine and upper body muscles. It uses elastomeric materials to reinforce the spine and control the movement of muscles. The Intelliskin Posture Shirt employs a similar technology to ALIGNMED. The mechanism of posture correction is also similar. The TruPosture smart shirt is be considered smart clothing in which sensors are embedded into the garment itself to measure the curvature of the spinal column. TruPosture features connectivity via Bluetooth, enabling the transmission of spine curvature data to a free app available for iOS and Android.

Even though all of these products have their own pros and cons, they have certain general drawbacks. Despite the high correlation between the anatomy of the spine and LBP, previous products tend to focus less on the spinal anatomy. Given the importance of the vertebral column, any product intended to provide relief for LBP must adjust its features according to the spinal flexion-extension behaviour. Another deficiency in previous products is a lack of scientific proof of the effectiveness of the products. Commercial products tend to rely on consumer feedback as proof of product effectiveness. Consumer feedback is subjective, and is not the best practice to determine the effectiveness of a product. This can be identified as another research gap in the field, as there are no widely accepted test methods for posture correction garments. Furthermore, it has been noted that most of products with good user feedback are priced above $100, making them expensive for most developing countries. While it is surmised that a textile-based solution may be cheaper to manufacture, this research concentrated on the development of a prototype, while not attempting to evaluate the cost-effectiveness of the solution.

When a posture modification product is developed, a method for measuring posture, before, during and after use, is essential. Several methods have been developed to measure posture, including qualitative methods, such as posture rating scales, or quantitative methods, such as body angle/distance calculation methods. However, qualitative evaluations require subjective judgments by the evaluators, and were thus unsuitable for this research. The two methods utilized in this research are motion analysis and wearable sensors. In the motion analysis method, markers are placed on various body segments and their relative positions are analysed for different postures. Yi-Liang Kuo *et al.* [15] used this method to quantify and compare sagittal spinal posture in standing and sitting positions between young and older adults using a two-dimensional revised skin marker model. The researchers stated that the angular relationship between adjacent spinal regions in the sagittal plane can be objectively quantified using image-based analysis [15]. Another method is the use of wearable sensors to measure relative positions and the movement of the body. This is somewhat similar to motion analysis in the sense that markers and sensors are placed on various body parts in both methods. The advantage of this method is its high degree of accuracy. Most recent research is based on this method. One of the disadvantages of wearable sensors is the cost of the required equipment. Dunne *et al.* [16] used this method to monitor seated spinal posture with a wearable plastic optical fibre (POF) sensor. They stated that with a very minimal compromise of the user's comfort and status quo, it is possible to monitor their seated posture with greater accuracy than expert visual analysis.

Lyu and Labat devised a Posture Modification System using Soft material Structures (PMSS), in which textile elastic bands were used to simulate the body structure and the placement of muscles and spinal column in a woman's torso. The PMSS was incorporated into a shapewear garment, and the researchers claim that in a survey on the use of the system, most participants were more satisfied with the effects of the PMSS-incorporated shapewear than with other garments. However they acknowledged that the developed garment was more difficult to put on and take off [17].

2 Materials and methods

The product presented is a stretchable tailor-made garment with a separate structure attached to the back of the garment called the backbone structure. This separately made structure imparts postural controls to the body, supported by the anchoring hem panel (Figure 1). The specially made backbone structure has two main functions. First, it reinforces the spinal column, and second, it applies a sensory tension on specific muscle groups. It was developed in such a way that it models the flexion-extension behaviour of the spine. The specific design concepts will be explained in the subsequent sections. The product design was constructed using following the steps given below.

i. Establishment of the preliminary design and posture correction mechanism
ii. Development of the backbone structure
iii. Construction of the posture correction garment

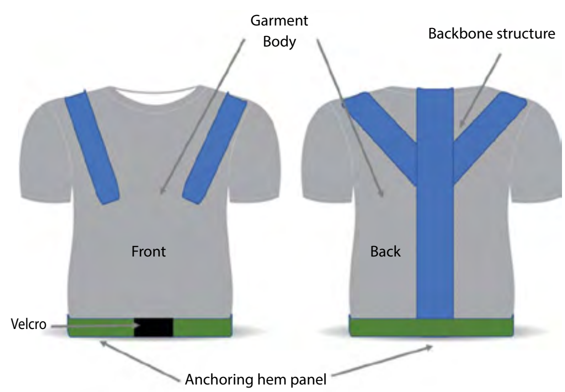


Figure 1: Design of the product

2.1 Establishment of the preliminary design and posture correction mechanism

In the first step, the basic structure of the garment was developed. The idea was to use a biomimicry approach for the design. Biomimicry is the imitation of the models, systems and elements of nature to solve complex human problems [18]. Here, elastic bands were strategically positioned at the posterior of the garment aligned with the skeleton and specific back muscles. They were then combined with a compressive garment to provide support through compression and to apply corrective forces in the form of tension. Primarily garment design has three basic structures, as seen in Figure 1.

i. Backbone structure: the backbone structure was made with elastomeric materials to reinforce the spine and control the movement of the upper body. It was made separately and attached to a tight-fitting garment body. The material stretches in the longitudinal direction but not in the width-wise direction. The structure is composed of three main parts. Part 1 is known as the reinforcement panel and is responsible for reinforcing the spine (reinforcing action). The remaining two panels are known as side panels, and they prevent the upper body from slouching or flexing forward. When the wearer flexes forward the side-straps are activated and produce a sensory tension, letting the wearer know that their posture is incorrect (sensory action).
ii. Garment body: the garment body is responsible for holding the backbone structure against the body. A porous low modulus warp knitted fabric was considered for the body material so that it will not affect the stretch properties of the backbone. Moreover, the moisture management and flexibility of the garment can be achieved due to its porous structure.
iii. Anchoring hem panel: the backbone structure will not produce any tension if it is held only at one end. If the garment is not anchored at the bottom it will slip as the garment stretches. The anchoring hem panel is therefore responsible for providing the necessary grip so that the backbone structure is maintained at an optimum tension. The anchoring hem panel is also an elastic material with a Velcro panel attached at the front so that wearer can adjust its tightness.

2.2 Development of the backbone structure

The construction of the backbone was determined in this step. The idea here was to mimic the flexion-extension behaviour of the vertebral column and position the backbone structure strategically to assist back trunk muscles. The flexion-extension behaviour of the spine is nonlinear [19]. That is the extensions/flexions of the spine in different regions are different from each other. In order to model this behaviour with the backbone structure, the reinforcement panel was made with three different tensile moduli to provide different levels of tightness along the spine. These three moduli are meant to be positioned along the lumbar, lower thoracic and upper thoracic regions. The extension behaviour of the different regions of the spine was studied utilizing the stretch sensor-based posture measuring method explained in the experiments. The sensor was attached to the posterior of the test subject, who adjusted its effective length using crocodile clips and scotch tape so that the sensor was in line with the lumbar, lower thoracic and upper thoracic regions. The experimental set up is shown in Figure 4. The wearer was asked to perform a predetermined slouching action while wearing the sensor. The details of the use of the sensor are given in Section 4.2, while the experimental protocol is the same as explained in Section 4.1. Experimental results showed that the extension of the lumbar, lower thoracic and upper thoracic regions increases in the same order during the slouching action. Hence, to model the extension behaviour of the spine, the backbone structure must be tightest in the lumbar region, and the tightness should gradually reduce from the lumbar to the upper thoracic region. Based on prior literature and experimental results, the following inferences and decisions were made:

- The lumbar region has the least amount of extension during slouching, while the upper thoracic region extends the most. The extension of the lower thoracic region falls between the extension level of the other two regions. Therefore, the reinforcement panel should be tighter in the lumbar region than in the other two regions, and in the lower thoracic compared than in the upper thoracic region.

- Based on the experimental findings, the modulus of the reinforcing panel was chosen such that the ratio of moduli is 3:2:1 in the lumbar, lower thoracic and upper thoracic regions, respectively.
- Since the trapezius muscle plays a crucial role in stabilizing the shoulders and the side panels are intended for applying a sensory tension on the shoulders, they should be positioned along with the trapezius muscle.
- The width of the reinforcing panel should be at least the width of the widest part of the vertebral column.
- The widths of the panels should be chosen such that the tension on the backbone structure is sufficient for posture correction action.

Once the modulus ratio of the backbone structure was finalized, the next step was to determine how to develop a variable modulus elastomeric material. There are various methods to develop a material with variable moduli, and each of them has advantages and disadvantages. A few examples are stretchable woven narrow fabric, stretchable knitted fabric and silicon printed fabric. Given that the intended product is an innerwear, comfort properties must be considered when choosing the material. Being able to model the elastic behaviour is another factor that requires consideration, since the modulus of the material needs to be precisely controlled. To meet these requirements, an elastic woven material was chosen. Woven elastics are extensively used in innerwear products due to their superior stretch and comfort properties. The manufacturing method is well-developed and widely used. The cost of manufacturing is also relatively low. In contrast to knitted materials, modelling the tensile properties of woven fabrics is more intuitive. Even though modelling the elastic modulus of woven fabrics is not as straightforward as with silicon printed materials, given the better comfort and tactile properties, a woven material was chosen for developing the backbone structure.

Identifying how different fabric parameters can affect the tensile properties of woven materials is crucial when modelling the elastic modulus. Also, due to the complex nature of woven fabrics, the mathematical modelling of elastic modulus is extremely difficult. As an alternative, a machine learning-based approach was investigated. To understand how various fabric parameters influence elastic properties and to model the behaviour, extended research has been conducted. A full review of the research is given in Kularatne *et al.* [20].

Based on the findings of Kularatne *et al.* [20], the weave structure was identified as the principal component of the elastic behaviour of stretch woven materials, while two Artificial Neural Network (ANN) based models were used to model the behaviour. The first model takes modulus, yarn count, warp count and weft count as inputs, and predicts the appropriate weave structure to achieve the given modulus values based on provided fabric parameters. The model selected the weave structures for each region of the reinforcement panel so that the above ratio of moduli can be achieved for the selected yarn count. It is important to note that there is not a perfect method to calculate the modulus value required for generating the ideal posture correction force. Hence a trial-and-error method was used to find the optimum modulus values required to correct the posture of the selected test subject. The finalized moduli ratio of the backbone structure was maintained in all test cases.

In the final user trial, the elastic bands were made of nylon and the selected yarn count was 2/78d/24f [R9/2 Tex]. The ANN model predicted a plain weave for the lumbar region, a 2/2 twill for the lower thoracic region and an 8-end sateen for the upper thoracic region based on the provided moduli values. A second ANN model for predicting tensile modulus based on provided weave structure was used to validate the results (cross-validation).

Selecting one particular width of the reinforcement panel was a difficult task. Even though the spine is 43 mm wide at its widest place, the main spinal muscle erector spinae is much wider. The exact width of the muscle is not well understood. According to Structure and Function of the Vertebral Column by P. J. Mansfield, it is roughly one hand's width from spinous processes [20]. Another factor that was considered is the maximum width of the machine on which the elastic is to be produced. Hence, 7 cm and 6 cm were selected as the width of panels (reinforcement and side panels, respectively). In this way, it is possible to support erector spinae while producing enough tension to correct posture.

2.3 Construction of the posture correction garment

In this step, the backbone structure was combined with a stretchable garment. The garment was designed so that it is custom-made for a selected subject. The backbone structure was stitched to the back of the garment. The garment was specially made with a design that enables the anchoring of the backbone structure below the hip.

The reinforcement panel of the backbone structure is aligned with the vertebral column of the wearer, as depicted in Figure 2. The reinforcement panel has a length of 71 cm according to the length of the vertebral column of the selected candidate. The side straps of the backbone, which control the slouching action of the wearer, start from the mid-thoracic T9 disc and extend along with the trapezius muscle of the posterior view of the person (Figure 2). The straps end on the pectoralis major region of the anterior view, crossing the deltoid muscle. The two sidebands start at 20–25 cm from the top of the back panel and extend to the front panel through the shoulder. The bands have a width of 6 cm and a length of 52 cm. The sidebands are sewn to both the front and back panels of the body. Warp knit mesh fabric with 20% spandex and 80% nylon was used as the body fabric. Since the garment is worn as an innerwear, mesh fabric was chosen. A medium-size T-shirt pattern was constructed according to the candidate's measurements.

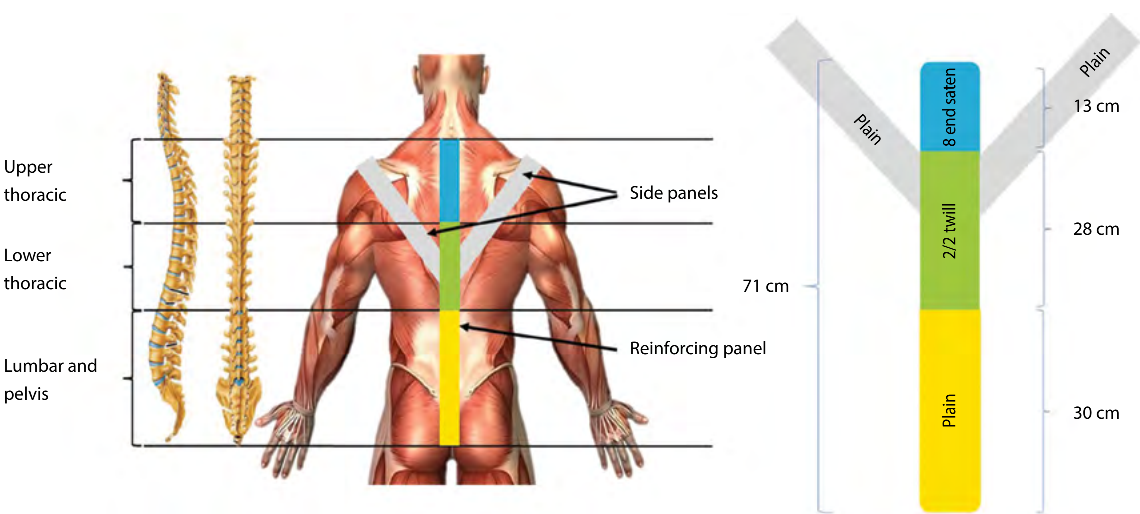


Figure 2: Positioning of the backbone structure along spine and back muscles, and the structure and dimensions of different components

2.4 Experiments

A performance evaluation of the garment was conducted as a final step. The experiment was conducted as two separate tests, to evaluate the reinforcement action of the garment and to evaluate the sensory action. In the first test, the idea was to evaluate the mechanical support provided by the garment for reinforcing the spine, i.e. how the tension applied by the reinforcement panel prevents the wearer from slouching. A motion analysis posture measuring technique was used in combination with a Surface Electromyography (sEMG) device to measure muscle activation levels before and after wearing the garment to determine the reinforcement action. The second test investigated how the side panel activation will prevent the user from slouching. Here, the objective was to quantify how the activation of side panels will help the wearer to correct their posture. A stretch sensor-based method was used to evaluate involuntary posture, with and without the garment in the second experiment.

2.5 Evaluation of the reinforcement action

In this experiment, a test subject was asked to perform a predetermined slouching action while wearing markers and sEMG electrodes on the back (Figure 3). The markers were placed on selected vertebral positions to measure the length of the lumbar, lower thoracic and upper thoracic regions while performing a predetermined action. When the test subject was performing the task, the positions of the markers in space were captured by taking a video graph, as shown in Figure 3a. The distances between these markers were evaluated using a motion analysis tool called Kinovea. Kinovea is a free and open-source solution for motion analysis. It is mostly used by sports coaches and athletes to explore, study or comment on performance, and is useful in ergonomics and animation studies. The software provides an annotation facility that is done with the help of markers placed on the body of the subject. With this method, it was possible to quantify postural position at a given time based on the distance between the markers. The sEMG electrodes were placed on the skin over specific back muscles to measure their activation when performing the task. The test was conducted with and without the garment to identify changes in muscle activation for given postural positions in time. A Delsys Surface-EMG Acquisition and Analysis system was used to analyse the EMG signals generated while performing the task.

sEMG is the characterization of skeletal muscle fibre contraction, and is closely related to the impulse of the motor unit biological signals and muscle activity. An electromyograph detects the electric potential generated by muscle cells when these cells are electrically or neurologically activated. The signals can be analysed to detect medical abnormalities, activation level or recruitment order, or to study the biomechanics of human or animal movement. An EMG sensor subtracts EMG potentials detected at two distinct locations on the surface of the skin directly above an active muscle. The EMG potentials are always measured with respect to the electric potential of a neutral site located away from the EMG muscle source. This potential is detected by a reference electrode. The EMG sensor is fitted with two silver bar contacts for detecting the EMG signal at the skin surface.

a) b) c) d)

Figure 3: Experimental set up of motion analysis test method with sEMG: a) video camera placement, b) the view captured by the camera, c) marker and electrode placement without the garment, and d) marker placement with the garment

2.6 Experimental set up

Equipment: A Delsys Surface-EMG Acquisition and Analysis system was used for measuring muscle activation. A DSLR camera was used to capture the video for motion analysis.

Marker and sensor locations: Markers were placed along the spine to measure the spinal flexion. Four plastic hemispherical markers were placed to represent L5, L1, T6 and T1 vertebrae. The marker placement is shown in Figure 3b. The distance between these markers represents the lumbar, lower thoracic and upper thoracic regions respectively. EMG electrodes were placed on respective muscles to acquire signals. The muscles were the trapezius, multifidus and erector spinae. Two electrodes were positioned for each muscle on either side of the body. A total of six electrodes were placed to capture EMG signals. The reference electrode was placed on the lower abdomen. Before placing the electrodes, the skin was scrubbed and cleansed with an alcohol solution to reduce the impedance. When the T-shirt was worn, the markers were placed on the T-shirt itself while the EMG electrodes were placed on the back before the T-shirt was worn. Marker and electrode placement are shown in Figures 3c and 3d.

Data capturing and processing: The raw sEMG signals were acquired with a sampling frequency of 4000 Hz. EMGworks Analysis software was used for the pre-processing of data, while MATLAB was used for post-processing. Using EMGworks Analysis software, the root mean square (RMS) of noise-filtered raw data was calculated using equation (1) where $sEMG_{RMS}$, x_n and N represent the RMS of channel n (n=1,2 …), the raw sEMG of channel n and sample size, respectively. The subsequent exponential smoothing of EMG signals was carried out to further filter out the noise. A Kinovea motion analysis tool was used to calculate the distance between the markers.

$$sEMG_{RMS} = \sqrt{\frac{1}{N}\left(\sum_{n=1}^{N} x_n^2\right)} \quad (1)$$

Experimental protocol

A physically fit university undergraduate student (age: 25; weight: 60 kg; and height: 160 cm) took part in the study. The experiment was carried out in two parts. The subject was seated on a backless desk chair in front of a computer. The seat height was adjusted such that he could place both feet on the floor. The subject first sat for five seconds as straight and tall as possible, in a hyperextended position, then flexed into a full "slump" position which was held for five seconds, after which the action was repeated three times. All positions and movements were practiced by the subject prior to testing. The camera was positioned to the left of the subject so that the markers were clearly visible. The camera was perpendicular to the sagittal plane of the body. The subject performed two trials: one without the posture correction garment and the other with the garment.

2.7 Evaluation of sensory action

In the second experiment, a stretch sensor was used to measure the sensory action of the garment. In the experiment, the test subject was asked to wear an apparatus to measure involuntary posture. The apparatus, shown in Figure 4, consists of a stretch sensor, two elastic bands to attach the sensor to the body and crocodile clips to adjust the sensor's effective length. The two ends of the stretch sensor were connected to the elastic bands so that during the upright sitting posture, the stretch sensor had no residual stretch. Based on spinal flexion, the sensor stretches relative to its initial length. The subject was seated as described in the first experiment and the stretch sensor was attached to the back of the subject. The crocodile clips were attached at the L5 and T1 vertebrae positions. When the garment was worn, it was attached on the back of the garment. To measure the involuntary postural changes, the subject was instructed to work on the computer for an hour, and the stretch behaviour of the sensor was recorded using an ESP8266 d1 mini-board (D1 Mini Board 2020). It was subsequently averaged to obtain the mean stretch length for a 1-hour time period. The initial length of the sensor cord was 58cm. Before conducting the experiment, the resistance of the stretch sensor was validated by taking manual measurements and checking for the presence of hysteresis.

The conductive rubber stretch sensor was made of carbon-black impregnated rubber, and when it stretched or relaxed, the distance between individual carbon particles changed, affecting the resistance. The resistance in a relaxed state was 350 Ω per inch. The sensor was connected to a voltage dividing circuit with 10k and 250 Ω resistors. An ESP8266 d1 mini-board was used for monitoring resistance and voltage change in the sensor. The resistance change was directly proportional to the extension of the sensor. When the person wearing the apparatus slouched, the ESP8266 d1 mini-board outputted voltage change and resistance change associated with the extension of the rubber cord. This measurement was associated with the bending of the backbone, meaning posture changed in various seated positions. The same technique was implemented for measuring the movements of individual segments of the vertebral column by adjusting the position of the stretch sensor along the spine accordingly.

a) b)

Figure 4: Use of the stretch sensor-based method for measuring upper body posture

3 Results and discussion

The findings of the first experiment are given in Figure 5 and Figure 6. An example for filtered and unfiltered signals is given in Figure 5a. Here, the filtered signal is after the application of exponential smoothing. The results of the motion analysis are given in Figure 5b. According to the plot, the variation in the upper thoracic region is more prominent. Here, the valleys represent the upright sitting posture, while hills represent the slouched posture. To compare EMG signals of the two different postures (upright and slouched), the EMG signals were combined with the results of motion analysis. Both EMG signals and motion analysis results were obtained as a function of time, and then the two timeframes were matched to combine the normalized motion analysis plot with the normalized EMG signal. This was done by assuming that data is normally distributed and by statistically standardizing the signal amplitudes. Using this approach, it was possible to identify whether there was a change in the EMG signal in the slouched posture and upright posture. An example for combined plots of the EMG signal and upper thoracic movement is shown in Figure 5c, according to which there was an increased muscle activation in the slouched posture for the selected EMG signal. All the EMG signals were analysed in this way.

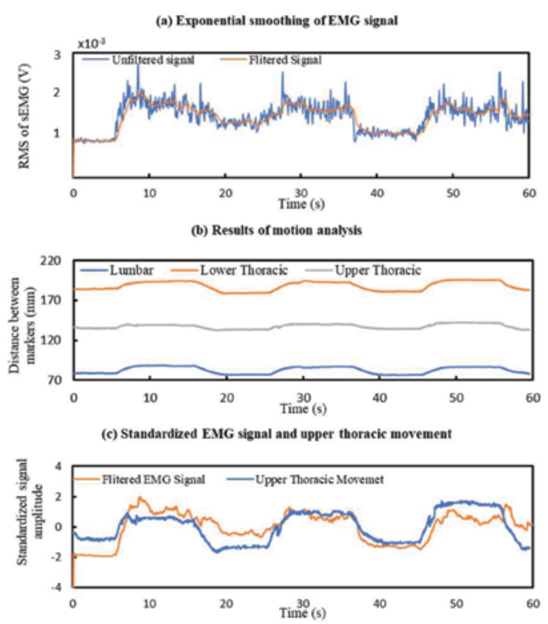


Figure 5: Results of the evaluation of the reinforcement action

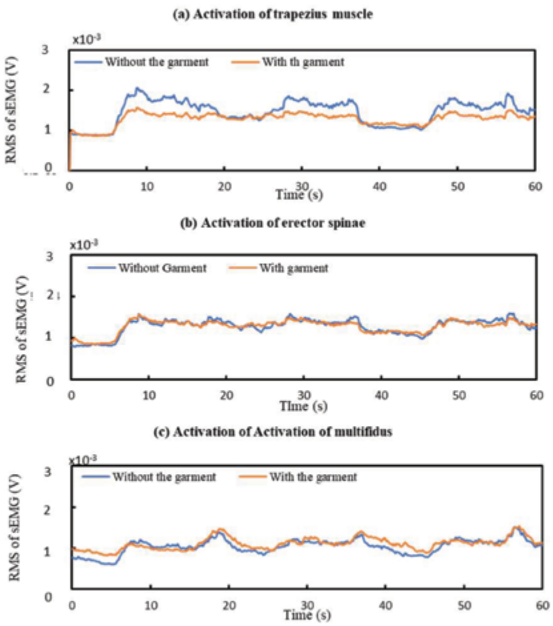


Figure 6: Muscle activation of major back muscles during the experiment of evaluating reinforcement action

The EMG signals of the three muscles without wearing the garment and with the garment are given in Figures 6a–6c. For the sake of clarity, only the EMG signals are given. According to the results of the first part of testing and evaluation (evaluation of the reinforcement action), there was a noticeable reduction in the muscle activity of the trapezius, while the difference is not noticeable for the other two muscles. The reduction in trapezius muscle activation means that the slouching of the shoulders was reduced when the garment is worn. For the other two muscles, the insignificant change in muscle activity could be due to several reasons. Reinforcement provided by the garment might not be sufficient to reduce muscle activity. Another possibility is that since both erector spinae and multifidus are deep back muscles, the EMG electrode placed on the surface might not detect the electrical signal in the muscles properly.

Based on the second experiment, the mean stretch lengths, with and without the garment, are given in Table 1. When interpreting the results, it is fair to say that the garment performs a certain sensory action. According to the results, there was a 28.87% reduction in mean stretch length when the garment was worn. This indicates that the garment promotes upright posture.

Table 1: Results of posture measuring with stretch sensor

Test case (mean stretch length as a percentage of initial length)	Mean stretch length (mm)	Mean stretch percentage (%)
Without wearing the garment	15.878	2.738
Wearing the garment	11.420	1.970
Difference	-4.458	

4 Conclusion

This study explored the development of a textile-based posture correction product with the goal of designing a garment that comfortably and effectively modifies posture. The garment was developed by experimenting with elastic bands positioned in a stretchable tight-fitting garment to mimic the structure and placement of the anatomical postural features (muscles and spinal column) of the human back. Moreover, it is important to mention that the research was not to treat patients suffering postural deformities, but rather as a precaution to avoid such situations with a primary focus on low back pain. In the proposed design and in the prototype, elastic bands were strategically placed on the back of a garment to mimic the loading and bending behaviour of the vertebral column and to assist upper body back muscles. Measuring the effectiveness of posture correction is very important to make the product scientifically acceptable. A motion analysis method was used in combination with an sEMG acquisition system. The muscle activations of three major muscles were evaluated for an upright seating posture and a slouched seated posture. The results indicate that there was a certain reduction in the activation level of the trapezius muscle. It can therefore be said that the developed garment is capable of helping the wearer correct their posture. Based on the results of the second experiment, it is possible to conclude that the garment also performs a sensory action. Even though there is a reduction in the activity of certain muscles, the sensory action remained to be the main posture correction mechanism. However, it is possible to increase the reinforcement action by increasing the elastic modulus of the backbone structure, but this will be at the expense of the wearer's comfort. High tensile modulus will restrict the body movements more, resulting in wear discomfort. It is therefore important to find a balance between the sensory action and reinforcement action. The principles stated above provide a plausible explanation of the physical effects of the garment on posture.

In terms of future improvements, it is possible to investigate the incorporation of electronics to measure posture. Electronic posture measuring can be identified as a promising posture correction technique with a great deal of potential. Moreover, there is the possibility of using other elastomeric materials apart from woven narrow fabrics. Silicon printed knitted fabrics are one such option. However, further research is required to evaluate the suitability of such products.

References

1. OWEN, N., HEALY, G.N., MATTHEWS, C.E., DUNSTAN, D.W. Too much sitting: the population-health science of sedentary behavior. *Exercise and Sport Sciences Reviews*, 2010, **38**(3), 105–113, doi: 10.1097/JES.0b013e3181e373a2.
2. BEVAN, S. Economic impact of musculoskeletal disorders (MSDs) on work in Europe. *Best Practice and Research Clinical Rheumatology*, 2015, **29**(3), 356–373, 10.1016/j.berh.2015.08.002.
3. LEVANGIE, P.K., NORKIN, C.C., LEWEK, M.D. *Joint structure & function: a comprehensive analysis.* 6th ed. Philadelphia : F.A. Davis Company, 2019.
4. WANG, T., ZHAO, Y.L., HAO, L.X., JIA, J.G. Prevalence of musculoskeletal symptoms among industrial employees in a modern industrial region in Beijing, China. *Chinese Medical Journal*, 2019, **132**(7), 789–797.
5. KANG, J.H., PARK, R.Y., LEE, S.J., KIM, J.Y., YOON, S.R., JUNG, K.I. The effect of the forward head posture on postural balance in long time computer based workers. *Annals of Rehabilitation Medicine*, 2012, **36**(1), 98–104, doi: 10.5535/arm.2012.36.1.98.
6. MOODLEY, R., NAIDOO, S., VAN WYK, J. The prevalence of occupational health-related conditions among oral health practitioners in KwaZulu-Natal, South Africa. *The Journal of the Dental Association of South Africa*, 2017, 72(10) 448–454, doi: 10.17159/2519-0105/2017/v72no10a1.
7. AGHILINEJAD, M., TAVAKOLIFARD, N., MORTAZAVI, S.A., MOKAMELKHAH, E.K., SOTUDEHMANESH, A., MORTAZAVI, S.A. The effect of physical and psychosocial occupational factors on the chronicity of low back pain in the workers of Iranian metal industry: a cohort study. *Medical Journal of the Islamic Republic of Iran,* 2015, **29**(1), 1–8.
8. HORAK, F.B. Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? *Age and Ageing,* 2006, **35**(2), 7–11, doi: 10.1093/ageing/afl077.
9. LYU, S. Posture modification effects using soft materials structures. PhD thesis. University of Minnesota, 2016.
10. WANG, Q., CHEN, W., TIMMERMANS, A., KARACHRISTOS, C., MARTENS, J., MARKOPOU-LOS, P. Smart rehabilitation garment for posture monitoring. In *37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Milan, Italy, 2015,* 5736–5739, doi: 10.1109/EMBC.2015.7319695.
11. CHOW, D.H., KWOK, M.L., CHENG, J.C., LAO, M.L., HOLMES, A.D., AU-YANG, A., YAO, F.Y., WONG, M.S. The effect of backpack weight on the standing posture and balance of schoolgirls

with adolescent idiopathic scoliosis and normal controls. *Gait & Posture*, 2006, **24**(2), 173–181, doi: 10.1016/j.gaitpost.2005.08.007.

12. FRONTERA, W.R., SILVER, J.K., RIZZO T.D. *Essentials of physical medicine and rehabilitation: musculoskeletal disorders, pain, and rehabilitation*. 4th ed. Philadelphia : Elsevier, 2018.
13. KIM, M., KIM, H., PARK, J., JEE, K.-K., LIM, J. A., PARK, M.-C. Real-time sitting posture correction system based on highly durable and washable electronic textile pressure sensors. *Sensors and Actuators A: Physical*, 2018, **269**, 394–400, doi: 10.1016/j.sna.2017.11.054.
14. MITSUNO, T.T. Gradient of clothing pressure for comfortable support wear. *Journal of the Textile Engineering and Fashion Technology*, 2023, **9**(4), 86–89.
15. KUO, Y.-L., TULLY, E.A., GALEA, M.P. Video analysis of sagittal spinal posture in healthy young and older adults. *Journal of Manipulative and Physiological Therapeutics,* 2009, **32**(3), 210–215, doi: 10.1016/j.jmpt.2009.02.002.
16. DUNNE, L.E., WALSH, P., HERMANN, S., SMYTH, B., CAULFIELD, B. Wearable monitoring of seated spinal posture. *IEEE Transactions on Biomedical Circuits and Systems,* 2008, **2**(2), 97–105, doi: 10.1109/TBCAS.2008.927246.
17. LYU, S., LABAT, K.L. Posture modification effects using soft materials structures. *International Journal of Industrial Ergonomics*, 2021, **84**, 1–17, doi: 10.1016/j.ergon.2021.103125.
18. VINCENT, J.F., BOGATYREVA, O.A., BOGATYREV, N.R., BOWYER, A., PAHL, A.K. Biomimetics: its practice and theory. *Journal of The Royal Society Interface*, 2006, **3**, 471–482, doi: 10.1098/rsif.2006.0127.
19. NÄGERL, H., HAWELLEK, T., LEHMANN, A., HUBERT, J., SAPTSCHAK, J., DÖRNER, J., RAAB, B.W., FANGHÄNEL, J., KUBEIN-MEESENBURG, D., WACHOWSKI, M.M. Non-linearity of flexion-extension characteristics in spinal segments. *Acta of Bioengineering and Biomechanics*, 2009, **11**(4), 3–8.
20. KULARATNE, S., RANAWAKA, R., FERNANDO, E., NILES, S., JAYAWARDANE, T., RANAWEERA, R. Machine learning-based approach for modelling elastic modulus of woven fabrics. In *2020 Moratuwa Engineering Research Conference (MERCon), Moratuwa, Sri Lanka, 2020,* 470–475, doi: 10.1109/MERCon50084.2020.9185295.
21. MANSFIELD, P.J., NEUMANN, D.A. Structure and function of the vertebral column. In *Essentials of Kinesiology for the Physical Therapist Assistant*. 3rd ed. Elsevier, 2019, 178–232, doi: 10.1016/B978-0-323-54498-6.00008-4.

Cholthicha Sarikanon, Thanate Piromgarn, Songwut Egwutvongsa
Department of Architecture Education and Design, School of Industrial Education and Technology, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand

Extraction of Fibre from Young Bamboo for Application in Textile Production

Pridobivanje vlaken iz mladega bambusa za tekstilne namene

Original scientific article/*Izvirni znanstveni članek*
Received/*Prispelo* 1-2024 • Accepted/*Sprejeto* 5-2024

Corresponding author/*Korespondenčni avtor:*
Cholthicha Sarikanon
E-mail: 63603018@kmitl.ac.th
ORCID: 0009-0001-5176-4962

Abstract

Natural bamboo fibres have the potential for use in the production of eco-friendly and sustainable textile materials, and have numerous advantages over synthetic fibres. As such, the main aim of this study was to assess the benefits of using raw materials in textile production, including a reduction in energy consumed and time spent, and the reduced use of chemicals that impact the environment, suggesting a sustainable alternative to conventional materials. Thus, natural bamboo fibres exemplify a raw material that can be used in textile applications in various sectors. To investigate the chemical and mechanical separation of young 30–120-day-old bamboo fibres for the purpose of bamboo fibre extraction, experiments were conducted in which the concentration of caustic soda (NaOH) used to separate the fibres was reduced to 5 *g/l* at 100 °C for 90 minutes, demonstrating that natural 60-day-old bamboo fibres can be separated effectively into single fibre. Furthermore, when natural bamboo fibres are combined with recycled polyester (r-PET) at a blend ratio of 30% to 70% (% by weight), respectively, the fabric's unique textural characteristics during weaving make it suitable not only for the fabrication of various textile products, but also for a wide range of additional applications.
Keywords: cellulose fibre, fibre extraction, recycled fibres, r-PET, fibre blends, ring spinning

Izvleček

Naravna bambusova vlakna so primerna za izdelavo okolju prijaznih in trajnostnih tekstilij, saj imajo številne prednosti pred sintetičnimi vlakni. Namen raziskave je bil proučiti prednosti uporabe naravnih bambusovih vlaken v tekstilni proizvodnji, ki so z zmanjšano porabo energije, časa in za okolje obremenjujočih kemikalij trajnostna alternativa obstoječim materialom. Naravna bambusova vlakna so primer vlaknin, ki se lahko uporabijo za različne tekstilne in tehnične namene. Za ekstrakcijo bambusovih vlaken iz 30–120 dni starih bambusovih stebel so bili uporabljeni kemični in mehanski postopki. V izvedenih poskusih so bila uporabljena 60 dni stara bambusova vlakna, ki so se pri 90-minutni obdelavi v vodni raztopini 5 g/l kavstične sode (NaOH) in temperaturi 100 °C dobro ločila v elementarna vlakna. Tkanina iz mešanice 30 ut.% naravnih bambusovih vlaken in 70 ut.% recikliranih poliestrskih vlaken (r-PET) je zaradi edinstvenega otipa primerna za različne tekstilne izdelke in različne namene uporabe.
Ključne besede: celulozno vlakno, ekstrakcija vlaken, reciklirana vlakna, r-PET, mešanice vlaken, kolobarjenje

1 Introduction

Of the approximately 1,500 species of bamboo worldwide, Thailand is home to about 69 species across 17 genera, all distributed widely and representing fast-growing versatile plants that thrive in areas with limited space and on empty land, helping to improve the ecological conditions of degraded forest areas [1–4]. Bamboo is a biodegradable raw material and an eco-friendly agricultural resource in the advancement of renewable energy, while its biodiversity represents an excellent example of the sustainable development of natural fibres. Furthermore, it plays a key role in the bio–circular–green (BCG) economy model towards sustainable and economic development potential in the textile industry [1–3, 5]. Textiles from bamboo have tremendous potential to become alternative plant fibres, leveraging bamboo's potential applications across various industries and leading to the growth and development of the local community and Thai society [1–2, 6]. Government agencies generally focus on and promote research and development in science, technology and innovation to enable the creation of textile products from bamboo fibres. As such, when incorporated into a bio-based economic development model, the bioeconomy of Thailand appears to focus on the production and conversion of renewable biomass. In addition, research and innovation in life sciences play an important role in the development of sustainable textiles towards achieving economic growth according to future trends in energy security in the textile and garment industries, and in environmental sustainability [2–4, 7]. At present, there is growing interest in the use of natural fibres that are greener and more sustainable and in biodegradable processes. This interest has played an important role in creating products for the future to protect the environment [8]. For instance, bamboo has good hygroscopicity and abrasion resistance, as well as natural antibacterial and antibacterial functions, [5, 9–16] offering ultraviolet protection and a texture that feels cool to the touch [15, 17].

However, a significant problem is that the fibre separation process requires elevated chemical concentrations and takes considerable time, with the resulting fibres being hardened, reducing their widespread use, except in the form of semi-synthetic fibres [9, 18]. China produces semi-synthetic bamboo fibres by dissolving pulp from bamboo with chemicals and then spinning it into fibres using industrial systems [15, 17–21]. Based on past research concerning the use of natural bamboo fibres in textile production, when separating fibres using chemicals, an alkaline solution offers good results, with the concentration of alkalis directly affecting the destruction of lignin, a three-dimensional structure that binds to fibrous walls and has a lignin content directly proportional to the age of the bamboo. Therefore, young bamboo will have a low amount of lignin, so the wood will remain soft. When using an alkaline solution, however, the concentration volume and boiling time can be reduced [12, 20, 22–24].

Concerning the chemical composition of bamboo fibre, it consists of cellulose, hemicellulose and lignin, and is characterised by its fineness and small sizes. However, the amount of cellulose decreases as bamboo ages, so hemicellulose and lignin act as interfering agents to increase the strength and adhesion of fibres over time [12, 23]. In a study of bamboo aged two to four years, it was found that the size and length of its fibres varied with age, where younger bamboo had a small fibre size that increased in size and length over time. Bamboo is considered mature when it reaches three years old [23–25], at which point the natural bamboo fibres are coarse and hardened. As such, obtaining fine and soft bamboo fibres requires a multi-stage process beginning with boiling the fibres in caustic soda, sodium triphosphate, sodium sulphite and an absorber [26–28]. Thereafter, bamboo fibres aged one–four years are separated using different methods, though boiling with caustic soda at a concentration of 16 *g/l*, bleaching with hydrogen peroxide and pre-treating with a softening agent produced suitable properties for the fibres to be spun into yarn [29]. The study also compared the antibacterial properties of regenerated bamboo and natural bamboo, demonstrating that semi-synthetic bamboo fibres have a lower bacterial resistance than natural bamboo fibres because semi-synthetic bamboo strands require a multi-step chemical manufacturing process. As a result, the antibacterial substances in bamboo are eliminated, reducing their antibacterial ability [25, 29–31].

Based on the data and results of the research studies referenced herein, it was found that bamboo undergoes fibre size and lignin content increases with age, suggesting that older bamboo comprises coarse and hard fibres because lignin will adhere to the bamboo fibre walls. Though the separation of bamboo fibres from plants aged one year and older has been studied, the separation of bamboo fibres from plants aged below one year has not, as young bamboo is soft with a low lignin content, making it easy to use in the production of raw materials because it has not yet branched. Generally, achieving bamboo fibre separation with good results is a multi-stage chemical process. For this reason, the researcher chose to improve the separation of natural bamboo fibres by studying the relationship with bamboo age (between 30 and 120 days old) and by separating fibres using a low-concentration alkaline solution to obtain soft fibres but retain the outstanding properties of the fibres for use in the blending process with recycled polyester fibres owing to their exceptional characteristics, including resistance to abrasion and wrinkles. The production of recycled polyester fibres from plastic bottles represents the use of renewable resources, as we well as oil fuel waste reduction and overall carbon footprint mitigation.

2 Experiment

2.1 Materials

Three age groups of bamboo samples – 30, 60 and 90 days – were treated separately to identify differences in properties. The project area in Roi-Et Province, Thailand, supplied the bamboo culms of *Dendrocalamus asper*, and bamboo fibres were procured from fresh bamboo specimens. Furthermore, a knife was used to remove the exodermis (green skin) of the culms and to split the strip size at a length of 5 cm and thickness of 0.01 cm, as shown in Figure 1.

Figure 1: Splitting bamboo into strips (raw material for the boiling process)

2.2 Methods

2.2.1 Extraction of raw young bamboo fibres

Fibres were produced from fresh bamboo (*Dendrocalamus asper*) specimens that were boiled in a packaged yarn dyeing machine (Hisaka works, Japan). About 1 kg of the sample was weighed and loaded into a packaged yarn dyeing machine, after which 10 litres of water was added. The specimen was treated with a sodium hydroxide solution at a ratio of 5 *g/l* and Alkon KSW (scouring agent, Phisit Intergroup Co., Ltd., Thailand) at a ratio of 2 *g/l* at 100 °C for 90 minutes. It was then washed thoroughly and neutralised with acetic acid.

The bamboo was boiled and compressed to break apart the fibres, after which it was washed with water and bleaching to make the fibres clean and white, along with hydrogen peroxide (H_2O_2)(50%) at a ratio of 5 *g/l*, sodium hydroxide at a ratio of 1.5 *g/l*, Oxystab OST (stabiliser, Phisit Intergroup, Thailand) at a ratio of 3 *g/l* and Alkon KSW (scouring agent, Phisit Intergroup, Thailand) at a ratio of 2 *g/l* at 100 °C for 60 minutes. The softness of the fibres was then adjusted with apcosoft sock (Phisit Intergroup, Thailand) at a ratio of 3 *g/l* at room temperature for 10 minutes and the fibres were dried.

2.2.2 Carding of fibres

The process of boiling bamboo fibres was adopted from a laboratory carding machine (MESDAN LAB, Italy), involving the mechanical disentangling of the boiled fibres to provide suitable natural bamboo, which was then examined for its physical properties. The average length of the bamboo fibres was long enough for use in the ring spinning process. These yarns can be spun from most natural or man-made fibres, or from a blend of short staple fibres in the 2.5–5 cm range [32].

2.2.3 Ring spinning of yarn

The obtained natural bamboo fibres were used in a prepared ring spinning machine (Toyota, Japan), and ring spinning yarn was prepared by spinning a blend ratio of 30% natural bamboo fibres to 70% r-PET (% by weight, Indorama Polyester Industries PCL, Thailand). The process is shown in Figure 2.

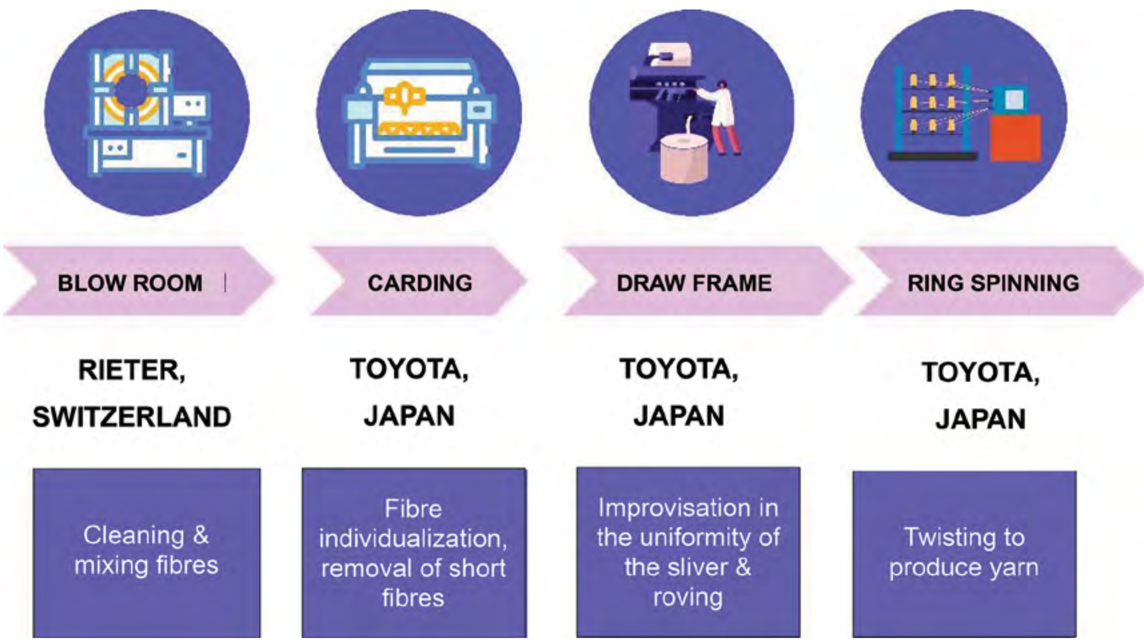


Figure 2: Diagram of ring spinning

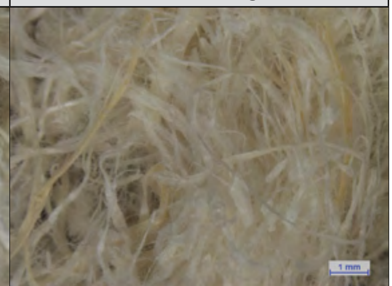
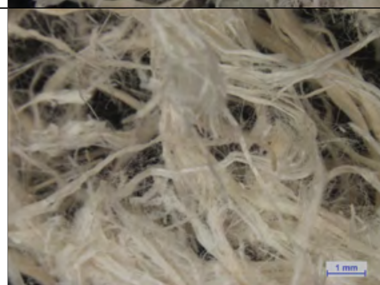
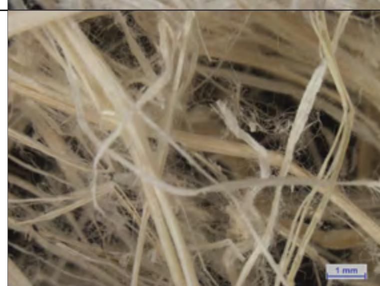
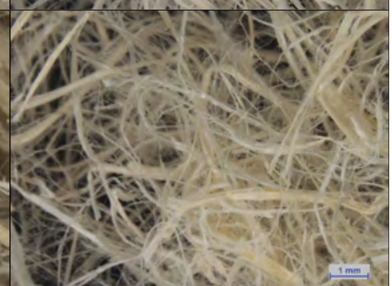
2.2.4 Weaving

Bamboo and r-PET yarns were used as weft yarns, and 18.5 tex/2 (Ne 32/2) cotton was used as warp yarns and then woven in an air jet room (Toyota, Textile Machinery, Japan.) The weft yarn was inserted into the warp shed with compressed air. Air-jet weaving machines can weave almost all kinds of yarns without any problem at higher speeds compared to projectile and rapier systems [33].

2.2.5 Evaluation of the physical properties of young raw bamboo fibres

The physical properties of the obtained young bamboo fibres were examined, including length (comb sorter method: BS 4044:1989) [34]. Separated fibres were examined using a microscope (Nikon SMZ 1500 Stereo Microscope, Japan), while optimal surface properties were examined using a scanning electron microscopy (SEM Model JSM-7800F, JEOL Ltd., Japan), including yarn number (ASTMD 1059-01) [35], the tensile strength of yarn (ASTM D 2256-02) [36], thread and stitch density per unit length (ISO7211/2:1984) [37], fabric thickness (ASTM D1777-96)[38], tear strength (ISO 13937-1: 2000) [39], the tensile strength of fabrics (ASTM-D5034-09)[40] and fabric weight (ASTM D3776/D3776M-09) [41].

Table 1: Physical characteristics of natural bamboo fibres (microscope scan, 10-X magnification)

Ages of natural bamboo fibres	Physical characteristics of natural bamboo fibres	
	Before carding	After carding
30 days old		
60 days old		
90 days old		
120 days old		Unable to separate fibres

3 Results and discussion

3.1 Physical properties of natural bamboo fibres

After separating bamboo fibres using young bamboo and reducing chemical use in the separation process, the results of studying the physical properties of fibres after boiling, separating and grinding, but before the carding of fibres, are shown in Table 1. It was found that 30-day-old bamboo fibres separated well and were soft, but they had a relatively crushed appearance, whereas 60-day-old bamboo fibres were separated successfully, were soft and maintained a consistent length. Meanwhile, 90-day-old bamboo fibres were separated less effectively into single fibres and were stiffer than the 60-day-old bamboo fibres. Moreover, the 120-day-old bamboo fibres did not separate well, sticking together and demonstrating a hard texture, such that they could not fit into the fibre carding machine.

Analysing the characteristics of bamboo fibres after carding revealed that bamboo age is related to fibre separation efficiency. That is, due to changes in the structure of bamboo fibres as they age, their high crystallinity connects lignin and hemicellulose to the cell walls of bamboo fibres [42]. For these reasons, bamboo fibres have increased hardness and are more difficult to separate. Meanwhile, younger bamboo fibres have low crystallinity and high porousness, meaning they are ground, short and suitable for other applications, such as paper pulp.

3.2 Fibre length

A fibre length analysis was performed using the comb sorter method (BS 4044:1989). A fringe or tuft was prepared, with all fibres aligned at one end. The separation or withdrawal of fibres was performed in order of decreasing length, while a sorter diagram was prepared by laying the fibres on a black velvet pad in decreasing order of length, with the fibres parallel and their lower ends aligned along a horizontal base line, as shown in Figure 3. The sorter diagram, which brings together bamboo fibres of various ages to determine fibre length, was analysed. Natural bamboo fibres have an effective length of 1.70 cm ± 0.17 cm at 30 days old, 3.87 cm ± 0.18 cm at 60 days old and 3.88 cm ± 0.29 cm at 90 days old. However, bamboo fibres aged 120 days are unable to be carded because they do not separate. When comparing the physical properties of fibres at each bamboo age, it was discovered that 60-day-old bamboo is soft, separates easily into single fibres and has a uniform length suitable for spinning into yarn, as shown in Table 2. The resulting length, compared to the length of short fibre polyesters, is generally a cut length of 3.8 cm [43–44]. Therefore, the resulting bamboo fibre can be blended with polyester fibres.

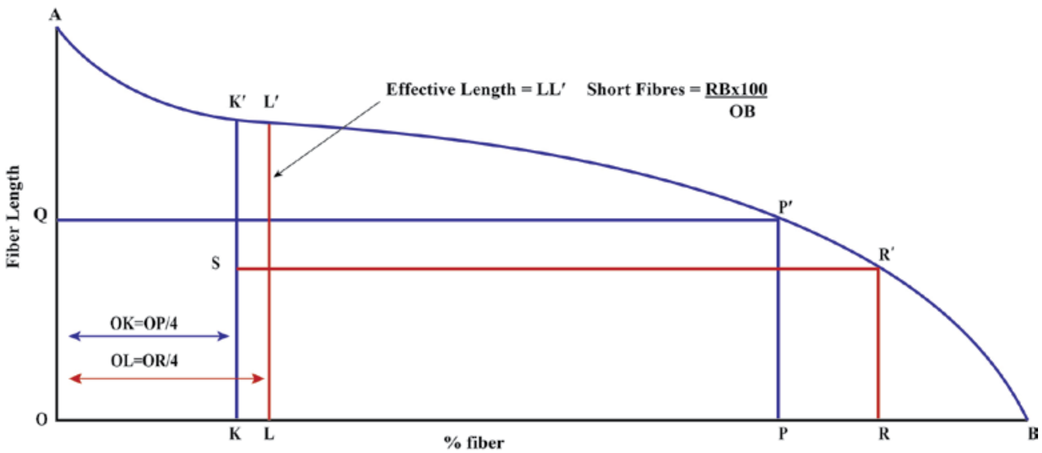


Figure 3: Fibres diagram analysis

Table 2: Physical properties of the obtained natural bamboo fibres

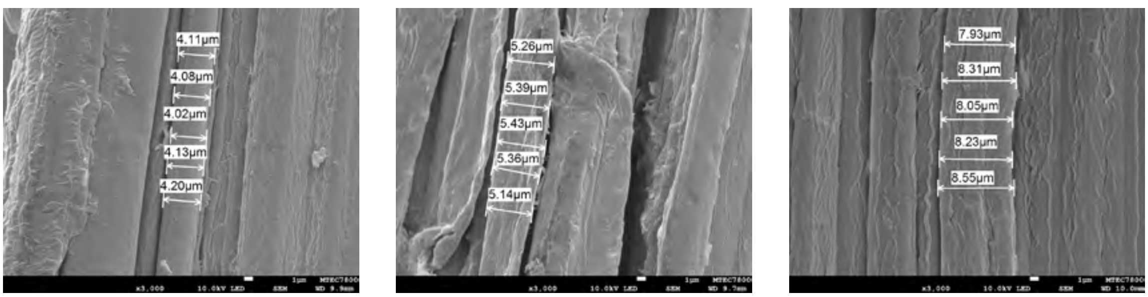
Fibre	Ages of natural bamboo fibres		
	30 days old	60 days old	90 days old
Maximum length (cm)	2.74	4.96	5
Effective length (cm)	1.70	**3.87**	3.88
Amount of short fibre (%)	17.06	15.71	16.68

3.3 Surface morphology of treated natural bamboo fibres

Figure 4 shows the dimensions of natural bamboo fibres across various age groups. It was determined that as bamboo ages, its fibre size increases, such that the average diameter of bamboo fibre aged 30, 60 and 90 days is 4.11 μm ± 0.07 μm, 5.32 μm ± 0.12 μm and 8.21 μm ± 0.24 μm, respectively. Furthermore, when comparing bamboo fibres aged two–four years, current fibre size ranged from 13.95 to 14.44 μm [24]. Concerning the separation process, according to previous studies, the average fibre size using steam explosion was 16.7 μm ± 4.8 μm, while the average fibre size with boiling using the alkaline and bleach process was7.5 μm ± 3.2 μm [45], which is consistent with the experimental results and when compared with natural fibres obtained from other strains, such as flax fibres sized 15–25 μm, hemp fibres sized 10–17 μm and jute fibres sized 15–35 μm [46]. An analysis of fibre size and length revealed that 60- and 90-day-old bamboo fibres have features and properties beneficial for textile work. However, 60-day-old bamboo fibres broken effectively into a single fibre are softer than fibres of any other age.

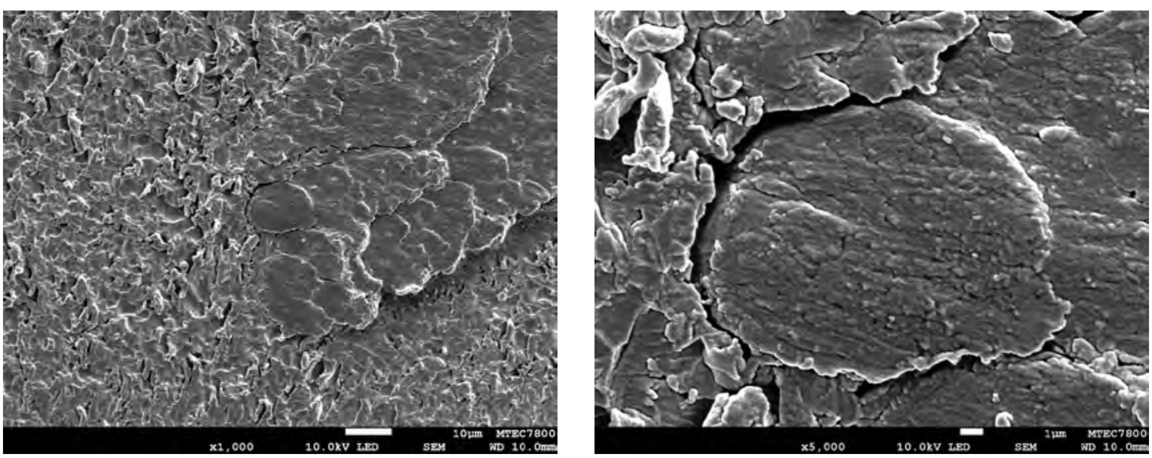
We took a sample that was buried with resin and left for a night and cut it perpendicularly with a microtome, then placed it in a gold coating so that the workpiece could be electrified and subjected to scanning electron microscopical (SEM) images.

Figure 5 shows a cross-section of 60-day-old bamboo fibres, characterised by hollow polygons. Due to the large lumen, attributed to the porous cell wall, impurities remain on the fibre surface [28, 47]. These characteristics can be attributed to the bamboo fibre's high moisture absorption capacity and breathability.



a) b) c)

Figure 4: SEM micrograph of a bamboo fibre surface: (a) diameter of natural bamboo fibre aged 30 days (3000x), (b) diameter of natural bamboo fibre aged 60 days (3000x) and (c) diameter of natural bamboo fibre aged 90 days (3000x)



a) b)

Figure 5: Characteristics of natural bamboo fibre extracted at 60 days old: (a) cross-section of a fibre bundle at 1000x magnification and (b) cross-section of a single fibre at 5000x magnification

3.4 Characteristics of ring spinning yarn

The fibres obtained from 60-day-old bamboo were chosen for use in ring spinning in this study. Natural bamboo fibres were successfully used to prepare ring spinning yarn using a ring spinning machine at a blend ratio of 30% natural bamboo fibres to 70% r-PET (% by weight). In general, natural bamboo fibres can blend at a ratio of no more than 20%, [48–49], but it was shown that 60-day-old bamboo can be blended at a ratio up to 30% when the yarn is tested for physical properties, as shown in Table 3.

Table 3: Physical properties of the blended bamboo ring spinning yarn

Properties	Result
Yarn count (tex)	56.7 (Ne 10.4)
Tensile strength (N)	15.67
Elongation at break (%)	20.95

3.5 Characteristics of a woven fabric blend of natural bamboo fibres

Natural bamboo fibres were blended with r-PET fibres into bamboo fibres used as weft yarn and cotton yarn as warp yarn, yielding a woven fabric interspersed with bamboo fibres that possesses a distinctive texture. Dispersed bamboo fibres adorn the fabric. The fabric's texture resembles the protruding hairs of bamboo fibres on its surface. After subjecting it to physical testing, the fabric exhibited various properties, as shown in Table 4.

Table 4: Characteristics of a woven fabric blend of natural bamboo fibres with r-PET

Properties	Result	
	Warp	Weft
Tensile strength (N)	473.8	1896.4
Elongation (%)	20.768	23.04
Tear strength (N)	24.332	15.886
Density (threads/cm)	28	24
Fabric weight (g/m²)	193.520	
Fabric thickness (mm)	0.286	

4 Conclusion

From this research study, it was determined that 60-day-old bamboo has young flesh that has not yet branched, making it easy to use in the preparation of raw materials. It can reduce the concentration of chemicals used, as well as the time and steps required in the fibre separation process. When using caustic soda, the concentration is only5 *g/l* at 100 °C for 90 minutes, compared to bamboo older than one year, for which the concentration of caustic soda required is 20 *g/l* at100 °C for 120 minutes [50]. Isolated young bamboo has soft fibres, can break effectively into single fibres and has an effective length of 3.87 cm ± 0.18 cm. Furthermore, it can be blended with r-PET fibres at a mixture rate of up to 30%, which is greater than that facilitated by bamboo older than one year. Generally, at a maximum churn of 20%, the yarn spun in the ring spinning machine demonstrated good uniformity, where a spinning yarn count of 56,7 tex (Ne 10.4) produced a tensile strength of 15.67 N and an elongation distance of 20.95%. It can also be woven into fabrics using an air jet system. The fabric weight was 193.520 g/m^2 with a tensile strength in warp yarn of 473.8 N, and weft yarn of 1896.4 N, and a fabric thickness of 0.286 mm, and it has a unique texture suitable for use in textile products. With regard to the mechanical characteristics of polyester fabrics, a high sheen is one such characteristic, as are superior resistance to abrasion, elasticity and wrinkles, and low moisture absorption. Pure cotton fabrics are costly, possess inferior abrasion resistance compared to pure polyester, are pleasant to wear but prone to wrinkling, and absorb moisture exceptionally well. Woven fabric composed of recycled polyester and bamboo fibres is a sustainable and reusable material that offers numerous benefits over conventional fibres. Its future popularity is expected to increase, especially as consumers become more cognizant of the necessity for environmentally friendly and minimally damaging substitutes for conventional materials.

References

1. CHANTARAT, P., POOLSIRI, R., WANNALANGKA, I., KAITPRANEET, S., PUANG CHIT, L., JENKE, M. Aboveground biomass productivity and nutrient use dynamics of clumping tropical bamboos in Northern Thailand. *Forests*, 2023, **14**(7), 1–15, doi: 10.3390/f14071450.
2. Get to know ‚bamboo' from a new perspective, being a green plant that drives the BCG economy [online]. SALIKA [accessed 22.05.2024]. Available on World Wide Web: <https://www.salika. co/2022/02/21/bamboo-new-bcg-economic-products>.
3. Bamboo value chain analysis in Thailand [online]. Thailand Environment Institut [accessed 22.05.2024]. Available on World Wide Web: <https://www.tei.or.th/file/library/2021-bamboo-eng_58.pdf>.
4. YU, Y., WANG, H., LU, F., TIAN, G., LIN, J. Bamboo fibers for composite applications: a mechanical and morphological investigation. *Journal of Materials Science,* 2014, **49**(6), 2559–2566, doi: 10.1007/s10853-013-7951-z .
5. JAIS, F.N.M., MOKERAMIN, M., ROSLAN, M.N., HALIP, J.A., JUSOH, W.A.W. Bamboo fiber for textile applications. In *Multifaceted bamboo: engineered products and other applications.* Edited by Paridah Md Tahir, Seng Hua Lee, Syeed SaifulAzry Osman Al-Edrus and Mohd Khairun Anwar Uyup. Singapore : Springer, 2023, 275–290, doi: 10.1007/978-981-19-9327-5_14.
6. WANNAJUN, S., CHANTACHON, S., LAOAKKA, S. Bamboo fabric: a study of using thick bamboo fiber for producing and developing thai textile. *Journal of Social Sciences,* 2011, **7**(3), 462–465.
7. YAMUNA DEVI, S., INDRAN, S., DIVYA, D. Futuristic prospects of bamboo fiber in textile and apparel industries: fabrication and characterization. In *Bamboo fiber composites: processing, properties and application.* Edited by Mohammad Jawaid, Sanjay Mavinkere Rangappa and Suchart Siengchin. Singapore : Springer, 2020, 189–213, doi: 10.1007/978-981-15-8489-3_11.
8. HASAN, K.F., HASAN, K.M.N.A, AHMED, T., GYÖRGY, S.T., PERVEZ, M.N., BEJÓ, L., SÁNDOR, B., ALPÁR, T. Sustainable bamboo fiber reinforced polymeric composites for structural applications: a mini review of recent advances and future prospects. *Case Studies in Chemical and Environmental Engineering*, 2023, **8**, 1–16, doi: 10.1016/j.cscee.2023.100362.
9. AFRIN, T., KANWAR, R.K., WANG, X., TSUZUKI, T. Properties of bamboo fibres produced using an environmentally benign method. *The Journal of The Textile Institute*, 2014, **105**(12), 1293–1299, doi: 10.1080/00405000.2014.889872.
10. GOKARNESHAN, N., KHAN, A. Antimicrobial properties of bamboo fibres. *Biomedical Journal of Scientific & Technical Research*, 2020, **32**(5), 25299–25302, doi: 10.26717/BJSTR.2020.32.005309.
11. IMADI, S.R., ISRA, M., KAZI, A.G. Bamboo fiber processing, properties, and applications. In *Biomass and bioenergy: processing and properties*. Edited by Khalid Rehman Hakeem, Mohammad Jawaid and Umer Rashid. Cham : Springer, 2014, 27–46, doi: 10.1007/978-3-319-07641-6_2.
12. CHEN, C., LI, H., DAULETBEK, A., SHEN, F., HUI, D., GAFF, M., LORENZO, R., CORBI, I., CORBI, O., ASHRAF, M., Properties and applications of bamboo fiber – a current-state-of-the art. *Journal of Renewable Materials,* 2022, **10**(3), 605–624, doi: 10.32604/jrm.2022.018685.
13. BABU, K.M., CHANDRASEKHARA, S.M. *Bamboo fibres: processing, properties and applications*. Cambridge : Elsevier, 2022.
14. PRAKASH, C. Bamboo fibre. In *Handbook of natural fibres. Volume 1: Types, properties and factors affecting breeding and cultivation*. Edited by Ryszard M. Kozłowski and Maria Mackiewicz-Talarczyk. Cambridge : Elsevier, 2020, 219–230, doi: 10.1016/B978-0-12-818398-4.00009-8.

15. TAUSIF, M., AHMAD, F., HUSSAIN, U., BASIT, A., HUSSAIN, T. A comparative study of mechanical and comfort properties of bamboo viscose as an eco-friendly alternative to conventional cotton fibre in polyester blended knitted fabrics. *Journal of Cleaner Production,* 2015, **89**, 110–115, doi: 10.1016/j.jclepro.2014.11.011.
16. VARGHESE, A.M., MITTAL, V. Surface modification of natural fibers. In *Biodegradable and biocompatible polymer composites: processing, properties and applications*. By Navinchandra Gopal Shimpi. Elsevier, 2018, 115–155, doi: 10.1016/B978-0-08-100970-3.00005-5.
17. XU, Y., LU, Z., TANG, R. Structure and thermal properties of bamboo viscose, Tencel and conventional viscose fiber. *Journal of Thermal Analysis and Calorimetry,* 2007, **89**(1), 197–201, doi: 10.1007/s10973-005-7539-1.
18. NAYAK, L., MISHRA, S.P. Prospect of bamboo as a renewable textile fiber, historical overview, labeling, controversies and regulation. *Fashion and Textiles*, 2016, **3**(1), 1–23, doi: 10.1186/ s40691-015-0054-5.
19. SHEN, Q., LIU, D. S., GAO, Y., CHEN, Y. Surface properties of bamboo fiber and a comparison with cotton linter fiber. *Colloids and Surfaces B: Biointerfaces,* 2004, **35**(3–4), 193–195, doi: 10.1016/j.colsurfb.2004.04.002.
20. WATE, M. Sustainable textiles: the role of bamboo and a comparison of bamboo textile propertie – part I. *Journal of Textile and Apparel, Technology and Management,* 2009, **6**(2), 1–21.
21. YUEPING, W., GE, W., HAITAO, C., GENLIN, T., ZHENG, L., FENG, X.Q., XIANGQI, Z., XIAOJUN, H., XUSHAN, G. Structures of bamboo fiber for textiles. *Textile Research Journal,* 2010, **80**(4), 334–434, doi: 10.1177/0040517509337633.
22. EBISSA, D.T., TESFAYE, T., AYELE, D.W. Characterization of thermal properties of highland bamboo fibers. *International Journal of Polymer Science*, 2022, **2022**, 1–12, doi: 10.1155/2022/8294952.
23. LIU, B., TANG, L., CHEN, Q., ZHU, L., ZOU, X., LI, B., ZHOU, Q., FU, Y., LU, Y. Lignin distribution on cell wall micro-morphological regions of fibre in developmental *Phyllostachys pubescens* culms. *Polymers*, 2022, **14**(2), 1–12, doi: 10.3390/polym14020312.
24. SADIKU, N.A., BADA, S.O. Technical rotation age for naturally-grown *Bambusa vulgaris* for fibre, fuel and structural application. *Journal of Tropical Forest Science*, 2017, **29**(4), 541–548, doi: 10.26525/jtfs2017.29.4.541548.
25. ARFIN, T., MOHAMMAD, F., YUSOF, N.A. Biomass resources in environmental and socio-economic analysis of fuel-wood consumption. In *Biomass and bioenergy: processing and properties*. Edited by Khalid Rehman Hakeem, Mohammad Jawaid and Umer Rashid. Cham : Springer, 2014, 191–206, doi: 10.1007/978-3-319-07641-6_12.
26. FARUK, O., BLEDZKI, A.K., FINK, H.P., SAIN, M. Biocomposites reinforced with natural fibers: 2000–2010. *Progress in Polymer Science*, 2012, **37**(11), 1552–1596, doi: 10.1016/ j.progpolymsci.2012.04.003.
27. HU, M., WANG, C., LU, C., ANUAR, N.I.S., YOUSFANI, S.H.S., JING, M., CHEN, Z., ZKARIA, S., ZUO, H. Investigation on the classified extraction of the bamboo fiber and its properties. *Journal of Natural Fibers*, 2020, **17**(12), 1798–1808, doi: 10.1080/15440478.2019.1599311.
28. LIU, L., WANG, Q., CHENG, L., QIAN, J., YU, J. Modification of natural bamboo fibers for textile applications. *Fibers and Polymers*, 2011, **12**, 95–103, doi: 10.1007/s12221-011-0095-3.
29. ROCKY, B.P., THOMPSON, A.J. Production and modification of natural bamboo fibers from four bamboo species, and their prospects in textile manufacturing. *Fibers and Polymers,* 2020, **21**, 2740–2752, doi: 10.1007/s12221-020-1208-7.
30. ROCKY, B.P., THOMPSON, A.J. Investigation and comparison of antibacterial property of bamboo plants, natural bamboo fibers and

commercial bamboo viscose textile. *Journal of the Textile Institute,* 2021, **12**(7), 1159–117, doi: 10.1080/00405000.2020.1807300.
31. ROCKY, B.P., THOMPSON, A.J. Production of natural bamboo fibers-1: experimental approaches to different processes and analyses. *Journal of the Textile Institute,* 2018, **109**(10), 1381–1391, doi: 10.1080/00405000.2018.1482639.
32. HARI, P.K. Types and properties of fibres and yarns used in weaving. In *Woven textiles: principles, technologies and applications.* Edited by K.L. Gandhi. Elsevier, 2012, 3–34, doi: 10.1016/B978-0-08-102497-3.00001-5.
33. GÖKTEPE, Ö., BOZKAN, O. Study on reduction of air consumption on air-jet weaving machines. *Textile Research Journal*, **78**(9), 816–824, doi: 10.1177/0040517508090493.
34. BS 4044:1989 Methods for determination of fibre length by comb sorter diagram. London : British Standards Institution, 1–14.
35. ASTM D1059 Standard test method for yarn number based on short-length specimens. Pennsylvania : ASTM International, 2001, 1–7.
36. ASTM D2256 Standard test method for tensile properties of yarns by the single-strand method. Pennsylvania : ASTM International, 2002, 1–12.
37. ISO 7211-2:1984 Textiles - Woven fabrics - Construction - Methods of analysis - Part 2: Determination of number of threads per unit length. Geneva : International Organization for Standardization, 1–6.
38. ASTM D1777 Standard test method for thickness of textile materials. Pennsylvania : ASTM International, 2011, 1–5.
39. ISO 13937-1: 2000 Textiles -Tear properties of fabrics - Part 1: Determination of tear force using ballistic pendulum method (Elmendorf). Geneva : International Organization for Standardization, 1–13.
40. ASTM D5034 Standard test method for breaking strength and elongation of textile fabrics (Grab Test). Pennsylvania : ASTM International, 2009, 1–8.
41. ASTM D3776 Standard test methods for mass per unit area (weight) of fabric. Pennsylvania : ASTM International, 2009, 1–5.
42. ALWANI, M.S., KHALIL, H.P.S.A., ASNIZA, M., SUHAILY, S.S., AMIRANAJWA, A.S. N., JAWAID, M. Agricultural biomass raw materials: the current state and future potentialities. In *Biomass and bioenergy: processing and properties*. Edited by Khalid Rehman Hakeem, Mohammad Jawaid and Umer Rashid. Cham : Springer, 2014, 77–100, doi: 10.1007/978-3-319-07641-6_5.
43. HUSSAIN, U., YOUNIS, F.B., USMAN, F., HUSSAIN, T., AHMED, F. Comfort and mechanical properties of polyester/bamboo and polyester/cotton blended knitted fabric. *Journal of Engineered Fibers and Fabrics*, 2015, **10**(2), 61–69, doi: 10.1177/155892501501000207.
44. SARIOĞLU, E. Ecological approaches in textile sector: the effect of r-PET blend ratio on ring spun yarn tenacity. *Periodicals of Engineering and Natural Sciences,* 2017, **5**(2), 176–180, doi: 10.21533/pen.v5i2.110.
45. LI, Q., SU, G., CHAI, X., XIE, L., ZHOU, J., DU, G., ZHANG, L., WANG, S., XU, K. A comparative study on the comprehensive properties of natural microfibers isolated from the large-clustered bamboos in the southwest of China using steam explosion. *Journal of Natural Fibe*rs, 2023, **20**(1), 1–15, doi: 10.1080/15440478.2022.2164109.
46. CHONSAKORN, S., SRIVORRADATPAISAN, S., MONGKHOLRATTANASIT, R. Effects of different extraction methods on some properties of water hyacinth fiber. *Journal of Natural Fibers*, 2019, **16**(7), 1015–1025, doi: 10.1080/15440478.2018.1448316.
47. DAS, S. *Performance of home textiles*. New Delhi : Woodhead Publishing, 2010.
48. SOWMYA, R., VASUGI RAAJA, N., PRAKASH, C. Investigation of relationship between blend ratio and yarn twist on yarn properties of bamboo, cotton, polyester, and its blends. *Journal of Natural Fibers,* 2017, **14**(2), 228–238, doi: 10.1080/15440478.2016.1193087.

49. WITAYAKRAN, S., HARUTHAITHANASAN, M., AGTHONG, P., THINNAPATANUKUL, T. Green production on natural bamboo fibers for textiles. In *2013 ITCC: Silk aesthetic, culture, history, technology, fashion and innovation. 2013 International textiles and costume congress, Bangkok,* 198–203, https://kukr.lib.ku.ac.th/kukr_es/kukr/search_detail/result/353308.
50. LOBREGAS, M.O.S., BUNIAO, E.V.D., LEAÑO, J.L. Alkali-enzymatic treatment of Bambusa blumeana textile fibers for natural fiber-based textile material production. *Industrial Crops and Products,* 2023, **194**, 1–10, doi: 10.1016/j.indcrop.2023.116268.

SHORT INSTRUCTIONS FOR AUTHORS OF SCIENTIFIC ARTICLES

Scientific articles categories:

- **Original scientific article** is the first publication of original research results in such a form that the research can be repeated and conclusions verified. Scientific information must be demonstrated in such a way that the results are obtained with the same accuracy or within the limits of experimental errors as stated by the author, and that the accuracy of analyses the results are based on can be verified. An original scientific article is designed according to the IMRAD scheme (Introduction, Methods, Results and Discussion) for experimental research or in a descriptive way for descriptive scientific fields, where observations are given in a simple chronological order.
- **Review article** presents an overview of most recent works in a specific field with the purpose of summarizing, analysing, evaluating or synthesizing information that has already been published. This type of article brings new syntheses, new ideas and theories, and even new scientific examples. No scheme is prescribed for review article.
- **Short scientific article** is original scientific article where some elements of the IMRAD scheme have been omitted. It is a short report about finished original scientific work or work which is still in progress. Letters to the editor of scientific journals and short scientific notes are included in this category as well.

Language: The manuscript of submitted articles should be written in UK English or in Slovene with bilingual Figures and Tables. The authors responsibility to ensure the quality of the language.

Manuscript length: The manuscript should not exceed 30,000 characters without spacing.

Article submission: The texts should be submitted only in their electronic form in the *.doc (or *.docx) and *.pdf formats, where for each author must be given:

- first name and family name
- title
- full institution address
- ORCID ID
- e-mail.

The name of the document should contain the date (year-month-day) and the surname of the corresponding author, e.g. 20140125Novak.docx. The manuscripts proposed for a review need to have their figures and tables included in the text.

Detailed information on the preparation and submission of the manuscript is available on the website: https://journals.uni-lj.si/tekstilec/about/submissions.

Reviewer suggestions

Authors can suggest potential reviewers. Please provide their titles, ORCID IDs, institutions, and e-mail addresses. The proposed referees should not be current collaborators of the co-authors nor should they have published with any of the co-authors of the manuscript within the last three years. The proposed reviewers should be from institutions other than the authors.

Authors may also provide the names of potential reviewers they wish to exclude from reviewing their manuscript during the initial submission process.

Peer-review process

All submitted articles are professionally, terminologically and editorially reviewed in accordance with the general professional and journalistic standards of the journal Tekstilec. All articles are double-blind reviewed by two or more reviewers independent of editorial board.

The review process takes a minimum of two weeks and a maximum of one month. The reviewers' comments are sent to authors for them to complete and correct their manuscripts. If there is no consensus among the reviewers, the editorial board decides on the further procedure. We accept the articles for publication based on a positive decision.

Copyright corrections

The editors are going to send computer printouts for proofreading and correcting. It is the author's responsibility to proofread the article and send corrections as soon as possible. However, no greater changes or amendments to the text are allowed at this point.

Colour print of hard copies

Colour print is performed only when this is necessary from the viewpoint of information comprehension, and upon agreement with the author and the editorial board.

Copyright Notice

Authors who publish with this journal agree to the following terms:

- Authors are confirming that they are the authors of the submitting article, which will be published (print and online) in journal Tekstilec by University of Ljubljana Press / Faculty of Natural Sciences and Engineering, Unviersity of Ljubljana, Aškerčeva 12, SI-1000 Ljubljana, Slovenia).
- Author's name will be evident in the article in journal. All decisions regarding layout and distribution of the work are in hands of the publisher.
- Authors guarantee that the work is their own original creation and does not infringe any statutory or common-law copyright or any proprietary right of any third party. In case of claims by third parties, authors commit their self to defend the interests of the publisher, and shall cover any potential costs.
- Authors retain copyright and grant the journal right of first publication with the work simultaneously licensed under a Ceative Commons Attribution CC BY 4.0 that allows others to share the work with an acknowledgement of the work's authorship and initial publication in this journal.
- Authors are able to enter into separate, additional contractual arrangements for the non-exclusive distribution of the journal's published version of the work (e.g. post it to an institutional repository or publish it in a book), with an acknowledgement of its initial publication in this journal.
- Authors are permitted and encouraged to post their work online (e.g., in institutional repositories or on their website) prior to and during the submission process, as it can lead to productive exchanges, as well as earlier and greater citation of published work.

Privacy Statement

The personal data entered in this journal site, like names and addresses, will be used exclusively for the stated purposes of this journal and will not be made available for any other purpose or to any other party.