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Study of the Influence of the Surface Roughness of Knitted Fabrics from Natural Fibres on the Light Fastness of Their Colours

Študija vpliva površinske hrapavosti pletiv iz naravnih vlaken na barvno obstojnost proti sončni svetlobi

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Abstract

The article examines the influence of the surface properties of knitted fabrics from cotton and wool of various knitted structures on the light fastness of their colours. The surface properties of knitted fabrics of single plain, 1×1 rib and French piqué knitted structures were evaluated by determining their roughness using a non-contact optical method for processing digital images of the knitted fabric's surface. The roughness profiles of the corresponding knitted fabric samples were obtained, and the main indicators of surface roughness were calculated: the profile height at ten points R_z and the arithmetic mean profile deviation R_a. Cotton knitted fabrics were dyed with the Bezaktiv Cosmos dye brand, which are bifunctional reactive dyes with monochlorotriazine / vinyl sulfone active groups, and wool knitted fabrics were dyed with acid dyes. The light fastness of the samples was evaluated after exposure to the Light Fastness Tester (Mercury-Tungsten Lamp) RF 1201 BS (REFOND) with a PCE-TCR 200 colorimeter. Colour measurements were averaged for each sample. Total colour difference (dE) was measured on the dyed cotton knitted fabrics samples after light exposure. According to the obtained roughness profiles of cotton and wool knitted fabrics, it can be concluded that the studied knitted fabrics are characterized by different roughness, which depends on their knitted structures. At the same time, a relationship was found between an increase in the roughness of knitted fabrics and the photodestruction of colours by reactive and acid dyes on cotton and wool knitted fabrics, respectively. The results show that the surface structure of knitted fabrics, that is the knitted structure, impacts the process of colour photodestruction and that the amount of dye that has undergone photodestruction increases with the increasing surface roughness of the knitted fabric.

Keywords: knitted fabric, knitted structure, roughness, photodestruction, light fastness.

Izvleček

V članku je proučen vpliv površinskih lastnosti strukturno različnih bombažnih in volnenih pletiv na barvno obstojnost proti sončni svetlobi. Površinske lastnosti pletiv v enostavni levo-desni, 1x1 rebrasti in francoski vezavi piké so bile ovrednotene z določanjem hrapavosti z brezstično optično metodo za obdelavo površine pletiv na digitalnih slikah. Dobljeni so bili profili hrapavosti posameznih vzorcev pletiv in izračunani glavni kazalci površinske hrapavosti: višina profila v

desetih točkah, Rz, in aritmetična sredina odstopanja profila, Ra. Bombažna pletiva so bila barvana z bifunkcionalnimi reaktivnimi barvili znamke Bezaktiv Cosmos, z monoklorotriazinskimi oziroma vinilsulfonskimi aktivnimi skupinami. Volnena pletiva so bila barvana s kislimi barvili. Barvna obstojnost pletiv na svetlobi je bila ocenjena po izpostavitvi vzorcev osvetljevanju v aparatu Light Fastness Tester RF 1201 BS (REFOND), opremljenem z živosrebrno-volframovo žarnico, in kolorimetrom PCE-TCR 200. Meritve barve so bile povprečne za vsak vzorec. Skupna barvna razlika (dE) je bila izmerjena na vzorcih barvanih bombažnih pletiv po izpostavljenosti svetlobi. Glede na dobljene profile hrapavosti bombažnih in volnenih pletiv je bilo ugotovljeno, da imajo pletiva različno hrapavost, ki je odvisna od strukture pletiv. Hkrati je bila ugotovljena povezava med povečanjem hrapavosti pletiv in fotorazgradnjo barve bombažnih in volnenih pletiv, obarvanih z reaktivnimi in kislimi barvili. Dobljeni rezultati prikazujejo vpliv strukture površine pletiv na proces fotorazgradnje barve in kažejo, da količina, razgrajenega zaradi delovanja svetlobe, narašča z večanjem površinske hrapavosti pletiva.
Ključne besede: pletivo, pletilske vezave, hrapavost, fotorazgradnja, svetlobna obstojnost

1 Introduction

The roughness of fibrous materials is an important aspect of their quality and determines the surface properties and appearance of fabrics and knitted fabrics as well as products made from them [1, 2].
We have already examined the effect of the nature of the polymer matrix [3], preparation technologies [4, 5], chemical properties [6, 7] and dye concentration [8] on the light fastness of cotton and wool knitted fabrics colours. Despite the fact that the light fastness of colours largely depends on the chemical structure of dyes, in order to obtain comprehensive data, in this work, we planned to study the effect of structural characteristics of knitted fabrics from natural fibres on the light fastness of their colours. The irregularity of the surface of knitted fabrics of various knitted structures is proposed to be assessed by determining roughness indicators.
The roughness of material is characterized by the parameters given in ISO 4287:1997. Geometrical Product Specifications – Surface texture: Profile method – Terms, definitions and surface texture parameters [9]. According to these parameters, surface roughness is a set of surface irregularities with a relatively small step that is usually determined by its profile (Figure 1), which is formed in the cross section of this surface by a plane perpendicular to the nominal surface. In this case, the roughness profile is considered along the length of the baseline and is used to highlight the irregularities and quantify the parameters.
The assessment of surface roughness is based on the accepted reference system, in which the middle line of the profile serves as the baseline – this is the baseline *m*, which has the shape of a nominal profile and is drawn, so that the standard deviation of the profile to this line is minimal within the base length. The middle line of the profile is at the same distance from the lines of the peaks and valleys of the profile, which respectively pass through the highest and lowest points of the profile within the base length.
The main characteristics of the roughness profile are the height of its peak y_{pm} and the depth of its valley y_{vm}. These are the distances from the midline of the profile to the highest point of the peak and the lowest point of the valley, respectively.
To assess the surface roughness of fibrous materials, the height criterion R_z is common – the height of the profile at ten points [9]. It is the sum of the average absolute values of the heights of the five largest peaks of the profile and the depths of the five largest valleys of the profile within the length of the profile. The criterion of the arithmetic mean deviations of the R_a profile, which is the arithmetic mean absolute value of profile deviations within the basic profile length [9, 10], is also significant for assessing surface roughness. Thus, to calculate the roughness parameters of knitted fabrics, it is necessary to obtain their roughness profiles.

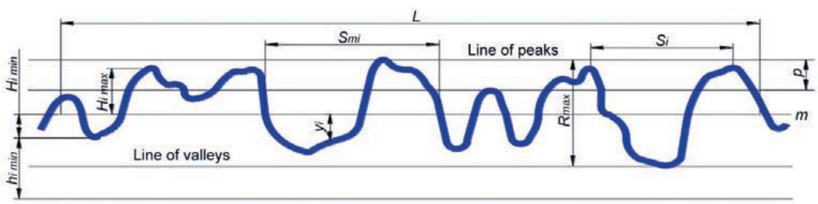


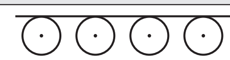
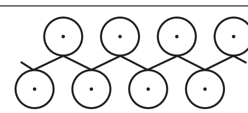
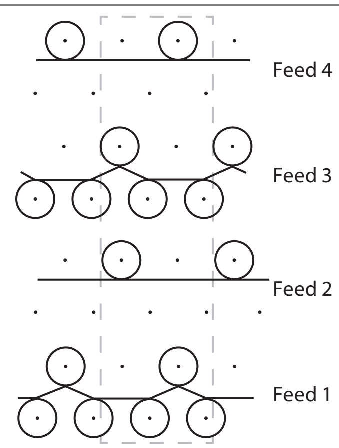
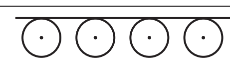
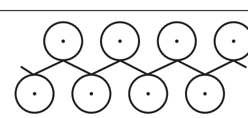
Figure 1: Roughness profile and its characteristics

Studies aimed at measuring and evaluating the profile characteristics of the roughness of textile materials using various devices are presented in [11, 12, 13], where all methods are divided into contact and non-contact. Contact methods for determining roughness involve a direct measurement of the relief of a textile material using a multidirectional tribometer [12], an optical multidirectional roughness meter [14], the so-called “vibrating blade” [15], and an inductive sensor converting displacement into an electric stream [16]. Non-contact measurement of roughness is performed using a variety of optical profilometer systems: Talysurf CCI 6000 [17], Micro Measure 3D Station [18], MicroXAM-100 and MicroXAM-1200 [19], Puotech 0918 [20], helium-neon laser [21, 22], triangulated laser technology [23], and microscopy and confocal microscopy [22]. However, these devices are expensive and not widely available.
The method for determining the roughness of textile materials using software products for processing scanned images, proposed in [24], does not require additional equipment and is available. Therefore, in this work, the determination of the roughness indicators of knitted fabrics was carried out in a non-contact way, that is by the optical method of processing digital images of the knitted fabrics surface in the JMicroVision 1.3.2 software environment.

2 Materials and methods

In the work, cotton and wool knitted fabrics of various knitted structures and surface density were investigated. Their main characteristics are given in Table 1.
Cotton knitted fabric was dyed with Bezaktiv Cosmos reactive dyes: Rot S-C, Blue S-C, Gold S-C, which are bifunctional reactive dyes with monochlorotriazine / vinyl sulfone active groups. Dyeing cotton knitted fabric was carried out using the exhaust dyeing method with a 1/50 solution rate. The mass of the knitted fabric sample was 1 g. The dye

Table 1: Characteristics of knitted fabrics

Raw material	Knitted structure	Surface density (g/m²)	Schematic representation of knitted structure
100% cotton	Single plain	150	
	1×1 rib	150	
	1×1 rib	280	
	French piqué	170	
100% wool	Single plain	420	
	1×1 rib	380	
	1×1 rib	450	

solution contained 1% dye and dyeing auxiliaries (30 g/l NaCl + 15 g/l Na_2CO_3). The dyeing was performed for 60 min at 60 °C, followed by applying overflow cold, hot washing, boiling soaping and cold rinsing procedures [25].

For dyeing the wool knitted fabric, the following acid dyes were used according to the corresponding dyeing methods: Acid Red 150 (method I), Acid Blue 92 (method II), Acid Green 27 (method followed by chroming). Dyeing technologies with acid dyes depend on their chemical structure. Dyeing of wool knitted fabric was carried out with the exhaust dyeing method. Samples of wool knitted fabric with a mass of 1 g and a liquor to fabric ratio of 50:1 were used. The dyebath contained 1% owf dye, 10% owf sodium sulphate, 4% owf acetic acid 30% (method I) or 4% owf ammonium sulphate (method II). Sodium sulfate and an acid agent (acetic acid or ammonium sulfate) were introduced into the total volume of water, heated to 40 °C , and knitted fabric samples were immersed in the solution. The treatment was carried out for 10 min. Then, the samples were taken out, the dye was added to the solution and the knitted fabric was immersed again. Next, the dye bath was heated to boiling point for 30 min. and dyed for 45 min. The dyed samples were washed with cold water and dried [26, 27].

The technology of dyeing wool knitted fabric with chrome dyes was followed by chroming. The liquor to fabric ratio was 50:1. The dyebath contained 1% owf dye, 10% owf sodium sulfate, 4% owf acetic acid. 30% Sodium sulfate, acetic acid and knitted fabric were introduced into the total volume of water at 30–45 °C, heated to boiling point for 45 minutes. Then, concentrated sulfuric acid measuring 1% of weight of the knitted fabric was introduced into the bath and dyed for another 20 min until the dye was completely exhausted. Afterwards, the temperature was lowered to 80 °C by adding cold water and a solution of potassium dichromate was introduced

Table 2: Indicators of light fastness of colours of the dyes used

Reactive dyes	Light fastness	Acid dyes	Light fastness
Bezaktiv Cosmos Rot S-C	4–5	Acid Red 150	4
Bezaktiv Cosmos Blue S-C	5–6	Acid Blue 92	4
Bezaktiv Cosmos Gold S-C	6	Acid Green 27	6

in the amount of 1% of the weight of knitted fabric. Chroming was carried out at boiling point for 20 min. Afterwards, the dyed samples were washed with cold water and dried [26, 27].

Table 2 shows the light fastness of colours obtained by the reactive and acid dyes used in the work as declared by the manufacturers [25, 28–30].

The study of the surface roughness of knitted fabrics was conducted by obtaining roughness profiles of the corresponding knitted fabrics samples by processing digital images of the surface of knitted fabrics in the JMicroVision 1.3.2 software environment. Next, the main indicators of surface roughness were calculated: the profile height at ten points R_z and the arithmetic mean profile deviation R_a using formulas (1), (2), according to ISO 4287:1997 [9].

$$R_z = \frac{\sum_{i=1}^{5} y_{pmi} + \sum_{i=1}^{5} |y_{vmi}|}{10} \tag{1}$$

where y_{pmi} is height of the ith largest peak of the profile and

y_{vmu} is depth of the ith largest valley of the profile.

$$R_a = \frac{1}{2n}\sum_{i=1}^{n} y_{pmi} + \frac{1}{2n}\sum_{i=1}^{n} |y_{vmi}| \tag{2}$$

where n is the number of selected points on base length.

The studied indicators were determined for samples of knitted fabrics walewise and coursewise.

The light fastness of samples was evaluated after exposure to the Light Fastness Tester (Mercury-Tungsten Lamp) RF 1201 BS (REFOND) with a PCE-TCR 200 colorimeter. The exposure time of the dyed knitted fabric samples was 320 hours. Colour measurements were averaged for each sample. Total colour difference (*dE*) was measured on the dyed cotton knitted fabrics samples after light exposure. Colour difference was calculated according to CIE 1976 L*a*b* equation (3):

$$\mathrm{dE} = [(dL)^2 + (da)^2 + (db)^2]^{1/2} \tag{3}$$

where *dL* is difference in lightness-darkness, *da* is difference in redness-greenness; *db* is difference in yellowness-blueness.

3 Results and discussion

The obtained profiles of the surface roughness of the cotton knitted fabrics samples of the studied knitted structures and surface density walewise and coursewise are shown in Figure 2.

According to the obtained roughness profiles of cotton knitted fabric, it can be concluded that the studied knitted fabrics vary in roughness, depending on their knitted structures. Knitted fabric with a single plain knitted structure has a uniform roughness of low values in both directions. For the rib, there is an increase in roughness coursewise. Piqué knitted fabric is characterized by high levels of roughness both walewise and coursewise.

Figure 3 depicts the roughness profiles of wool knitted fabric samples of the studied knitted structures and surface density.

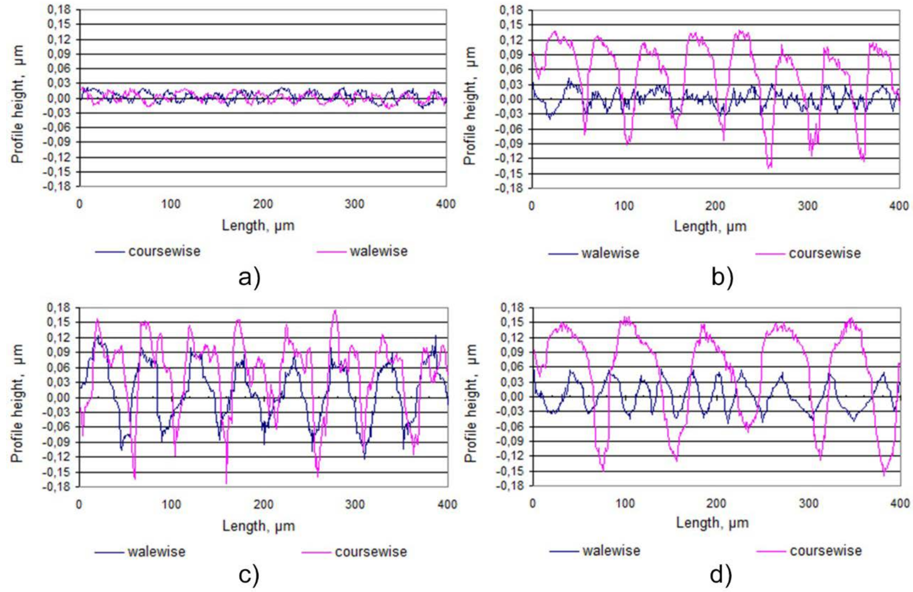


Figure 2: Roughness profiles of cotton knitted fabric samples: a) single plain; b) 1×1 rib 150 g/m²; c) French piqué; d) 1×1 rib 280 g/m²

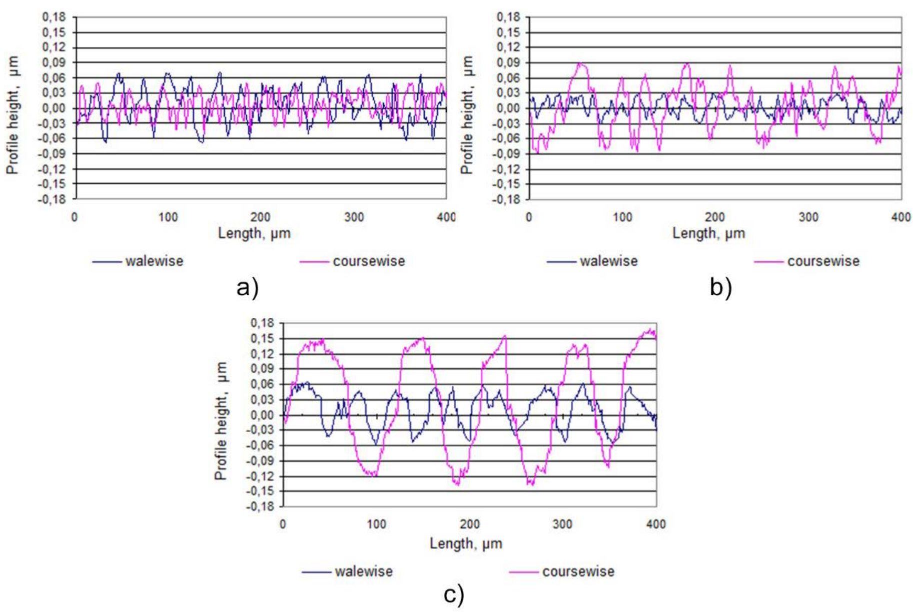


Figure 3: Roughness profiles of wool knitted fabric samples: a) single plain; b) 1×1 rib 380 g/m²; c) 1×1 rib 450 g/m²

Table 3: Influence of knitted structure and surface density on the roughness characteristics of cotton and wool knitted fabrics

Knitted fabric	Knitted structure and surface density	Profile height by ten points, R_z (μm)			Arithmetic mean of profile deviations, R_a (μm)		
		walewise	coursewise	mean	walewise	coursewise	mean
Cotton	Single plain	0.018	0.018	0.018	3.09	4.08	3.58
	1×1 rib, 150 g/m^2	0.029	0.122	0.076	6.39	6.36	6.38
	1×1 rib, 280 g/m^2	0.044	0.142	0.093	6.62	7.11	6.86
	French piqué	0.152	0.139	0.146	8.57	7.75	8.16
Wool	Single plain	0.030	0.047	0.039	7.12	7.25	7.19
	1×1 rib, 380 g/m^2	0.068	0.087	0.078	6.97	8.39	7.68
	1×1 rib, 450 g/m^2	0.089	0.099	0.094	7.56	9.12	8.34

The obtained surface roughness profiles of wool knitted fabric samples of plain and rib knitted structures, as in the case of cotton knitted fabrics, differ. The plain has a more uniform roughness walewise and coursewise on the canvas. The rib is characterized by a uniform surface walewise and an increase in roughness coursewise. For the rib, there is an increase in roughness coursewise, irrespective of the surface density of the knitted fabric.

Based on the obtained roughness profiles, the main roughness characteristics were calculated: the profile height at ten points R_z and the arithmetic mean profile deviation R_a. The research results are presented in Table 3.

The results of calculating the main roughness indicators R_z and R_a (Table 3), which characterize the unevenness of the knitted fabrics surface, show that the roughness of knitted fabrics from natural fibres depends on the knitted structure and increases in the series single plain < 1×1 rib < French piqué and with an increase in surface density. The plain knitted structure has a more uniform roughness walewise and coursewise compared to the rib knitted structure, but less uniformity compared to the plain knitted structure of cotton knitted fabric.

Figure 4 depicts the study results of the colours' photodestruction in knitted fabrics for 320 hours of insolation and the roughness indicators depending on the knitted fabrics' knitted structures.

The results presented in Figure 4 show that with an increase in the roughness of knitted fabrics, the photodestruction of dyes by reactive and acid dyes on cotton and wool knitted fabrics increases, respectively.

Figure 5 presents the study results of the photodestruction of knitted fabrics colours for 320 hours of insolation and the roughness indicators depending on the surface density of knitted fabrics.

Presented in Figure 5, the results indicate that with an increase in the surface density of knitted fabrics from natural fibres, the roughness increases and the photodestruction of reactive and acid dyes increases on cotton and wool knitted fabrics, respectively.

The obtained results confirm the impact of the surface structure of knitted fabrics, that is the knitted structure and surface density, on the photodestruction process of colours and show that the amount of dye that has undergone photodestruction increases with an increase in the surface roughness of the knitted fabric.

Taking into account the results of determining the surface roughness of knitted fabrics and the features of the photodestruction process of colours depending on their knitted structures, Figure 6 shows schematic images of the studied knitted fabrics and the mechanism of light exposure to them.

Thus, the studies on the roughness of knitted fabrics make it possible to determine the relationship between the light fastness of colours and the structural properties of knitted fabrics. The relatively uniform surface of a single plain structure knitted fabric distributes energy evenly and reflects more incident light than knitted fabrics with an uneven rough surface of 1×1 rib and French piqué knitted structures. Knitted fabrics with a more uneven rough surface- 1×1 rib and French piqué reflect less light, the incident rays are refracted and again fall on the surface of the knitted fabrics, which leads to a greater photodestruction of its colours.

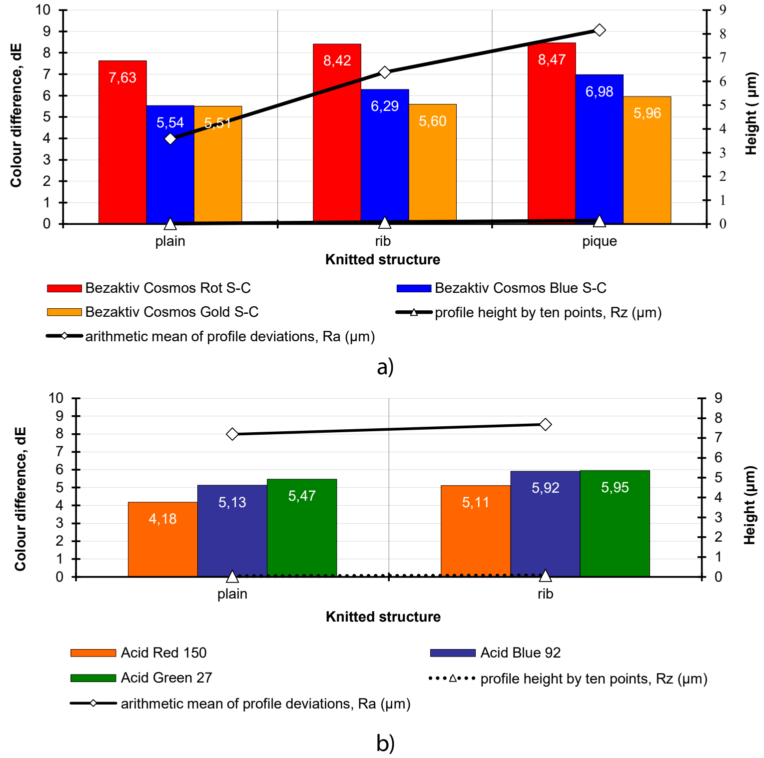


Figure 4: Influence of knitted structure on surface roughness and photodestruction of colours: a) cotton knitted fabrics dyed with reactive dyes; b) wool knitted fabrics dyed with acid dyes

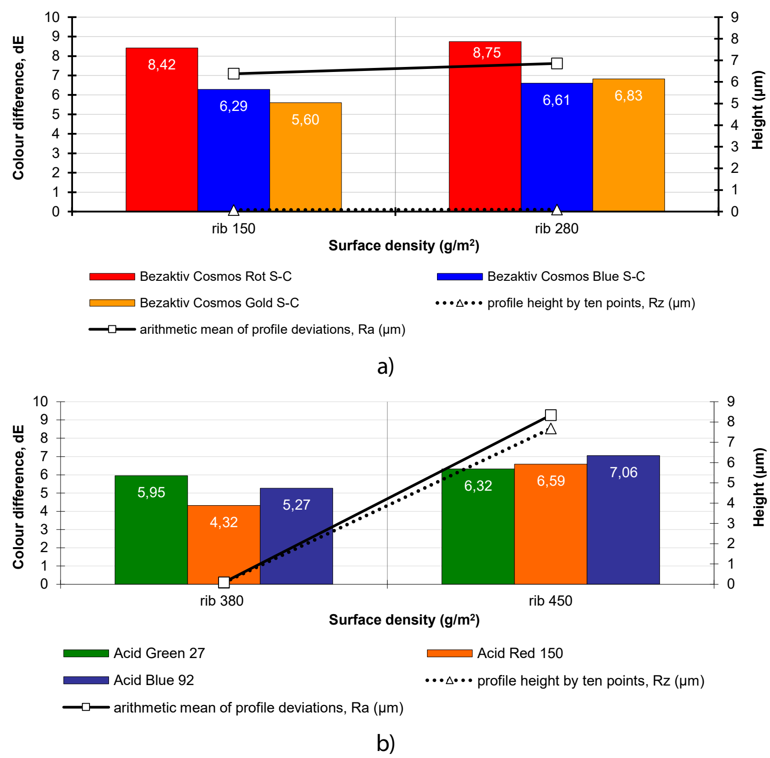


Figure 5: Influence of surface density on surface roughness and photodestruction of colours: a) cotton knitted fabrics dyed with reactive dyes; b) wool knitted fabrics dyed with acid dyes

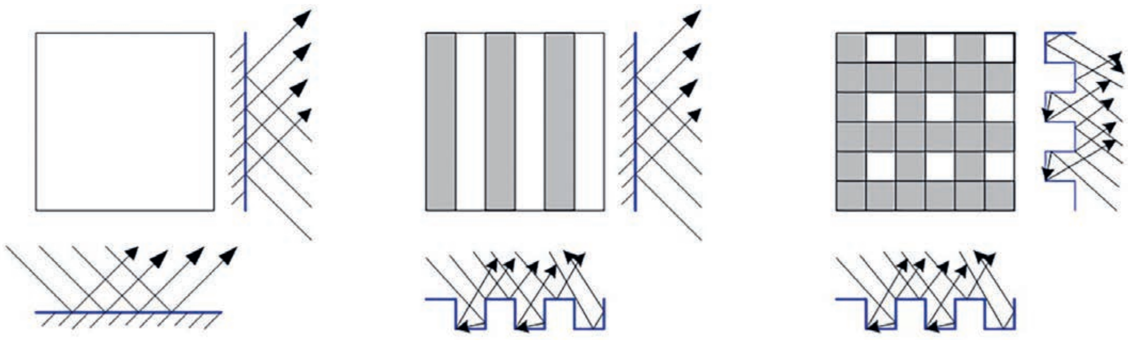


Figure 6: Mechanism of action of light on knitted fabrics of different knitted structures: a) single plain; b) 1×1 rib; c) French piqué

Therefore, on the basis of the obtained roughness profiles by calculating the main characteristics of roughness – the profile height at ten points R_z and the arithmetic mean deviations of the profile R_a – it has been found that for the studied knitted fabrics, the photodestruction of colours increases with the increasing roughness in the series single plain < 1×1 rib < French piqué and with an increase in the surface density of knitted fabrics. Based on the conducted research, we can conclude that knitted fabrics with an uneven rough surface structure necessarily need light-protective treatment.

4 Conclusion

Studies on the dependence of the light fastness of knitted fabrics from natural fibres on the structure of knitted fabrics have showed that the type of knitted structure and the surface density of knitted fabrics have a significant impact on their light fastness. The research of the effect of knitted structure and surface density on the photodestruction kinetics of colours of knitted fabrics from natural fibres showed that both for cotton and wool knitted fabrics, the light fastness of colours increases in the series French piqué < 1×1 rib < single plain and with a decrease in the surface density of the studied knitted fabrics.

On the basis of the obtained roughness profiles and the analysis of the calculated basic characteristics of roughness, it has been found that for the studied knitted structures of knitted fabrics, the increase in roughness coincides with a decrease in the light fastness of colours in the series single plain < 1×1 rib < French piqué. Thus, based on the conducted studies of the effect of the structure of knitted fabrics from natural fibres on its light fastness, it is possible to claim that knitted fabrics with an uneven rough surface structure require a protective treatment that will ensure their light fastness.

References

1. NAJEH, M., MEHDI, S., FAOUZI, S. Statistical analysis of surface roughness parameters for weft knitted fabrics measured by the Textile Surface Tester (TST). *Journal of Engineered Fibers and Fabrics*, 2012, **7**(4), 104–112, doi: 10.1177/155892501200700407.
2. SÜLAR, V., ÖNER, E., OKUR, A. Roughness and frictional properties of cotton and polyester woven fabrics. *Indian Journal of Fibre & Textile Research*, 2013, **38**(4), 349–356.
3. SEMESHKO, O.Ya. Study of the influence of the chemical nature of textile materials on the color fastness by reactive dyes to the light. *Visnyk of Kherson National Technical University*, 2019, **4**(71), 84–92, doi: 10.35546/kntu2078-4481.2019.4.9 [in Ukrainian].
4. SEMESHKO, O.Ya, ASAULYUK, T., SKALOZUBOVA, N., SARIBYEKOVA, Yu.G. Study of influence of the preparation method on the light fastness of cotton knitted fabric. *Vlakna a Textil*, 2019, **26**(2), 48–53.
5. SEMESHKO, O.Ya., ASAULYUK, T.S., SARIBYEKOVA, Yu.G. Study of the influence of preparation technologies on the wear resistance of wool knitted fabric dyed with acid dyes. *Visnyk of Kherson National Technical University*, 2021, **3**(78), 99–108, doi: 10.35546/kntu2078-4481.2021.3.10 [in Ukrainian].

6. SEMESHKO, O.Ya. Study of the influence of the chemical structure of acid dyes on the lightfastness of colours. *Bulletin of the Kyiv National University of Technologies and Design. Technical Science Series*, 2019, **130**(1), 56–63, doi: 10.30857/1813-6796.2019.1.6 [in Ukrainian].
7. SEMESHKO, O.Ya., ASAULYUK, T.S., SARIBYEKOVA, Yu.G. Study of the influence of reactive dyes chemical properties on the process of dyed knitted fabrics photodestruction. *Visnyk of Kherson National Technical University*, 2021, **4**(79), 123–134, doi: 10.35546/kntu2078-4481.2021.4.14 [in Ukrainian].
8. SEMESHKO, O.Ya. Study of the concentration effect of reactive dyes on the lightfastness of colours cotton knitted fabrics. *Scientific notes of V.I. Vernadsky TNU. Series: technical sciences*, 2019, **30**(69/2), 172–175 [in Ukrainian], https://www.tech.vernadskyjournals.in.ua/eng/journals/2019/2_2019/part_2/2-2_2019.pdf#page=180.
9. ISO 4287:1997. *Geometrical product specifications – surface texture: profile method – terms, definitions and surface texture parameters*. Geneva : International Organization for Standardization, 1997, 1–25.
10. CHANG, W.-R., KIM, I.-J., MANNING, D.P., BUNTERNGCHIT, Y. The role of surface roughness in the measurement of slipperiness. *Ergonomics*, 2001, **44**(13), 1200–1216, doi: 10.1080/00140130110085565.
11. 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.
12. KOLCAVOVA SIRKOVA, B. Description of fabric thickness and roughness on the basis of fabric structure parameters. *AUTEX Research Journal*, 2012, **12**(2), 40–43.
13. MAÂTOUG, N., SAHNOUN, M., SAKLI, F. Surface roughness evaluation of weft knitted fabric by using a textile surface tester. *Research Journal of Textile and Apparel*, 2011, **15**(4), 44–54, doi::10.1108/RJTA-15-04-2011-B006.
14. BUENO, M.A., LAMY, B., RENNER, M. Effect of grain size and abrasion duration on the state of textile fabric surfaces. *Wear*, 2002, **253**(3–4), 448–457, doi: 10.1016/S0043-1648(02)00146-1.
15. FONTAINE, S., MARSIQUET, C., NICOLETTI, N., RENNER, M., BUENO, M.A. Development of a sensor for surface state measurements using experimental and numerical modal analysis. *Sensors and Actuators A*, 2005, **120**(2), 507–517, doi: 10.1016/j.sna.2005.02.017.
16. ROMDHANI, Z., HAMDAOUI, M., BAFFOUN, A., MAATOUG, N., ROUDESLI, S. 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.
17. de GROOT, P. Principles of interference microscopy for the measurement of surface topography. *Advances in Optics and Photonics*, 2015, **7**(1), 1–65, doi: 10.1364/AOP.7.000001.
18. HAYNES, M., WU, C.-H.J., BECK, B.T., PETERMAN, R. 3D non-contact profilometry for reinforcement steel quality control. In *Proceedings of the 2013 Industrial and Systems Engineering Research Conference*. Edited by A. Krishnamurthy and W.K.V. Chan. Institute of Industrial and Systems Engineers (IISE), 2013, doi: 10.13140/2.1.4825.6327.
19. MicroXAM – 100 3D Surface Profilometer [online]. Direct industry [accessed 29.03.2022]. Available on World Wide Web: <https://pdf.directindustry.com/pdf/kla-tencor/microxam-100-3d-surface-profilometer/113449-633786.html>.
20. CHAE, Y. Color appearance shifts depending on surface roughness, illuminants, and physical colors. *Scientific Reports*, 2022, **12**(1371), 1-16, doi: 10.1038/s41598-022-05409-2.
21. EZAZSHAHABI, N., TEHRAN, M.A., LATIF, M., MADANIPOUR, K. Surface roughness assessment of woven fabrics using fringe projection moiré techniques. *Fibres & Textiles in Eastern Europe*, 2015, **3**(111), 76–84, doi: 10.5604/12303666.1152508.
22. 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.
23. MOONEGHI, S. A., VARKIYANI, S. M. H., SAHARKHIZ, S. Study on fabric surface roughness and its influence on worsted fabric abrasion resistance. *Journal of Engineered Fibers and Fabrics*, 2015, **10**(4), 1–18, doi: 10.1177/155892501501000419.
24. KANG, T.J., KIM, S.C., SUL, I.H., YOUN, J. R., CHUNG, K. Fabric surface roughness

evaluation using wavelet-fractal method. Part I: wrinkle, smoothness and seam pucker. *Textile Research Journal*, 2005, **75**(11), 751–760, doi: 10.1177/0040517505058855.
25. Bezaktiv S-Matrix, Bezaktiv Cosmos S-C [online]. CHT [accessed 29.03.2022]. Available on World Wide Web: <https://www.cht.com/cht/medien.nsf/gfx/med_RSCR-B8EGMQ_447998/$file/Colourshadecard-Bezaktiv-S-Matrix-Cosmos-de-en-WEB.pdf>.
26. *Handbook of textile and industrial dyeing. Volume 2: Applications of dyes*. Edited by M. Clark. Cambridge : Woodhead Publishing, 2011, 307 p.
27. *Textile dyes*. Edited by N. N. Mahapatra. Boca Raton : Woodhead Publishing India, 2016, 197 p.
28. Acid Red 150 [online]. dye|World dye variety [accessed 04.08.2022]. Available on World Wide Web: <http://www.worlddyevariety.com/acid-dyes/acid-red-150.html>.
29. Acid Blue 92 [online]. dye|World dye variety [accessed 04.08.2022]. Available on World Wide Web: <http://www.worlddyevariety.com/acid-dyes/acid-blue-92.html>.
30. Acid Green 27 [online]. dye|World dye variety [accessed 04.08.2022]. Available on World Wide Web: <http://www.worlddyevariety.com/acid-dyes/acid-green-27.html>.

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Designing Functional Clothing for People with Locomotor Disabilities
Oblikovanje funkcionalnih oblačil za ljudi z motnjami gibanja

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Abstract
This article presents a study on functional clothing for people with disabilities. The clothing items which were the subject of research, i.e. polo shirt, T-shirt, shirt, trousers and jeans, were designed for people with physical disabilities, namely for daily activities for people who often sit in wheelchairs. The study used the research method of anthropometric theory, pattern design, textile materials, and an actual survey to analyse and evaluate the reality of movement ability and perception of clothes to determine the requirements for people with disabilities. The authors proposed suitable materials and provided solutions to adjust the basic pattern to become more suitable for people with locomotor disabilities. Finished sewing products were tested and evaluated experimentally by people with leg disabilities at the Center for Sponsoring - Vocational Training and Employment Introduction of Ho Chi Minh City and the Association for the support of people with Disabilities and Orphans of Ho Chi Minh City according to the Likert scale with 5 rating levels for each criterion. The results showed that the Cronbach's Alpha index was over 0.7. The research addressed the comfort of disabled people's clothing, indicating promising further development of other functional clothing.
Keywords: pattern design, functional clothes, locomotor disabilities, leg disability, bamboo fibre, pants, shirt

Izvleček
Članek predstavlja študijo funkcionalnih oblačil za osebe s posebnimi potrebami za dnevno nošenje, kot so polo majica, majica, srajca, hlače in kavbojke. Izdelki so na podlagi raziskav zasnovani tako, da so primerni za ljudi z motnjami v telesnem razvoju, predvsem za vsakodnevne aktivnosti ljudi, ki pogosto sedijo na invalidskih vozičkih. Na podlagi uporabljene raziskovalne metode antropometrične teorije, krojenja, izbire tekstilnih materialov in ankete so bile analizirane in ovrednotene realne gibalne zmožnosti in zaznavanje oblačil, da bi določili zahteve za kostumiranje oseb s posebnimi potrebami. Avtorji predlagajo materiale in rešitve za prilagoditev osnovnega vzorca, ki je primernejši za osebe z motnjami v gibanju. Oblačila so testirale in po Likertovi 5-stopenjski lestvici eksperimentalno individualno ocenile osebe z invalidnostjo stopal v Centru za poklicno podporo in ustvarjanje delovnih mest v mestu Ho Ši Minh in Centru za poklicno usposabljanje invalidov in otrok sirot v mestu Ho Ši Minh. Pokazalo se je, da je Cronbachov indeks alfa višji od 0,7. Raziskava, ki obravnava udobnost nošenja oblačil za invalide, je potencialno ustrezna tudi za nadaljnji razvoj drugih funkcionalnih oblačil.
Ključne besede: krojenje, funkcionalna oblačila, gibalna oviranost, oviranost nog, bambusova vlakna, hlače, srajca

1 Introduction

Clothes, which protect our bodies, also enhance the beauty, hide the flaws of the wearer, and express their style and personality. In the world, there are about 600 million people with disabilities, accounting for about 10% of the population, most of them living in developing countries [1]. In Vietnam, there are about seven million people with disabilities [2]. The demand for clothes for people with mobility impairments is not small. However, the offer of the clothing market for people with disabilities in general and especially for people with locomotor disabilities is still limited, not focused, and needs the attention of designers and fashion brands. Research was conducted that focuses on people with hemiplegia, multiple sclerosis, other injuries, and on people with limited mobility who use a wheelchair. Physical characteristics of people with disabilities cause losing balance due to spinal trauma and change in body shape to disproportion [3]. The lack of blood circulation, low body temperature, physical inactivity of damaged body parts tend to impair muscle functions and lead to muscle atrophy in the extremities. To compensate for the loss of affected body parts, the unaffected body parts are forced to work more than normally; hence, people with lower extremity disabilities have stronger trunks and upper extremities. Using wheelchair leads to the development of related muscle groups of upper extremities [4, 5]. Clothing for people with disabilities should provide ergonomic comfort in sitting positions, improve the quality of life, be designed for everyone, and be suitable for the wearer's physique and awareness. Adaptive or function clothing helps minimise joint movements and pain that patients face when dressing or undressing [6, 7]. In addition, apparel must also be suitable for the socio-cultural context and ensure the comfort of the outfit [8, 9]. Wheelchair users frequently experience difficulty when dressing, as studied by Pruthi and partners, since they feel pain in the upper extremities when putting on clothes and undressing, when undressing the inactive leg, due to incontinent motion, often lying in bed resulting from the loss of mobility, trauma from traction belt [10]. Research showed that the comfort of pants is influenced by four main areas, affected by pressure, i.e. waist (39.17%), knees (16.4%), crotch (13.96%) and calves (6.95%), while the pressure on the areas below the knees and calves does not significantly affect dressing. Comfort is acceptable if the pressure is as low as 20 kPa on hips, waist and crotch, and less than 10 kPa on the back of the thighs and knees. Research which was conducted in 2013 on 10 young women aged 18 to 38 with various disabilities found that design, form, function, self-expression and social identity are essential factors for choosing their clothes. Standing measurements are not applicable to sitting posture measurements due to anatomical variations and different defects [9, 10]. The proportion of people with disabilities tends to increase. The products on the market are not capable of meeting their needs. Therefore, it is extremely important to design and make a suitable garment for people with disabilities in the legs to bring the most convenience to them.

This study proposes options for designing clothes for people with disabilities. The authors recommend suitable materials and, at the same time, provide solutions to adjust the basic pattern suitable for sitting posture and experiment with some designs.

2 Materials and methodology

The study included people with atrophy of legs, poor legs and those in wheelchairs.

The survey locations were the Center for Sponsoring – Vocational Training and Employment Introduction of Ho Chi Minh City and the Association for the support of people with Disabilities and Orphans of Ho Chi Minh City.

Gerber V9.0 software was used to design patterns [11]. IBM SPSS [12] software was used to evaluate the reliability of the fit and comfortable clothes through the Cronbach's Alpha coefficient.

In the study, a 2/1 twill weave (cf. Figure 1) and combined twill weave (cf. Figure 2) bamboo fabric was used. Bamboo fibres give the fabric antibacterial properties, which means that the garment does not leave body odour, it absorbs sweat and creates a soft feeling for the wearer. As it has superior properties, this material is widely used in the garment industry. Due to the fibre structure and constituent compounds, a bamboo fibre fabric has a soft surface and good hygroscopicity. It is also antibacterial, deodorising and UV resistant, making it environmentally friendly to meet the customers' needs [13].

The selected fabric was of moderate strength since the product was intended for the disabled. If the strength is too high, the fabric is of high thickness or high cost, and both of these properties do not

Figure 1: White bamboo fabric: surface of white bamboo fabric (left), performance of rapport 2/1 twill weave of white bamboo fabric (right)

Figure 2: Blue bamboo fabric: surface of blue bamboo fabric (left), performance of rapport of white bamboo fabric (right)

meet the criteria for our study. The fabric was basic in colour, easy to apply and suitable for clothing designs, objects and circumstances. Used accessories were zipper, button, elastic band and elbow pad. Zippers and buttons were arranged in appropriate positions, helping to expand the clothes for easier putting on and taking off. The elastic band helped keep the back of pants snug against the waist while still being easy to wear. Elbow pads, which are frequently used to support hands in wheelchairs or desks, were used as well.

For the purpose of the study, we used theoretical research methods about anthropometric methods, and textile materials to design and sew complete products. The basic pattern set was designed according to the pattern design method of the document [14]. The experimental method was used in surveying, analysing and evaluating research results according to the Cronbach's Alpha coefficient [12].

3 Results and discussion

3.1 Effects of wheelchairs on physical activity of people with leg disabilities

People with leg disabilities often use their upper limbs and upper body musculoskeletal system in their daily activities. At the same time, their sitting posture greatly influences their body shape (cf. Figure 3). Therefore, the design of clothes needs to be adjusted in several positions on the body for more comfort and convenience. Wheelchairs are assistive tools to help improve life, and create an optimistic spirit for users in general, especially people with disabilities. They use wheelchairs during most of their daily activities, especially for mobility, meaning that they need to use a lot their hands and

Figure 3: Body shapes of people with disabilities are disproportionate and abnormal [15]

the upper body musculoskeletal system [16]. As a result of using a wheelchair for longer periods of time, the upper limb musculoskeletal system is much more flexible. At the same time, the lower limbs are weaker and the weight of the entire upper body is concentrated on lower limbs. People with leg disabilities are thus prone to losing balance and falling forward in cases of moving downhill with a sudden change in height [17]. Problems that wheelchair users experience with dressing are pain in the upper extremities when dressing and undressing, difficulty removing clothing from the inactive leg, problem with incontinence hygiene, injuries caused by belt pulling etc. [9, 10, 18].

3.2 Plan for designing clothing

Clothing for people with disabilities must be specially designed and adjusted to provide ergonomic comfort in the sitting position and functional requirements when worn, not causing health problems for the wearer, e.g. skin irritation, sores resulting from pressure, or blockage of blood flow [10, 19]. Garment products must also have an aesthetic and fashionable appearance to help people with disabilities integrate into the society [5]. The plan for the design of apparel products was divided into two groups from the base of the initial survey of 90 people with leg disabilities about clothes ergonomic (cf. Figure 4). In the first group, the pattern was designed in some positions to suit body characteristics to provide the most comfort and convenience. For the pants, it was important to pay attention to the design at the back; the bottom ring was hence higher than that of standard clothes and more elastic at the waist for convenience. Due to the limited mobility in the legs, additional pleats were required at the knee position. In addition, there had to be an opening in the leg and pants for them to be easily put on or taken off. To avoid skin chafing due to seizures of the back and the wheelchair seat, pockets were not to be sewn on the back of the pants. At the same time, the pants' door was opened wider by extending the length of the zipper fly. For the shirt, extra wide adjustments needed to be made at the neck position as most disabled people's necks are more developed than those of non-disabled people. Moreover, the width of shoulders and armhole depth needed to be adjusted to make hand movements more flexible. Furthermore, in order not to sit on the shirt, its length had to be shorter than for an able-bodied person. The sleeves in the elbow area also had to be shaped according to the comfort principle. Sleeves had elbow pads added to increase the durability of the shirt and to make the wearer more comfortable when moving the wheelchair. In the second group, the pattern design, attention was paid to the manipulation required when using the clothes.

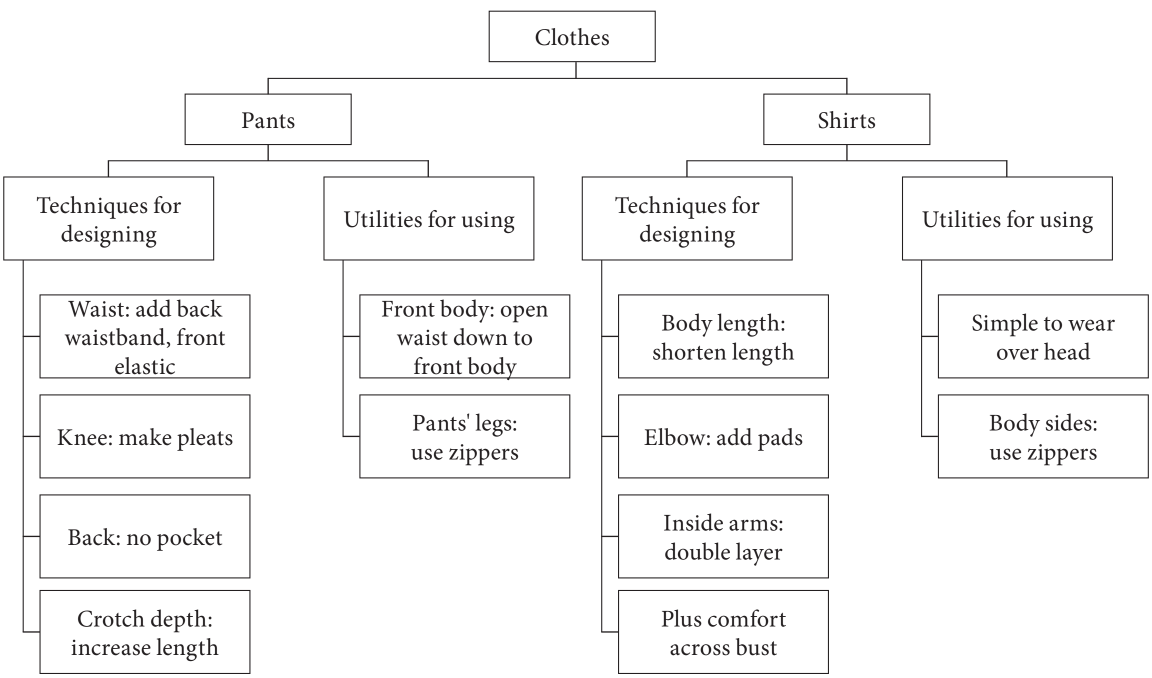

Figure 4: Plan for designing clothing

3.3 Adjusting basic pattern to suit body shape

The patterns for the T-shirt, shirt, trousers and jeans were designed according to the method basic block by Winifred Aldrich [14] with a non-disabled's body dimensions. The unit of measurement was centimetre (cm). In line with section 3.2, the basic block was edited accordingly for the pattern to suit the disabled people's body dimensions.

3.3.1 Adjusting basic trousers pattern

The length of the front bottom pants was reduced, and the width of the front waistline was increased to create a comfortable sitting position for the waist and abdomen. In addition, a 4-cm ply fold was at the front knee to prevent the knee position from being stretched. In the back, the curvature of the buttocks and the height of the back was increased to best suit the sitting posture. The front of the pants was lower than the back by 0.5–1 cm (cf. Figure 5). In the knee-level position, it was open by 3–4 cm to arrange the pillow pleats. The back of the pants was extended by 4–5 cm, and the width of the buttocks was by 2–3 cm larger. The bottom was extended by 0.5–1 cm and by 0.5–1 cm down (cf. Figure 6).

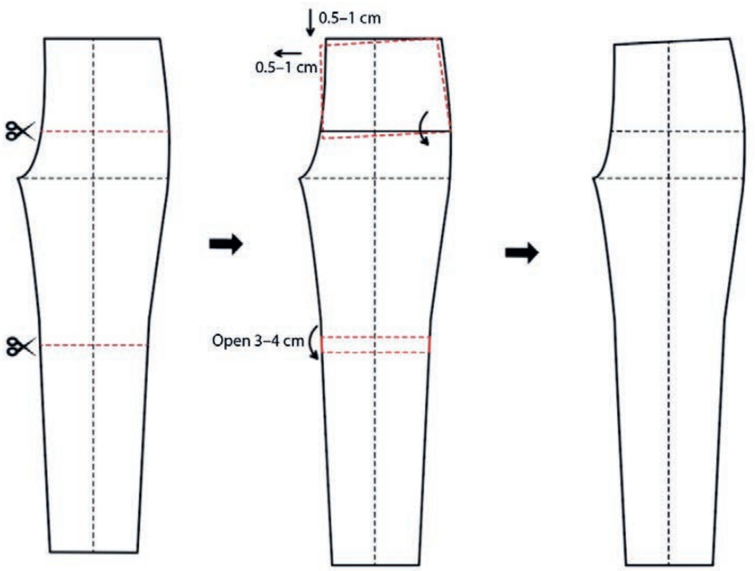

Figure 5: Trousers' front pattern (left), adjustment position (middle), pattern after alterations (right)

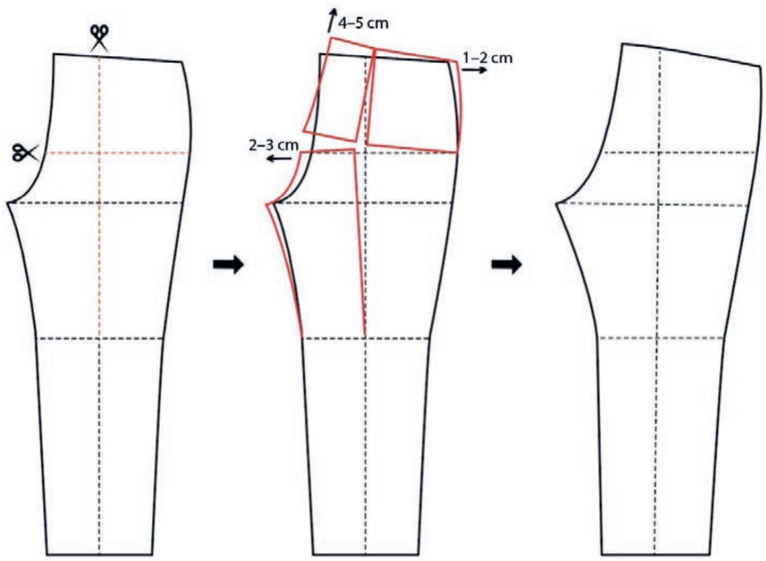

Figure 6: Trousers' back pattern (left), adjustment position (middle), pattern after alterations

3.3.2 Adjusting basic shirt pattern

The neck was extended by 0.5–1 cm (cf. Figure 7). 2–3 cm were added to the length of shoulders and 1–2 cm to the length of lower armpit. The armpit ring was curled and the shirt length was reduced by 3–5 cm (cf. Figure 8).

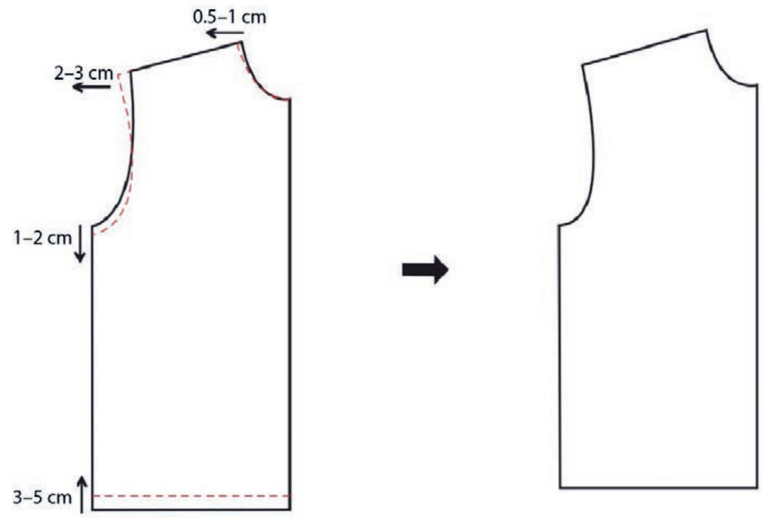

Figure 7: Pattern's front: adjustment position (left), pattern after adjustment (right)

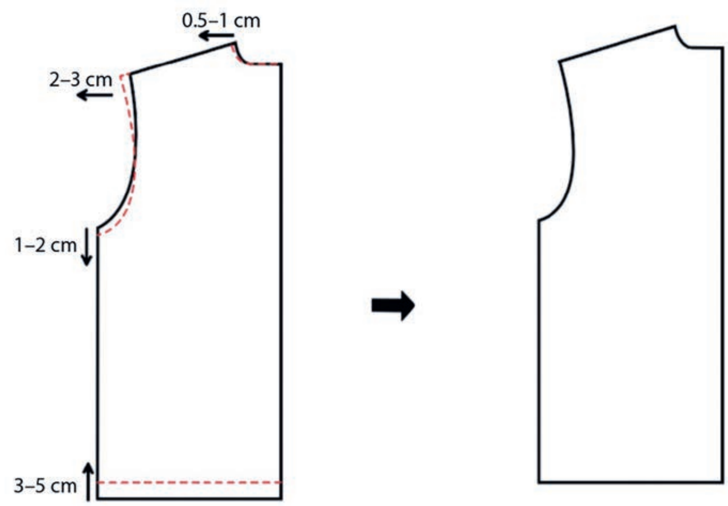

Figure 8: Pattern's back: adjustment position (left), pattern after adjustment (right)

3.4 Adjusting pattern design to support operation of people with disabilities

From the analysed content, the research team experimented with four designs for people with leg disabilities according to the plan of assisting manipulation when using clothes. Figure 9 shows design 1, a polo shirt on a 100% cotton knit base with a side zipper, which makes it easier to put on or take off the shirt.

In design 2, the inner ribs of the sleeves and body were sewn with a mesh fabric for ventilation. In addition, the shirt pillar was cut deeper than for a regular shirt, making it easier for the wearer to put the shirt on through the head (cf. Figure 10).

In design 3, a long-sleeved shirt from bamboo fabric (50% bamboo) was sewn with elbow pads (cf. Figure 11) to help support the lower arm for extended periods of time on a table or wheelchair armrest (cf. Figure 12).

In design 4, pants which could be easily put on with no or less help from the caregiver were designed. The length of zippers was increased or zippers were used on the sides of pants' pockets to make the pants wider (cf. Figure 13). Simultaneously, the back

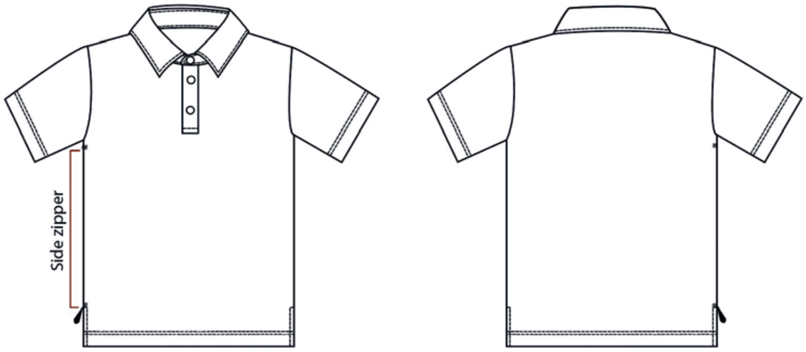

Figure 9: Descriptive drawing of polo with side zipper

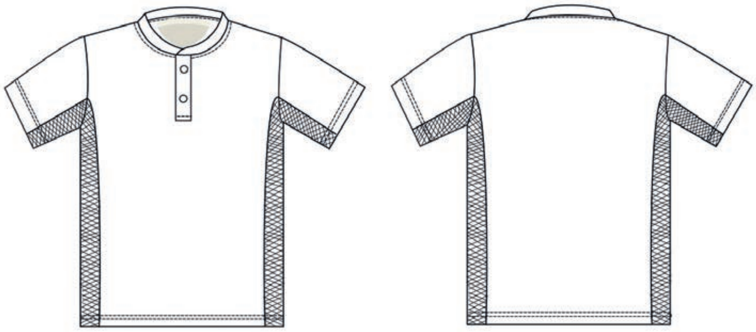

Figure 10: Drawing of T-shirt with mesh

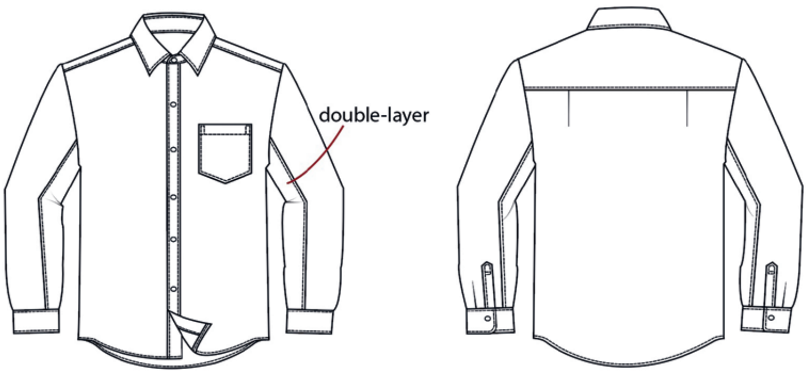

Figure 11: Double-layer long-sleeved shirt

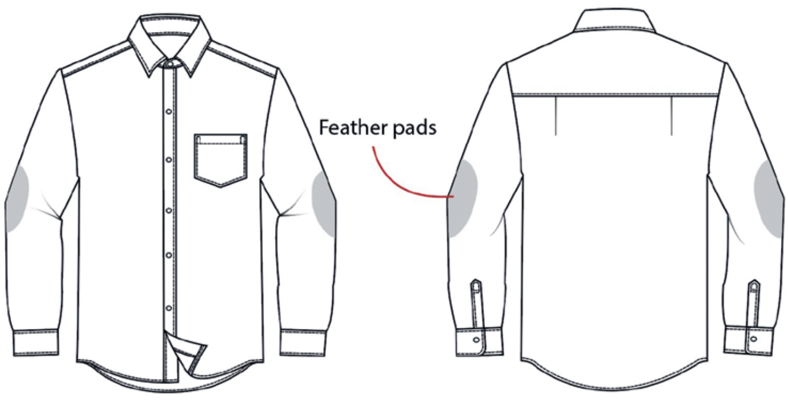

Figure 12: Shirt with sewn elbow patch

of the pants was raised, increasing the curvature of the buttocks and the ply at the knees was folded to suit the sitting position for a longer period of time. A teardrop zipper was added to the inner side of the bottom of trousers' legs to widen the leg while still preserving the look of the pants (cf. Figure 14).

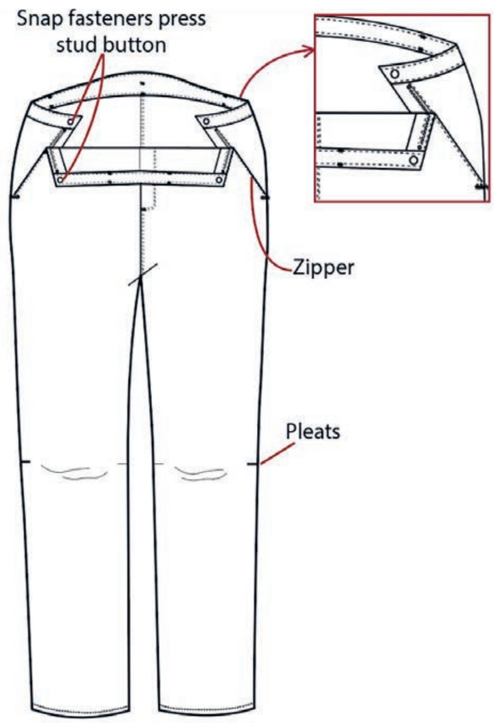

Figure 13: Jeans with open zipper

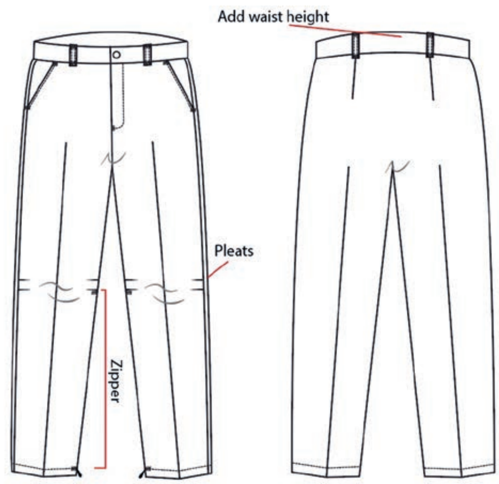

Figure 14: Trousers with inner side zippers

People with severe disabilities need their caregiver's support in dressing and personal activities. Therefore, the authors propose in design 5 models of pants using a knit fabric and an elastic waistband with an open back, which make it easier when going to the restroom and provide comfort during wearing. Moreover, the pants' design makes opening them easier, aiding their personal activities. In these samples, the authors still added length of the buttocks, waist of the pants (cf. Figure 15) and pleats at the knee (cf. Figure 16).

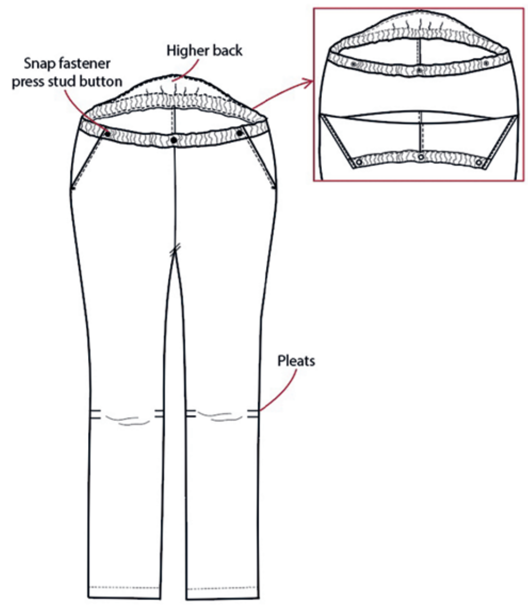

Figure 15: Knit pants with elastic waistband and open front

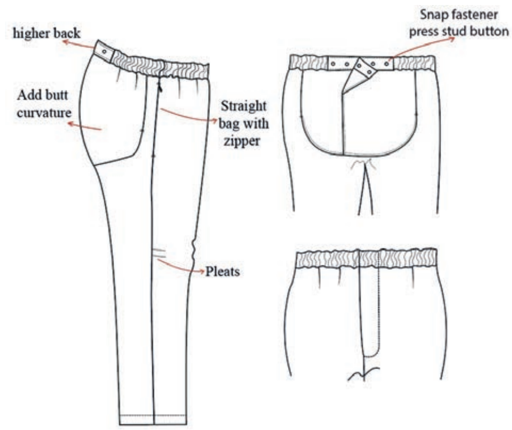

Figure 16: Knit pants with elastic waistband and open back

3.5 Testing and evaluating product feasibility

The products were surveyed and tested on 76 people with leg disability to evaluate the feasibility of the study through the criteria according to the Likert scale in terms of material, design, convenience, colour, product cost and external assessment. Each criterion was evaluated on a scale from one to five, namely completely dissatisfied, unsatisfied, no idea, satisfied, completely satisfied. The survey was conducted in the Center for Sponsoring - Vocational Training and Employment Introduction of Ho Chi Minh City and the Association for the support of people with Disabilities and Orphans of Ho Chi Minh City. The survey results were analysed according to the Cronbach's Alpha coefficient and showed that the majority of survey participants were satisfied with the given criteria. The survey also showed that the templates need certain changes. The external assessment of all products was acceptable. In design 1, some people had difficulties wearing the trousers. In design 2, a few people felt uncomfortable about the material as bamboo and jeans fabrics were not as soft as the cotton fabric. In design 3, the fabric's colour was quite good. In design 4, the product's shape was evaluated as appealing. However, the test results showed that all observed variables had a suitable total correlation coefficient (over 0.3). The Cronbach's Alpha coefficient of the samples for designing were 0.776, 0.837, 0.807, 0.810 – all over 0.7. The results of the scale used were good in terms of reliability (cf. Table 1), which shows that the products would be highly applicable for people with disabilities.

4 Conclusion

The study provides options for designing clothes and trousers suitable for the physical characteristics of people with disabilities, combined with actual surveys at vocational training centres for people with disabilities to come up with solutions. They

Table 1: Evaluation of reliability through Cronbach's Alpha coefficient

Design	Material	Designs	Convenience	Colour	Cost	External assessment	Cronbach's Alpha
1 (Figure 17)	0.78	0.750	0.728	0.756	0.756	0.671	0.776
2 (Figure 18)	0.795	0.828	0.822	0.833	0.812	0.766	0.837
3 (Figure 19)	0.804	0.771	0.797	0.761	0.784	0.737	0.807
4 (Figure 20)	0.801	0.761	0.786	0.799	0.787	0.745	0.810

Figure 17: Try-on shirt with double layers and trousers with inside zipper

Figure 18: Try-on shirt with elbow pads, and jeans with open waist down the front

Figure 19: Try-on polo shirt with zipper at side and knit pants with elastic at the front and waist opening down the body with pleats at knees, and higher waistband at the back

Figure 20: Try-on T-shirt with zipper at side and knit pants with open back

shared their clothes requirements, proposed suitable materials and solutions to adjust the basic stamping design, suggested the direction to correct the pattern and experimented with some sewing samples for home T-shirts, front and back elastic waist pants. Furthermore, the authors designed shirts and trousers with zippers for use when going out. In each model, the authors paid attention to the manipulation of wearing and taking off the product easily in usual state as well as when needing to go to the toilet. The designs are suitable for people who are often in wheelchairs. The products were after being designed and sewn tested at two initial survey facilities. After analysing the reliability according to the Cronbach's Alpha coefficient, all 4 outfits were over 0.7. The research opened up a new direction in functional apparel design. In the future, designs should be developed to be more diverse for people with disabilities to have more options for their fashion styles, and at the same time develop clothes for other types of disabilities.

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References

1. Vietnam National Coordination Committee for People with Disabilities (NCCD). *The 2011 annual report on people with disabilities and support for people with disabilities in Vietnam*. Hanoi : NCCD, 2012, https://pdf.usaid.gov/pdf_docs/PA00KCH5.pdf.
2. UNFPA. *People with disabilities in Vietnam: key findings from the 2009 Viet Nam population and housing census*. Hanoi: United Nations Population Fund, 2011, https://vietnam.unfpa.org/sites/default/files/pub-pdf/Disability_ENG.pdf.
3. RUDOLF, Andreja, CUPAR, Andrej, STJEPANOVIČ, Zoran. Designing the functional garments for people with physical disabilities or kyphosis by using computer simulation techniques. *Industria Textila*, 2019, **70**(2), 182–191, doi: 10.35530/IT.070.02.1592.
4. RUDOLF, Andreja, CUPAR, Andrej, KOZAR, Tatjana, STJEPANOVIĆ, Zoran. Study regarding the virtual prototyping of garments for paraplegics. *Fibers and Polymers*, 2015, **16**(5), 1177–1192, doi: 10.1007/s12221-015-1177-4.
5. CHANG, Wei Min, ZHAO, Yu-Xiao, GUO, Rui-Ping, WANG, Qi, GU, Xiao-Dan. Design and

study of clothing structure for people with limb disabilities. *Journal of Fiber Bioengineering and Informatics*, 2009, **2**(1), 62–67.
6. NEENU, Poonia, PINKI. Adaptive clothing for disabled people. *International Journal of Home Science*, 2020, **6**(2), 238–241, https://www.homesciencejournal.com/archives/2020/vol6issue2/PartE/6-2-21-378.pdf.
7. FLOREA BURDUJA, Elena, RARU, Aliona, FARÎMA, Daniela, IROVAN, Marcela. The analysis of the system "human–clothing–environment" with application in the design of functional adaptive products. *Annals of the University of Oradea: Fascicle of Textiles, Leatherwork*, 2021, **22**(1), 17–20.
8. CURTEZA, Antonela, CRETU, Viorica, MACOVEI, Laura, POBORONIUC, Marian. Designing functional clothes for persons with locomotor disabilities. *AUTEX Research Journal*, 2014, **14**(4), 281–289, doi: 10.2478/aut-2014-0028.
9. WANG, Yunyi, WU, Daiwei, ZHAO, Mengmeng, LI, Jun. Evaluation on an ergonomic design of functional clothing for wheelchair users. *Applied Ergonomics*, 2014, **45**(3), 550–555, doi: 10.1016/j.apergo.2013.07.010.
10. PRUTHI, Neelam, SEETHARAMAN, Chanchal, SEETHARAMAN, P. Protective clothing for paraplegic women. *Journal of Human Ecology*, 2006, **19**(4), 267–271, doi: 10.1080/09709274.2006.11905889.
11. SHARP, J.R., ELSASSER, V.H. *Introduction to AccuMark, pattern design, and PDM*. Fairchild Publications, 2007.
12. TRONG, H., NGOC, C.N.M. *Research data analysis with SPSS. Vol. l.* Ho Chi Minh City : Hong Duc Publisher, 2008.
13. ZHANG, J., ZHANG, B., CHEN, X., MI, B., WEI, P., FEI, B., MU, X. Antimicrobial bamboo materials functionalized with ZnO and graphene oxide nanocomposites. *Materials (Basel)*, 2017, **10**(3), 1–12, doi: 10.3390/ma10030239.
14. ALDRICH, Winifred. *Metric pattern cutting for menswear*. 5th Edition. Chichester : Wiley, 2011.
15. QUYNH, Tran. A series of touching photos about the energy of people with disabilities on the 5km running track in Saigon [online]. KENH14 [accessed 14.09.2022]. Available on World Wide Web: <https://kenh14.vn/bo-anh-xuc-dong-ve-nghi-luc-cua-nhung-nguoi-khuyet-tat-tren-duong-chay-5km-o-sai-gon-2017011523442982.chn>.
16. ROUSSEAU-HARRISON, K., ROCHETTE, A., ROUTHIER, F., DESSUREAULT, D., THIBAULT, F., CÔTÉ, O. Impact of wheelchair acquisition on social participation. *Disability and Rehabilitation. Assistive Technology*, 2009, **4**(5), 344–352, doi: 10.1080/17483100903038550.
17. ARIAS, S., CARDIEL, E., GARAY, L., TOVAR, B., PLA, M., ROGELI, P. A pressure distribution measurement system for supporting areas of wheelchair users. In *Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2013, 4751–4754, doi: 10.1109/EMBC.2013.6610609.
18. BROOKS, A.L., BROOKS, E. Towards an inclusive virtual dressing room for wheelchair-bound customers. In *2014 International Conference on Collaboration Technologies and Systems (CTS)*, 2014, 582–589, doi: 10.1109/CTS.2014.6867629.
19. KABEL, A., DIMKA, J., MCBEE-BLACK, K. Clothing-related barriers experienced by people with mobility disabilities and impairments. *Applied Ergonomics*, 2017, **59**(A), 165–169, doi: 10.1016/j.apergo.2016.08.036.

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Physical-mechanical Properties of Aged Knitted Fabric for Swimsuits
Fizikalno-mehanske lastnosti staranih pletiv za kopalke

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Abstract
The physical and mechanical properties of knitted fabrics for sports swimsuits are analysed in this paper. The knitted fabrics were experimentally aged in seawater and exposed to the sun continuously for 100 hours. Data were processed for nine knitted fabrics with the same raw material composition, polyamide and elastane in different proportions. The physical-mechanical properties of all nine samples before and after aging, as well as the drying rate and water absorption capacity, were examined. The results show that the properties of the knitted fabric changed in all samples. The sample with a higher elastane content (59% PA and 41% EL) is less sensitive to changes in mass per unit area and thickness after aging (–0.89% and 0.40%). The results of maximum wetted radius absorption water on the top and bottom of the knitted fabric, spreading speed absorption and drying time are shown. The results show that the values of the maximum wetted radius of absorbed water and the spreading speed increase for all samples, while the drying time for the knitted fabrics show different results.
Keywords: fabric, knitwear, physical-mechanical properties, swimwear, mechanical functionalization

Izvleček
V članku so analizirane fizikalne in mehanske lastnosti pletiv za športne kopalke. Pletiva so bila poskusno starana v morski vodi in neprekinjeno sto ur izpostavljena soncu. Meritve so bile izvedene za devet pletiv z enako surovinsko sestavo, poliamidom in elastanom v različnih razmerjih. Preučene so bile fizikalno-mehanske lastnosti vseh devetih vzorcev pred staranjem in po njem, hitrost sušenja in sposobnost vpijanja vode. Rezultati kažejo, da so se lastnosti pletiv pri vseh vzorcih spremenile. Vzorec z višjo vsebnostjo elastana (59 % PA in 41 % EL) je bil najmanj občutljiv na spremembe ploščinske mase in debeline po staranju (–0,89 % in 0,40 %). Prikazani so rezultati največjega omočenja na zgornjem in spodnjem delu pletiva (največji polmer kroga absorbirane vode), največje hitrosti vpijanja in časa sušenja. Vrednosti največjega omočenja in hitrosti vpijanja se povečajo za vse vzorce, čas sušenja za pletiva pa kaže različne rezultate.
Ključne besede: ploskovna tekstilija, pletenina, fizikalno-mehanske lastnosti, kopalke, mehanska funkcionalizacija

1 Introduction

The swimsuits used in sports today have undergone many transformations throughout history. From heavy woollen swimsuits to performance-enhanced sports swimsuits for competition. The first swimsuit manufacturers shifted their former underwear into the range of fashionable swimwear. The materials for swimsuits are knitted and, as such, are a relatively small, narrowly specialized manufacturing area in the textile industry. Thanks to technological innovations, swimwear manufacturing experienced revolutionary success in the 1980s and 1990s. In the late 1990s, new materials with a lower hydrodynamic resistance than shaved skin were developed. Reducing friction and hydrodynamic resistance has been a major issue recently. It is believed that the swimmer uses almost 90% of the energy to overcome hydrodynamic resistance during swimming. Swimsuit manufacturers invest a great deal of effort in developing new materials and cuts for swimsuits to reduce hydrodynamic resistance [1–4].

Flexibility, comfort, drying speed, high chlorine resistance and durability are desirable characteristics of knitwear for swimwear. Materials made from a mixture of polyamide and elastane, and often from 100% polyester fibres, are usually used to make swimsuits. Recently, swimsuits made of recycled materials have become popular, and sports swimsuits made of 100% recycled polyester can be found at well-known manufacturers. In sports swimwear, there is a classification of swimwear for competition, the so-called "fast suits" and training suits. Fashion swimsuits usually contain between 10% and 20% elastane, while in training swimsuits the most common blend is 68% PA and 32% EL. Competition swimsuits have an even higher percentage of elastane and have recently begun to contain carbon fibres, e.g. 65% PA/34% EL/1% carbon. Integrated carbon fibres, known for their strength and low density, work to apply compression before the fabric is fully stretched, giving the suit additional stretch capacity for excellent flexibility and mobility. Raw materials made from synthetic polymers are now an integral part of sportswear and equipment. Fast drying, lightness, perfect fit and resistance represent the characteristics and many advantages of these materials.

Polyamide 6 and polyamide 6.6 are most commonly used to make swimwear because they have higher resistance to wear, chemicals and oils, as well as good mechanical properties. However, polyamides have the ability to absorb moisture, which affects their overall properties. Polyester is a synthetic material that also offers numerous advantages and has similar properties to polyamide but has lower water absorption, which makes it more difficult for bacteria to grow. These fibres are characterized by the fact that they are resistant to deterioration and seawater compared to natural fibres. The maintenance of such synthetic fibres is easy, they dry quickly, can be mixed with other fibres and are susceptible to dying. Today, however, a great deal of research relates to the degradation of synthetic polymers such as PES and PA and their impacts on the environment. Under the influence of UV radiation, polyamide and polyester decompose at the molecular level, which consequently affects the properties of the material, durability and comfort [5–8].

As mentioned above, polymers are combined with elastane in different proportions in the manufacture of swimsuits. Elastane has a wide range of applications and is used for fashion or functional clothing, which is intended to adhere to the body and at the same time provide comfort and dimensional flexibility. Invented in Germany in 1937, spandex has exceptional elasticity, i.e. a temporary stretch of more than 200%, and also recovers quickly after exposure to stress. These fibres have a rubber-like behaviour with a high reversible elongation of between 400% and 800% [9].

The decomposition of swimwear knitted fabric is influenced by several factors. The most important factors in aging swimsuits are chlorinated water, sweat in an aqueous medium and on dry land, and swimsuit maintenance and care after each workout. In the summer months, UV radiation, high temperature and seawater are important factors for swimsuit aging. Swimsuit knitwear is expected to be resistant to UV rays, seawater, and chlorinated water. The durability of the colour in the sun is also an important requirement for the longevity and successful performance of swimsuit materials.

Previous studies have shown that the properties of materials made of polyamide, polyester and elastane change when exposed to aging conditions. The change in these properties also affects changes in the comfort and durability of the material. In the study by Salopek Čubrić et al [4], it was found that the aging of knitted fabrics made of a mixture of polyester or polyamide with elastane reduces resistance to tensile forces, and after prolonged exposure and the reduction of the mass per unit area of the knitted fabric.

Due to a number of influential research parameters related to the comfort and durability of knitwear, they represent a major challenge but have been the focus of much research for many years. The physical and mechanical properties of nine swimwear knitted fabrics from commercial manufacturers were investigated in this paper. The selected knitted fabrics were made from polyamide or polyester and elastane fibre blends in varying proportions and with different construction characteristics. The research presented in this paper is focused on the exposure of the knitted fabrics to external natural weather conditions during the summer. According to the manufacturer's description, all knitted fabrics are intended for fashion swimsuits, while six of them are for sports swimsuits. They are described as knitted fabric with maximum comfort, stretchable in both directions, easy to clean, with UV protection, and resistant to chlorine and pilling. The purpose of this study was to determine the physical and mechanical changes in the fabric after 100 hours of exposure to seawater and sun. A protocol was developed for the aging of knitwear for swimwear. The target group of the research was cadets for whom a training regimen of 120 minutes, six times a week was set, with athletes spending 10 hours training in the water. In this work, training sessions over 10 weeks were taken into account, for a total of 100 hours (June to August) spent in a water medium outdoors. The test results before and after exposure of the knitted fabric to aging conditions were compared.

2 Materials and methods

2.1 Material selection

Materials were selected to include knitted fabrics made from a blend of polyamide and elastane in varying proportions and mass per unit area, with one exception of PES and elastane. Selected materials are intended for use in the manufacture of swimsuits and are characterized by durability, resistance to chlorine, elasticity in both main directions that allows high comfort, and medium-strong compression to support the muscles. The selected sample with the highest elastane content of 41% was designated as S5. Of the nine samples, three have the same polyamide and 80/20 elastane content (Table 1.) All samples are marked with the letter S (swimming) and an ordinal number. Aged samples are marked with a letter "X".

2.2 Methods of measurement

In the experimental part, the following physical and mechanical properties of the fabric were studied: horizontal and vertical density of the fabric, mass per unit area, thickness of the fabric, breaking forces, resistance to bursting forces, maximum wetting radius during absorption, the water spreading speed of the knitted fabric and drying rate. All measurements were performed on samples before and after aging in seawater.

The horizontal and vertical densities of the knitted samples were measured using a Dino-Lite Pro AM7000 microscope at 200× magnification. The sample was placed on a flat surface and, after calibrating the microscope to the appropriate magnification, the loops in the measurement area were counted. The mass per unit area of the fabric was measured according to ISO 3801[10], method 5, where a circular sample for surfaces of 100 cm^2 was cut and measured on an analytical balance with an accuracy of +/– 0.001 g. The sample thickness was measured as the distance between the reference plate and the parallel circular feet. During the test, a pressure of 1 kPa was applied to the surface of the

Table 1: Materials for swimwear

Fabric sample	Fibre composition		Yarn linear density	
	PA (%)	EL (%)	PA (dtex)	EL (dtex)
S1	80	20	110/7	0.4/2
S2	80	20	62/7	0.6/2
S3	78	22	150/14	0.4/3
S4	78	22	150/14	0.4/3
S5	59	41	44/28	44/4
S6	73	27	33/28	33/3
S7	80	20	88/56	78/5
S8	72	28	44/28	44/4
S9	71	29	58/34	60/5

test sample. This test was performed in accordance with EN ISO 5084: 1996 [11].

Tensile force at break was measured according to ISO 13934-1 [12]. Test samples measuring 20 cm × 5 cm were prepared in the direction of the courses and in the direction of the wales. The test samples were placed between the clamps of the dynamometer and subjected to a tensile elongation at a constant speed of 100 mm/minute. The test procedure was repeated for all fabrics in both directions with five test samples. The knitted fabric was stretched to break, and the values of breaking force and breaking elongation were determined.

The resistance to bursting force was tested according to ISO 13938-2 [13]. Circular samples measuring 50 mm in diameter were secured to the bursting test ring with two circular stainless-steel rings. The samples were exposed to a steel ball with a diameter of 2.45 cm, which stretched the material in a spherical shape, and the angle of application of the force and the surface of the material on which the force acts changed continuously during the testing of the material [14]. The values obtained by this method are the force required to burst the knitted fabric.

The liquid moisture management of the fabric was measured according to the AATCC Test Method 195 [15]. This method evaluates and qualifies the moisture transfer properties of a particular knitted fabric. The instrument used for these measurements is the MMT (Moisture Management Tester) [16]. Samples measuring 8 cm × 8 cm were prepared for the test, and the test was repeated four times for each knitted sample. The values obtained and taken into account in this test were the maximum wetted radius for top and bottom surfaces, and the spreading speed for top and bottom surfaces of the knitted fabric [17].

Thermography was used as an additional method to observe liquid transport on the surface of s sample. It was used both to compare the values with the results obtained using the MMT and to describe this phenomenon in detail with regard to the parameters that were not observed using MMT, such as drying time and spreading in the x and y direction. This method has previously been used by investigators in different fields, including textiles, and authors have shown that this method is valuable in obtaining additional details that are used to observe the properties of materials [5,18]. An E6 infrared camera from Flir Systems Inc., USA was used for the measurements. The camera used has a measurement accuracy of ±2%, and thermal sensitivity of 0.06 °C. A square sample measuring 100 cm × 100 mm was prepared for the measurements. During the measurement, the sample was placed on a flat surface in a room with an air temperature of 20 °C ± 2 °C and relative humidity of 65% ± 3%. A solution of distilled water and artificial sweat (amount of 0.1 mL) was applied vertically with a pipette at a distance of 20 mm from the surface of the sample. A thermal imaging camera was placed vertically above the sample at a distance of 300 mm. It was used to detect the different phases of liquid transport and capture images, which were then used to measure the corresponding parameters. The experiment focused on the following parameters:

- wetting time (determined as the time required to absorb the solution),
- wetting area (the area of the wetted zone on the sample, determined from the image captured using the thermal camera),
- spreading speed in x- and y-direction (the spreading radii in x- and y- direction were determined from the thermal image, and those values were further used to calculate the spreading speed taking into account the wetting time), and
- drying time (after applying the solution to a sample, the temperature of the wetted zone changed, which can be seen as a colour change on a thermal image. Drying time was determined as the time taken from the moment of solution application until the moment when there was no longer a difference between the temperatures of the wetted and non-wetted zones).

FLIR Thermal Studio Suite software was used to analyse the thermograms. The liquid transport on the sample was determined by observing the histograms of the thermal images. More precisely, the histogram of the image at the beginning of the measurement was compared to the histogram of the image during the drying process of the material. At the point when it was determined that there were no differences between the two histograms (i.e., when these two histograms were equal), the material was deemed dry. The total time that elapsed from the application of the liquid to the point where the two histograms were equal was measured and noted as the drying time. The total number of repetitions was five.

2.3 Aging method

Aging conditions were defined by observing the training conditions of swimmers who trained for 120 minutes, six times a week, which means that they trained in the water for 10 hours a week, taking into account the washing of swimsuits after each training. The conditions of aging in seawater were taken into account in this work. The aging order of 100 hours of soaking in water in the sun was defined, followed by washing 10 times and air drying. All samples were immersed in seawater outdoors for a period of 100 hours during the summer in August 2021 in the Mediterranean climate zone in Dubrovnik. Maximum daily temperatures ranged from 32.2 °C to 33.5 °C, and the lowest from 27 °C to 28.3 °C, without precipitation with a mean daily relative humidity of 61% to 46%. Weather data was obtained from the Croatian Meteorological and Hydrological Service. After 100 hours of immersion in seawater, the samples were washed in a washing machine on a short program for 30 minutes at a temperature of 30 °C. ECE Formulation Non-Phosphate Reference Detergent (without optical brightener), manufactured by James Heal, was used to wash the samples, in a ratio of 5 g of detergent per 1 kg of textile. The samples were air dried in the shade and the washing procedure was repeated 10 times.

3 Results and discussion

The results of the measurements of physical and mechanical properties before and after aging are shown in the table for all samples. Table 2 shows the mean values of horizontal and vertical knitted fabric density, mass per unit area and thickness of the nine selected samples before the aging process. The results show that there are no significant differences in knitted fabric density for the first four samples (from S1 to S4), while the approximate values of mass per unit area range from 171 g/m^2 for sample S2 to 209 g/m^2 for sample S4. The thicknesses of these knitted samples are also very similar, ranging from 0.527 mm for sample S4 with the lowest knit density and the largest mass per unit area, to a thickness of 0.655 mm, which is the same for samples S1 and S2. Samples S1 and S2 are made with the same ratio of polyamide and elastane, 80%/20%, while S3 and S4 have a ratio of 78%/22%. Samples S5 to S9 have similar values for vertical and horizontal density, while the values for mass per unit area and thickness are very different. Sample S6 has a minimum thickness of 0.358 and a mass per unit area of 113 g/m^2, while the vertical and horizontal densities are 28%/26%. The sample with the largest mass per unit area is sample S5 with 226 g/m^2, while the maximum thickness of 0.655 mm was recorded for S1 and S2.

After the aging procedure, the same tests were performed on the samples under the same conditions. The results show that all samples changed to a greater or lesser extent. The change in density of knitted fabrics is shown graphically and numerically in Figure 1. The coefficient of loop density, which is the ratio between the horizontal and the vertical density, was calculated using the formula:

$$C = D_h/D_v \tag{1}$$

where D_h is horizontal knitting density and D_v is vertical knitting density.

Table 2: Results of measured density, mass per unit area and thickness of the knitted fabric samples before aging

Fabric sample	Vertical/horizontal loop density (1/cm)	Mass per unit area (g/m^2)	Thickness (mm)
S1	46/26	187	0.655
S2	42/26	171	0.655
S3	44/26	198	0.561
S4	42/25	209	0.527
S5	26/24	226	0.495
S6	28/26	113	0.358
S7	20/24	216	0.502
S8	28/26	160	0.404
S9	26/20	184	0.450

The coefficient of loop density C was calculated for the values before and after the aging of the knitted fabric. It can be noted that no or insignificant change occurred in samples S4, S5 and S6. The change in the coefficient of loop density shows that the relationship between horizontal and vertical density changed, i.e. that the knitted fabric shrank more in the horizontal or vertical direction than in the other direction. This change can be observed in samples S1, S7 and S9, which leads to the dimensional instability of the knitted fabric after aging and ultimately to a change in the shape of the swimsuit.

The decrease in the coefficient of loop density in samples S1, S2 and S7 indicates that initial damage to the elastane occurred, which in other samples would occur after prolonged exposure to sun and sea. The change in mass per unit area and thickness is shown as a percentage in Table 3. Mass per unit area increased in most knitted fabrics, except in samples S4, S5 and S6, where the greatest mass loss occurred in sample S4 at 2.96%, while S5 and S6 recorded a smaller mass loss of 0.89%. The greatest change in mass per unit area was seen in sample S7, and the least in S5 and S6. A similar trend was observed for the change in thickness, with an increase in thickness for most samples except S4 and S6. The results show that the smallest change in thickness and mass per unit area occurred in sample S5 with the highest elastane content of 59% PA/41% EL, which gives it very good dimensional stability (Table 3).

Swimsuits, and particularly swimsuits for sports, are expected to fit the body very tightly, ensuring faster body movement in the water. In other words, the knitted fabrics are expected to be more resistant to multiple stresses. Since the aging process leads to changes in tensile properties, data on bursting strength were processed using the bursting test method. This method is recommended for testing the resistance of knitted fabrics to the increasing penetration load because the knitted structure stretches simultaneously in all directions.

The negative effect of UV rays and seawater on the resistance of knitted fabrics to breaking force is

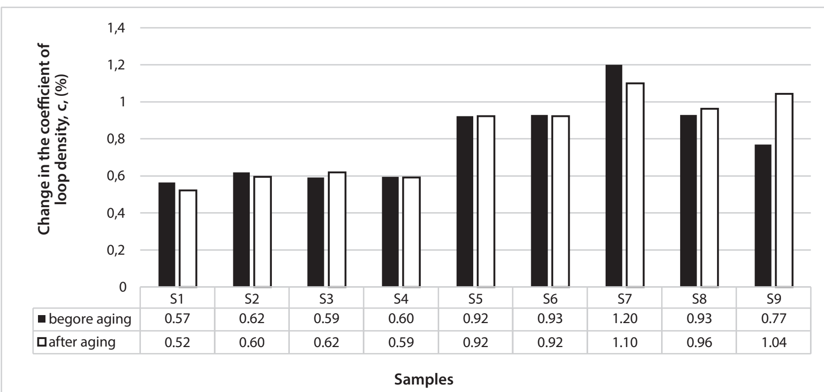
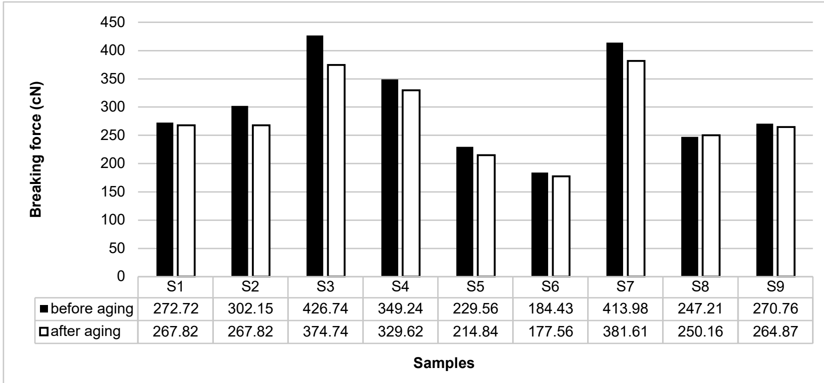


Figure 1: Change in the coefficient of loop density before and after aging

Table 3: Changes in mass and thickness, expressed in %, compared to non-aged materials

Fabric sample	Changes in mass per unit area (%)	Change in thickness (%)
S1	2.09	3.68
S2	6.56	1.34
S3	4.35	1.41
S4	–2.96	–1.74
S5	–0.89	0.4
S6	–0.89	–1.99
S7	9.62	3.65
S8	7.51	1.7
S9	2.13	3.43

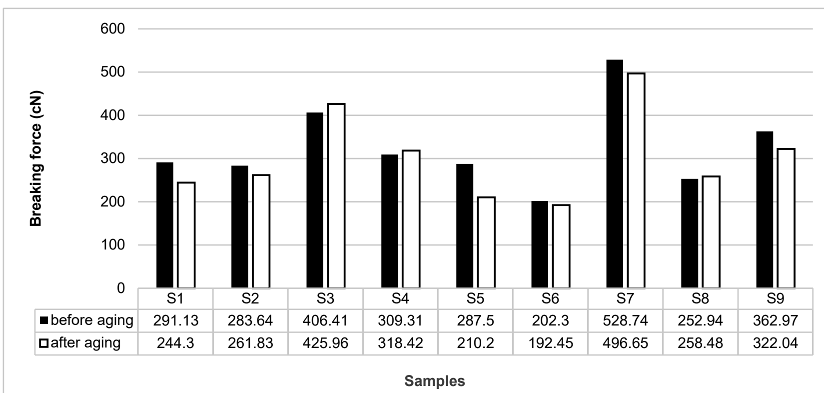


	S1	S2	S3	S4	S5	S6	S7	S8	S9
■ before aging	272.72	302.15	426.74	349.24	229.56	184.43	413.98	247.21	270.76
□ after aging	267.82	267.82	374.74	329.62	214.84	177.56	381.61	250.16	264.87

Figure 2: Change in the breaking force (bursting test) after aging

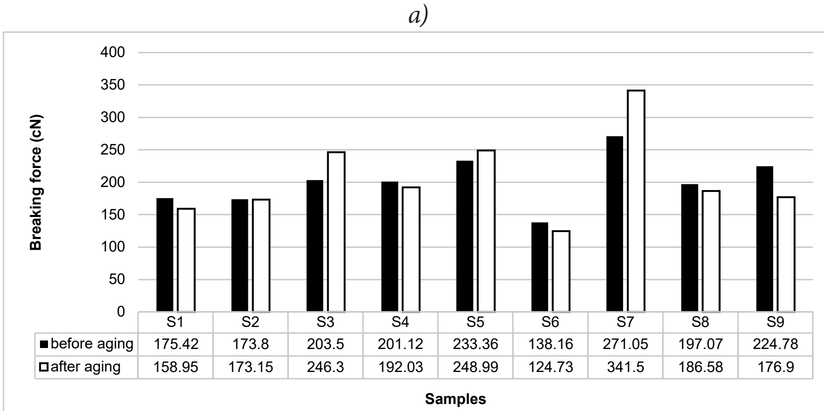
evident from the results shown in Figure 2. Eight of the nine samples showed a decrease in breaking force, while sample S8 showed a slight increase of 1.18%. This sample also showed one of the largest mass per unit area increases (because of shrinkage), which led to a small increase in the breaking force, although it can be assumed that this material was also damaged under the influence of UV radiation and seawater. The percentage decrease in resistance ranged from 1.83% to 13.88%, with S3 showing the greatest sensitivity to aging conditions.

The results of the knitted fabrics tensile strength test are shown in Figure 3a in the wale direction and 3b in the course direction. Eight samples showed a decrease in average breaking force in one of the directions, which is directly related to the lower stress tolerance. The highest percentage change was seen in S9-X with -27.07% in the wale direction and



	S1	S2	S3	S4	S5	S6	S7	S8	S9
■ before aging	291.13	283.64	406.41	309.31	287.5	202.3	528.74	252.94	362.97
□ after aging	244.3	261.83	425.96	318.42	210.2	192.45	496.65	258.48	322.04

a)



	S1	S2	S3	S4	S5	S6	S7	S8	S9
■ before aging	175.42	173.8	203.5	201.12	233.36	138.16	271.05	197.07	224.78
□ after aging	158.95	173.15	246.3	192.03	248.99	124.73	341.5	186.58	176.9

b)

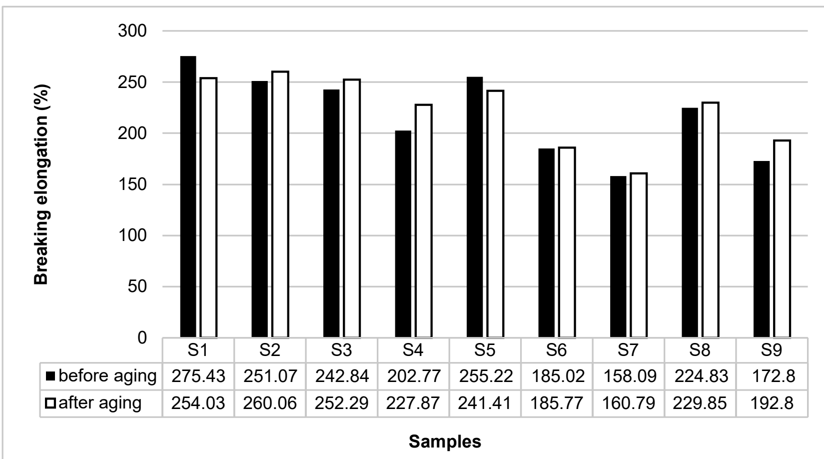
Figure 3: Change in the breaking force after aging (a) in the direction of wale (b) in the direction of course

-12.71% in the course direction. This sample recorded the largest change in the density coefficient of wales and courses from 0.77 to 1.04, i.e. the dimensional instability of the knitted fabric after aging. The next largest changes in the compaction coefficient were observed in S7 (from 1.20 to 1.10) and S3 (from 0.59 to 0.62), which was also reflected in the unexpected behaviour with increasing resistance to tensile forces in the row direction.

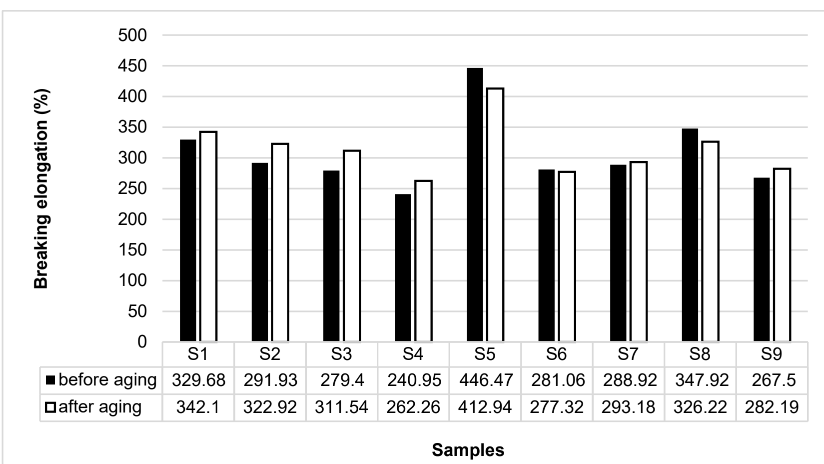
The influence of aging conditions was also reflected in the measured values of elongation at break, which gave the expected results of increasing elongation under the influence of aging. Of interest is sample S5, where the elongation at break was reduced in both observed directions. S5 is the sample with the highest mass per unit area and the highest percentage of elastane (Figure 4).

In order to better understand the influence of aging conditions on the changes in fabric strength, the changes of the individual measured values are given in Table 4.

Sports swimsuits are expected to absorb and retain less water, particularly in competitive swimsuits where water repellent finishes are used. The AATCC Test Method 195 and MMT tester test also evaluated the qualified moisture absorption capacity of aged and unaged samples. Figure 5 shows the results of the maximum wetted radius absorption on the top (a) and bottom (b) of the knitted fabric. These results suggest that the knitted fabric has a greater capacity to absorb water after aging, which is an undesirable characteristic for swimwear.



a)

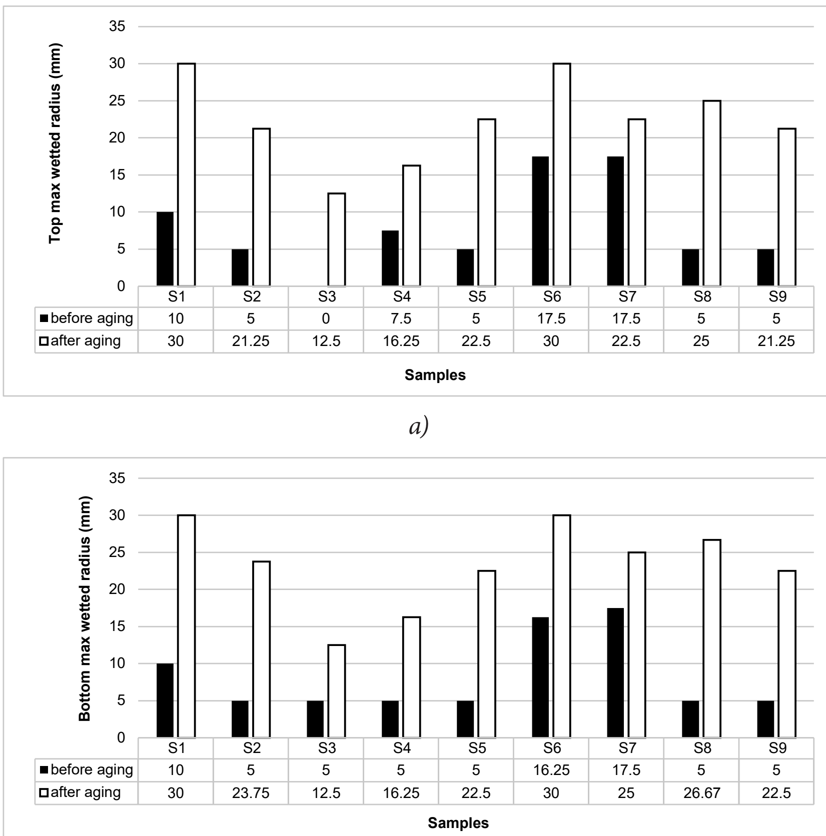


b)

Figure 4: Change in the breaking elongation after aging (a) in the direction of wale (b) in the direction of course

Table 4: Changes in breaking force and elongation, expressed in %, compared to non-aged materials

Fabric sample	Measured properties				
	Breaking force (N)			Breaking elongation (%)	
	Bursting test	Strip test/wale	Strip test/ course	Wale	Course
S1-X	−1.83	−19.17	−10.36	−8.42	3.63
S2-X	−12.82	−8.33	−0.38	3.46	9.6
S3-X	−13.88	4.59	17.38	3.75	10.32
S4 -X	−5.95	2.86	−4.73	11.02	8.13
S5 -X	−6.85	−36.77	6.28	−5.72	−8.12
S6 -X	−3.87	−5.12	−10.77	0.4	−1.35
S7-X	−8.48	−6.46	20.63	1.68	1.45
S8-X	1.18	2.14	−5.62	2.18	−6.65
S9-X	−2.22	−12.71	−27.07	10.37	5.21

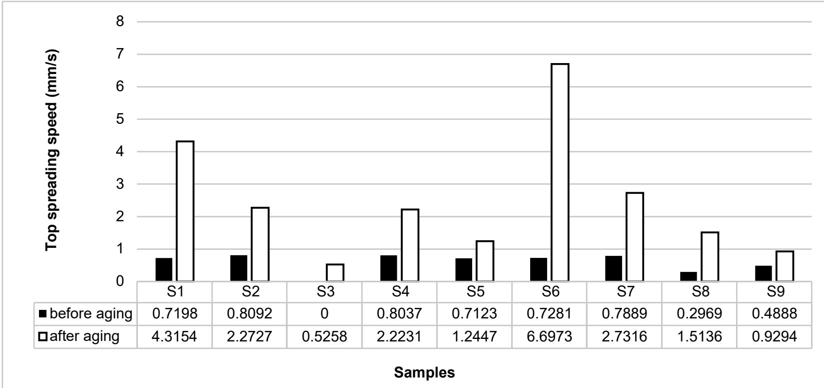


a)

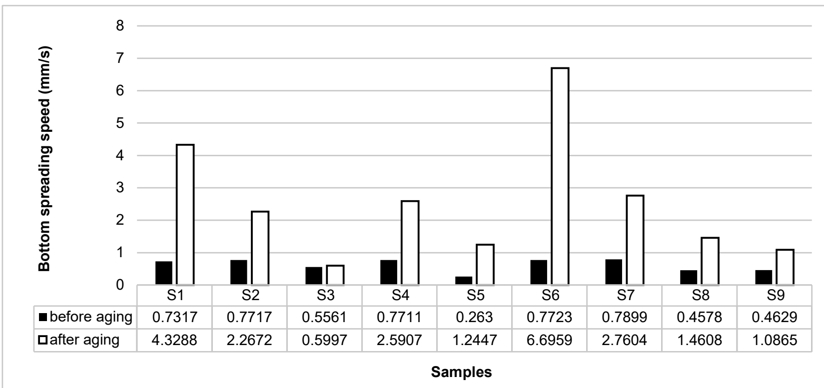
b)

Figure 5: Change in the wetted radius on the top (a), and bottom (b) on the knitted fabric

As a result of the test, the spreading speed on the top and bottom side of the knitted fabric was also recorded. Figure 6 shows that the spreading speed increases after aging for all tested fabrics. The results show that the highest spreading speed after aging was recorded on S6 with the lowest mass per unit area and thickness.



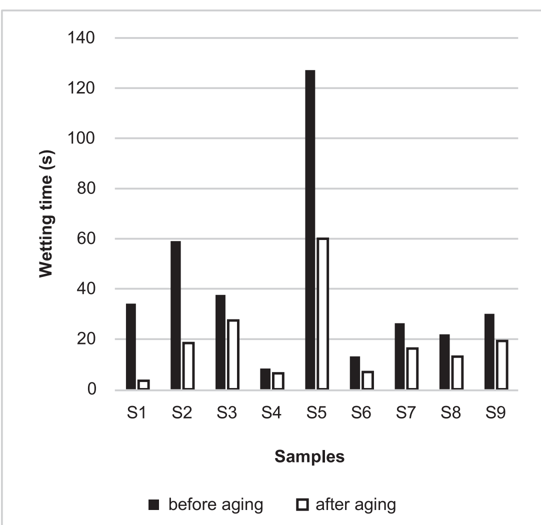
a)



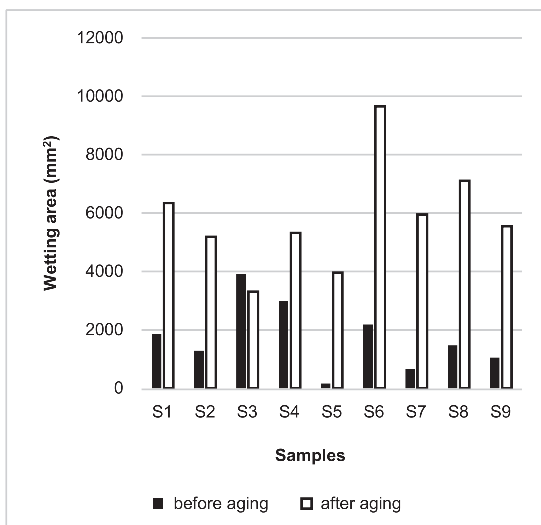
b)

Figure 6: Change in the water spreading speed on the top (a), and bottom side (b) of the knitted fabric

The results of measurements using the thermal camera are presented in Figure 7. Results relate to the wetting time, wetting area, spreading speed on the top of a sample (in both x and y direction) and drying time.



a)



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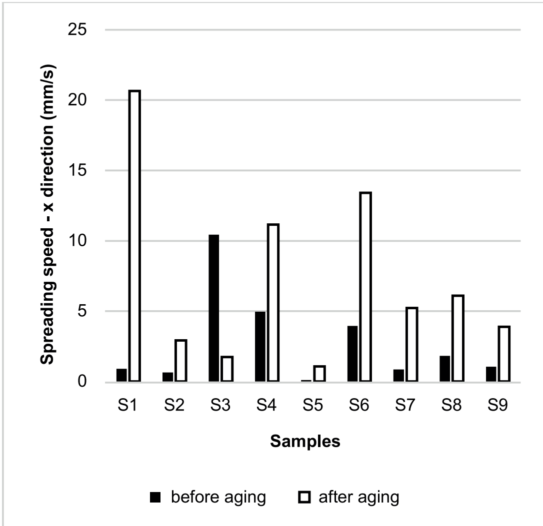
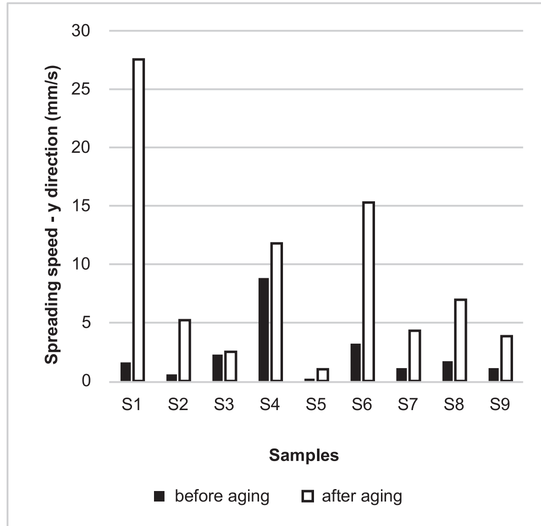
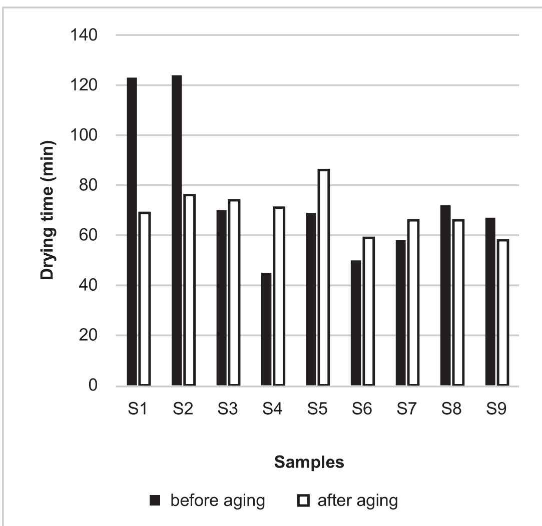


c)



d)



e)

Figure 7: Results of measurement using the thermal camera: (a) wetting time, (b) wetting area, (c) spreading speed of the top of a sample in the x-direction, (d) spreading speed of the top of a sample in the y-direction and (e) drying time

The wetting time of observed materials was in the range of 3 to 60 seconds, and decreased for all samples studied. The longest wetting time of both unaged and aged samples was recorded for S5, which stands out for its highest mass per unit area (226 g/m^2, Table 2). The results of the measured wetting area were in accordance with the measured maximal wetted radius (measured using MMT, Figure 5). As can be seen from the presented graph (Figure 7 (b)), the wetting area also increases after aging for all samples studied. The increase is especially prominent for samples S1, S2, and S5-S9. The results of the spreading speed measured using the thermal camera correspond to the results of top/bottom spreading speed obtained using the MMT apparatus. For both spreading speeds (i.e. in x- and y- direction), the values increased due to aging. The most significant differences caused by aging were observed for S6 (the sample with the lowest mass per unit area and thickness among studied samples) and S1. It is interesting to note the results of the measured drying time. It can be observed from these results that the drying time was longer for the majority of samples after aging. A significant difference between the drying time of unaged and aged samples was clear for the samples with the highest initial thickness, i.e. samples S1 and S2 (both with a thickness of 0.655 g/m^2). For those two samples, the drying time decreased due to aging for up to 40% of the original drying time. As previously noted, a shorter drying time is preferable for the final purpose of the studied materials, but only if other properties are not negatively affected by aging.

4 Conclusion

All knitted fabrics had a similar raw material composition, but in different proportions and with different yarn constructions, and as expected they showed different resistance to the effects of aging conditions. However, it can be clearly seen that there were more or less significant changes in the performance of knitted fabrics in all samples. Knitted fabrics with the same content of PA and EL (S1, S2 and S7) of 80%/20% intended for fashionable swimwear showed similar behaviour after aging, in the form of a decrease in the density coefficient and an increase in the mass per unit area and thickness of the knitted fabrics. Resistance to breaking force decreasesd and elongation at maximum force increased. The wetted radius of water absorption and water spreading speed increased. Samples S3 and S4 had different raw material compositions (polyamide and polyester) in the same proportion with elastane of 72%/28%. From the results, as in the previous three samples, the sample with polyamide recorded an increase in the mass per unit area and thickness of the knitted fabric, while the sample with polyester recorded a decrease in the mass and thickness of the knitted fabric. However, their tensile properties under force were the same. The sample with the highest percentage of elastane of 41% showed slight changes in the mass per unit area and thickness of the knitted fabric, but the largest changes were observed under force, which is to be expected given the elastane content in the knitted fabric. The last three samples of polyamide and elastane with very similar proportions (73%/27%, 72%/28% and 71%/29%) showed similar changes in mass per unit area and thickness, although it can be observed that the sample with the higher elastane proportion was more sensitive to tensile and breaking forces and had higher elasticity.

The results show that the wetting time of observed materials decreased due to aging, while the wetting area and spreading speed increased. Fabrics showed different behaviours in terms if drying time. For the majority of fabrics, the aging process resulted in a slight increase in drying time, while that time decreased significantly for two out of nine fabrics.

References

1. POTOČIĆ MATKOVIĆ, Vesna Marija, SALOPEK ČUBRIĆ, Ivana, KRSTOVIĆ Katarina. Characterization of physical-mechanical properties of functional fabrics for fashion and sports swimwear. In *MATRIB 2021. Book of Proceedings*. Edited by Danko Ćorić, Sanja Šolić and Franjo Ivušić. Vela Luka : HDMT – Hrvatsko društvo za materijale i tribologiju, 2021, 355–366.
2. CUNNINGHAM, Patricia A. From underwear to swimwear: branding at atlas and B.V.D. in the 1930s. *The Journal of American Culture*, 2009, **32**(1), 38–52, doi: 1 0.1111/j.1542-734X.2009.00692.x.
3. MORIA, Hazim, CHWGHURY, Harun, ALAM, Firoz, SUBIC, Aleksandar, SMITS, Aleksander J., JASSIM, Rahim, BAJABA, Nasser S. Contribution of swimsuits to swimmer's performance. *Procedia Engineering*, 2010, **2**(2), 2505–2510, doi: 10.1016/j.proeng.2010.04.023.
4. MORALES, Alfonso T., FAJARDO, Javier A.T., GONZÁLEZ-GARCÍA, Higinio. High-speed swimsuits and their historical development in competitive swimming. *Frontiers in Psychology*, 2019, **10**, 1–11, doi: 10.3389/fpsyg.2019.02639.
5. SALOPEK ČUBRIĆ, Ivana, ČUBRIĆ, Goran, POTOČIĆ MATKOVIĆ, Vesna M. Behavior of polymer materials exposed to aging in the swimming pool: focus on properties that assure comfort and durability. *Polymers*, 2021, **13**(15), 1–19, doi: 10.3390/polym13152414.
6. HERRERO, Marta, ROVIRA, Joaquim, ESPLUGAS, Roser, NADAL, MartÍ, DOMINGO, José L. Human exposure to trace elements, aromatic amines and formaldehyde in swimsuits: assessment of the health risks. *Environmental Research*, 2019, **181**, 1–10, doi: 10.1016/j.envres.2019.108951.
7. ARHANT, Mael, LE GALL, Maelenn, LE GAC, Pierre-Yves, DAVIES, Peter. Impact of

hydrolytic degradation on mechanical properties of PET - towards an understanding of microplastics formation. *Polymer Degradation and Stability*, 2019, **161**, 175–182, doi: 10.1016/j.polymdegradstab.2019.01.021.

8. CIONEK, Caroline A., NUNES, Catia, FREITAS, Adonilson, HOMEM, Natalia, MUNIZ, Edvani, AMORIM, Teresa. Degradation study of polyester fiber in swimming pool water. *Textile Research Journal*, 2021, **91**(1-2), 51–61, doi: 10.1177/0040517520934507.
9. SENTHILKUMAR, Mani, ANBUMANI, Natarajan, HAYAVADANA, J. Elastane fabrics – a tool for stretch applications in sports. *Indian Journal of Fibre & Textile Research*, 2011, **36**(3), 300–307.
10. ISO 3801:1977. *Textiles – Woven fabrics – Determination of mass per unit length and mass per unit area.* Geneva : International Organization for Standardization, 1977, 1–4.
11. ISO 5084:1996. *Textiles – Determination of thickness of textiles and textile products.* Geneva : International Organization for Standardization, 1996, 1–5.
12. ISO 13934-1. *Textiles – Tensile properties of fabrics — Part 1: Determination of maximum force and elongation at maximum force using the strip method.* Geneva : International Organization for Standardization, 2013, 1–24.
13. ISO 13938-2:2019. *Textiles – Bursting properties of fabrics – Part 2: Pneumatic method for determination of bursting strength and bursting distension*. Geneva : International Organization for Standardization, 2019, 1–6.
14. POTOČIĆ MATKOVIĆ, Vesna Marija, SKENDERI, Zenun. Mechanical properties of polyurethane coated knitted fabrics. *Fibres and Textiles in Eastern Europe*, 2013, **100**(4), 86–91.
15. AATCC TM195-2021. *Test Method for Liquid Moisture Management Properties of Textile Fabrics*. Englewood : American Association of Textile Chemists and Colorists (AATCC), 2000, 1–5.
16. M290 Moisture Management Tester, Instruction Manual, Rev. 1.4 (06/18), SDL Atlas
17. SALOPEK ČUBRIĆ, Ivana, ČUBRIĆ, Goran, KATIĆ KRIZMANČIĆ, Ines, KOVAČEVIĆ, Monika. Evaluation of changes in polymer material properties due to aging in different environments. *Polymers*, 2022, **14**(9), 1–23, doi: 10.3390/polym14091682.
18. DEMA, Mesfin, TURNER, Chris, SARI-SARRAF, Hamed, HEQUET, Eric. Machine vision system for characterizing horizontal wicking and drying using an infrared camera. *IEEE Transactions on Industrial Informatics*, 2016, **12**(2), 493–502, doi: 10.1109/TII.2016.2516441.

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Investigating Properties of Electrically Conductive Textiles: A Review
Raziskave lastnosti elektroprevodnih tekstilij: pregled

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Abstract
Electro-conductive textiles are mostly fabrics that have conductive elements or electronics integrated into them to achieve electrical characteristics. They have acquired considerable attention in applications involving sensors, communications, heating textiles, entertainment, health care, safety etc. To produce electro-conductive textiles, several techniques, e.g. chemical treating with conductive polymers on various textile materials, or using different technologies, e.g. knitting, weaving, embroidery techniques to include conductive threads into fabric interconnections etc., are being used. Electro-conductive fabrics are flexible enough to be adapted to quick changes in any particular application, beginning with wearable purposes and sensing needs as specified by many different groups. The ability of electro-conductive textiles to conduct electricity is the most essential property they must possess. In addition, the applications that may be worn should have stable electrical, thermal and mechanical qualities. The most recent developments in the field of electro-conductive textiles represent the aim of this review, which analyses these properties, including the investigation of methods that are used to obtain conductive textiles, their electrical properties, thermal properties, and beyond that, the scientific methods that are used to measure and investigate electro-conductive textiles. We also focused on the textile materials used in studies, as well as the technologies used to make them conductive, which may be a guide for different interested groups for use in a variety of smart applications.
Keywords: electro-conductive textiles, electrical resistivity, electro-thermal behaviour

Izvleček
Elektroprevodne tekstilije so večinoma tekstilije, v katere so vgrajeni prevodni elementi ali elektronika za doseganje električnih lastnosti. Veliko pozornosti so pridobili v aplikacijah, ki vključujejo senzorje, komunikacije, grelne tekstilije, zabavo, varovanje zdravja in varnost. Za izdelavo elektroprevodnih tekstilij se uporabljajo številne tehnike, kot je kemična obdelava s prevodnimi polimeri na različnih tekstilnih materialih ali uporaba različnih tehnologij, kot so pletenje, tkanje, tehnike vezenja za vključevanje prevodnih niti v strukturo ploskovnih tekstilij idr. Elektroprevodne ploskovne tekstilije so dovolj upogibljive, da se lahko prilagodijo hitrim spremembam v kateri koli posebni aplikaciji, začenši z namenom nošenja in potrebami zaznavanja, ki jih določajo različne skupine. Sposobnost elektroprevodnega tekstila za prevajanje električnega toka je najpomembnejša lastnost, ki jo mora ta imeti. Poleg tega morajo aplikacije, ki so nosljive, imeti stabilne električne, toplotne in mehanske lastnosti. Namen tega pregleda je podati analizo najnovejšega razvoja na področju elektroprevodnih tekstilij, vključno z raziskavo metod, ki se uporabljajo za pridobivanje prevodnih tekstilij, njihovih električnih lastnosti, toplotnih lastnosti in poleg tega znanstvenih metod, ki se uporabljajo za mer-

jenje in raziskovanje elektroprevodnih tekstilij. Pregled se osredinja tudi na tekstilne materiale in tehnologije, ki so jih avtorji uporabili za dosego prevodnosti, kar je lahko vodilo različnim zainteresiranim skupinam za uporabo v različnih pametnih aplikacijah.
Ključne besede: elektroprevodne tekstilije, električna upornost, elektrotoplotno obnašanje

1 Introduction

Over the last decades, smart textiles have become popular as a concept. In order to manufacture wearable textile systems, electro-conductive textiles are needed. These textiles are materials which can conduct electric current [1]. They are made by means of different methods, e.g. using conductive fibres, yarns, coatings, polymers or inks, with the most common manufacturing techniques (cf. Figure 1) [2–4]. Furthermore, Figure 2 depicts the percentage of e-textile players who use various types of textile material.

Different conductive yarn manufacturers can be found on the market, and their growth and development have followed a traditional path. As new electro-conductive materials have become available on the market, manufacturers have found different ways of developing and improving the properties of conductive fibres and yarns [5–7].

As a building block for intelligent textile components, electrically conductive yarns must offer stable and reliable electrically conductive properties while maintaining textile properties, which ensure good processing and pleasant wearing comfort. The reliability and stability requirements may vary depending on the application.

Electro-conductive textiles can be made using traditional techniques, e.g. knitting, weaving, sewing and embroidering. When it comes to smart textiles that monitor vital functions and also need to be close to the human body, like a second skin, the knitting technology can be chosen [9–12]. The latter can provide a textile structure that can conform to the shape of our body by giving the wearer a comfortable feeling while moving freely. In this way, a knitted fabric can be stretched when subjected to a force and return to its original shape when the force is removed. When this technology combines textiles with electrically conductive materials, it is

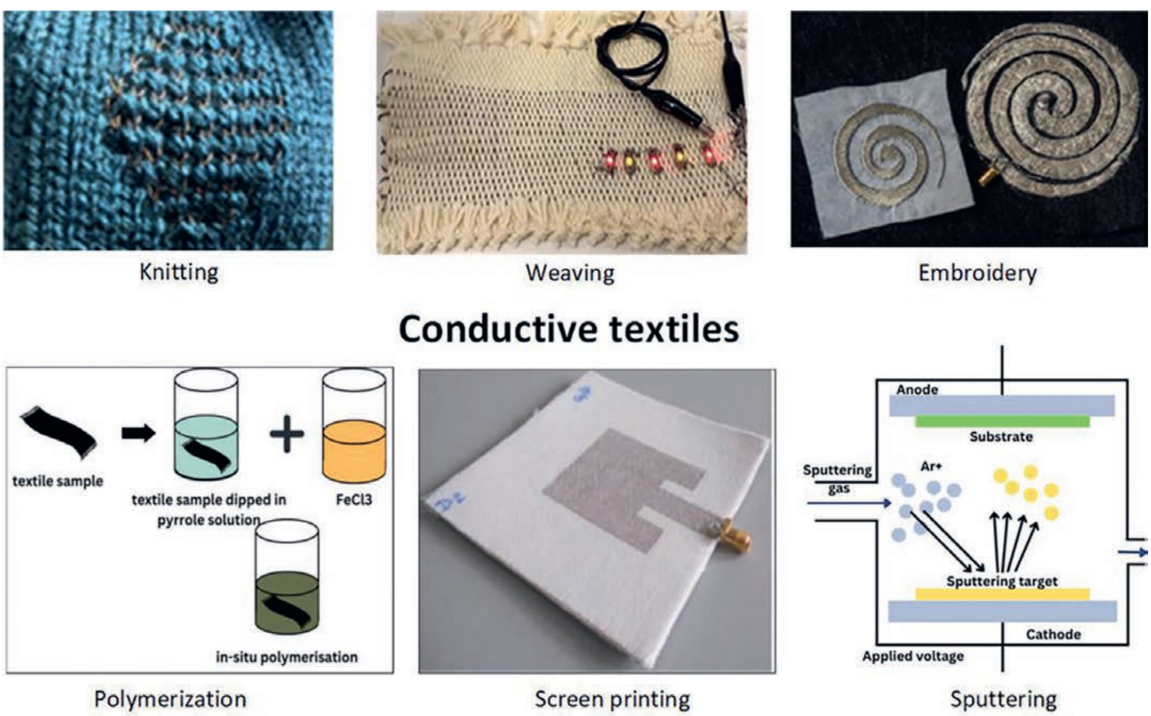

Figure 1: Different manufacturing techniques of conductive textiles:
a) knitting, b) weaving, c) embroidery, d) coating methods, d) screen printing, e) magnetron sputtering

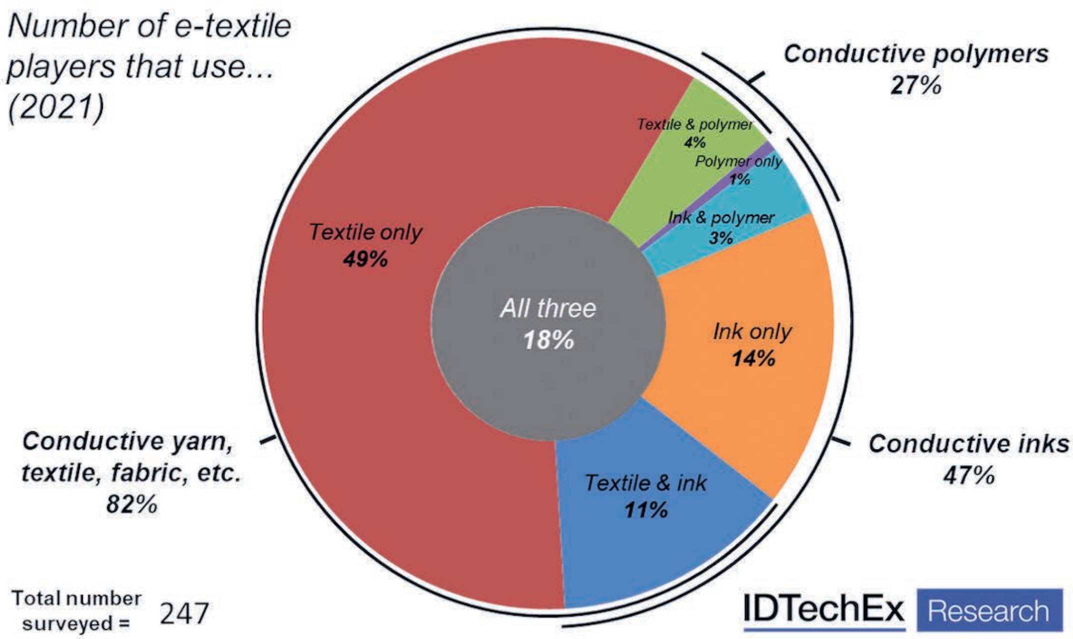

Figure 2: Percentage of e-textile players using different types of material (Image source: E-Textiles 2021–2031, IDTechEx Research [8])

important that the knitted fabric is combined with elastic yarn without loop formation during its use.

The second method to obtain conductive textiles is to chemically treat the fibres/yarns/fabrics to make them conductive. This can be achieved by coating them in different processes, e.g. electroless deposition, electroplating, physical vapour deposition (PVD), chemical vapour deposition (CVD) and conductive polymer coating, the latter being used more on textiles, which is the focus of this article. Conductive polymers, e.g. polypyrrole, polyaniline or polythiophene, are applied to textile surfaces with in situ polymerisation.

The first electronic textile introduced to the market was the ICD+ (Industrial Clothing Design Plus) jacket in 2000 by Levi Strauss & Co. and Philips Research Laboratories [13], which could house an MP3 player and a mobile phone. When the jacket goes into the washing machine for maintenance, all appliances and cords must be removed. From the textile point of view, the challenge for researchers (even nowadays) is to produce as many components as possible from textile materials. Therefore, it was necessary to develop electro-conductive textiles that can be obtained in several ways, e.g. by integrating conductive fibres or yarns, by applying conductive coatings or by using conductive inks [2, 4, 14].

Electro-conductive textiles have emerged as a new trend in recent decades. Based on the above, we study electrical and thermal properties of conductive textiles obtained with various chemical processes, in particular polymerisation, carbon-based technologies, or technologies such as knitting, weaving, embroidery, sewing and needle felting.

It is of crucial importance to study the properties of textile materials to predict their future applications, human comfort and lifespan due to aging factors. Table 1 shows a chronological overview of published work focusing on the properties of conductive textiles and their applications. The overview continues with the analysis of conductive fabrication process, methods of measuring electrical resistance, thermo-mechanical properties and modelling techniques as an approach to simulate the electrical behaviour of conductive textiles. In the end, the applications of conductive textiles as electrical devices, e.g. sensors and antennas, are mentioned.

Table 1: Chronological overview of papers published on electro-conductive textiles

First author, published year, ref.	Journal/ Conf.	Title	Conductive type	Methodology
Hersh, S. P. 1952 [15]	Textile Research Journal	Electrical Resistance Measurements on Fibres and Fibre Assemblies	Poorly conducting hydrophobic synthetic fibres, such as nylon, Dynel and Dacron	Static electricity, resistance measurement
Azoulay, J. 1988 [16]	IEEE Transactions on Electrical Insulation	Anisotropy in Electric Properties of Fabrics Containing New Conductive Fibres	2/1 warp-faced twill fabric containing 10% new conductive fibre	Surface resistance measurement, anisotropy
Berberi, P. 1998 [17]	Textile Research Journal	A New Method for Evaluating Electrical Resistivity of Textile Assemblies	Textile assemblies	Electrical resistivity, volume resistivity
Meoli, D. 2002 [18]	Journal of Textile and Apparel, Technology and Management	Interactive electronic textile development: A review of technologies	Smart fabrics, interactive textiles	Review the possibilities to develop smart textiles
Tappura, K. 2003 [19]	Journal of Electrostatics	Computational modeling of charge dissipation of fabrics containing conductive fibres	Twenty different fabrics with base fabric cotton and polyester	Analyse electrostatic properties in conductive fibres and discharging properties
Kaynak, A. 2003 [20]	Polymer International	Effect of synthesis parameters on the electrical conductivity of polypyrrole-coated poly(ethylene terephthalate) fabrics	Coated fabrics polypyrrole, poly(ethylene terephthalate) (PET)	Conductive resistance measurement, temperature affection on conductivity
Xue, P. 2004 [21]	Textile Research Journal	Electromechanical Behavior of Fibres Coated with an Electrically Conductive Polymer	Polymer fibres coated with conductive polymer, polypyrrole (PPy). PPy-coated PA6 fibres and PPy-coated Lycra fibres	Electrochemical behaviour, electrical resistance, electromechanical model, resistance as function of strain, damage level, relative humidity, air temperature.
Dhawan, A. 2004 [22]	Textile Research Journal	Woven Fabric-Based Electrical Circuits: Part I: Evaluating Interconnect Methods	Fabric-based electrical circuits, woven textile structures	Develop fabric-based electrical circuits
Wu, J. 2005 [23]	Synthetic Metals	Conducting polymer coated lycra	Conducting polymer using pyrrole, nylon lycra	In situ polymerisation process is used to produce conductive polymer nylon lycra
Varesano, A. 2005 [24]	Polymer Degradation and Stability	A study on the electrical conductivity decay of polypyrrole coated wool textiles	Wool fibres coated with electrically conducting polypyrrole (PPy)	Electrical conductivity stability due to dry cleaning and other factors
Kim, B. 2006 [25]	Journal of Applied Polymer Science	Polyaniline-coated PET conductive yarns: Study of electrical, mechanical, and electro-mechanical properties	Conductive polymer and polyethylene terephthalate (PET) yarns, polyaniline (PANI)	Electrical, mechanical, and electro-mechanical properties of PET conductive yarns
Gasana, E. 2006 [14]	Surface and Coatings Technology	Electroconductive textile structures through electroless deposition of polypyrrole and copper at polyaramide surfaces	Polyaramide fabrics, metal coated textile fibres, pyrrole monomer	Polymerisation of polyaramide textile structures using polypyrrole combined with copper metallisation

First author, published year, ref.	Journal/ Conf.	Title	Conductive type	Methodology
Wang, J. 2006 [26]	Journal of the Textile Institute	Thermal conductivity studies on wool fabrics with conductive coatings	Wool fabrics, PPy-coated, Anthraquinone-2-sulfonic acid (AQSA) sodium salt monohydrate 97% was the dopant and iron chloride hexahydrate ($FeCl_3 \cdot 6H_2O$) as the oxidising agent	Surface resistivity measurements, thermal conductivity measurements, investigation the relation between electrical conductivity and thermal conductivity
Asanovic, K. 2007 [27]	Journal of Electrostatics	Investigation of the electrical behavior of some textile materials	Textiles, wool, hemp, cotton, pan, flax, jute	Electrical behaviour, dielectric loss tangents and relative dielectric permeabilities
Locher, I. 2008 [28]	Textile Research Journal	Enabling Technologies for Electrical Circuits on a Woven Monofilament Hybrid Fabric	Woven fabric with embedded copper wires	Electrical proprieties, frequency transmission, transmission lines, electronic circuits
Banaszczyk, J. 2009 [29]	Quantitative InfraRed Thermography Journal	Infrared thermography of electroconductive woven textiles	Woven stainless steel sheet (Bekintex)	Current distribution modelling, anisotropy, IR thermography
Banaszczyk, J. 2009 [4]	FIBRES & TEXTILES in Eastern Europe	Current Distribution Modelling in Electroconductive Fabrics	Woven electroconductive textiles sheets	Model current distribution of woven conductive textiles using resistive networks
Latifi, M. 2010 [30]	Technical Textile Yarns	Electro-conductive textile yarns	Electro-conductive yarn, metallic fibre, electro-conductive polymers, composite fibres	Manufacturing process of electro-conductive yarns
Gu, J. F. 2010 [31]	Smart Materials and Structures	Soft capacitor fibres using conductive polymers for electronic textiles	Conductive polymer-based fibre	High capacitance fibres frequency analysation
Schwarz, A. 2010 [3]	Surface and Coatings Technology	Gold coated para-aramid yarns through electroless deposition	Para-aramid yarns, (Teijin Aramid). polypyrrole PPy and copper coatings	Gold, polypyrrole and copper coated para-aramid yarns proved to offer good electroconductive properties and endurable due to washing
Li, L. 2010 [32]	Textile Research Journal	A Resistive Network Model for Conductive Knitting Stitches	Conductive knitting yarn	Resistance of knitting yarn, electrical modelling
Ding, Y. 2010 [33]	ACS Applied Materials and Interfaces	Conductivity trends of PEDOT-PSS impregnated fabric and the effect of conductivity on electrochromic textile	Stretchable fabric (SPANDEX), cotton, polyester, Lycra, rayon were treated with PEDOT-PSS conductive polymer	Electrical conductivity measurements
Kazani, I. 2011 [34]	Textile Research Journal	Van Der Pauw method for measuring resistivities of anisotropic layers printed on textile substrates	Woven textile substrates, screen printed	Van Der Pauw method for electrical resistance measurement
Yoon, B. 2011 [35]	Fibres and Polymers	Designing waterproof breathable materials based on electrospun nanofibres and assessing the performance characteristics	Layered fabric structures based on electrospun nanofibre	Examine waterproofness and breathability performances

First author, published year, ref.	Journal/ Conf.	Title	Conductive type	Methodology
Petersen, P. 2011 [36]	Textile Research Journal	Electronic textile resistor design and fabric resistivity characterization	Highly conductive metallic coated thread knitted into fabric	Electrical resistance characterisation for different knitting methods
Kacprzyk, R. 2011 [37]	Fibres and Textiles in Eastern Europe	Measurements of the volume and surface resistance of textile materials	Textile materials	Surface and volume resistance measurement
Patel, P. C. 2012 [38]	IEEE International Conference on Power System Technology, POWERCON	Applications of electrically conductive yarns in technical textiles	High conductive fibres, metal fibres, electro-conductive yarns etc.	Electromechanical properties of conductive yarns and fibres
Tokarska, M. 2013 [39]	Indian Journal of Fibre and Textile Research	Measuring resistance of textile materials based on Van der Pauw method	Electro-conductive Shieldex® fabric	Van Der Pauw resistance measurement, surface resistance measurement, anisotropy
Yen, R. H. 2013 [40]	International Journal of Numerical Methods for Heat and Fluid Flow	Numerical study of anisotropic thermal conductivity fabrics with heating elements	Electrically conductive yarns	Numerical analysis, temperature control, temperature uniformity
Hamdani, S. 2013 [41]	Materials	Thermo-mechanical behavior of textile heating fabric based on silver coated polymeric yarn	Conductive silver yarn	Heating of conductive textiles, thermography of conducting elements, heating due to knitting methodology
Tokarska, M. 2013 [42]	Journal of Materials Science: Materials in Electronics	Electrical properties of flat textile material as inhomogeneous and anisotropic structure	Electro-conductive plain-weave polyester woven fabric	Electrical resistance as function of electrode placement, electrode properties
Odhiambo, S. 2013 [43]	Mixed Design of Integrated Circuits and Systems	Comparison of Commercial Brands of PEDOT : PSS in Electric "Capattery" Integrated in Textile Structure	PEDOT:PSS are used in making "capatteries" and Ag coated yarns and stainless steel filament yarn used as electrodes	Measuring discharging characteristics of capattery
Stoppa, M. 2014 [44]	Sensors	Wearable electronics and smart textiles: A critical review	Conductive fabrics, Smart textiles	Reviewing materials, methods of manufacturing, energy consumption, ergonomics etc.
Wegene, J. 2014 [45]	Industrial and Engineering Chemistry Research	Conducting leathers for smart product applications	Conductive leather	Infrared spectroscopy, Fourier transform, electron microscopic analysis
Capineri, L. 2014 [46]	Procedia Engineering	Resistive sensors with smart textiles for wearable technology: From fabrication processes to integration with electronics	Conductive fabrics using copper wire, steel wire	Fabrication of smart textiles, sensors
Tokarska, M. 2014 [47]	Autex Research Journal	Determination of fabric surface resistance by Van der Pauw method in case of contacts distant from the sample edge	Antioxidant silver fibre shielding rip-stop fabric, silver fibre shielding canvas fabric	Surface resistance measurement, Van der Pauw, electrode placement

First author, published year, ref.	Journal/ Conf.	Title	Conductive type	Methodology
Usma, C. 2015 [48]	Procedia Technology	Fabrication of Force Sensor Circuits on Wearable Conductive Textiles	Sn-Ag-Cu (SAC) plated Nylon fabric	Fabrication possibilities of pressure sensors based on conductive textiles
Vásquez Quintero, A. 2015 [49]	Procedia Engineering	Capacitive strain sensors inkjet-printed on PET fibres for integration in industrial textile	PET fibres	Printed strain sensors, sensor measurement
Arogbonlo, A. 2015 [50]	Procedia Technology	Design and Fabrication of a Capacitance Based Wearable Pressure Sensor Using E-textiles	Zell sensor; a Tin/Copper over Silver (Sn/Cu/Ag)-(SAC) plated Nylon Fabric – Shieldex – U.S	Analysis of design parameters for pressure sensor
Felczak, M. 2015 [51]	Fibres and Textiles in Eastern Europe	Lateral and perpendicular thermal conductivity measurement on textile double layers	Fleece produced from blends of 40% flax, 40% steel and 20% polyester	Thermographic measurements, theoretical model and experimental measurements
Lipol, L. 2016 [52]	European Scientific Journal	The Resistance Measurement Method of the Conducting Textiles	Conductive threads through adding: Metal, Carbon, Polyaniline (PANi) – Poly (3, 4-ethylenedioxythiophene) (PEDOT) – Polypyrrole (PPy)	Two and four probe resistance measurements
Karim, N. 2017 [53]	ACS Nano	Scalable Production of Graphene-Based Wearable E-Textiles	Conductive graphene textiles	Sheet resistance and electrical proprieties due to different factors such as washing, mechanical stability analysis
Bahadir, S. 2017 [54]	Textile Research Journal	Modelling of surface temperature distributions on powered e-textile structures using an artificial neural network	Conductive textile yarns, stainless steel, Silver plated PA	Temperature distributions modelling, artificial neural network
Ryan, J. D. 2017 [55]	ACS Applied Materials and Interfaces	Machine-Washable PEDOT:PSS Dyed Silk Yarns for Electronic Textiles	Degummed silk yarn and cotton yarn were treated with water dispersion of PEDOT:PSS	Produced and tested a high conductive silk yarn which was durable to washing and dry cleaning
Alhashmi A., F. 2017 [56]	Journal of Alloys and Compounds	A simple method for fabricating highly electrically conductive cotton fabric without metals or nanoparticles, using PEDOT:PSS	Cotton fabric treated with PEDOT:PSS	Investigating conductive fabric surface morphology, electrical resistance measured using four line probe
Nuramdhani, I. 2017 [57]	Materials	Electrochemical impedance analysis of a PEDOT: PSS-based textile energy storage device	Textile-based energy storage device treated with PEDOT:PSS stainless-steel electro-conductive yarn as the electrodes	Cyclic Voltammetry, electrochemical impedance analysis, equivalent electric circuit model simulation
Chaves, F. A. 2018 [58]	Nanotechnology	Mechanical, in-situ electrical and thermal properties of wearable conductive textile yarn coated with polypyrrole / carbon black composite	Bare and coated cotton yarn using polypyrrole/carbon black composite	Electrical properties measured with a source meter in conjunction with the KickStart Software to obtain resistance, resistivity, and conductivity, thermal conductivity was measured using Transient Hot Bridge

First author, published year, ref.	Journal/ Conf.	Title	Conductive type	Methodology
Lund, A. 2018 [59]	Materials Science and Engineering R: Reports	Electrically conducting fibres for e-textiles: An open playground for conjugated polymers and carbon nanomaterials	Fibres and yarns treated to be conductive using conjugated polymers and carbon materials	Reviewing possible technologies, methods and properties of conductive textiles treated with conjugated polymers and carbon materials including areas of application
Hughes-Riley, T. 2018 [60]	Fibers	A historical review of the development of electronic textiles	Electronic textiles, smart textiles	Chronological review of e-textiles and their applications, mainly sensors and technological approaches
Chatterjee, K. 2019 [61]	Fibres	Electrically conductive coatings for fibre-based E-Textiles	Conductive polymers	Fabrication process of electrically conductive textiles
Mohamed, A. A. 2019 [62]	Journal of Textile and Apparel, Technology and Management	Suitability of conductive knit fabric for sensing human breathing	Silver coated Polyamide (Nylon) Fibre (Ag/ Nylon); yarn count 70 denier ratio of silver to Nylon is 20%–80 %	Electrical resistance measurement, human breathing simulator design
Shabani, A. 2019 [63]	Textile & leather review	Resistivity behavior of leather after electro-conductive treatment	White sheep crust leather coated pyrrole, ferric chloride, anthraquinone –2-sulfonic acid sodium salt monohydrate	Volume resistance measurement, relation of resistivity and air humidity
Shabani, A. 2019 [64]	Textile & leather review	The anisotropic structure of electro conductive leather studied by Van Der Pauw method	White sheep crust leather coated pyrrole, ferric chloride, anthraquinone – 2-sulfonic acid sodium salt monohydrate	Surface resistance measurement, Van Der Pauw, anisotropy
Akbarpour, H. 2019 [65]	Journal of Nanostructure in Chemistry	Comparison of the conductive properties of polyester/viscose fabric treated with Cu nanoparticle and MWCNTs	Polyester/viscose fabric treated with nanoparticles MWCNT and Cu	Treated fabrics using nanoparticles, conductivity test, electrical resistance, strength and voltametric charts
Hardianto, H. 2019 [66]	Journal of Engineered Fibres and Fabrics	Textile yarn thermocouples for use in fabrics	Nickel-coated carbon fibre adding stainless steel yarn, polypyrrole-coated carbon fibre, or carbon fibre	Different conductive textile yarns were tested to use as thermocouple and thermopile
Kamyshny, A. 2019 [67]	Chemical Society Reviews	Conductive nanomaterials for 2D and 3D printed flexible electronics	Printed nanomaterials, ink-based metal nanoparticles	Reviewing materials and methods used to incorporate into 2D and 3D printed electronic textiles
Nuramdhani, I. 2019 [68]	Polymers	Charge-discharge characteristics of textile energy storage devices having different PEDOT:PSS ratios and conductive yarns configuration	Twill woven polyester-cotton fabric treated with PEDOT:PSS, two types of conductive yarn, firs is pure stainless steel and silver-coated polybenzoxazole (Ag-PBO) used as electrodes	Electrical characterisation charge and discharge measured using microcontroller
Lund, A. 2020 [69]	Journal of Power Sources	A polymer-based textile thermoelectric generator for wearable energy harvesting	Wool fabrics treated with conducting polymer: polyelectrolyte complex poly(3,4ethylenedioxy-thiophene): poly(styrene sulfonate) (PEDOT: PSS)	Electrical conductivity measurements, thermal resistance, design thermoelectric generators

First author, published year, ref.	Journal/ Conf.	Title	Conductive type	Methodology
Afroj, S. 2020 [70]	Advanced Functional Materials	Highly Conductive, Scalable, and Machine Washable Graphene-Based E-Textiles for Multifunctional Wearable Electronic Applications	Graphene-based e-textiles	Analysation for electronic applications
Tseghai, G. B. 2020 [71]	Sensors	PEDOT:PSS-based conductive textiles and their applications	PEDOT:PSS and composites	Analysing possible applications of PEDOT:PSS conductive textiles, methods of treatment for producing conductive textiles
Hylli, M. 2020 [72]	IOP Conference Series: Materials Science and Engineering	The color fastness properties of conductive leather improved by the use of mordants	Leather samples using mordant $FeSO_4$, $Na_2SO_4 \times 10\ H_2O$	Colour fastness, Surface resistance, dry rubbing
Krifa, M. 2021 [73]	Textiles	Electrically Conductive Textile Materials—Application in Flexible Sensors and Antennas	In situ polymerisation of aniline on nylon, Electrospun doped PANi, PPy/PPTA fibres	Electrical conductivity, application-based textiles antennas
Angelucci, A. 2021 [74]	Sensors	Smart textiles and sensorized garments for physiological monitoring: A review of available solutions and techniques	Conductive fibres and filaments	Reviewing applications of smart textiles to different wearable sensor applications
Jin, I. S. 2021 [75]	Polymers	A facile solution engineering of PEDOT: PSS-Coated conductive textiles for wearable heater applications	Microfibre fabric (Welcron, nylon/polyester splitting yarn) was treated using PEDOT:PSS	Electrical sheet resistance was measured using four probe method, temperature distribution was measured using the thermal camera, crystalline properties were measured by an X-ray diffraction instrument
Shakeri V. 2021 [76]	Journal of Industrial Textiles	Highly stretchable conductive fabric using knitted cotton/lycra treated with polypyrrole / silverNPs composites post-treated with PEDOT:PSS	Cotton/lycra stretchable fabric is treated polypyrrole (PPy), silver nanoparticles (SNPs) composites, and post-treating PEDOT:PSS	Linear four probe method was used to measure electrical resistance, morphology of fabrics and fibres cross-section observed with a field emission scanning electron microscopy
Rogale, S. 2021 [77]	Materials	Measurement method for the simultaneous determination of thermal resistance and temperature gradients in the determination of thermal properties of textile material layers	M3 Fabric upper-side: 100% polyester; membrane: polytetrafluoroethylene; fabric inner-side: 100% polyester fleece M4 (100% polyester) M5 (lining: 100% polyester; membrane: 100% polypropylene; padding: 100% polypropylene) M6 (100% polyester micro-fleece)	Thermal proprieties, electrical resistance, temperature gradients

First author, published year, ref.	Journal/ Conf.	Title	Conductive type	Methodology
Kaynak, A. 2021 [78]	Materials	Electrothermal modeling and analysis of polypyrrole-coated wearable e-textiles	Polypyrrole coated fabric	Thermal modelling, surface resistivity
Adak, B. 2021 [79]	Journal of Textile Science & Fashion Technology	Utilization of Nanomaterials in Conductive Smart-Textiles: A Review	Conductive textiles, Graphene, MXene, Polymer nanocomposite	Review of nanomaterials used in conductive textiles
Wang, P. 2022 [80]		Fabrication of durable and conductive cotton fabric using silver nanoparticles and PEDOT:PSS through mist polymerization	Cotton fabrics are coated using silver nanoparticles and PEDOT:PSS	Surface electrical resistance measured according to the AATCC-76–2005
Luo, Y. 2022 [81]	Journal of the Korean Society of Clothing Industry	Fabrication of Electro-conductive Textiles Based Polyamide/ Polyurethan Knitted Fabric Coated with PEDOT:PSS/Non-oxidized Graphene	Knitted fabric treated with PEDOT:PSS/Non-oxidised Graphene	Four probe method was used to measure sheet electrical resistance, tensile properties were evaluated
Penava, Ž. 2022 [82]	Materials	Heat as a Conductivity Factor of Electrically Conductive Yarns Woven into Fabric	Silver-coated conductive yarns were weaved in woven fabric using different techniques	Sample heat dissipation was investigated as function of applied voltage and also it was investigated the change of electrical resistance influenced by temperature change
Repon, R. 2022 [83]	Polymers	Effect of Stretching on Thermal Behaviour of Electro-Conductive Weft-Knitted Composite Fabrics	Weft-knitted composite fabrics with silver coated polyamide multifilament yarns	Temperature measures as function of stretching, applied voltage as function of time
Alamer, F. 2022 [84]	Nanomaterials	Overview of the Influence of Silver, Gold, and Titanium Nanoparticles on the Physical Properties of PEDOT:PSS-Coated Cotton Fabrics	Cotton fabrics coated with PEDOT:PSS	Reviewing applications and technologies used in e-textiles formed by PEDOT:PSS coatings of cotton
Kalaoglu-Altan, O. 2022 [85]	iScience	Improving thermal conductivities of textile materials by nanohybrid approaches	Passive conductive textiles	Reviewing methods for producing passive conductive textiles to improve thermal conductivity
Tokarska, M. 2022 [86]	Materials	A Mixing Model for Describing Electrical Conductivity of a Woven Structure	Polyamide woven fabric; nickel and copper metalized, polyester woven fabric; nickel metalized and polyester woven fabric; nickel metalized	Investigating Archie's law as it can be used to describe electrical conductivity of woven textiles
Abou Taleb, M. 2022 [87]	Journal of Industrial Textiles	Facile development of electrically conductive comfortable fabrics using metal ions	Wool, polyester, and wool/ polyester fabrics were treated with two metal salt solutions, 0.005 M $CuSO_4$5H2O and 0.005 M AgNO3 and 0.01 M nano-ZnO	Scanning electron microscopy, energy dispersive X-ray, Fourier transform infrared and atomic absorption spectroscopy, AC electrical conductivity, air and water permeability

2 Electro-conductive textiles

Conductive textiles can be made by using conductive fibres, yarns, coatings, polymers or by applying inks to textiles. All smart textile components require to some extent electro-conductive materials, which can be conductive yarns or fabrics. These conductive yarns serve as a functional material forming the basis for the functionality of the whole smart textile system.
Electro-conductive fibres/yarns can be divided into two main groups:

a) Fibres/yarns which are applied in forms such as conductive wires
These can be pure metals, mainly silver, copper and stainless steel, produced with methods such as wire drawing, bundled wire drawing, cutting production, melt spinning and melt extraction [88].
Metal fibres have several advantages, including their strength, composition, biological inertness and immediate availability in textile form at low production costs. They are unaffected by washing or sweating due to its inertness. However, they are unable to deliver homogeneous heating and their brittle nature can cause long-term damage to the spinning machinery [44].

b) Fibres/yarns chemically treated to be conductive
Metal-based fibres, as mentioned above, have highest conductivity, but are not stretchable enough and by using more elastic interconnects, conductivity decreases. The second group of fibres/yarns is coated using conventional conductive polymers, galvanic substances or metallic salts. The most commonly used coating processes are electroless plating, evaporative deposition, sputtering and coating with conductive polymers. Although conductive textiles can be obtained also by treating the surface of traditional textiles, which can be achieved by coating them with polymers such as polypyrrole [4], deposited onto the surface of textile substrates or by printing with conductive inks and forming a conductive layer. Polypyrrole (PPy) is an organic conductive polymer formed with a chemical or electrochemical polymerisation of pyrrole. The polymerisation solution contains a monomer, dopant and oxidising agent to start the polymerisation of monomers. Different textile materials have been used to produce polypyrrole-coated textiles obtained with chemical reaction, e.g. polyester [89], polyamide [20, 90] cotton [91] and wool [92]. Different methods follow in chemical polymerisation. While often a two-step polymerisation has been the method of choice [23, 90, 91, 93], in situ polymerisation [73, 94] and emulsion polymerisation [95] are applied as well. Polyaniline has been applied as a coating on polyester and polyamide fabrics via in situ polymerisation [96]. Moreover, a two-step polymerisation of aniline on fabrics is commonly used [97]. Possible techniques are also a chemical coating with conducting polymers [98] or a reinforcement of polymeric materials with conductive compounds via spinning [99].
Furthermore, one of the most explored conventional conductive polymers is also polystyrene sulfonate (PEDOT:PSS). This polymer was used by Ding et al. [33] to treat stretchable fabrics by soaking them into a conductive polymer, resulting in the concentrate being homogeneously dispersed on the fabrics. Stretchable cotton textiles post-treated with PEDOT:PSS were investigated in [76]. Moreover, Ryan et al. [55] tested PEDOT:PSS to produce high conductive silk yarns, which were good for e-textile used in different applications, retaining conductive properties also after several washing cycles. In addition, the washing durability of conductive textiles treated with PEDOT:PSS was investigated in [100]. Furthermore, cotton fabrics have been treated using PEDOT:PSS to produce electrically conductive textiles by various authors [56, 69, 80, 84]. The applications of commercially available PEDOT:PSS as a potential to produce energy storage and capacitors from electro-conductive textiles were studied [43]. The energy storage devices gained from textiles treated with PEDOT:PSS were the subject of research in [57, 68], where the obtained devices acted as capacitors and their electrical characteristics in charging and discharging were studied.
Tseghai et al. [71] offered a comprehensive overview of most state-of-the-art applications, of electro-conductive textiles, which are treated with PEDOT:PSS and their composites, and also an overview of treatment methods.

– *Carbon-based conductive materials*
Traditional conductive fabrics like metallic filaments and conducting polymers have several drawbacks. Different research groups have combined carbon-based conductive materials with textile materials, as it will be described below.
Due to its high electrical conductivity, enhanced mechanical qualities, environmental stability and

potential for low-cost manufacture, the most widely used carbon-based material for electro-conductive textiles is graphene. Graphene was used in [101], where the authors investigated graphene-coated cotton fabrics to obtain low-cost and high conductive cotton-based homogenous nano sheets for further use in smart textile applications. Furthermore, cotton-based fabrics were analysed in [102], where they were treated with graphene oxide (GO) and reduced graphene oxide (rGO) to produce antibacterial electro-conductive textiles. This resulted in Ag^0/rGO-coated samples not developing bacterial growth.

Recently, there has been a surge of interest in producing conductive smart textiles by incorporating active conductive nanoparticles into textiles. Due to their high electrical and thermal conductivity, particular emphasis has been placed on carbon-based nanomaterials, i.e. carbon nanotubes (CNTs). These are found in a variety of diverse and critical applications, including nano-electronic devices, nano-scale structural materials, actuators and sensors, functional fabric and e-textiles etc., which is due to their exceptional properties, i.e. mechanical, thermal and electrical behaviours. In the textile industry, CNTs are used in the production of conductive fibres and yarns with different techniques [30], e.g. electro-spun fibre [103, 104], electrophoretic spun fibre [105], recondensed fibre [106], solution spun fibre [107], melt spun fibre [108].

Another common conductive material is also carbon black, which is a low-cost material easy to fabricate [109]. Gültekin et al. [110] investigated the electrical and thermal properties of carbon black coated cotton fabric by achieving conductivity increase. Besides, carbon black and PPy were used together to coat cotton fabrics by Chaves et al. [58], where they investigated mechanical and electrical properties focusing on the production of durable samples for use in real world applications.

An outstanding review of fabrication procedures of common carbon-based electronic materials and relevant applications was presented in [109]. Moreover, carbon-based nanomaterials applied in e-textiles were reviewed in [59, 79, 111, 112].

– *Conductive inks printed on textile surface*

Printing using conductive inks is another method, which has found usage in a variety of applications in the electronics area – not only at the beginning of smart/intelligent textiles, but this technique was also used to produce conductive fabrics. There are different textile printing methods that can be used, e.g. rotogravure, offset lithography, flexography, screen and inkjet printing technologies [18, 73]. Printing electrical traces directly on a fabric is a versatile method that occasionally displays its shortcomings, e.g. the thickness of the silver paste during the printing is one of its limits. Most of the applications, especially on textiles, are limited to screen and inkjet printing as they are very good for low volume and high-precision work. Although inkjet printing offers greater design versatility and production flexibility, screen printing is more economic and covers a huge range of products.

3 Resistance measurement methods

The electrical resistance of materials is related to other electrical properties like voltage and current, while the surface resistivity is the resistance to current leakage along the surface of an insulating material. The most common method to measure the resistance is the two probe method as shown in Figure 3a, where the voltage drop between two electrodes is measured as an effect of the applied known current. However, this method has drawbacks due to neglecting the contact resistance of electrodes. Consequently, four probe techniques come into play. There are two types of these techniques, i.e. linear placement and peripheral placement. Wenner [113] found and resolved the issue of neglecting contact resistance by proposing an inline four probe geometry technique to decrease the electrode contact resistance, as it can be seen in Figure 3b. The method using four probes circumferentially along the sample was proposed by Van Der Pauw [114]. Initially, this method was devoted to any arbitrary shape surface resistance measurement, while later, this method was adopted by many authors in order to measure electrical resistance of conductive textiles, as given in Figure 3c. An improvement of the measurement accuracy can be achieved by applying a correction factor to asymmetrical samples.

The problem of measuring electrical resistance of textiles began with issues caused mostly by the static electricity, this leading to many problems, even when the processed fibres were natural, e.g. cotton, wool, silk and flax, which are hydrophilic and have moderate conductivity. With the advent of poorly conducting hydrophobic synthetic fibres, e.g. nylon,

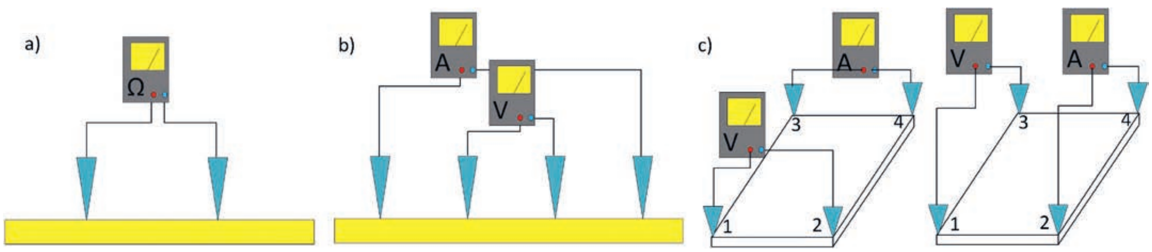

Figure 3: Surface resistance measurement methods: a) two probes, b) linear four probes, c) Van Der Pauw

Dynel and Dacron, the effects of static electricity changed from a minor to a major problem, as described by Hersh and Montgomery [15]. They used a novel apparatus to study the electrical resistance of a textile fibre and fibre assemblies to investigate the effects of static electricity in fibrous materials. Electrostatic properties of natural fibres were investigated under various environmental conditions, discovering that the electrical properties of those fibres are highly dependent on the moisture content of the material.

Volume resistivity is the resistance to the flowing current through the body of an insulating material, and in the case of textile materials with a very rich structure and highly developed surface, measurements of volume and surface resistances (measured in a two-electrode system) should correlate with each other. The basis for such a correlation may be the assumption that a conduction current (volume or surface), measured in a two-electrode system, flows through the bulk material [115]. Another novel method for evaluating the electrical properties of textile assemblies was proposed by Berberi [17], where the proposed idea was a novel multi-step method for assessing electrical resistance. He has developed a novel probe for measuring resistance that makes use of the material's volume fraction properties. Also, this novel probe was used to measure the electrical properties of electro-conductive leather and by applying this multi-step method, it was concluded that the electrical properties of conductive leather were not influenced by the sample form [63]. The measurement of surface and volume resistance of textile materials was discussed by Kacprzyk et al. [37], who compared various electrode placement systems in order to measure the resistance.

The methods mentioned above focused on the electrical properties of textile fibres; however, most of the existing researches measure surface resistance due to their application purposes. Furthermore, the conductivity of threads was studied by Dhawan et al. [22] and they developed efficient conductive threads by interconnecting them orthogonally. The aim of their research was to reduce the DC resistance associated with interconnections, which was achieved by trying different materials and a specific bonding/welding procedure. The interconnecting resistance was measured using a DC multimeter. They found that the welding procedure was the most effective in producing efficient and uniform interconnections.

On the other hand, determining the electrical resistance of textile samples with various forms and raw material compositions was challenging for Asanovic et al. [27], who developed a measuring device based on direct current measurement through textile samples. Dielectric loss tangents and relative dielectric permeability for textile samples were measured by using specially capacitance cells. Their study results showed that the resistance of textile materials was strongly dependent on their absorbed moisture.

On the other hand, the ageing of conductive fibres coated with electrically conducting doped polypyrrole (PPy) plays an important role in electrical and thermal characteristics, which was investigated by Varesano et al. [24], who used simulated ageing tests. They evaluated performance decay during the processing stages and final product used, and their findings indicated that the fabrics made of PPy coated wool fibres had acceptable conductivity decay.

Similarly, hybrid yarns were in focus of various publications, e.g. Šafářová et al. [115] tried to develop models that describe the dependence of electrical resistivity R on wire length L. They concluded that this behaviour was highly nonlinear and in contradiction with metals.

As already mentioned, the most commonly used resistance measurement methods are the two and four probe. Lipol et al. [52] investigated two and four

terminal methods for the novel conducting threads, concluding that the two terminal method was more informative than the four terminal method, and that the latter had no advantage over the former.
Another method for measuring sheet resistance is the so-called Van Der Pauw method, which was used in the case of electro-conductive textiles by various researchers [34, 39, 47, 64, 116, 117]. Tokarska et al. [39] investigated the contact diameter of electrodes and their arrangement on sample edges, while their main focus was the proper placement of electrodes. This research was extended and exploited more by this group [42], as they conducted a multivariant research on electrical properties of woven fabrics.
Furthermore, the Van Der Pauw method was used to investigate the electrical properties of conductive woven fabrics, analysing the effect of electrode placement on resistance measurements, concluding that surface resistance was a function of electrode placement. During the investigation of surface resistance by applying the Van Der Pauw method, authors also investigated homogeneity and anisotropy. Anisotropy was also studied by Azoulay et al. [16], who focused on the electrical properties of textile fabrics and measured the surface resistivity in various directions, revealing an anisotropy effect attributed to the sample weave pattern. The anisotropy structure of screen printed textiles was studied by Kazani et al. [34], who measured the electrical surface resistance of screen printed textiles by using the Van Der Pauw's method, which showed the anisotropic behaviour of electro-conductive textiles.
Apart from the conductive textile materials mentioned above, Shabani et al. [64] recently focused on electro-conductive leather, where the Van Der Pauw method was used to measure the electro-conductive properties. It was concluded that a different electrode placement along the sample circumference revealed the anisotropic structure of samples.
The anisotropy behaviour of conductive textiles together with other properties, e.g. electrical or thermal, was studied by various groups [29, 37, 40, 51, 63, 104, 109, 118].

4 Electro-thermal proprieties

Conductive textiles are widely used to provide comfort to humans, from heating to life monitoring functions. Thus, investigating the electro-thermal properties of conductive textiles plays an important role in their applicability. Many research groups that have investigated conductive textiles have found a strong relation of thermal conductivity with electrical conductivity. Similarly, Wang et al. [26] evidenced that increasing electrical conductivity by coating a wool fabric with PPy led to an increase in thermal conductivity. The correlation between the heat conductivity and electrical conductivity of PPy-coated wool textiles was investigated, demonstrating that when these materials were coated with conductive PPy to create electro-conductive textiles, their thermal conductivity improved. Meanwhile, the heat dissipation caused by an electric current flow at certain voltages was studied by Penava et al. [82], observing how heat influences the changes in the electrical resistance of electro-conductive yarns. It was concluded that the temperature change in conductive yarns resulted due to the contribution of an external source or due to the passing electric current in a linear change in the resistance of conductive yarns. Moreover, the temperature distribution and heat generation for stretchable conductive textiles used for medical purposes was investigated in [83]. The research revealed that the required temperature of 40 °C was achieved within 2–3 minutes, but the increase of sample surface had a negative impact on heat generation.
The thermal properties of knitted structures, their manufacturing methods and the effect of contact pressure at structural binding points on the degree of heating were analysed by Hamdani et al. [41]. They were interested in analysing generated heat as a function of distance between the supply terminals and yarn decay properties due to the heating. By taking thermographic images, they discovered that knitted fabrics, with silver and elastomeric yarn, can generate enough heat to warm the body. Moreover, the thermography was used to analyse the woven conductive textiles for the non-homogeneity and anisotropy, using the modelling and infrared thermography to analyse the contact resistance [29].
Furthermore, the temperature distribution was investigated by Felczak et al. [51] for a double-layered fleece textile by studying the thermographic measurements. They developed a theoretical model and compared it to experimental data.
Designing technically comfortable electro-thermal textiles has been a challenging task due to the lack of adequate measurement devices and methods.

Consequently, Rogale et al. [77] developed a new measuring device and method for simultaneous measurements to determine the thermal resistance in one or more textile material layers, e.g. multilayer composite clothing, where the temperature gradients of textile material layers, as well as the theoretical principles of operation and practical results were presented. The analysis of electrical properties sensing behaviour and the mechanical analysis of polymer fibres coated with an intrinsically conductive polymer, and their electromechanical behaviour under tensile load was performed experimentally by Meoli et al. [18]. The investigated electromechanical behaviour of these conductive fibres showed a correlation of various mechanical and environmental factors with electrical resistance.

The heat transfer properties of anisotropic conductive textiles analysed by Yen et al. [40], revealed that by employing non-electric high effective thermal conductive yarns perpendicularly to the electro-conductive yarns increases temperature distribution uniformity. In order to analyse the heating fabric, a numerical program based on a spectral element method was used. The investigation of textiles does not focus only on electro-thermal properties. Reiners et al. [119] also considered cutting resistance. Meanwhile, for the textiles such as tarpaulin fabrics used to protect against vandalism, it was determined based on the analysis that in addition to cutting resistance, the tearing strength and the seam slippage should be tested.

Prior to experimentally analysing the thermal distribution of conductive textiles, the temperature distribution in textile materials was modelled as an effect of single laser pulse treatment using simulation software. The surface heat sources were modelled for different shapes in Comsol Multiphysics to verify experimental results [120]. Similarly, the modelling was used by Banaszczyk et al. [4] to analyse current distribution in conductive textiles. They used a large electrical resistor network to investigate contact resistance, surface resistance and also homogeneity of the structure. The research results showed that this method was able to measure current distribution using modelled prototype, as it was difficult for direct measurements. A similar methodology was used, again by Banaszczyk et al. [29], where the modelling method was compared with the four probe method to measure the contact resistance of conductive textiles. The results gained from both methods were complementary to each other. Moreover, Wai et al. [32] developed a resistive network to analyse the electrical resistance of knitting stitches, concluding in simulated results being comparable with experimental results. The modelling methods mentioned above were based on software or electrical modelling, while Bahadir et al. [54] applied Artificial Neural Networks to derive surface temperature distribution of conductive textiles. Based on this research, not only that the temperature distribution can be analysed, but also the sample temperature distribution can be predicted. Conductive fibres can cause problems due to the electrostatic charge. To analyse these behaviours, theoretical modelling was applied by Tappura et al. [19], showing that the induced charge was a strong correlation of base material conductivity and dielectric properties.

Passive electro-conductive textiles were investigated in [85], where an overview of most commonly used methods and materials used to improve the thermal conductivity of samples was presented.

5 Smart applications of electro-conductive textiles

Smart textiles, known as electronic textiles (e-textiles), incorporate electronic components in order to perform different functions. Thereby, using electrical, thermal, mechanical, chemical, magnetic, and other inputs and outputs, they can perform the following functions:

- *Passive smart textiles:* they can sense sensor outputs from user or environment.
- *Active smart textiles:* they can integrate a sensing device to control actuator behaviour.
- *Very smart textiles:* they can react and adapt behaviour to given circumstances.

In this section, we are going to highlight smart textile applications of electro-conductive textiles, which are used to produce resistive sensors, where different etching techniques revealed the possibility of obtaining customised wearable sensors [48]. The fabrication of resistive sensors was analysed by Capineri et al. [46], who applied conductive textiles to obtain pressure and temperature sensors for use in measuring human interaction parameters, e.g. step measurements. Moreover, conductive wires were used by Uzun et al. [88] to produce smart textiles for the purpose of protection, and also to be able to install various sensors for measuring life body parameters. In this way, by using different yarn production techniques, they analysed the effectiveness of smart textiles. The production of smart sensors, using textiles and screen printed technology, was studied by Khan et al. [121]. The used technology revealed the possibility of using screen printing to produce pressure sensors. A further investigation is to follow to improve this idea. Moreover, obtaining capacitive sensors from PET conductive fibres through printing on them was the focus of Vásquez Quintero et al. [49]. These sensors were integrated into industrial textiles, mainly used in the automotive industry. Moreover, Lee et al. [122] integrated a fibre-based pressure sensor into textiles to monitor human body parameters.

Recently, conductive textiles were integrated with temperature measurement technology, more specifically by using thermocouples, where Hardianto et al. [66] integrated the thermocouples for measuring body temperature and this temperature was then used to generate low power electricity used for portable electronic devices. The idea of energy harvesting by integrating thermocouples into wearable textiles was elaborated by Lund et al. [69]. Furthermore, Root et al. [123] analysed related work in order to observe human comfort when sensory technology and textiles are integrated together. It was observed that combining the conductivity of metal coatings with flexibility, low weight and stretch of a fabric may lead to significant advancements in miniaturised textile thermocouple fabrication.

Based on the literature review, it was established that until now, the used smart textile sensors were fabricated from incorporated metal-based technologies, whereas Afroj et al. [70]current reduced graphene oxide (rGO applied graphene-based textiles. They developed washable electronic textiles intended for ultraflexible supercapacitors.

Furthermore, smart textiles have been fabricated not only from fabrics, but also from leather. Conductive leather for smart applications was investigated by Wegene et al. [45], where it was proposed to use conductive leather for gloves to operate on touch-screen technologies. Moreover, a screen printed technology on conductive textiles was used in [124] to produce a piezoresistive sensor from graphene nanoplates.

Conductive textiles based on PEDOT:PSS that have been used in the development of sensors, actuators, energy harvesting and storage devices were reviewed in [71]. Similarly, conductive leather was investigated by Hylli et al. [72], revealing that after the treatments with mordants and polymerisation, the colourfastness of dyed leather increased and also, the ability to maintain their conductive properties remained. The authors were able to obtain coloured electro-conductive samples.

A wide variety of applications of smart textiles encouraged many researchers to devote the focus of their work on the areas of textile sensors. Krifa et al. [73] reviewed the application of smart fabrics in wearable technology with the focus on sensors and antennas. Another review, a review of applications of smart sensors for psychological monitoring, was described by Angelucci et al. [74]. The combination of electronics with textiles, and the possible techniques and their solutions was reviewed by Stoppa et al. [44]. Cho et al. [125] reviewed wearable e-textiles used for sensing, their methods being construction, used materials and applications. Furthermore, the application of textile-based sensors was conducted in [126], where they had in focus the recent developments in the field of electrochemical sensors and biosensors. A historical overview of how electronic textiles have evolved, their areas of applications, especially sensors and wearable textiles, was elaborated in [60].

This paper discussed various strategies for making smart fabrics, a very interesting and promising area also being 3D printing approaches. Direct 3D printing of polymers into textile fibres with the purpose of developing wearable electronic textiles was studied in [127].

Mellin et al. [128] used the 3D printing technology to produce the metal-based nanosized metal powders for use in electro-conductive textiles.

6 Conclusion

The incorporation of conductive elements into textiles has produced the so-called electrically conductive textiles, which enable the production of interactive electronic textiles (smart textiles). As the wearable systems have become more feasible in the recent years due to the advancements in textile technologies, innovative materials, nanotechnology and miniaturised electronics, the most important factor for the user acceptance of wearable devices is the fit comfort. Moreover, we are convinced that certain requirements must be satisfied for their usage in these applications, including electrical characteristics, thermal characteristics, comfort, and durability to different environmental and mechanical influences. In this paper, we briefly described the most common processes and materials for obtaining conductive materials, beginning with conducting metals (most often silver, copper and stainless steel) integrated into textiles, continuing with carbon conductive nanotube utilised to generate conductive yarns, and techniques for processing textiles, e.g. chemical treatment with electrically conductive polymers employing in situ polymerisation. Based on the studies, polypyrrole was the most often employed, as well as the PEDOT:PSS applications. In addition to the use of nanoparticles, the printing of textiles employing ink was another form of textile processing.

All of these methods used to produce electro-conductive textiles served as the starting point in the development of smart wearable textiles, making the exploration of electrical characteristics the central focus of this article.

Moreover, the two probe, four probe and Van Der Pauw resistance measurement methods were explored, where the Van Der Pauw method was proven to be the most practical one, since it was dedicated to measuring the resistance of flat and arbitrary-shaped materials.

The primary purpose of electro-conductive fabrics is their use in wearable technology, where they must fulfil comfort standards necessary to provide the warmth for the body, or in a wide variety of other applications. Therefore, the thermal features, e.g. temperature distribution, were researched in order to bring many study results into the focus. Nonetheless, it should be highlighted that the usage of conductive materials is going to increase, as will their capacity to meet the comfort criteria.

To conclude, we believe that the development of smart textiles necessitates a multidisciplinary approach that fundamentally integrates the knowledge of circuit design, smart materials, microelectronics and chemistry with comprehensive understanding of textile manufacturing.

References

1. WWW.CEN.EU, CEN/TC 248/WG 31. Technical Report, Textiles and textile products-Smart textiles - Definitions, categorisation, applications and standardisation needs.
2. XUE, Pu. TAO, Xiaoming. LEUNG, Mei Yi. and ZHANG, Hui. Electromechanical properties of conductive fibres, yarns and fabrics, in *Wearable Electronics and Photonics. Elsevier*, 2005, p. 81–104.
3. SCHWARZ, Anne *et al.* Gold coated para-aramid yarns through electroless deposition, *Surface and Coatings Technology*, **204**(9–10), p. 1412–1418, 2010, doi: 10.1016/j.surfcoat.2009.09.038.
4. BANASZCZYK, Jedrzej. MEY, Gilbert De. and SCHWARZ, Anne. Current Distribution Modelling in Electroconductive Fabrics 1), *FIBRES & TEXTILES in Eastern Europe*, **17**(2), p. 28–33, 2009.
5. BAEKAERT. Conductive fibres and yarns for smart textiles - Bekaert.com, *Conductive fibres and yarns for smart textiles*, 2017. https://www.bekaert.com/en/products/basic-materials/textile/conductive-fibres-and-yarns-for-smart-textiles
6. TIBTECH. Heating or conductive metallic yarns and fabrics for energy transfer within flexible structures or composite parts. https://www.tibtech.com/.
7. SHIELDEX. Yarns/Threads, Shieldex Trading, Inc. https://www.shieldex.de/en/products_categories/fibres-yarns/.
8. JAMES HAYWARD. E-Textiles 2021-2031: Technologies, Markets, Players, 2021. https://www.idtechex.com/en/research-report/e-textiles-and-smart-clothing-2021-2031-technologies-markets-and-players/828.
9. PACELLI, Maria. LORIGA, Giannicola. TACCINI, Nicola. and PARADISO, Rita. Sensing fabrics for monitoring physiological and biomechanical variables: E-textile solutions, *Proceedings of the 3rd IEEE-EMBS International Summer School and Symposium on Medical Devices and Biosensors, ISSS-MDBS 2006*, p. 1–4, 2006, doi: 10.1109/ISSMDBS.2006.360082.
10. GUO, Li. PETERSON, Joel. QURESHI, Waqas. MEHRJERDI, Adib Kalantar. BERGLIN, Lena. and SKRIFVARS, Mikael. Knitted Wearable Stretch Sensor for Breathing Monitoring Application, in *Ambience*, 2011, (January).
11. FREIRE, Rachel. HONNET, Cedric. and STROHMEIER, Paul. Second skin: An exploration of etextile stretch circuits on the body, *TEI 2017 - Proceedings of the 11th International Conference on Tangible, Embedded, and*

Embodied Interaction, p. 653–658, 2017, doi: 10.1145/3024969.3025054.
12. FAN, Wenjing *et al.* Machine-knitted washable sensor array textile for precise epidermal physiological signal monitoring, *Science Advances*, **6**(11), p. 1–10, 2020, doi: 10.1126/sciadv.aay2840.
13. MEOLI, Dina. Interactive Electronic Textiles: Technologies, Applications, Opportunities, and Market Potential, 2002.
14. GASANA, Emmanuel *et al.* Electroconductive textile structures through electroless deposition of polypyrrole and copper at polyaramide surfaces, *Surface and Coatings Technology*, **201**(6), p. 3547–3551, 2006, doi: 10.1016/j.surfcoat.2006.08.128.
15. HERSH, S. P. and MONTGOMERY, D. J. Electrical Resistance Measurements on Fibres and Fibre Assemblies, *Textile Research Journal*, **22**(12), p. 805–818, 1952, doi: 10.1177/004051755202201207.
16. AZOULAY, J. Anisotropy in Electric Properties of Fabrics Containing New Conductive Fibres, *IEEE Transactions on Electrical Insulation*, **23**(3), p. 383–386, 1988, doi: 10.1109/14.2378.
17. BERBERI, Pellumb G. A New Method for Evaluating Electrical Resistivity of Textile Assemblies, *Textile Research Journal*, **68**(6), p. 407–412, 1998, doi: 10.1177/004051759806800604.
18. MEOLI, Dina and MAY-PLUMLEE, Traci. Interactive electronic textile development: A review of technologies, *Journal of Textile and Apparel, Technology and Management*, **2**(2), p. 1–12, 2002.
19. TAPPURA, K. and NURMI, S. Computational modeling of charge dissipation of fabrics containing conductive fibres, *Journal of Electrostatics*, **58**(1–2), p. 117–133, 2003, doi: 10.1016/S0304-3886(02)00202-4.
20. KAYNAK, Akif and BELTRAN, Rafael. Effect of synthesis parameters on the electrical conductivity of polypyrrole-coated poly(ethylene terephthalate) fabrics, *Polymer International*, **52**(6), p. 1021–1026, 2003, doi: 10.1002/pi.1195.
21. XUE, P. TAO, X. M. KWOK, Keith W.y. LEUNG, M. Y. and YU, T. X. Electromechanical Behavior of Fibres Coated with an Electrically Conductive Polymer, *Textile Research Journal*, **74**(10), p. 929–936, 2004, doi: 10.1177/004051750407401013.
22. DHAWAN, Anuj. SEYAM, Abdelfattah M. GHOSH, Tushar K. and MUTH, John F. Woven Fabric-Based Electrical Circuits: Part I: Evaluating Interconnect Methods, *Textile Research Journal*, **74**(10), p. 913–919, 2004, doi: 10.1177/004051750407401011.
23. WU, Jian. ZHOU, Dezhi. TOO, Chee. O. and WALLACE, Gordon G. Conducting polymer coated lycra, *Synthetic Metals*, **155**(3), p. 698–701, 2005, doi: 10.1016/j.synthmet.2005.08.032.
24. VARESANO, Alessio. DALL'ACQUA, Lorenzo. and TONIN, Claudio. A study on the electrical conductivity decay of polypyrrole coated wool textiles, *Polymer Degradation and Stability*, **89**(1), p. 125–132, 2005, doi: 10.1016/j.polymdegradstab.2005.01.008.
25. KIM, Bohwon. KONCAR, Vladn. and DUFOUR, Claude. Polyaniline-coated PET conductive yarns: Study of electrical, mechanical, and electro-mechanical properties, *Journal of Applied Polymer Science*, **101**(3), p. 1252–1256, 2006, doi: 10.1002/app.22799.
26. WANG, Jiajun. KAYNAK, Akif. WANG, Lijing. and LIU, Xin. Thermal conductivity studies on wool fabrics with conductive coatings, *Journal of the Textile Institute*, **97**(3), p. 265–270, 2006, doi: 10.1533/joti.2005.0298.
27. ASANOVIC, Koviljka A. MIHAJLIDI, Tatjana A. MILOSAVLJEVIC, Svetlana V. CEROVIC, Dragana D. and DOJCILOVIC, Jablan R. Investigation of the electrical behavior of some textile materials, *Journal of Electrostatics*, **65**(3), p. 162–167, 2007, doi: 10.1016/j.elstat.2006.07.008.
28. LOCHER, Ivo and TRÖSTER, Gerhard. Enabling Technologies for Electrical Circuits on a Woven Monofilament Hybrid Fabric, *Textile Research Journal*, **78**(7), p. 583–594, 2008, doi: 10.1177/0040517507081314.
29. BANASZCZYK, Jedrzej. ANCA, Anamaria. and DE MEY, Gilbert. Infrared thermography of electroconductive woven textiles, *Quantitative InfraRed Thermography Journal*, **6**(2), p. 163–173, 2009, doi: 10.3166/qirt.6.163-173.
30. LATIFI, Masoud. PAYVANDY, Pedram. and YOUSEFZADEH-CHIMEH, Maryam. Electro-conductive textile yarns, *Technical Textile Yarns*, p. 298–326, 2010, doi: 10.1533/9781845699475.2.298.
31. GU, Jian Feng. GORGUTSA, Stephan. and SKOROBOGATIY, Maksim. Soft capacitor fibres using conductive polymers for electronic textiles, *Smart Materials and Structures*, **19**(11), 2010, doi: 10.1088/0964-1726/19/11/115006.
32. LI, Li. WAI MAN AU. WAN, Kam Man. SAI HO WAN. CHUNG, Wai Yee. and WONG,

Kwok Shing. A Resistive Network Model for Conductive Knitting Stitches, *Textile Research Journal*, **80**(10), p. 935–947, 2010, doi: 10.1177/0040517509349789.
33. DING, Yujie. INVERNALE, Michael A. and SOTZING, Gregory A. Conductivity trends of pedot-pss impregnated fabric and the effect of conductivity on electrochromic textile, *ACS Applied Materials and Interfaces*, **2**(6), p. 1588–1593, 2010, doi: 10.1021/am100036n.
34. KAZANI, Ilda *et al*. Van Der Pauw method for measuring resistivities of anisotropic layers printed on textile substrates, *Textile Research Journal*, **81**(20), p. 2117–2124, 2011, doi: 10.1177/0040517511416280.
35. YOON, Boram and LEE, Seungsin. Designing waterproof breathable materials based on electrospun nanofibres and assessing the performance characteristics, *Fibres and Polymers*, **12**(1), p. 57–64, 2011, doi: 10.1007/s12221-011-0057-9.
36. PETERSEN, Pam. HELMER, Richard. PATE, Margaret. and EICHHOFF, Julian. Electronic textile resistor design and fabric resistivity characterization, *Textile Research Journal*, **81**(13), p. 1395–1404, 2011, doi: 10.1177/0040517511404591.
37. KACPRZYK, Ryszard. Measurements of the volume and surface resistance of textile materials, *Fibres and Textiles in Eastern Europe*, **84**(1), p. 47–49, 2011.
38. PATEL, Pinal C. VASAVADA, Divyam. and MANKODI, Hireni R. Applications of electrically conductive yarns in technical textiles, *2012 IEEE International Conference on Power System Technology, POWERCON 2012*, 2012, doi: 10.1109/PowerCon.2012.6401374.
39. TOKARSKA, Magdalena. Measuring resistance of textile materials based on Van der Pauw method, *Indian Journal of Fibre and Textile Research*, **38**(2), p. 198–201, 2013.
40. YEN, Ruey Hor. CHEN, Chien Yu. HUANG, Ching Tang. and CHEN, Pei Jing. Numerical study of anisotropic thermal conductivity fabrics with heating elements, *International Journal of Numerical Methods for Heat and Fluid Flow*, **23**(5), p. 750–771, 2013, doi: 10.1108/HFF-03-2011-0050.
41. HAMDANI, Syed Talha Ali. POTLURI, Prasad. and FERNANDO, Anura. Thermo-mechanical behavior of textile heating fabric based on silver coated polymeric yarn, *Materials*, **6**(3), p. 1072–1089, 2013, doi: 10.3390/ma6031072.
42. TOKARSKA, Magdalena. FRYDRYSIAK, Michał. and ZIĘBA, Janusz. Electrical properties of flat textile material as inhomegeneous and anisotropic structure, *Journal of Materials Science: Materials in Electronics*, **24**(12), p. 5061–5068, 2013, doi: 10.1007/s10854-013-1524-4.
43. ODHIAMBO, Sheilla. HERTLEER, Carla. LANGENHOVE, Lieva Van. MEY, Gilbert De. DEFERME, Wim. and STRYCKERS, Jeroen. Comparison of Commercial Brands of PEDOT : PSS in E lectric " Capattery " Integrated in Textile Structure, in *Mixed Design of Integrated Circuits and Systems, MIXDES*, 2013, p. 389–392.
44. STOPPA, Matteo and CHIOLERIO, Alessandro. Wearable electronics and smart textiles: A critical review, *Sensors (Switzerland)*, **14**(7), p. 11957–11992, 2014, doi: 10.3390/s140711957.
45. WEGENE, Jima Demisie and THANIKAIVELAN, Palanisamy. Conducting leathers for smart product applications, *Industrial and Engineering Chemistry Research*, **53**(47), p. 18209–18215, 2014, doi: 10.1021/ie503956p.
46. CAPINERI, Lorenzo. Resistive sensors with smart textiles for wearable technology: From fabrication processes to integration with electronics, *Procedia Engineering*, **87**, p. 724–727, 2014, doi: 10.1016/j.proeng.2014.11.748.
47. TOKARSKA, Magdalena. Determination of fabric surface resistance by van der pauw method in case of contacts distant from the sample edge, *Autex Research Journal*, **14**(2), p. 55–60, 2014, doi: 10.2478/v10304-012-0050-4.
48. USMA, Clara. KOUZANI, Abbas. CHUA, Julian. AROGBONLO, Adetokunbo. ADAMS, Scott. and GIBSON, Ian. Fabrication of Force Sensor Circuits on Wearable Conductive Textiles, *Procedia Technology*, **20**(July), p. 263–269, 2015, doi: 10.1016/j.protcy.2015.07.042.
49. VÁSQUEZ QUINTERO, Andrés *et al.* Capacitive strain sensors inkjet-printed on PET fibres for integration in industrial textile, *Procedia Engineering*, **120**, p. 279–282, 2015, doi: 10.1016/j.proeng.2015.08.613.
50. AROGBONLO, Adetokunbo. USMA, Clara. KOUZANI, Abbas. and GIBSON, Ian. Design and Fabrication of a Capacitance Based Wearable Pressure Sensor Using E-textiles, *Procedia Technology*, **20**(July), p. 270–275, 2015, doi: 10.1016/j.protcy.2015.07.043.
51. FELCZAK, Mariusz. DE MEY, Gilbert. WIĘCEK, Bogusław. and MICHALAK, Marina.

Lateral and perpendicular thermal conductivity measurement on textile double layers, *Fibres and Textiles in Eastern Europe*, **23**(4), p. 61–65, 2015, doi: 10.5604/12303666.1152728.

52. LIPOL, Lefayet Sultan. ISLAM, Mayedul. and SULTANA, Nazrima. The Resistance Measurement Method of the Conducting Textiles, *European Scientific Journal, ESJ*, **12**(27), p. 242, 2016, doi: 10.19044/esj.2016.v12n27p242.
53. KARIM, Nazmul *et al.* Scalable Production of Graphene-Based Wearable E-Textiles, *ACS Nano*, **11**(12), p. 12266–12275, 2017, doi: 10.1021/acsnano.7b05921.
54. BAHADIR, Senem Kursun. SAHIN, Umut Kivanc. and KIRAZ, Alper. Modeling of surface temperature distributions on powered e-textile structures using an artificial neural network, *Textile Research Journal*, (65), 2017, doi: 10.1177/0040517517743689.
55. RYAN, Jason D. MENGISTIE, Desalegn Alemu. GABRIELSSON, Roger. LUND, Anja. and MÜLLER, Christian. Machine-Washable PEDOT:PSS Dyed Silk Yarns for Electronic Textiles, *ACS Applied Materials and Interfaces*, **9**(10), p. 9045–9050, 2017, doi: 10.1021/acsami.7b00530.
56. ALHASHMI ALAMER, Fahad. A simple method for fabricating highly electrically conductive cotton fabric without metals or nanoparticles, using PEDOT:PSS, *Journal of Alloys and Compounds*, **702**, p. 266–273, 2017, doi: 10.1016/j.jallcom.2017.01.001.
57. NURAMDHANI, Ida. GOKCEOREN, Argun Talat. ODHIAMBO, Sheilla Atieno. DE MEY, Gilbert D. HERTLEER, Carla. and LANGENHOVE, Lieva Van. Electrochemical impedance analysis of a PEDOT: PSS-based textile energy storage device, *Materials*, **11**(1), p. 1–11, 2017, doi: 10.3390/ma11010048.
58. VILLANUEVA, Rolando. GANTA, Deepak. and GUZMAN, Carlos. Mechanical, in-situ electrical and thermal properties of wearable conductive textile yarn coated with polypyrrole/carbon black composite, *Materials Research Express*, **6**(1), 2018.
59. LUND, Anja. VAN DER VELDEN, Natascha M. PERSSON, Nils Krister. HAMEDI, Mahiar M. and MÜLLER, Christian. Electrically conducting fibres for e-textiles: An open playground for conjugated polymers and carbon nanomaterials, *Materials Science and Engineering R: Reports*, **126**(January), p. 1–29, 2018, doi: 10.1016/j.mser.2018.03.001.
60. HUGHES-RILEY, Theodore. DIAS, Tilak. and CORK, Colin. A historical review of the development of electronic textiles, *Fibres*, **6**(2), 2018, doi: 10.3390/fib6020034.
61. CHATTERJEE, Kony. TABOR, Jordan. and GHOSH, Tushar K. Electrically conductive coatings for fibre-based E-Textiles, *Fibres*, **7**(6), p. 1–45, 2019, doi: 10.3390/fib7060051.
62. MOHAMED, Aliaa Abdel Aziz. ABDEL-HAMED, Hebatullah A.A. EL-OKDA, Enas A.H. EZZAT, Mohamed M. MEGEID, Zaynab M.Abdel. and SAEED, Ahmed. Suitability of conductive knit fabric for sensing human breathing, *Journal of Textile and Apparel, Technology and Management*, **11**(1), p. 1–7, 2019, doi: 10.21608/jsrs.2016.15319.
63. SHABANI, Aulon. HYLLI, Majlinda. KAZANI, Ilda. and BERBERI, Pellumb. Resistivity behavior of leather after electro-conductive treatment, *Textile & leather review*, **2**(1), 2019, doi: 10.31881/tlr.2019.15.
64. SHABANI, Aulon. HYLLI, Majlinda. KAZANI, Ilda. BERBERI, Pellumb. ZAVALANI, Orion. and GUXHO, Genti. The anisotropic structure of electro conductive leather studied by Van der Pauw method, *Textile & leather review*, **2**(3), 2019, doi: 10.31881/tlr.2019.16.
65. AKBARPOUR, Hamed. RASHIDI, Alimorad. MIRJALILI, Mostafa. and NAZARI, Ali. Comparison of the conductive properties of polyester/viscose fabric treated with Cu nanoparticle and MWCNTs, *Journal of Nanostructure in Chemistry*, **9**(4), p. 335–348, 2019, doi: 10.1007/s40097-019-00322-z.
66. HARDIANTO, Hardianto. MALENGIER, Benny. DE MEY, Gilbert. VAN LANGENHOVE, Lieva. and HERTLEER, Carla. Textile yarn thermocouples for use in fabrics, *Journal of Engineered Fibres and Fabrics*, **14**, 2019, doi: 10.1177/1558925019836092.
67. KAMYSHNY, Alexander and MAGDASSI, Shlomo. Conductive nanomaterials for 2D and 3D printed flexible electronics, *Chemical Society Reviews*, **48**(6), p. 1712–1740, 2019, doi: 10.1039/c8cs00738a.
68. NURAMDHANI, Ida *et al.* Charge-discharge characteristics of textile energy storage devices having different PEDOT:PSS ratios and

conductive yarns configuration, *Polymers*, **11**(2), 2019, doi: 10.3390/polym11020345.

69. LUND, Anja. TIAN, Yuan. DARABI, Sozan. and MÜLLER, Christian. A polymer-based textile thermoelectric generator for wearable energy harvesting, *Journal of Power Sources*, **480**, p. 228836, 2020, doi: 10.1016/j.jpowsour.2020.228836.
70. AFROJ, Shaila. TAN, Sirui. ABDELKADER, Amr M. NOVOSELOV, Kostya S. and KARIM, Nazmul. Highly Conductive, Scalable, and Machine Washable Graphene-Based E-Textiles for Multifunctional Wearable Electronic Applications, *Advanced Functional Materials*, **30**(23), 2020, doi: 10.1002/adfm.202000293.
71. TSEGHAI, Granch Berhe. MENGISTIE, Desalegn Alemu. MALENGIER, Benny. FANTE, Kinde Anlay. and VAN LANGENHOVE, Lieva. PEDOT:PSS-based conductive textiles and their applications, *Sensors (Switzerland)*, **20**(7), p. 1–18, 2020, doi: 10.3390/s20071881.
72. HYLLI, Majlinda. SHABANI, Aulon. KAZANI, Ilda. DRUSHKU, Spiro. and GUXHO, Genti. The color fastness properties of conductive leather improved by the use of mordants, *IOP Conference Series: Materials Science and Engineering*, **827**(1), 2020, doi: 10.1088/1757-899X/827/1/012036.
73. KRIFA, Mourad. Electrically Conductive Textile Materials—Application in Flexible Sensors and Antennas, *Textiles*, **1**(2), p. 239–257, 2021, doi: 10.3390/textiles1020012.
74. ANGELUCCI, Alessandra *et al.* Smart textiles and sensorized garments for physiological monitoring: A review of available solutions and techniques, *Sensors (Switzerland)*, **21**(3), p. 1–23, 2021, doi: 10.3390/s21030814.
75. JIN, In Su. LEE, Jea Uk. and JUNG, Jae Woong. A facile solution engineering of PEDOT: PSS-Coated conductive textiles for wearable heater applications, *Polymers*, **13**(6), p. 0–9, 2021, doi: 10.3390/polym13060945.
76. SHAKERI SIAVASHANI, Vahid. NEVIN, Gursoy. MONTAZER, Majid. and ALTAY, Pelin. Highly stretchable conductive fabric using knitted cotton/lycra treated with polypyrrole/silver NPs composites post-treated with PEDOT:PSS, *Journal of Industrial Textiles*, **51**, p. 4571–4588, 2021, doi: 10.1177/15280837211059212.
77. ROGALE, Snježana Firšt. ROGALE, Dubravko. and KNEZI, Željko. Measurement Method for the Simultaneous DeterMination of Thermal Resistance and Temperature Gradients in the DeterMination of Thermal Properties of Textile Material Layers, *Materials*, 2021.
78. KAYNAK, Akif. ZOLFAGHARIAN, Ali. FEATHERBY, Toby. BODAGHI, Mahdi. PARVEZ MAHMUD, M. A. and KOUZANI, Abbas Z. Electrothermal modeling and analysis of polypyrrole-coated wearable e-textiles, *Materials*, **14**(3), p. 1–16, 2021, doi: 10.3390/ma14030550.
79. ADAK, Bapan. Utilization of Nanomaterials in Conductive Smart- Textiles: A Review, *Journal of Textile Science & Fashion Technology*, **8**(1), p. 14–16, 2021, doi: 10.33552/jtsft.2021.08.000678.
80. WANG, Peng. WANG, Yong. XU, Qingbo. CHEN, Qian. ZHANG, Yan Yan. and XU, Zhenzhen. Fabrication of durable and conductive cotton fabric using silver nanoparticles and PEDOT:PSS through mist polymerization, *Applied Surface Science*, **592**(February), p. 153314, 2022, doi: 10.1016/j.apsusc.2022.153314.
81. LUO, Yuzi and CHO, Gilsoo. Fabrication of Electroconductive Textiles Based Polyamide/Polyurethan Knitted Fabric Coated with PEDOT:PSS/Non-oxidized Graphene, *Journal of the Korean Society of Clothing Industry*, **24**(1), p. 146–155, 2022.
82. PENAVA, Željko. PENAVA, Diana Šimić. and KNEZIĆ, Željko. Heat as a Conductivity Factor of Electrically Conductive Yarns Woven into Fabric, *Materials*, **15**(3), 2022, doi: 10.3390/ma15031202.
83. REPON, Md Reazuddin. LAURECKIENE, Ginta. and MIKUCIONIENE, Daiva. Effect of Stretching on Thermal Behaviour of Electro-Conductive Weft-Knitted Composite Fabrics, *Polymers*, **14**(2), 2022, doi: 10.3390/polym14020249.
84. ALAMER, Fahad Alhashmi and BEYARI, Rawan F. Overview of the Influence of Silver, Gold, and Titanium Nanoparticles on the Physical Properties of PEDOT:PSS-Coated Cotton Fabrics, *Nanomaterials*, **12**(9), 2022, doi: 10.3390/nano12091609.
85. KALAOGLU-ALTAN, Ozlem Ipek. KAYAOGLU, Burcak Karaguzel. and TRABZON, Levent. Improving thermal conductivities of textile materials by nanohybrid approaches, *iScience*, **25**(3), p. 103825, 2022, doi: 10.1016/j.isci.2022.103825.
86. TOKARSKA, Magdalena. A Mixing Model for Describing Electrical Conductivity of a Woven Structure, *Materials*, **15**(7), p. 2512, 2022.

87. ABOU TALEB, Marwa. MOWAFI, Salwa. EL-SAYED, Hosam. and EL-NEWASHY, Rania. Facile development of electrically conductive comfortable fabrics using metal ions, *Journal of Industrial Textiles*, **51**(7), p. 1100–1120, 2022, doi: 10.1177/1528083719893713.
88. UZUN, Muhammet. SANCAK, Erhan. and USTA, Ismail. The use of conductive wires for smart and protective textiles, *2015 E-Health and Bioengineering Conference, EHB 2015*, (November 2015), 2016, doi: 10.1109/EHB.2015.7391494.
89. AVLONI, Jamshid. LAU, Rosa. OUYANG, Meng. FLORIO, Luca. HENN, Arthur R. and SPARAVIGNA, Amelia. Polypyrrole coated Nonwovens for Electromagnetic Shielding, *Journal of Industrial Textiles*, **38**(1), p. 55–68, 2008.
90. FERRERO, Franco. NAPOLI, Liuba. TONIN, Claudio. and VARESANO, Alessio. Pyrrole chemical polymerization on textiles: Kinetics and operating conditions, *Journal of Applied Polymer Science*, **102**(5), p. 4121–4126, 2006, doi: 10.1002/app.24149.
91. BHAT, Narendra V. SESHADRI, Devender T. NATE, Mandar M. and GORE, Ajit V. Development of conductive cotton fabrics for heating devices, *Journal of Applied Polymer Science*, **102**(5), p. 4690–4695, 2006, doi: 10.1002/app.24708.
92. KAYNAK, Akif. WANG, Lijing. HURREN, Chris. and WANG, Xungai. Characterization of conductive polypyrrole coated wool yarns, *Fibres and Polymers*, **3**(1), p. 24–30, 2002, doi: 10.1007/BF02875365.
93. SEUNG LEE, Han and HONG, Juan. Chemical synthesis and characterization of polypyrrole coated on porous membranes and its electrochemical stability, *Synthetic Metals*, **113**(1), p. 115–119, 2000, doi: 10.1016/S0379-6779(00)00193-4.
94. KINCAL, Dilek. KUMAR, Anil. CHILD, Andrew D. and REYNOLDS, John R. Conductivity switching in polypyrrole-coated textile fabrics as gas sensors, *Synthetic Metals*, **92**(1), p. 53–56, 1998, doi: 10.1016/s0379-6779(98)80022-2.
95. LEKPITTAYA, Porntip. YANUMET, Nantaya. GRADY, Brian P. and REAR, Edgar A O. Resistivity of Conductive Polymer – Coated Fabric, *Applied Polymer*, **92**(4), p. 2629–2636, 2003.
96. KIM, Bohwon. KONCAR, Vladan. DEVAUX, Eric. DUFOUR, Claude. and VIALLIER, Pierre. Electrical and morphological properties of PP and PET conductive polymer fibres, *Synthetic Metals*, **146**(2), p. 167–174, 2004, doi: 10.1016/j.synthmet.2004.06.023.
97. OH, Kyung Wha. KIM, Seong Hun. and KIM, Eun Ae. Improved surface characteristics and the conductivity of polyaniline-nylon 6 fabrics by plasma treatment, *Journal of Applied Polymer Science*, **81**(3), p. 684–694, 2001, doi: 10.1002/app.1485.
98. SCHOLZ, Jana. NOCKE, Günter. HOLLSTEIN, Frank. and WEISSBACH, Alexander. Investigations on fabrics coated with precious metals using the magnetron sputter technique with regard to their anti-microbial properties, *Surface and Coatings Technology*, **192**(2–3), p. 252–256, 2005, doi: 10.1016/j.surfcoat.2004.05.036.
99. KUMAR, Satish. DOSHI, Harit. SRINIVASARAO, Mohan. PARK, Jung O. and SCHIRALDI, David A. Fibres from polypropylene/nano carbon fibre composites, *Polymer*, **43**(5), p. 1701–1703, 2002, doi: 10.1016/S0032-3861(01)00744-3.
100. ISLAM, G. M.Nazmul. ALI, M. Azam. and COLLIE, Stewart. Polydopamine Treated and PEDOT:PSS Coated Wash Durable Conductive Textiles for Wearable Applications, *Fibres and Polymers*, **23**(4), p. 914–924, 2022, doi: 10.1007/s12221-022-3080-0.
101. SHATERI-KHALILABAD, Mohammad and YAZDANSHENAS, Mohammad E. Fabricating electroconductive cotton textiles using graphene, *Carbohydrate Polymers*, **96**(1), p. 190–195, 2013, doi: 10.1016/j.carbpol.2013.03.052.
102. MAKOWSKI, Tomasz *et al.* Antibacterial Electroconductive Composite Coating of Cotton Fabric, *Materials*, **15**(3), p. 1–9, 2022, doi: 10.3390/ma15031072.
103. BLACHOWICZ, Tomasz and EHRMANN, Andrea. Conductive electrospun nanofibre mats, *Materials*, **13**(1), 2020, doi: 10.3390/ma13010152.
104. YEO, Leslie Y. and FRIEND, James R. Electrospinning carbon nanotube polymer composite nanofibres, *Journal of Experimental Nanoscience*, **1**(2), p. 177–209, 2006, doi: 10.1080/17458080600670015.
105. GOMMANS, Hans H. ALLDREDGE, Jacob W. TASHIRO, Hideo. PARK, Jin. MAGNUSON,

John. and RINZLER, Andrew G. Fibres of aligned single-walled carbon nanotubes: Polarized Raman spectroscopy, *Journal of Applied Physics*, **88**(5), p. 2509–2514, 2000, doi: 10.1063/1. 1287128.

106. VIGOLO, Brigitte *et al.* Macroscopic fibres and ribbons of oriented carbon nanotubes, *Science*, **290**(5495), p. 1331–1334, 2000, doi: 10.1126/ science.290.5495.1331.
107. JESTIN, Simon and POULIN, Philippe. *Wet Spinning of CNT-based Fibres*. Elsevier, 2013. doi: 10.1016/B978-1-4557-7863-8.00006-2.
108. HAGGENMUELLER, Reto. GOMMANS, Hans H. RINZLER, Andrew G. FISCHER, John E. and WINEY, Karen I. Aligned single-wall carbon nanotubes in composites by melt processing methods, *Chemical Physics Letters*, **330**(3–4), p. 219–225, 2000, doi: 10.1016/S0009-2614(00)01013-7.
109. KHAIR, Nipa. ISLAM, Rashedul. and SHAHARIAR, Hasan. Carbon-based electronic textiles: materials, fabrication processes and applications, *Journal of Materials Science*, **54**(14), p. 10079–10101, 2019, doi: 10.1007/s10853-019-03464-1.
110. GÜLTEKİN, Nergis Demirel. Investigation of Thermal and Electrical Conductivity Properties of Carbon Black Coated Cotton Fabrics, *Marmara University Journal of Science*, **27**(3), p. 91–94, 2015, doi: 10.7240/mufbed.67752.
111. HASSAN, BS. ISLAM, GMN. and HAQUE, ANMA. Applications of Nanotechnology in Textiles : A Review, *Advanced Research in Textile Engineering*, **4**(2), p. 1–9, 2019.
112. SABOOR, Fahimeh Hooriabad. HADIAN-GAZVINI, Samaneh. and SHAHSAVARI, Shadab. *Applications of carbon-based conductive nanomaterials on e-textiles*. INC, 2021. doi: 10.1016/b978-0-12-820777-2.00015-7.
113. WENNER, Frank. A Method of Measuring Earth Resistivity, *National Bureau of Standards*, Scientific Paper, **12**(4), p. 469, 1916, doi: 10.6028/ bulletin.282.
114. PAUW, L. Van der. A method of measuring specific resistivity and Hall effect of discs of arbitrary shape, *Philips Research Reports*, **13**(334), p. 1–9, 1958.
115. ŠAFÁŘOVÁ, Veronika and MILITKÝ, Jiří. A Study of Electrical Conductivity of Hybrid Yarns Containing Metal Fibres, *Journal of Materials Science and Engineering B*, **2**(2), p. 197–202, 2012, Online.. Available: https://pdfs.semanticscholar.org/234e/5fce337ad10b37c5c918c5afc02024a2b-ded.pdf.
116. AUSSERLECHNER, Udo. Closed form expressions for sheet resistance and mobility from Van-der-Pauw measurement on 90° symmetric devices with four arbitrary contacts, *Solid-State Electronics*, **116**, p. 46–55, 2016, doi: 10.1016/j. sse.2015.11.030.
117. RAMADAN, Ahmed A. GOULD, Robert D. and ASHOUR, Ahmed. On the Van der Pauw method of resistivity measurements, *Thin Solid Films*, **239**(2), p. 272–275, 1994, doi: 10.1016/0040-6090(94)90863-X.
118. RÄTHEL, Jan. HERRMANN, Mathias. and BECKERT, Wieland. Temperature distribution for electrically conductive and non-conductive materials during Field Assisted Sintering (FAST), *Journal of the European Ceramic Society*, **29**(8), p. 1419–1425, 2009, doi: 10.1016/j. jeurceramsoc.2008.09.015.
119. REINERS, Priscilla. KYOSEV, Yordan. SCHACHER, Laurence. and ADOLPHE, Dominique. About the Cutting Resistance Measurement of Textiles, in *International Izmir Textile and Apparel Symposium*, 2014, p. 447–452.
120. PAWLAK, Ryszard. LEBIODA, Marcin. MARIUSZ, Tomczyk. RYMASZEWSKI, Jacek. KORZENIEWSKA, Ewa. and WALCZAK, Maria. Surface heat sources on textile composites - Modeling and implementation, *2017 18th International Symposium on Electromagnetic Fields in Mechatronics, Electrical and Electronic Engineering, ISEF 2017*, 2017, doi: 10.1109/ ISEF.2017.8090740.
121. KHAN, Saleem. TINKU, Sajina. LORENZELLI, Leandro. and DAHIYA, Ravinder S. Flexible tactile sensors using screen-printed P(VDF-TrFE) and MWCNT/PDMS composites, *IEEE Sensors Journal*, **15**(6), p. 3146–3155, 2015, doi: 10.1109/ JSEN.2014.2368989.
122. LEE, Jaehong *et al.* Conductive fibre-based ultrasensitive textile pressure sensor for wearable electronics, *Advanced Materials*, **27**(15). p. 2433–2439, 2015. doi: 10.1002/adma.201500009.
123. ROOT, Waleri. BECHTOLD, Thomas. and PHAM, Tung. Textile-Integrated thermocouples for temperature measurement, *Materials*, **13**(3), 2020, doi: 10.3390/ma13030626.
124. ARRUDA, Luisa M. MOREIRA, Inês P. SANIVADA, Usha Kiran. CARVALHO,

Helder. and FANGUEIRO, Raul. Development of Piezoresistive Sensors Based on Graphene Nanoplatelets Screen-Printed on Woven and Knitted Fabrics: Optimisation of Active Layer Formulation and Transversal/Longitudinal Textile Direction, *Materials*, **15**(15), p. 5185, 2022, doi: 10.3390/ma15155185.

125. CHO, Seungse. CHANG, Taehoo. YU, Tianhao. and LEE, Chi Hwan. Smart Electronic Textiles for Wearable Sensing and Display, *Biosensors*, **12**(4), 2022, doi: 10.3390/bios12040222.

126. SINHA, Ankita. DHANJAI. STAVRAKIS, Adrian K. and STOJANOVIĆ, Goran M. Textile-based electrochemical sensors and their applications, *Talanta*, **244**(December 2021), 2022, doi: 10.1016/j.talanta.2022.123425.

127. PEI, Eujin. SHEN, Jinsong. and WATLING, Jennifer. Direct 3D printing of polymers onto textiles: Experimental studies and applications, *Rapid Prototyping Journal*, **21**(5), p. 556–571, 2015, doi: 10.1108/RPJ-09-2014-0126.

128. MELLIN, Pelle *et al.* Nano-sized by-products from metal 3D printing, composite manufacturing and fabric production, *Journal of Cleaner Production*, **139**, p. 1224–1233, 2016, doi: 10.1016/j.jclepro.2016.08.141.

129. WENNER, Frank. A Method of Measuring Earth Resistivity, *National Bureau of Standards*, Scientific Paper, **12**(4), p. 469, 1916, doi: 10.6028/bulletin.282.

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The Influence of Water Hardness on the Agronomic Traits of Foreign Fibre Flax Varieties in the Republic of Croatia
Vpliv trdote vode na agronomske lastnosti tujih sort vlaknatega lanu v Republiki Hrvaški

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Abstract
The amount and quality of fibres depend on a whole range of factors, the most important being variety, agroecological conditions, agrotechnics and the degree of fibre flax plant maturity, the purpose for which flax is grown, retting and processing. The retting of fibre flax is the most complex stage in the processing of flax into fibre. The aim of this study was to gain knowledge about the acclimatization ability of foreign varieties that can potentially be adapted to climatic in Republic Croatia. Therefore, this paper presents the results of achieved agronomic traits (dry stem yield, dry stem after retting, total fibre yield, long fibre yield, share of total fibre and share of long fibre) of five foreign varieties of fibre flax. The selected varieties were retted in very soft, medium hard and hard water. Variety trials with fibre flax were set up over three years (2012–2014) at two locations (Zagreb) on anthropogenized eutric cambisol and (Križevci) on pseudogley on level terrain. The trials were carried out according to the RCBD in four replications. According to the results of the three-year research into the agronomic traits of fibre flax, significant differences were identified among the varieties studied. The varieties Agatha, Viola and Electra recorded the highest values of studied traits. Statistically significant differences were only recorded among different water hardness for long fibre yield in 2012 and share of total fibre in 2013 in Zagreb. The highest yields and share of fibres were recorded when the fibre flax was retted in very soft water.
Keywords: agronomic traits, fibre flax, varieties, water hardness

Izvleček
Količina in kakovost vlaken iz vlaknatega lana sta odvisni od vrste dejavnikov, med katerimi so najpomembnejši sorta, agroekološke razmere, agrotehnika, stopnja zrelosti stebel, namen uporabe, godenje in predelava. Godenje stebel vlaknatega lana je najzahtevnejša faza v celotnem procesu predelave stebla v vlakno. Cilj teh študij je pridobiti znanje o aklimatizacijskih sposobnostih tujih sort, ki se potencialno lahko prilagodijo podnebnim razmeram Republike

Hrvaške. V tem članku so zato predstavljeni rezultati doseženih agronomskih lastnosti (pridelek suhih stebel, suhih stebel po namakanju, skupni pridelek vlaken, pridelek dolgih vlaken, delež vseh vlaken in delež dolgih vlaken) petih tujih sort lanu, namenjenih za pridobivanje vlaken. Stebla izbranih sort so bila namakana v zelo mehki, srednje trdi in trdi vodi. V raziskavo so bili zajeti sortni poskusi iz treh let (2012–2014) na dveh lokacijah, in sicer na antropogeni evtrični rjavi prsti v Zagrebu in na psevdogleju na ravnih terenih v Križevcih. Poskusi so bili izvedeni v naključnih blokih v štirih ponovitvah. Glede na rezultate triletnega raziskovanja agronomskih lastnosti lanu so bile med obravnavanimi sortami ugotovljene pomembne razlike. Najboljše preiskovane lastnosti so zabeležili pri sortah Agatha, Viola in Electra. Statistično značilne razlike so bile zabeležene med različnimi trdotami vode le za donos dolgih vlaken v letu 2012 in v deležu vseh vlaken v letu 2013 v Zagrebu. Največji pridelek in največji delež vlaken sta bila zabeležena pri namakanju lanenih stebel v zelo mehki vodi.
Ključne besede: agronomske lastnosti, lan za vlakna, sorte, trdota vode

1 Introduction

A review of available literature covering the fields of textiles and agriculture showed insufficient cooperation among researchers, particularly with a focus on flax and flax fibres. There is thus a need for an interdisciplinary approach to research, taking into account agricultural and textile knowledge. Twenty years ago, collaboration between researchers at the Faculty of Agriculture and Faculty of Textile Technology, University of Zagreb, was established with the aim of reviving flax production in Republic Croatia, and defining and improving the quality of flax fibres.

Setting the yield and quality parameters of fibre flax depends on many factors, such as soil-climatic, breeding-genetic and anthropogenic factors. Furthermore, the quality of fibres depends on a combination of a number of properties that in turn depend on the variety characteristics of plants, their growing conditions, harvesting technology and retting process, and raw material processing methods. One of the most important factors that determines the quality of long flax fibres is the retting process. Traditional retting methods include dew retting and water retting. Alternative methods include mechanical decortication, and chemical, heat, and enzymatic treatments [1]. In addition, ultrasound retting has been used for fibre flax in recent years [2]. Water retting is one of the best but also one of the most expensive flax fibre production methods. In principle, the method is analogous to stream retting but the flax stems are retted for four to seven days depending on the quality of the flax in heated tanks or pits maintained at 40 °C. Warm water retting, which can be used all year round, normally results in finer fibres of better quality than those produced by dew retting [3]. The advantage of water retting over dew retting is that it is more easily controlled and avoids the risk of the crop being spoilt by inclement weather during the weeks that it lies on the ground [4]. However, it also has serious disadvantages. The main disadvantage is that the water in which the straw has been steeped is highly polluted and in Europe must be treated before being discharged as wastewater. It has almost completely disappeared in Western Europe and in most Eastern European countries, but is still widely practised in China and Egypt. It also requires high water treatment maintenance and the costs are very high.

In Croatia, after the fibre flax pulling during July, the weather conditions (warm and dry) are not suitable for dew retting. Therefore, the fibre flax was traditionally retted in Croatia in rivers, lakes and ponds until the Second World War, and after the war in pools and tanks with cold or warm water. Today, small quantities of water-retted flax are still produced in Croatia. According to Pasković, [5] the quality and yield of fibre depends on water hardness, while bleaching also affects the colour and the characteristics of flax fibres. If the water is softer, the retting of flax fibres is faster and produces the highest quality, characterized by good fineness, strength, softness and whiteness. In the lowland continental area of Croatia, where fibre flax is grown, the natural water that is used for retting is medium hard to hard. In Croatia, there are only a few studies dealing with the retting of fibre flax in different water hardnesses [2, 6, 7].

The commercial breeding of fibre flax started in Europe at the end of the 19th century. Before Western European varieties became available, European varieties of seeds were imported from Russia. Cross breeding is still the main breeding method for fibre flax [8]. The main task of the breeding programme is to develop flax genotypes that are

highly productive (both fibre and seeds) and highly adaptable to changing environmental conditions [9]. Standard European varieties are spring varieties adapted to the coastal climate and long days. At the beginning of the growth cycle, the flax plant does not tolerate negative temperatures, while excessively high temperatures accelerate the maturation of flax plants and there is no elongation of fibres, which ultimately reduces the quality of fibres. According to Rossini and Casa, [10] warm and dry weather conditions, predominant from late spring onwards, cause the excessive shortening of the growing cycle of spring crops, which results in lower yield and poorer seed and fibre quality. The environment has a strong influence on crop success, with some varieties showing more year-to-year stability than others [11]. According to the Liebieg's law, weather conditions (precipitation) represent the main limiting factor that frequently affects flax yield in many regions of Europe [12].
Fibre flax is traditionally cultivated in most parts of Croatia. In the lowland continental area of the country, flax is sown around the end of March, while the growth stage of flowering starts at the end of May [13]. The Croatia has no indigenous fibre flax varieties [14, 15]. Introduced varieties are from Western Europe and are less suitable for the climatic conditions of Croatia (yields and quality are usually lower) [16–24]).
The aim of these studies was to determine the agronomic traits (dry stem yield, dry stem yield after retting, total fibre yield, share of total fibre, long fibre yield and share of long fibre) of five fibre flax varieties that were retted in very soft, medium hard and hard water over three years at two locations. The obtained results will be of great importance for gaining knowledge about the acclimatization ability of foreign varieties that can potentially be adapted to the climatic conditions of Croatia.

2 Materials and methods

Variety trials with fibre flax were carried out in the experimental fields of the University of Zagreb Faculty of Agriculture (45°49'26" N, 16°02'07" E) on anthropogenized eutric cambisol, and of the College of Agriculture in Križevci (46°02'23" N, 16°54'62" E) on pseudogley on level terrain from 2012 to 2014. The trials involved five varieties: Viking (Cooperative Liniere de Fontaine Cany, France), Viola (Van de Bilt Zaden, Netherlands), Venica (Agritec, Czech Republic), and Agatha and Electra (Cebecco Seed, Netherlands). The content of the nutrients in the soil and pH values for both locations are given in Table 1.
Weather conditions were also monitored during the flax growing season for all the years and both locations (Tables 2 and 3).
Fertilization with100 kg/ha P (as superphosphate) and 150 kg/ha K (potassium salt) was carried within basic tillage for both locations. A total of 30 kg of N/ha (nitrogen) was added before sowing, as well as 30 kg/ha in a single fertilizer application at the average plant height of 0.1 m. The trials were designed according to the randomized complete block design (RCBD) with four replications. The main trial plot size was 10 m^2 (10 rows × 0.1 m row spacing × 10 m length). Sowing was carried out using a plot seeder (Wintersteiger, Austria). Fibre flax seeding was performed on 28 March 2012, 12 April 2013 and 14 April 2014. Sowing density was 2,500 germinable seeds/m^2.
The agronomic traits studied were dry stem yield, dry stem yield after retting, total fibre yield, share

Table 1: Content of nutrients in soils and pH

Year	Location	P_2O_5 (mg/100 g)	K_2O (mg/100 g)	Total nitrogen (%)	pH - 1M KCl (1:2.5)
2012	Zagreb	32.20	27.0	0.13	7.31
2013	Zagreb	34.54	25.0	0.11	6.20
2014	Zagreb	37.03	16.2	0.12	7.09
2012	Križevci	28.39	19.05	0.10	5.42
2013	Križevci	21.47	16.67	0.12	4.84
2014	Križevci	29.19	25.31	0.10	6.05

P_2O_5, K_2O – Al method; Total nitrogen – HRN ISO 13878:2004; pH – HRN ISO 10390:2004

Table 2: Mean monthly absolute minimum and maximum air temperatures (°C) and mean monthly precipitation amounts (mm) for 2012, 2013 and 2014 for Zagreb (Meteorological and Hydrological Services of the Republic of Croatia)

Year	Month	Mean monthly air temperature (°C)	Absolute minimum air temperature (°C)	Absolute maximum air temperature (°C)	Mean monthly precipitation amounts (mm)
2012	March	9.4	–3.1	23.9	4.5
	April	12.5	–2.3	30.5	51.3
	May	16.7	3.3	29.3	81.8
	June	22.0	7.0	35.3	127.9
2013	March	4.9	–4.8	17.9	121.7
	April	13.0	–1.2	29.2	56.1
	May	16.3	6.8	28.9	94.0
	June	20.0	8.4	33.6	48.7
2014	March	10.8	0.3	23.6	21.0
	April	13.3	2.5	25.0	70.4
	May	16.2	3.2	29.0	145.0
	June	20.2	8.8	33.9	147.0

Table 3: Mean monthly absolute minimum and maximum air temperatures (°C) and mean monthly precipitation amounts (mm) for 2012, 2013 and 2014 for Križevci (Meteorological and Hydrological Services of the Republic of Croatia)

Year	Month	Mean monthly air temperature (°C)	Absolute minimum air temperature (°C)	Absolute maximum air temperature (°C)	Mean monthly precipitation amounts (mm)
2012	March	9.2	–4.1	23.0	2.4
	April	12.2	–4.0	29.6	34.6
	May	16.1	1.4	29.5	99.4
	June	21.5	5.4	34.6	65.6
2013	March	4.2	–6.0	17.5	132.1
	April	12.3	–0.9	28.1	47.1
	May	15.8	5.9	29.1	108.2
	June	19.5	7.5	34.2	44.4
2014	March	10.3	–3.1	23.3	14.7
	April	12.7	1.9	24.4	56.5
	May	15.4	3.0	29.3	118.3
	June	19.8	9.2	34.1	99.4

of total fibre, long fibre yield and share of long fibre [13]. Manual harvest by hand pulling was carried out at yellow-green ripening and an area of 1 m^2. Dry stem yield was determined after de-seeding. Flax stems were then placed in a tank of water (very soft, medium hard and hard – Table 2) at 32 °C for three days (72 hours) under controlled conditions. Retted stems were then removed from the tank. They were dried at 60 °C for 30 hours and weighed. A scutching machine was used to separate straw (woody matter) from fibre, where the yields of total and long fibres (using a set of hackling pins), and their respective share, were estimated.

The water hardness is expressed in German degrees of hardness (°dH) and in ppm (determination by titration with 0.1 M HCl with methyl orange indicator) (Table 4).

Table 4: Hardness of water retting

Water	German degrees of hardness (°dH)	ppm
Very soft	0.8–1.5	14–26
Medium hard	5.2–5.7	88–98
Hard	15.5–21	263–357

Data regarding all of the traits studied were statistically processed using analysis of variance (two-factor trial – variety and water hardness) separately for each year and each location. Differences between mean values were analysed using Duncan's multiple range test [25].

3 Results and discussion

Statistically significant differences were recorded among the varieties for the studied traits of fibre flax, except for total fibre yield, share of total and long fibre in 2014 in Zagreb, share of total fibre in 2012 and 2014 in Križevci, all studied traits in 2013 in Križevci and dry stem yield in 2014 in Križevci (Tables 5 and 6). In addition, statistically significant differences were only recorded among different water hardnesses for long fibre yield in 2012 and share of total fibre in 2013 in Zagreb (Tables 7 and 8). No significant interaction was recorded for any traits or any location, so interactions were not included in the factors shown here and were not discussed any further. Accordingly, the factors affected the studied traits independently.

The highest dry stem yield was achieved by the varieties Viola in 2012 and 2013 in Zagreb, Venica in 2013 in Križevci and Agatha in 2014 at both locations (Tables 5 and 6). Viola gave the highest dry stem yield after retting in two years in Zagreb and Križevci, and Electra in one year in Zagreb. The highest total fibre yield was achieved by the varieties Viola in 2012 at both locations, in 2013 in Zagreb, and Agatha in 2014 in Križevci and Electra in Zagreb. Also, Viola gave the highest long fibre yield in 2012 and 2013 in Zagreb and Agatha in 2012 in Zagreb, and in three years in Križevci. However, Venica gave the highest share of total fibre in two years in Zagreb and one year in Križevci. The highest share of long fibre was achieved by the variety Agatha in 2012 in Zagreb, in 2013 at both locations and in 2014 in Križevci.

Comparing locations, all varieties achieved higher values of dry stem yield, dry stem yield after retting, total fibre yield, share of total fibre and long fibre yield in two years at Križevci. The higher values in Križevci were also the result of flax production on heavier soil (pseudogley on level terrain), in which some winter moisture remained available in April and at the beginning of May (Tables 2 and 3). According to previous studies of these varieties, dry stem yields after retting ranged between 4.5 and 9.0 t/ha, total fibre yield between 1.5 and 3.8 t/ha, share of total fibre between 25 and 45%, long fibre yield between 1.3 and 2.0 t/ha, and share of long fibre between 20 and 25%, depending on climatic conditions [11, 26–32].

The growth of flax plant is usually monitored in terms of accumulated temperature or effective cumulative temperature [33]. It was determined that optimum fibre richness is reached around an accumulated temperature of 850-1100 °C, which is a favourable condition for harvest. Higher accumulated temperatures (> 1100 °C) were found to be ineffective for the improvement of fibre richness. Higher accumulated temperatures cause lignin generation within the plant, and pose problems during the retting and mechanical separation of fibres. In our studies (Tables 2 and 3), excessively high temperatures in some years at the end of April and at the beginning of May in the intensive flax growth stage (absolute maximum temperature was recorded in April in Zagreb (30.5 °C) and in May in Zagreb (29.3 °C) accelerated the maturity of flax, and the elongation of fibre did not appear and the yield and quality was reduced. The annual precipitation also influenced the growth of fibres. It has been suggested that precipitation should be about 110-150 mm [28] during the growing period.

The below-mean values for dry stem yield after retting, total fibre yield, long fibre yield and share of long fibre in 2012 and 2014 in Zagreb and in 2013 in Križevci were influenced by plant lodging due to poor climatic conditions and strong winds at the end of May (in 2014 in Zagreb and in 2013 in Križevci) and at the beginning of June (in 2012 and 2014 in Zagreb), and excessive precipitation in May (in 2014 in Zagreb (145.0 mm); in 2013 in Križevci (108.2 mm) and in June (in 2012 and 2014 in Zagreb (127.9 mm and 147.0 mm) (Tables 2 and 3).

Table 5: Means of agronomic traits of fibre flax, depending on the varieties in Zagreb (2012, 2013 and 2014)

Year	Varieties	Dry stem yield (t/ha)	Dry stem yield after retting (t/ha)	Total fibre yield (t/ha)	Share of total fibre (%)	Long fibre yield (t/ha)	Share of long fibre (%)
2012	Viking	4.20b	3.20b	1.13b	35.27b	0.38b	11.71ab
	Viola	4.73a	3.86a	1.55a	40.18ab	0.50a	13.07ab
	Venica	4.27a	3.31b	1.35ab	41.14a	0.41ab	12.54ab
	Agatha	4.51a	3.39b	1.38ab	40.52ab	0.50a	14.81a
	Electra	4.71a	3.94a	1.53a	38.85ab	0.43ab	11.12b
2013	Viking	8.65b	6.23d	1.99b	32.34b	0.58c	9.42c
	Viola	12.77a	10.36a	3.66a	35.43b	1.41a	13.77b
	Venica	8.81b	6.69cd	2.31b	35.14b	0.93b	14.32ab
	Agatha	9.08b	7.76bc	3.29a	42.78a	1.40a	18.13a
	Electra	11.98a	8.92b	3.33a	37.70b	1.22ab	13.61b
2014	Viking	6.06b	3.70b	1.12a	30.65a	0.33c	9.10a
	Viola	8.65a	5.45a	1.36a	25.30a	0.54a	10.03a
	Venica	6.26b	3.73b	1.21a	32.76a	0.44b	11.96a
	Agatha	8.84a	4.21b	1.28a	31.53a	0.49ab	12.26a
	Electra	7.88ab	4.58ab	1.45a	32.65a	0.55a	12.47a

Values with the same letter are not significant at a level of 5%. As the significance values decrease, the letters descend, as they are in alphabetical order.

Table 6: Means of agronomic traits of fibre flax dependent on the varieties in Križevci (2012, 2013 and 2014)

Year	Varieties	Dry stem yield (t/ha)	Dry stem yield after retting (t/ha)	Total fibre yield (t/ha)	Share of total fibre (%)	Long fibre yield (t/ha)	Share of long fibre (%)
2012	Viking	8.43b	5.63b	1.63b	29.43a	0.47c	8.43b
	Viola	11.21a	8.10a	2.46a	31.63a	0.80a	10.35ab
	Venica	8.47b	5.55b	1.80b	32.58a	0.66ab	12.00a
	Agatha	9.68ab	6.86ab	2.18a	31.96a	0.82a	11.92a
	Electra	11.27a	7.68ab	2.43a	31.97a	0.55bc	7.35b
2013	Viking	4.94a	4.33a	1.84a	44.42a	0.47a	10.68a
	Viola	5.05a	4.36a	1.87a	43.62a	0.61a	14.04a
	Venica	5.33a	4.50a	1.89a	44.79a	0.60a	13.74a
	Agatha	4.92a	4.08a	1.83a	45.47a	0.67a	15.91a
	Electra	4.78a	4.05a	1.83a	47.53a	0.52a	12.89a
2014	Viking	9.18a	4.91b	1.93b	39.63a	0.57d	11.94d
	Viola	9.52a	6.54a	2.30ab	35.62a	1.15b	17.74bc
	Venica	9.39a	5.41ab	2.05ab	38.35a	0.75c	14.25cd
	Agatha	10.41a	6.08ab	2.49a	41.36a	1.33a	22.15a
	Electra	9.85a	6.20ab	2.43a	39.43a	1.30a	21.17ab

Values with the same letter are not significant at a level of 5%. As the significance values decrease, the letters descend, as they are in alphabetical order.

The highest values for all studied traits (Tables 7 and 8) were achieved when the plants were retted in very soft water. This does not apply for dry stem yield in 2013 and 2014 and dry stem yield after retting in 2013 in Zagreb, and share of total fibre in 2012, dry stem yield, long fibre yield and share of long fibre in 2013 in Križevci. These values were not significantly higher than the values when plants were retted in very soft water. During retting, it was observed that the maceration process was faster in softer water. This is consistent with previous studies reported in the literature [2, 5–7].

4 Conclusion

On the basic of the results obtained, the following conclusions can be drawn:

- Statistically significant differences were recorded among the varieties for the studied traits of fibre flax, except for total fibre yield, share of total and long fibre in 2014 in Zagreb, share of total fibre in 2012 and 2014 in Križevci, all studied traits in 2013 at Križevci and dry stem yield in 2014 in Križevci.
- Statistically significant differences were only recorded among different water hardnesses for long fibre yield in 2012 and share of total fibre in 2013 in Zagreb.

Table 7: Means of agronomic traits of fibre flax, depending on water hardness in Zagreb (2012, 2013 and 2014)

Year	Water hardness	Dry stem yield (t/ha)	Dry stem yield after retting (t/ha)	Total fibre yield, t/ha	Share of total fibre (%)	Long fibre yield (t/ha)	Share of long fibre (%)
2012	Very soft	4.50a	3.61a	1.45a	40.12a	0.49a	13.72a
	Medium hard	4.45a	3.54a	1.37a	39.03a	0.45a	12.92a
	Hard	4.49a	3.47a	1.33a	38.43a	0.39b	11.31a
2013	Very soft	10.01a	7.86a	3.08a	39.67a	1.12a	14.39a
	Medium hard	10.37a	7.85a	2.82a	36.03a	1.11a	14.28a
	Hard	10.40a	8.27a	2.85a	34.54b	1.08a	12.88a
2014	Very soft	7.58a	4.44a	1.37a	32.01a	0.49a	11.60a
	Medium hard	7.64a	4.35a	1.25a	29.71a	0.47a	11.00a
	Hard	7.40a	4.22a	1.23a	30.02a	0.45a	10.89a

Values with the same letter are not significant at a level of 5%. As the significance values decrease, the letters descend, as they are in alphabetical order.

Table 8: Means of agronomic traits of fibre flax dependent on the water hardness in Križevci (2012, 2013 and 2014)

Year	Water hardness	Dry stem yield (t/ha)	Dry stem yield after retting (t/ha)	Total fibre yield, t/ha	Share of total fibre (%)	Long fibre yield (t/ha)	Share of long fibre (%)
2012	Very soft	10.07a	6.89a	2.17a	31.63a	0.70a	10.45a
	Medium hard	9.74a	6.84a	2.12a	31.64a	0.66a	10.13a
	Hard	9.63a	6.56a	2.00a	31.27a	0.61a	9.45a
2013	Very soft	4.96a	4.49a	1.95a	45.80a	0.57a	12.68a
	Medium hard	5.05a	4.21a	1.79a	44.40a	0.59a	14.22a
	Hard	5.01a	4.10a	1.81a	45.30a	0.56a	13.46a
2014	Very soft	9.75a	5.96a	2.33a	39.66a	1.06a	17.62a
	Medium hard	9.61a	5.84a	2.23a	38.66a	1.02a	17.40a
	Hard	9.66a	5.69a	2.15a	38.32a	0.99a	17.33a

Values with the same letter are not significant at a level of 5%. As the significance values decrease, the letters descend, as they are in alphabetical order.

- No significant interaction was recorded for any traits or any location.
- The varieties Agatha, Viola and Electra recorded the highest values of studied traits.
- Comparing locations, all varieties achieved higher values of dry stem yield, dry stem yield after retting, total fibre yield, share of total fibre and long fibre yield in two years in Križevci.
- The highest values for all studied traits were achieved when the plants were retted in very soft water. This does not apply for dry stem yield in 2013 and 2014 and dry stem yield after retting in 2013 in Zagreb, and share of total fibre in 2012, dry stem yield, long fibre yield and share of long fibre in 2013 in Križevci.
- Croatia has extremely hard water, and it would be most economically advantageous to use hard water for flax retting. The results obtained in this research show that the retting process was faster in softer water, making that process a little more expensive. The presented research will therefore be continued and expanded.
- The obtained results are of great importance because they provided valuable knowledge about the acclimatization ability of foreign cultivars that can be potentially adapted to the climatic conditions of Croatia, which will ensure raw materials for making ecologically valuable products.

References

1. TAHIR, Paridah; AMEL, B. Basher; SYEED SAIFUL, Azry and ZAKIAH, Ahmed. Retting process of some bast plant fibres and its effect on fibre quality: A review. *Bioresurces*, 2011, **6**(4), 5260-5281. doi: https://doi.org/10.15376/BIORES.6.4.5260-5281.
2. BRUNŠEK, Ružica; ANDRASSY, Maja and BUTORAC, Jasminka. Retting of flax and characterization of fibres. In *Proceedings of 14th AUTEX World Textile Conference 2014, Bursa, Turkey*. Edited by Recep Eren, 2014, 1-6.
3. SHEKHAR SHARMA, H. S., SUMERE, VAN C. F. The biology and processing of flax. Belfast, Northern Ireland: M. Publications, 1992.
4. SALMON-MINOTTE, J. and FRANCK, R. R. Flax. *In Bast and other plant fibre*. Edited by R. R. Franck, Cambridge, Woodhead Publishing Limited, 2005, 94-175.
5. PASKOVIĆ, Fran. Predivo bilje. I dio Konoplja, lan i pamuk. Nakladni zavod znanje, Zagreb, 1966.
6. BRUNŠEK, Ruzica; ANDRASSY, Maja and BUTORAC, Jasminka. Influence of water hardness on retting and properties of fiber flax. In *Proceedings of the 7th International Textile, Clothing & Design Conference Magic World of Textiles*, 2014, Dubrovnik, Croatia. Edited by Dragčević Zvonko, Hursa Šajatović Anica, Vujasinović Edita, 116-121.
7. BUTORAC, Jasminka; ŠURINA, Ružica; BUJAN, Marija; POSPIŠIL, Milan and BRČIĆ, Maja. The influence of variety and of water hardness on fibre flax yield and share of fibre. In *Proceedings of 49th Croatian and 9th International Symposium on Agriculture*, 2014, Dubrovnik, Croatia, Edited by Marić Sonja, Lončarić Zdenko, 342-346.
8. WANG, Yu-Fu; JANKAUSKIENE, Zofija; QIU, Cai-Sheng; GRUZDEVIENE, Elvyra; LONG, Song-Hua; ALEXOPOULOU, Efthymia; GUO, Yuan; SZOPA, Jan; HAO, Dong-Mei; FERNANDO, Ana Luisa and WANG, Hui. Fiber Flax Breeding in China and Europe. *Journal of natural fibres,* 2018, **15**(3), 309-324, doi: https://doi.org/10.1080/15440478.2017.1325431.
9. STAFECKA, Inga; STRAMKALE, Veneranda and GRAUDA, Dace. Estimation of yield stability for flax genetic resource using regression and cluster analysis. *Research for rural development*, 2016, **1**, 15-22. doi: https://doi.org/10.13080/z-a.2019.106.047.
10. ROSSINI, Francesco CASA, Raffaele. Influence of sowing and harvest time on fibre flax (Linum usitatissimum L.) in the Mediterranean environment. *Journal of agronomy and crop science*, 2003, **189**(3), 191-196. doi: https://doi.org/10.1046/j.1439-037X.2003.00034.x.
11. DIMMOCK, J. P. R. E., BENNETT, S. J., WRIGHT, D., EDWARDS-JONES, G., HARRIS, I. M. Agronomic evaluation and performance of flax varieties for industrial fibre production. *Journal of agricultural science*, 2005, **143**, 299-309. doi: https://doi.org/10.1017/s0021859605005277.
12. HELLER, Krzysztof and BYCZYNSKA, Malgorzata. The Impact of Environmental Factors and Applied Agronomy on Quantitative and Qualitative Traits of Flax Fiber. *Journal of natural fibers*, 2015, **12**(1) 26-38. doi: https://doi.org/10.1080/15440478.2013.879088.

13. BUTORAC, Jasminka. Fibre flax. In *Fibre plants*. Edited by Kugler, B., Zagreb, Croatia, 2009, 34-67.
14. ANDRASSY, Maja; PEZELJ, Emira and BUTORAC, Jasminka. Povratak proizvodnji predivog lana. *Tekstil*, 2004, **53**(8), 385-391.
15. POSPIŠIL, Milan; BUTORAC, Jasminka and GOJŠIĆ, Tea. Flax-forgotten but useful culture. *Gazophylacium*, 2004, **9**, 81-86.
16. BUTORAC, Jasminka; POSPIŠIL, Milan and MUSTAPIĆ, Zvonko. Some characteristics of European fibre flax varieties. In *Proceedings of 41st Croatian and 1st International symposium on Agriculture*, 2006, Opatija, Croatia, Edited by Jovanovac Sonja, Kovačević,Vlado, 359-360.
17. BUTORAC, Jasminka; POSPIŠIL, Milan; MUSTAPIĆ Zvonko and ZORIĆ, Darko. Estimation of some important agronomic and morphological traits of fibre flax varieties in different plan densities. *Sjemenarstvo*, 2006, **23**, 437-445.
18. BUTORAC, Jasminka; POSPIŠIL, Milan; MUSTAPIĆ, Zvonko and DUVNJAK, Ivana. Estimation of agronomic and morphological traits of fibre flax varieties without and with topdressing by nitrogen. *Sjemenarstvo*, 2009, **26**, 119-129.
19. ANDRASSY, Maja; ŠURINA, Ružica and BUTORAC, Jasminka. Influence of agroecological conditions on the properties of flax fibres in Croatia. In *Proceedings of 5th International textile, clothing and design conference*, 2010, Dubrovnik, Croatia. Edited by Dragčević Zvonko, 32-37.
20. BUTORAC, Jasminka; ŠURINA, Ružica; ANDRASSY, Maja; POSPIŠIL, Milan and AUGUSTINOVIĆ, Zvjezdana.. The influence of vegetation ripening group of fibre flax cultivars on morphological and textile- technological traits. In *Proceedings of 46st Croatian and 6st International symposium on agriculture*, Opatija, Croatia. Edited by Pospišil Milan, 2011, 723-727.
21. ŠURINA, Ružica; BUTORAC, Jasminka and ANDRASSY, Maja. Ovisnost svojstava vlakana o svojstvima biljke lana. Tekstil, 2011, **60**(2-3), 87-101.
22. BRUNŠEK, Ružica, ANDRASSY, Maja and BUTORAC, Jasminka. Revitalizacija lana u Hrvatskoj. *Tekstil*, 2014, **63**(1-2), 49-58.
23. BUTORAC, Jasminka; BRUNŠEK, Ružica; AUGUSTINOVIĆ, Zvjezdana; POSPIŠIL, Milan and ANDRASSY, Maja. The influence of nitrogen on the agronomic traits of fibre flax cultivars. *Romanian Agricultural Research*. 2014, **31**(1-7), 253-259.
24. BUTORAC, Jasminka; BRUNŠEK, Ružica; AUGUSTINOVIĆ, Zvjezdana and POSPIŠIL, Milan. The influence of stages of maturity on the agronomic traits of fibre flax introduced varieties. *Journal of Central European Agriculture*. 2018, **19**(1), 142-152. doi: https://doi.org/10.5513/JCEA01/19.1.2032.
25. DUNCAN, D. B. Multiple range and multiple F tests. *Biometrics*, 1955, **11**, 1-42.
26. COUTURE, S. J.; ASBIL, Wendy. L.; DITOMMASO, Antonio and WATSON, Alan. Comparison of European fibre flax (Linum usitatissimum) cultivars under Eastern Canadian growing conditions. *Journal of Agronomy and Crop Science*. 2002, 188, 350-356. doi: https://doi.org/10.1046/j.1439-037X.2002.00582.x.
27. DAENEKINDT, A. Belgian flax varieties in 2002. *Vlas Berichten,* 2003, **4**, 1-4.
28. HELLER, Krzysztof; SHENG, Qiu Cai; GUAN, Fengzhi; ALEXOPOULOU, Efthimia, HUA, Long Song; WEN WU, Guang; JANKAUSKIENE, Zofija and YU FU, Wang. A comparative study between Europe and China in crop management of two types of flax: linseed and fibre flax. *Industrial Crops Production*, 2015, 68, 24–31. doi: https://doi.org/10.1016/j.indcrop.2014.07.010.
29. HORNE, M., HARWOOD, R., MCCORMICK, P., HARWOOD, J. The Commercial Production of Short-Fibre Flax for Cottonisation. In *International Conference on Flax and Other Bast Plants*, Saskaton, Canada, 2008.
30. JANKAUSKIENE, Zofija and BAČELIS, Kestutis. Evaluation of long fibre quality of fibre flax varieties and breeding lines by different methods. Žemdirbyste-*Agriculture*, 2008, **95**(1), 93-106.
31. NORTON, Andrew; BENNETT, Sarita Jane; HUGHES, Mark; DIMMOCK, J. P. R. E.; WRIGHT, D.; NEWMAN, Gary; HARRIS, Ian mark and EDWARDS-JONES, G.. Determining the physical properties of flax fibre for industrial applications: the influence of agronomic practice. *Annals of Applied Biology*, 2006, **149**(1), 15-25. doi: https://doi.org/10.1111/j.1744-7348.2006.00066.x.
32. PAVELEK, M. New varieties – Venica. Czech Journal of Genetics and Plant Breeding, 2001, 37, 103-104.
33. BERT, F. Lin Fibre: Culture Et Transformation. Arvalis-Institut du Vegetal Paris, France, 2013.

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Filtration in Pharmaceutical Industries and Role of Textile
Filtracija v farmacevtski industriji in vloga tekstilij

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Abstract
Filtration is considered the keystone for clarification and control of contamination in pharmaceutical and biopharmaceutical manufacturing. From production to in-process to chemical and research laboratories to the purification of water for sterile and nonsterile products, all of which involve some form of filtration in order to achieve a good manufacturing practice (GMP). Textile materials possess a significant contribution to the pharmaceutical filtration system. Textile material in pharmaceutical filtration is used in the form of filter media or medium. Flexible in nature, large pore distribution and non-metallic properties of textile materials have led to widespread use as filter media for many years. In filtration processes, a proper selection of filter media/membrane material is usually the most critical aspect for ensuring efficient separation. Generally, solid-liquid and solid-gas separation is done by the filter media. This paper emphasises solid-liquid filtration. Moreover, this paper reviews the water requirement, filtration processes and the role of textile in the filtration system of pharmaceutical industries. This paper also offers insight into the current market trend and COVID-19 impact on the pharmaceutical filtration industry. Furthermore, gathered information may be helpful to those studying and working in pharmaceutical engineering, filtration technology, and wastewater treatment and can get knowledge about filtration systems.
Keywords: liquid filtration, textile filter media, water treatment, pharmaceutical filtration, COVID-19 impact

Izvleček
Filtracija velja za temeljni kamen čiščenja in nadzora kontaminacije v farmacevtski in biofarmacevtski proizvodnji. Od proizvodnje do medprocesnih, kemijskih in raziskovalnih laboratorijev čiščenja vode za sterilne in nesterilne izdelke vsi vključujejo določeno obliko filtracije, da dosežejo dobro proizvodno prakso. Tekstilni materiali prispevajo pomemben delež k farmacevtskemu filtracijskemu sistemu. V farmacevtski filtraciji se uporabljajo v obliki filtrnega medija ali medija. Gibka narava, porazdelitev velikih por in nekovinske lastnosti tekstilnega materiala že vrsto let vodijo v široko uporabo filtracije kot filtrnega medija. Pri postopkih filtracije je pravilna izbira filtrnega medija/membranskega materiala po navadi najbolj kritičen vidik zagotavljanja učinkovitega ločevanja. Na splošno se ločevanji trdno-tekoče in trdno-plin izvajata s filtrirnimi mediji. Ta članek obravnava filtracijo trdno-tekoče. Poleg tega obravnava potrebe po vodi, postopke filtracije in vlogo tekstilij v filtrnem sistemu farmacevtske industrije. Daje tudi vpogled v trenutni tržni trend in vpliv COVID-a na filtracijo v farmacevtski industriji. Znanja o filtrnih sistemih so lahko koristna vsem, ki študirajo in delajo na področju farmacevtskega inženirstva, filtracijske tehnologije in čiščenja odpadne vode.
Ključne besede: filtracija tekočin, tekstilni filtrni mediji, priprava vode, farmacevtska filtracija, vpliv covida

1 Introduction

Filtration is the separation of solid particles suspended in a liquid or gas using a porous medium that traps the solids while allowing the fluid to flow through. When the amount of solids in a liquid is reduced, this is called clarification [1]. In the pharmaceutical sector, filtering is a common and well-known activity. Filtration is used to make sterile goods, bulk pharmaceuticals, liquid oral formulations, and wastewater treatment plants (WWTPs) and their effluent receivers [2]. A porous material used to hold particles is known as filter media. There is a variety of materials that may be utilised in the filter medium to satisfy the users' demands. A proper selection of filter media/membrane material in filtering procedures is frequently the most critical aspect for ensuring efficient separation [3]. Cotton, polyester, wool, linen, polypropylene, glass fibre, porous carbon, metals and rayons are some of the materials used to manufacture filter media [4]. New polymeric materials have recently been utilised in filtering processes to purify medications, fluids and wastewaters in the pharma industry, both separately and/or mixed [5]. Surface filtration relies heavily on textile materials and membranes. Textiles such as nonwoven textiles and natural or synthetic fibres may be selected for their ease of installation on the filter tank/module [6]. Apart from the nonwoven structure, metal glands may be installed in the weaving medium in specific situations, cartridge and wax filter can also be incorporated with a woven fabric. The usage of different chemicals (e.g. polymer blends) in the manufacturing of the filter material, as well as the addition of the base material (e.g. nanoparticles, nanotubes) may modify the surface of the existing material and can work as a highly efficient filter [7]. In recent years, textile nanofibers have gained popularity in liquid filtration due to their unique characteristics such as high aspect ratio, cohesiveness, high specific surface area, exclusive physicochemical properties, and the design flexibility for chemical/physical surface functionalisation. They are continually gaining popularity in the pharmaceutical industry as a filter material in liquid and gas filtration [2, 8]. Apart from the general production of drugs, sterile and non-sterile products, the current COVID-19 outbreak impacted the production trend of vaccines, and there has been a sudden rise in demand. Thus, filtration-based technologies are also gaining momentum in vaccine clarification [9].

2 Filtration mechanism used in industry

The pharmaceutical industry needs different filtration methods depending on what sort of chemical solution is being used. Generally, the pharmaceutical industry has three major types of filtration systems (surface, depth and crossflow filtration) [7, 8, 10]. Figure 1 depicts various mechanisms of filtration.

Surface filtration, which operates with direct interception, separates the substance from the medium through which it may travel more readily than other materials in the same environment. The separation is caused by the size of holes in the filter, since the screen enables particles of specific size to pass through but traps molecules which are too big to fit through the pores. The technology is also known as membrane filtration, since it occasionally uses a porous membrane [8, 10, 64]. Deep-bed filters (also known as depth filtration) have been utilised in water and wastewater treatment for over a century. The creation of wells or springs in nature, which are drained from porous media such as rocks and sand, is similar to the principle of deep-bed filtration. Depth filtration holds particle matter further down from the surface than surface filtration [7, 11]. Its primary function is to clarify solutions. Ceramic-filter, sintered filters and nonwoven textile filters are the most frequently used in depth filtering. Recent advances in sintered metal filters include electrostatic precipitators, cyclones and disposable filters that were once highly used in the pharmaceutical industry [12].

Nanofiltration, also known as crossflow filtration, is a recently created device used by pharmaceutical industries seeking a solution of polyvalent cation removal in a low total dissolved solids water (surface or fresh ground water). The term nanofiltration refers to using a filtration membrane with holes that are one nanometre in diameter or smaller. It is comparable to reverse osmosis; however, the trans-membrane pressure required for functioning is much lower. As a result, the procedure is more cost-effective. Nevertheless, nanofiltration has flaws, e.g. the possibility of fouling and scaling on nanofiltration membranes [10, 13].

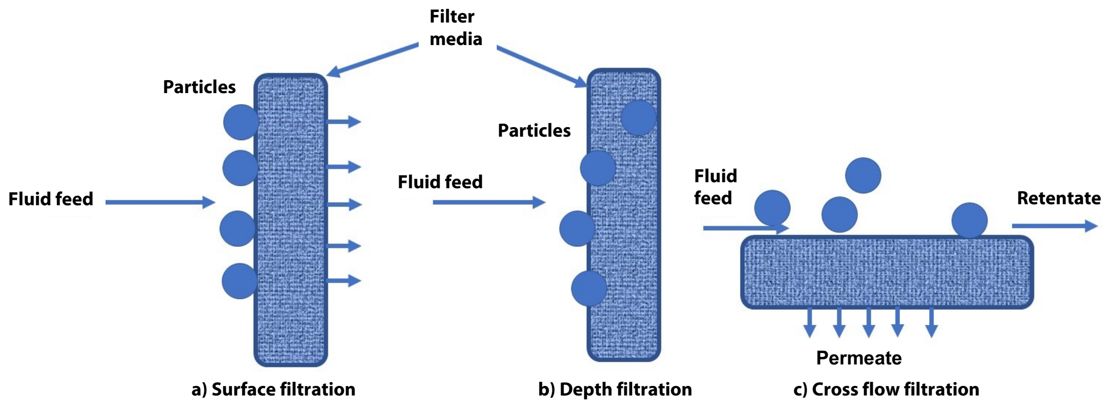

Figure 1: Filtration mechanism [8–13]

3 Water quality and filtration in pharmaceutical industries

Water is an essential component in pharmaceutical and life science processes. Water is utilised as a raw material in the processing, formulation, and production of various pharmaceutical products and active pharmaceutical ingredients (API). Most pharmaceutical industries rely heavily on surface water and groundwater supplies. Water from these sources is contaminated in its natural condition and must be filtered before being used for pharmacological purposes [14]. For pharmaceutical use, water must be treated according to established protocols. Distillation and deionisation are used in this water purification procedure to lower the number of polluted particles, parasites, bacteria, algae, viruses and fungi [15]. Medicinal water systems of varying quality are required depending on the mode of administration of the pharmaceutical medication. Numerous types of water used for medicinal applications are listed below, based on water quality. Water standards are included in pharmacopoeias for both bulk and dosage forms of water [16]. National, regional and worldwide pharmacopoeias specify the pharmacopeial requirements or guidelines for WPU (water for pharmaceutical use), and limits for specific impurities or groups of impurities are either stated or suggested [17]. Companies that want to serve several markets create specifications that match the most stringent criteria of each pharmacopeia [18].

3.1 Drinking water

Potable water is the best way to describe drinking water. Drinking water should be available under constant positive pressure in a plumbing system that is devoid of any flaws that might lead to product contamination. The minimal quality of water should be used to manufacture drugs and other bulk pharmaceutical compounds in drinking water [19]. After assessing the source water's condition, the treatment necessary to make it safe for human consumption is decided. Except for a minor treatment of water drawn from a natural or stored source, drinking water is unaltered [20].

3.2 Bulk purified water (BPW)

In preparing non-parenteral dosages and other pharmaceutical uses, bulk purified water is mainly employed as an excipient. Non-parenteral is most usually used to refer to the route through which oral drugs are taken; consequently, it is critical that the water used in non-parenteral preparations meet the ionic and organic chemical purity criteria [20, 21]. As feedwater for this should be at least a drinking-water source or filtered water which has at least the parameters equalling the drinking water. It must meet the applicable pharmacopeial requirements for chemical and microbiological purity, as well as action and warning limitations. It should also be protected from microbial multiplication and recontamination. A combination of reverse osmosis (RO), RO/electro-deionisation (EDI) and vapour compression can be used to make BPW [22].

3.3 Bulk highly purified water (BHPW)

BHPW is a unique water specification available only in the European Pharmacopoeia. Drinking water should be utilised as an input water source for the preparation of BHPW. This water grade must meet the same quality standards as water for injections (WFI), including endotoxin limits. In combination with other required processes, e.g. ultrafiltration and deionisation, double-pass RO is one of current manufacturing methods. BHPW can be made in various ways, including RO, ultrafiltration and deionisation. Highly cleansed water needs to be protected from recontamination and microbiological multiplication [18, 19, 23].

3.4 Bulk water for injections (BWFI)

BWFI is a common excipient in the production of parenteral and other pharmaceutical preparations where endotoxin is a concern. BWFI should be prepared with drinking water or filtered water as minimum quality feed water [21].

For pharmaceutical companies, chemical purity in BWFI is a crucial issue. The microbiological quality of the water should be consistent in testing and meet the standards for bacterial endotoxins, which are less than 0.25 IU per ml. Multi-effect distillation is the sole method for obtaining consistent BWFI. It is still the only official way of manufacturing BWFI. BWFI is not sterile water and is not intended to be used as a final dose form. BWFI is an intermediate bulk product that can be used as a component in a recipe. Sterlite water for injection (SWFI) is used for vials. The most outstanding quality of pharmacopeial WPU is BWFI. As a part of the BWFI definition, certain pharmacopoeias set restrictions on the allowed purification processes. Only distillation is permitted as the last purification stage in the International Pharmacopoeia and the European Pharmacopoeia [21–23]. Chemical and microbiological purity (including endotoxin) should be met by BWFI, with appropriate action and warning limits. BWFI should also be safeguarded from microbial multiplication and recontamination [23].

4 Textile materials for pharmaceutical filtration

Pharmaceutical filtration is divided into two-step prefiltration and main filtration. Prefiltration is any filtration procedure that takes place before the final filtration in the manufacturing process [19, 24]. The main goal is to achieve adequate particle removal. The filtration rate and throughput are other factors to consider. Fibre, yarn and fabrics (woven and nonwoven) are the basic textile products. All these textile products are used as filter media for liquid filtration. Textile fibres can be natural or manmade. Table 1 shows the properties of various textile fibres which are frequently used in liquid filtration. The aspect ratio (length and breadth or diameter) of textile fibres made them most suitable for the filter

Table 1: Fibres used in pharmaceutical filtration and characteristics [6, 10, 13]

No.	Fibre category	Fibre name	Maximum service temp (°C)	Principal properties
1	Cellulosic	Cotton, viscose, jute	90	good abrasion and very good alkali resistance, poor acid resistance, inexpensive
2	Polyamide	Nylon	100	excellent abrasion and alkali resistance, poor acid resistance, high strength or flexibility
3	Polyester	Decron, Trevira	150	very good abrasion, good acid resistance, poor alkali resistance, easy cake discharge, long life
4	PTFE (Polytetrafluoroethylene)	Teflon, Rastex	200	fair abrasion, excellent acid resistance, excellent alkali resistance, extreme, excellent cake discharge
5	Polypropylene	Moplefan (trol)	90 (120)	good abrasion, excellent acid resistance, excellent alkali resistance, low moisture absorption
6	Copolymer Acrylic	Dynel, Orlon	120	good abrasion, good acid resistance, and fair alkali resistance
7	Polypeptide	Wool	110	good abrasion, good acid resistance, poor alkali resistance
8	Silicate	Glass fibre	250	poor abrasion, fair acid resistance, poor alkali resistance, suitable for a wide range of chemical solutions

media. Strand in the form of sliver, roving or yarn is also used for the filter media. Fabrics, woven or nonwoven are the largest used textile products as filter materials.

The number of pores, pore size, yarn count and weave type define the fabric filter media. More yarns and a finer yarn count result in smaller pores and a greater number of pores in the woven fabric. Nonwoven filter media is manufactured directly from the fibre and can be used in a variety of liquid filtering systems, including filter presses, horizontal disc filters and rotary drum vacuum filters. Due to the mechanical, chemical and thermal treatments, individual fibres in nonwoven filter media are often interconnected. To preserve the filter media, loose woven materials can be utilised on both sides of the filter [6, 10, 31].

The cellulose textile fibre-based depth filter, which comes in sheet or lenticular cartridge type, is one of the most prevalent prefilters used in biopharmaceutical processes. These prefilters are particularly cost-effective due to comparatively inexpensive raw materials used in their construction, and the thickness and structure of the filter matrix created during the manufacturing process [6]. Cellulose or manufactured textile fibres, inorganic filter aid, fabrics and a polymeric wet-strength resin are the main raw components utilised to make these filters. By refining the fibres, void volume and particle retention capacity of the fibre component of the filter can be adjusted [2–6, 24].

The filter aid is the second most crucial part of the filter sheet. Perlite is volcanic ash with a smooth, glass-like texture and is also used with a mixture of cellulose fibre matrix. The particles of Perlite have a somewhat uniform shape and form thickly within the cellulose fibre matrix. The powder comes in various particle sizes, allowing for a wide range of porosity [3].

Instead of cellulosic prefilters, glass fibres are also used, especially in serum filtrations. These may be borosilicate glass or glass fibres with special coatings such as nitrocellulose polymers. The adsorption of process contaminants, particularly protein-like materials and lipids, is quite successful with these coatings. The adsorptive elimination of pollutants with a nitrated polymer is most likely accomplished through hydrogen bonding. Polypropylene fibres are also a common material for filter media [3, 25]. To limit or eliminate media movement, they can be shaped into fleeces and mats of varying fibre diameters bound together and permanently crosslinked by heat, then bonded by melting. The adhesives and mechanical manipulations of older and less effective sheet creation methods replaced the melt-spinning way of permanently connecting the fibres. Varying the mean fibre size during the fleece formation enables the mat pore size to change progressively [3, 6, 25]. Due to this filtration, the effect will be like a series of prefilters combined into a single prefilter composite. Due to the effectiveness of thinner fibres, the asymmetric morphology provides less resistance to flows, requires lower differential pressures in their operations, can accommodate higher particle loadings and delivers more particle removal. Fibres with mean diameters as tiny as 0.3 µm are capable of retaining particles as small as 1 µm in diameter from a fluid stream. A smaller pore size is created by shrinking fibre diameters rather than tightening mat packing density. This improves filter porosity while allowing for lower operational differential pressures and bigger load capacities [25, 26].

5 Continuous filtration for pharmaceutical industries

Pharmaceutical water system operators strive to create bacteria-free water that meets or exceeds purity standards. To safeguard system components and ensure that the water distributed for use is free of bacteria and most other particle pollutants, water systems employ several filters [27]. Figure 2 depicts a continuous filtration system used in pharmaceutical industries.

Particle filtration and bacterial elimination are the two main filtration products used in pharmaceutical water systems [2]. Before the reverse osmosis (RO) unit, filters are used to reduce or remove particle contaminants, whereas filters after the RO unit are used to decrease or eliminate bacterial contamination. The use of filtration products in pharmaceutical water systems generally falls into two categories, i.e. particle filtration and bacterial removal. Filtration products located before the reverse osmosis (RO) unit reduce or remove particle contaminants, while the filters following the RO unit are intended to reduce or remove bacterial contaminants. Additional filters may be necessary if the water supply includes chemicals that, if not treated, could cause early filter blocking or fouling of RO membranes [2, 25, 28].

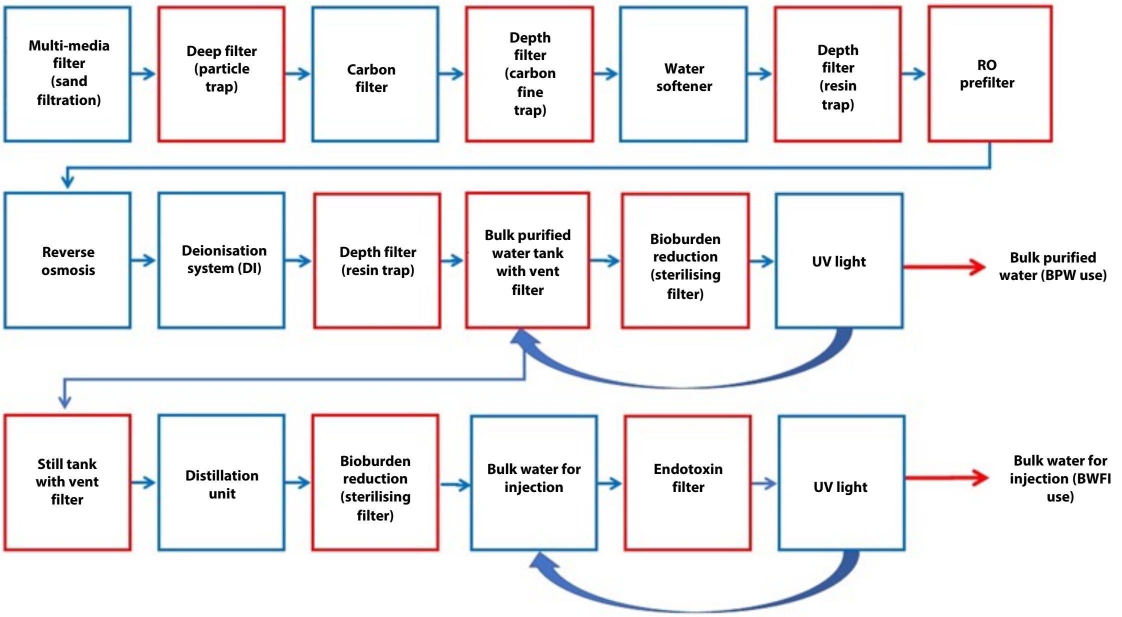

Figure 2: Filtered water system for pharmaceutical use [2, 21, 24, 25, 27, 28]

5.1 Before reverse osmosis (RO) unit

Coarse filtration is commonly used as the first step in water treatment to remove bigger particulates like sediment and silt. Figure 2 depicts a multimedia (sand) filter followed by a depth filter to remove the particles emitted by the multimedia filter. Both filters can be merged into a single particle filter housing in smaller systems [10, 27, 28, 64]. There are two types of depth media for cartridge filters. Self-supporting tubes consist of a polymer, most commonly made of polypropylene or nylon. The melt-blown or nano-spun process is used to create the tube. Pleated flat sheet media, most commonly made of polypropylene or fiberglass, is used in the other type of depth filter [10, 11]. Although polypropylene is the most frequently used material for water and chemical filtration, fiberglass offers a greater filter efficiency. It allows for higher flows and throughput in most applications than polypropylene. Through the thickness of the media, standard depth filters will catch a range of particle sizes. Pleated media filters have a larger surface area than ordinary depth filters and may hold a more significant number of particles on that surface. These items can hold a lot of silt or sediment before they need to be replaced. Yarn wound filters are also used; however, these filters add extractable surfactants to the water when they are installed [3, 6, 25].

Melt-blown and nano-spun polypropylene filters are available in a wide variety of configurations to fit the existing housings. Pleated filtration devices, such as commercial-grade pleated polypropylene (CPF) depth filters, can remove up to three times as much sediment and silt as melt-blown or nano-spun filters. However, pleated filters are more expensive; however, longer life and higher dirt holding capacity and labour savings from less frequent filter changes make pleated filters economically advantageous [2, 6, 29].

The activated carbon filter depicted in the Figure 2 is a granular carbon filter that eliminates chlorine, chloramine and other dissolved organic compounds from the water supply. Cartridges include activated carbon that is immobilised within the filter matrix. It is also possible to employ activated zeta plus carbon. It is made up of activated carbon, cellulose and a positively charged crosslinking polymer, and is designed to deliver the best filtering and purification results for a wide range of fluid issues. This prevents the oxidation of downstream treatment components, particularly RO membranes. Unfortunately, all carbon filters produce carbon fines, and fine carbon particles must be removed with depth/particulate to safeguard downstream equipment. Again, CPF melt-blown or nano-spun polypropylene depth filters and yarn wound filters can be used for carbon fines removal [2, 6, 30]. With their excellent dirt holding ability, pleated filters could also be used in this situation.

Water softening and deionisation are two resin-based treatment procedures depicted in the system diagram. These resin-based techniques will be used in small and big pharmaceutical water systems. Polishing is the term used to describe this process [30, 31].

These resin beds can be blended or separated. They are highly dependable when it comes to creating USP (US pharmacopeia) grade water; however, they do require regeneration once they are depleted. On-site or off-site regeneration is possible [32]. Before the regeneration, the resin must be separated if utilising a mixed bed. On-site regeneration capabilities are obviously more expensive in terms of capital, but they are cheaper for long-term maintenance. Continuous electro-deionisation is the advanced polishing method. Ion exchange resins in a stack remove cation and anion pollutants from the feedwater, and an electrical current runs through the stack to regenerate the resin continually [33]. The continuous regeneration eliminates the need for traditional ion exchange equipment to be shut down and regenerated regularly, allowing for the production of high-quality water [31–33]. The resin beads used to purify the water in both cases will break down over time and may release resin particles into the water supply. To remove these resin particulates from the water, textile-based depth filters must be fitted once again [34].

5.2 Reverse osmosis unit

The reverse osmosis process is supported by an RO prefilter, as illustrated in Figure 2, which protects the high-pressure RO pump and keeps the membranes from fouling due to particles. Protecting the RO membranes from particles is critical for extending membrane life. To safeguard the RO membranes, CPF offers melt-blown polypropylene, polyester filters, nano-spun polypropylene filters, pleated polypropylene, and nylon filters may be used. Though melt-blown or nano-spun cartridges may cost each less than a pleated cartridge, pleated filters may be desirable due to the lower number of filters and potentially longer filter life [2, 3, 36].

RO systems are the most common method for removing salt and organic material and inorganic and organic pollutants, colloids, microorganisms and endotoxins. Since it effectively removes inorganic/organic impurities (excluding gases), has relatively low operating costs, and is very reliable when pretreatment equipment is appropriately maintained, RO is the primary process for water purification [37].

5.3 After reverse osmosis (RO) unit

Vent filters are utilised at two points in the illustration. These are employed to filter the air directly in touch with the purified water or water for injection storage tanks and protect the water from bacterial and particle contamination. The air inside the tank must be allowed to go out as the tank fills, and when the tank is emptied, air (or a process gas like nitrogen) must be allowed to enter to replace the lost liquid volume [25, 35, 39]. Particle and bacterial contaminants must be eliminated from the tank's air or gas. The filter media must be dry for air to travel freely through it. Almost all vent filters used in biopharmaceutical manufacturing are hydrophobic membranes with pore sizes of 0.22 μm. A hydrophobic membrane such as polypropylene or PTFE is commonly used as such a membrane resists the water vapour [40]. Sterilising grade polypropylene melt-blown media (PPM) or PTM cartridges or capsules is used for ambient temperature storage tanks since most WFI storage tanks are kept at high temperatures [27, 40].

Different particle and bioburden loading are encountered in each biopharmaceutical process. Outside materials can be the path for such particles and organisms into processes. Organisms may be prevalent in the plant atmosphere, like moulds and yeasts, and can enter into the processes during mixing or are introduced through normal handling of ingredients and equipment [41]. Operators may opt to remove the majority of organisms before the sterilising filter or all of them, depending on the nature and amount of organisms. Membrane-based filters handle almost all bioburden reduction filtration [35]. However, high-efficiency pleated depth media filters can remove some big microorganisms, e.g. moulds and yeasts. Using pleated flat sheet media, polypropylene or fiberglass cartridge filters may remove organisms as minor as 1 μm in size. Most moulds and yeasts, as well as spores like Bacillus subtilis, fall into this category. Membrane filters for bioburden reduction come in various materials, with pore sizes ranging from 0.85 μm to 0.22 μm [25]. The filter material and pore size will be determined by the type of fluid being filtered, and the size and number of organisms present. If the fluid contains a more significant number of bacteria, a sub-micron-rated membrane filter with a pore size of 0.65 µm or 0.45 µm will remove the majority of the bacteria [6, 25]. It is crucial to find out how many and what size organisms there are to remove enough to prevent processes and the sterilising filter from being damaged [42]. The final filtration and point of use filtration WFI systems utilising distillation coupled with storage and distribution systems kept at elevated temperatures need no extra filtration since the water has been sterile and is preserved in a sterile state with heat [38, 43].

Due to the multitude of bacterial entry points into the system, the final filtration utilising "sterilising grade" membrane filters is regularly used as the final bacterial removal process in most ambient temperature pharmaceutical water systems [40]. Sterilising grade filters are typically rated to remove at least 100,000 bacterial colonies per ml without passing through to the product side of the filter. Filters not meeting these removal criteria are considered bioburden reduction filters rather than sterilising grade filters [41, 43]. Typical sterilising grade filters utilised in pharmaceutical water systems are rated to remove particles and bacteria that are 0.22 micron or 0.1 µm or larger in size; however, coarser filters are available as well [38, 42]. In the past, the standard was 0.22 µm. Now, one organism (Acholeplasma laidlawii) has been found to pass through these filters; therefore, manufacturers have developed a finer, 0.1-micron filter to remove this organism [42, 45, 46].

To remove endotoxins (cell fragments), ultrafiltration or charge modified filter media are utilised. Pleated nylon 6,6 membrane and single-layer charge modified nylon 6,6 membrane filter cartridge provides superior microorganism reduction while substantially increasing the life of downstream sterilising grade filters. This filter offers enhanced particle and pyrogenic removal via an electrostatic charge on the membrane [46, 47].

6 Ultrafiltration in pharmaceutical industries

Ultrafiltration (UF) is a pressure-driven membrane transport technology that has been used both in the lab and in the industry. UF is used in industries such as chemical and pharmaceutical manufacturing, food and beverage processing, and wastewater treatment to recycle flow or add value to later products [48]. The capacity of UF to purify, isolate and concentrate target macromolecules in continuous systems is its key selling point. Permeate is the solvent and other dissolved components that flow through the membrane. Retentate components are those that do not pass through [49]. UF is a separation technology that allows labile biopolymer streams (proteins, nucleic acids and carbohydrates) to be processed cost-effectively, even on a large scale, without using high temperatures, solvents or other chemicals. Low shear (e.g. positive displacement) pumps can help reduce shear denaturation. Infusion solvents, serum, vaccines and plasma are just a few of the pharmaceutical industry's products that are manufactured to the highest quality and purity standards [35,50]. UF provides solutions that have been designed to meet the needs of the pharmaceutical and biotechnology industries for a variety of applications [48, 51].

6.1 Wastewater treatment in pharmaceutical industries with ultrafiltration

Ultrafiltration plant for pharmaceutical sector is responsible for water treatment in the pharmaceutical industry [52]. This plant is utilised in the RO prefiltering stage. It helps reverse osmosis membranes by lowering the water's silt density index and removing particles. UF membranes improve RO performance and are widely utilised in desalination systems, pharmaceutical manufacturing and other industries. UF is a multi-skilled system that gives a reliable solution to wastewater problems or clean, reusable water after a complete treatment. The water produced as a result of this treatment can be used for various reasons. This method has water of such high quality that it can also be used for drinking [29].

UF utilises an air-sourced mechanism and provides excellent performance in the elucidation of wastewater. It addresses water scarcity and other water-related issues in enterprises. These systems are meant to eliminate bacteria and other microbiological debris from the water and meet the needs of enterprises across India [29, 53].

6.2 Recent and developing application of ultrafiltration

Ultrafiltration is becoming a potent separating tool for the constantly expanding biotechnology industry. Cell harvesting, depyrogenation of injectable medicines and enzyme purification are only a few examples. UF has a number of advantages over centrifugation when it comes to bacteria collection. Owing to these advantages, UF membranes are less prone to clogging by cells and debris than microporous filters due to their asymmetric nature. Another possible application of UF is plasma product processing [54]. When human plasma is fractionated using the Cohn process or other novel technologies, there is a requirement to concentrate the essential protein fractions (albumin and globulins) or remove alcohol and salt. UF is a convenient way to accomplish this [24, 55].

7 Selection and options of filter media

The heart of any filtration process is considered the filter media. While the solids to be retained are concentrated on the membrane's feed side, the liquid component is forced to pass through and delivered to the membrane's other side. A filter medium is not uniform by nature, and its dimensions and geometries are derived from irregular pores. The distribution of these pores on the membrane surface may also be uneven. The microfluidic velocity within the holes can produce considerable changes on the filter surface since the flow in the environment only occurs through the pores [56]. This implies that the top layers of the filter cake created on the membrane surface are not uniform and are shaped by the filter medium's composition and qualities. The basic structure of the cake is firmly related to the structure of initial layers since the number of channels in the filter cake is greater than the number in the filter media. This indicates that the filter crayon and the filter material influence one another [57].
In the pharmaceutical sector, various types of filters are employed. When it comes to choosing a suitable filter medium, it is worth considering two things. The first is the fluid's substance, which includes viscosity, the nature of the solids (particle size, shape, size distribution etc.) and the concentration of solids in suspension [42, 44, 46]. The second factor are the equipment and process-related issues, e.g. flow rate, particle size restriction for passing through the filter, sterilisation by heat, radiation or gas, and cost. Solid particles smaller than the narrowest cross-section of the route can be caught by the pores having channels extending along with the filter media. Particle bridging or, in rare situations, physical adsorption is commonly used to explain particle retention. Different filter media are employed depending on the intended use [57–58].
Sand, diatomite, coal, cotton or wool fabrics, fibres, yarn, metal wire cloth, porous quartz plates, chamotte, sintered glass, metal dust and powdered ebonite are some of the most often used filter media [59]. The size and shape of each element from which the filter material is made determine the average pore size and configuration (including tortuosity and connectivity). The average pore size and shape are also influenced by the filter material's manufacturing procedure. Pore characteristics are also influenced by the fibre qualities of the woven fabric or the sintering procedures used for glass and metal powders [26]. In addition, some filter media, particularly fibrous layers, experience substantial compression when exposed to common pressures used in industrial filtration operations. Under the same operating circumstances, other filter materials such as sintered ceramic plates, glass and metal powders are stable. The filtration/separation process also influences pore characteristics. Since the effective pore size decreases as filtering progresses, flow resistance rises. This is due to the particles penetrating the filter media's pores. Filtration is a complicated method for separating solid particles from liquid. The larger pore size in comparison to particle size can also be used. However, the chosen filter medium must be able to adsorb solids and have significant enough cohesive forces between the particles to cause particle aggregation around the pore holes [60]. The utilisation of various water filters and common recommendations are given in Table 2.
In the chemical and pharmaceutical industry, a belt filter is an industrial machine used for solid/liquid separation processes, particularly sludge dewatering. Filtration is accomplished principally by passing the solid for dewatering from a pair of filtering cloths and belts through a roller system.
Filter bags are another option for filtration [8]. Filter bags are composed of felt, which has the advantage of being a three-dimensional filter media that provides both surface and depth filtering. They are available in different sizes and types of filter media with different ratings [25, 40]. Polypropylene filter bags are chemically compatible and can be used in various applications. Polyester filter bags can withstand extreme temperatures and are compatible with acids and petroleum-based fluids. Filter bags

Table 2: Water filter application and recommendation for pharmaceutical industries [2, 6, 21, 28, 48, 61]

No.	Water filter application	Function of filtration	Recommended filter media
1	Particulate Reduction and Trap Filtration	Removal of larger particles and fractured softener or deionisation resin beads before further treatment or use	Polypropylene melt-blown media, nano-spun polypropylene media, polypropylene pleated depth media
2	RO Prefiltration	Protect reverse osmosis membranes from premature fouling by removing particles larger than 1 micron in size	Polypropylene melt-blown media, nano-spun polypropylene media, polypropylene pleated depth media
3	Bioburden Reduction	Used in water distribution systems to remove larger organisms and protect final filters that remove all bacteria	Polyethersulfone (PES) membrane – nylon 6,6 membrane, positively charged nylon 6,6 membrane, high capacity hydrophilic (PVDF) membrane, high capacity polyethersulfone membrane
4	Bacteria Removal, Sterilising Filtration	Protect water quality for the patient, consumer or end use; remove all bacteria; may remove viruses and mycoplasma	Polyethersulfone (PES) membrane – nylon 6,6 membrane, positively charged nylon 6,6 membrane,
5	Ultra-Fine Particle Removal	Prevent sub-micron particles from reaching processes requiring ultra-pure water, such as semiconductor fabrication	Polyethersulfone (PES) membrane – nylon 6,6 membrane, positively charged nylon 6,6 membrane.
6	Tank Vent Filtration	Prevent airborne bacteria and fine particles from contaminating process or product water as it is held in tanks	PTFE membrane, polypropylene membrane, high capacity hydrophobic PVDF membrane

are commonly used to prepare adhesives, syrups, fruit juices, petroleum compounds and fluids with high viscosity [6, 25, 61]. Various filter forms used in the filtration system are shown in Figure 3.

The filters are cleaned using various methods, including manual, mechanical and self-cleaning filter systems. Cleaning is done manually with a water jet. The filters may need to be soaked in chlorine or detergent on occasion. Brushes or knives are used for mechanical cleaning. Disposable trash and labour costs are reduced as a result of automation. Product loss is reduced by using a self-cleaning filter system that requires little user effort. Some examples are magnetically connected industrial filters, self-cleaning filters and tubular backwashing filters, e.g. clearamine and reactogard filters, and piezoelectric ceramic membrane (PCM) [62].

a) b)

Figure 3: Filter forms used in filtration system: a) cartridge of polypropylene and b) carbon filter sheet and cartridge [3, 6, 10, 29, 30]

8 Current market of pharmaceutical filtration and impact of COVID-19

According to the latest market research report "Pharmaceutical Filtration Market" published by Markets™, the global Pharmaceutical Filtration Market is projected to reach 29.7 billion USD by 2027 from 10.9 billion USD in 2022, a CAGR of 17.0% during the forecast period of 2022 to 2027 [63]. This growth can be attributed to the growing biopharmaceutical industry, advanced research, increasing adoption of single-use technologies, increasing the new product, high purity requirements in end-user segments and advances in nanofibre technology [25, 63]. The pharmaceutical filtration market covers filters, systems and other filtration products. The filters used in the current time are membrane filters and depth filters. Polyethersulfone (PES), polyvinylidene difluoride (PVDF), nylon, polytetrafluoroethylene (PTFE), mixed cellulose ester & cellulose acetate (MCE & CA), polycarbonate tracked etched (PCTE), polypropylene (PP), cellulose nitrate (CN), regenerated cellulose (RC) are commonly used membranes [9, 25, 40, 63].

COVID-19, a worldwide epidemic, has affected people and businesses in practically every field. It is an infectious disease caused by a new coronavirus that has only recently been discovered [65]. As the World Health Organisation named the COVID-19 outbreak a pandemic, several prominent pharmaceutical and biopharmaceutical businesses ramped up research and production efforts to create and distribute SARS-CoV-2 viral test kits, vaccines and treatments. The pandemic's economic and social costs have spurred governments worldwide to increase funding for vaccine development and production, resulting in a rise in the use of pharmaceutical filtration products in COVID-19 research and production. Pharmaceutical filtration goods are employed in the production process of vaccines and other therapeutic medications; therefore, demand has increased as government backing, research activities and mass production of vaccines after approvals have increased [9, 64–66]. Removing suspended particles from a fluid medium during vaccine clarification is an important step that affects product recovery and downstream purification. Biopharmaceutical companies are using various filtration techniques and materials to help the downstream process (including filtration and purification) of vaccine production. Merck Millipore has donated USD 0.086 million in research apparatus and supplies to Indonesia's Eijkman Institute for Molecular Biology to speed up vaccine development. Merck has contributed water purification equipment with integrated reverse osmosis membranes for pretreatment and high performance that generate high-quality type-3 clean water. Pall Corporation, a Danaher subsidiary, has provided syringe filters, membrane filters, air filters, and water filters for vaccine and medicine manufacture, and research and development [9, 63].

In addition, the pandemic has provided possibilities for filtration companies to expand their production facilities. In the pharmaceutical filtration industry, the impact of the coronavirus crisis on supply chains, manufacturing and shipments to consumers has been controllable, with positive organic growth. Short- and medium-term predictability is severely limited and has little impact [62, 63, 66].

9 Conclusion

In the pharmaceutical sector, filtration is a crucial process. There is not a single aspect of the pharmaceutical industry that is not touched by filtration. For the pharmaceutical industry, drinking water, purified water and water for injection are required and obtained by different filtration methods. Despite the negative effects of the COVID-19, the market for pharmaceutical filtrations continues to grow. Textile materials in any form play an important role in the pharmaceutical filtration system. The innovative applications of textile filtration fabrics have been widely accepted in the pharmaceutical industry in the process of separation and purification of liquids. Due to their unique characteristics, textile filtration materials help maintain the high level of separation of particles from the fluids. A variety of filters media made from textile products (fibre, yarn, fabric, pleated polypropylene, charged nylon, polyester, nanofibers etc.) is often used in the filtration systems of pharmaceutical industries. In the pharmaceutical industry, the use of novel technology, new polymeric materials, and commercially available patent filters in bag and cartridge forms results in shorter filtration times and higher product quality. Multimedia filter, carbon filter, resin filter, reverse osmosis, distillation and UV lights may be utilised for contamination and particulate removal, and bacteria control.

References

1. SUTHERLAND, K. *Profile of the international filtration & separation industry*. Elsevier Science, 2004, 11–67, doi: 10.1016/b978-185617448-0/50004-x.
2. MAJEKODUNMI, S.O., OLORUNSOLA, E.O. Review of some recent advances on filtration in the pharmaceutical industry. *IOSR Journal of Pharmacy and Biological Sciences*, 2014, **9**(4), 30–38, doi: 10.9790/3008-09443038.
3. JORNIT, M.K. Filter design. In *Filtration and purification in the biopharmaceutical industry*. 3rd ed. Edited by Maik W. Jornitz. Boca Raton : CRC Press, 2019, 41–56, doi: 10.1201/9781315164953.
4. CHAUHAN, V.K., SINGH, J.P., DEBNATH, S. Virgin and recycled polyester filter media: effect of coating, calender roller pressure and roller temperature on dust filtration. *The Journal of The Textile Institute*, 2021, **113**(3), 467–474, doi: 10.1080/00405000.2021.1884361.
5. OSTREICHER, E.A., ARNOLD, T.E., CONWAY, R.S. Charge-modified filter media. In *Filtration and purification in the biopharmaceutical industry*. 3rd ed. Edited by Maik W. Jornitz. Boca Raton : CRC Press, 2019, 1-20.
6. EYVAZ, M., ARSLAN, S., GÜRBULAK, E., YÜKSEL, E. Textile materials in liquid filtration practices: current status and perspectives in water and wastewater treatment. In *Textiles for advanced applications*. Edited by Bipin Kumar and Suman Thakur. London : IntechOpen, 2017, doi: 10.5772/intechopen.69462.
7. MUKHOPADHYAY, A. Pulse-jet filtration: an effective way to control industrial pollution part II: process characterization and evaluation of filter media. *Textile Progress*, 2010, **42**(1), 1–97, doi: 10.1080/00405160903438367.
8. FRANCHI, A., SANTORO, D. Current status of the rotating belt filtration (RBF) technology for municipal wastewater treatment. *Water Practice and Technology*, 2015, **10**(2), 319–327, doi: 10.2166/wpt.2015.038.
9. Global pharmaceutical filtration market research report 2021 - Impact of COVID-19 on the market [online]. Market Growth Reports [accessed 2. 10. 2022]. Available on World Wide Web: <https://www.marketgrowthreports.com/TOC/19614702#TOC accessed on 17/05/2022>.
10. ROY, S. GHOSH, S., BHOWMICK, N. Mechanism of colloidal attachment on textile fibrous media. *Tekstilec*, 2018, **62**(2), 101-109, doi: 10.14502/Tekstilec2019.62.101-109.
11. PERLMUTTER, B.A. *Solid-liquid filtration. Practical guides in chemical engineering*. Elsevier, 2015, 57–77, doi: 10.1016/b978-0-12-803053-0.00005-5.
12. VIGNESWARAN, S., BEN AIM, R. Overview of deep bed filtration: different types and mathematical models. In *Water, wastewater, and sludge filtration*. CRC Press, 2020, 1–16, doi: 10.1201/9781003068655.
13. LI, X., LI, J. Cross-flow filtration. In *Encyclopedia of membranes*. Edited by Drioli E. and Giorno L. Berlin, Heidelberg : Springer, 2016, 1–2, 10.1007/978-3-662-44324-8_2194.
14. STRADE, E. KALNINA, D., KULCZYCKA, J. Water efficiency and safe re-use of different grades of water - topical issues for the pharmaceutical industry. *Water Resources and Industry*, 2020, **24**, 1-16, doi: 10.1016/j.wri.2020.100132.
15. JENKINS, J.O, ORAM, S. Water use attitudes in the UK pharmaceutical industry. *Water and Environment Journal*, 2013, **27**(4), 575–580, doi:10.1111/wej.12000.
16. McCORMICK, K. Water for pharmaceutical uses. *Quality*, 2002, **2**, 193–217, doi: 10.1016/b978-075065113-4/50014-3.
17. ISO 22519:2019. *Purified water and water for injection pretreatment and production systems*. Geneva : International Organization for Standardization, 2019, 35 p.
18. OLAITAN, M.O., MUHAMMAD, B. Assessment of microbiological quality of syrup and water used in pharmaceutical industries in Kano State, Nigeria. *Ife Journal of Science*, 2018, **20**(1), 119–126, doi: 10.4314/ijs.v20i1.12.
19. JORNITZ, M.W. Media and buffer filtration requirements. In *Filtration and purification in the biopharmaceutical industry*. 3rd ed. Edited by Maik W. Jornitz. Boca Raton : CRC Press, 2019, 331–348, doi: 10.1201/9781315164953-14.
20. SPELLMAN, F.R. Drinking water regulations. In *The drinking water handbook*. 3rd ed. Boca Raton : CRC Press, 2017, 25–51, doi: 10.1201/9781315159126-3.
21. SILVERSTEIN, I. Pharmaceutical excipient good manufacturing practices. In *Good manufacturing practices for pharmaceuticals*. 7th ed. Boca Raton : CRC Press, 2018, 227–240, doi: 10.1201/9781315120669-16.
22. SPINKA, H., JACKOWSKI, P. Purified water quality study : technical report (No. ANL-HEP-

TR-00-16). Argonne National Lab., IL (US). United States : N.P., 2000, doi: 10.2172/754234.

23. ABDALLAH, H., SHALABY, M.S., SHABAN, A.M. Design of low energy integrated membranes units for production of highly purified water. *Advanced Energy Conversion Materials*, 2020, **1**(1), 1–14, doi: 10.37256/aecm.112020129.
24. QUIGLEY, George. Prefiltration in pharmaceutical process. In *Filtration and purification in the biopharmaceutical industry.* 3rd ed. Edited by Maik W. Jornitz. Boca Raton : CRC Press, 2019, 1–20, doi:10.1201/9781315164953.
25. Filter Options for Small Molecule Drug Production [online]. Critical Process Filtration, Inc. [accessed 2. 10. 2022]. Available on World Wide Web: <https://www.criticalprocess.com/hubfs/Application%20Summaries%20and%20Selection%20Guides/Sel-Gd_PharmaAPI.pdf>.
26. SHARMA, P.K., MURUGESAN, S., TABORA, J.E. Design of filtration and drying operations. In *Chemical engineering in the pharmaceutical industry: active pharmaceutical ingredients. 2nd ed.* Edited by David J. am Ende and Mary T. am Ende. John Wiley, 2019, 799–831, doi: 10.1002/9781119600800.ch35.
27. VACURA, K. Filtration Industry overview: world pharma and biotechnology market 2008. *Filtration & Separation*, 2008, **45**(8), 22–24, doi: 10.1016/s0015-1882(08)70295-7.
28. PRAGER, Gary. Pharmaceutical water systems. In *Practical Pharmaceutical Engineering.* Wiley, 2018, 53–130, doi: 10.1002/9781119418764.ch2.
29. LEONHAUSER, J., PAWAR, J., BIRKENBEUL, U. Novel technologies for the elimination of pollutants and hazardous substances in the chemical and pharmaceutical industries. In *Industrial wastewater treatment, recycling and reuse.* Elsevier, 2014, 215–234, doi: 10.1016/B978-0-08-099968-5.00005-2.
30. YIGZAW, Y., PIPER, R., TRAN, M., SHUKLA, A. Exploitation of the adsorptive properties of depth filters for host cell protein removal during monoclonal antibody purification. *Biotechnology Progress,* 2008, **22**(1), 288-296, doi: 10.1021/bp050274w.
31. THAKUR, R., DAS, D., DAS, A. Optimization study to improve filtration behaviour of electret filter media. *The Journal of The Textile Institute*, 2016, **107**(11), 1456–1462, doi: 10.1080/00405000.2015.1128207.
32. TRABOCCHI, A. Principles and applications of small molecule peptidomimetics. In *Small molecule drug discovery*. Edited by Andrea Trabocchi and Elena Lenci. Elsevier, 2020, 163–195, doi: 10.1016/b978-0-12-818349-6.00006-6.
33. BARNES, R.G., CHU, C., EMOND, G.T., ROY, A.K. *Charge modified microporous membrane process for charge modifying said membrane, and process for filtration of fluids, U.S. Patent 4473475. 1984-09-25.*
34. LARSON, K.L., HANSEN, C., RITZ, M., CARREÑO, D. Acceptance and impact of point-of-use water filtration systems in rural Guatemala. *Journal of Nursing Scholarship*, 2016, **49**(1), 96–102, doi: 10.1111/jnu.12260.
35. ATKINSON, S. Pharmaceutical plant selects QUA EnviQ ultrafiltration membranes for MBR system. *Membrane Technology*, 2021, **2019**(1), doi: 10.1016/s0958-2118(19)30019-9.
36. CHEN, K.L., SONG, L., ONG S.L., NG, W.J. The development of membrane fouling in full-scale RO processes. *Journal of Membrane Science*, 2004, **232**(1-2), 63–72, doi: 10.1016/j.memsci.2003.11.028.
37. BELKACEM, M., BENSADOK, K., REFES, A., CHARVIER, P.M., NEZZAL, G. Water produce for pharmaceutical industry: role of reverse osmosis stage. *Desalination,* 2008, **221**(1-3), 298–302, doi: 10.1016/j.desal.2007.01.086.
38. PARKINSON, J., BARON, J.L., HALL, B., BOS, H., RACINE, P., WAGENER, M.M., STOUT, J.E. Point-of-use filters for prevention of health care acquired Legionnaires disease: field evaluation of a new filter product and literature review, *American Journal of Infection Control*, 2020, **48**(2), 132–138, doi: 10.1016/j.ajic.2019.09.006.
39. DOSMAR, M., WOLBER, P., BRACHT, K., TRÖGER, H., WAIBEL, P. The water pressure integrity test—A new integrity test for hydrophobic membrane filters. *Journal of Parenteral Science and Technology*, 1992, **46**(4), 102–106.
40. Sterile Tank Vent Filters [online]. Micropure Filtration [accessed 21. 5. 2022]. Available on World Wide Web: <http://www.micropure.com/tankventfilter.htm>.
41. TRABOCCHI, A. Principles and applications of small molecule peptidomimetics. In *Small molecule drug discovery.* Edited by Andrea Trabocchi and Elena Lenci. Elsevier, 2020, 163–195, doi: 10.1016/B978-0-12-818349-6.00006-6.
42. Jornitz, M.W, Membrane pore structure and distribution. In *Filtration and purification in the biopharmaceutical industry.* 3rd ed. Edited by Maik

W. Jornitz. Boca Raton : CRC Press, 2019, 57-67, doi: 10.1201/9781315164953.
43. CARTER, J.R., LEVY, R.V. Microbial retention testing in the validation of sterilizing filtration. In *Filtration in the biopharmaceutical industry*. Edited by T. H. Meltzer and M. W. Jornitz. New York : Marcel Dekker, 1997.
44. Filtration [online]. GMM Pfauder [accessed 12. 5. 2022]. Available on World Wide Web: <https://www.gmmpfaudler.com/lab-and-process-glass/units-processes/filtration>.
45. JOHNSTON, P.R. *Fluid sterilization by filtration*. 3rd edition. Boca Raton : CRC Press, 2004, 15-35.
46. ARANHA, H., MEEKER, J. Microbial retention characteristics of 0.2-microns-rated nylon membrane filters during filtration of high viscosity fluids at high differential pressure and varied temperatures. J*ournal of Pharmaceutical Science and Technology*, 1995, **49**(2), 67–70.
47. GUENEC, O. Sterility testing by filtration in the pharmaceutical industry. In *Filtration and purification in the biopharmaceutical industry*. 3rd ed. Edited by Maik W. Jornitz. Boca Raton : CRC Press, 2019, 571–586, doi: 10.1201/9781315164953-22.
48. ÇELEBIER, M. Ultrafiltration-based sample preparation for pharmaceutical analysis. *Current Pharmaceutical Analysis*, 2021, **17**(8), 951–959, doi: 10.2174/1573412916999200729172653.
49. EBERSOLD, M.F., ZYDNEY, A.L. The effect of membrane properties on the separation of protein charge variants using ultrafiltration. *Journal of Membrane Science*, 2004, **243**(1-2), 379–388, doi: 10.1016/j.memsci.2004.06.043.
50. RAO, S., ZYDNEY, A.L. Controlling protein transport in ultrafiltration using small charged ligands. *Biotechnology and Bioengineering*, 2005, **91**(6), 733–742, doi: 10.1002/bit.20543.
51. ETZEL, M.R., ARUNKUMAR, A. Charged ultrafiltration and microfiltration membranes for antibody purification. In *Process scale purification of antibodies*. 2nd ed. Edited by Uwe Gottschalk. Hoboken : John Wiley & Sons, 2017, 247–268, doi: 10.1002/9781119126942.ch12.
52. CHRISTY, C., RUBIN, D. Selecting the right ultrafiltration membrane for biopharmaceutical applications. *Pharmaceutical Technology Europe*, 2002, **14**(12), 39–45.
53. MAHIRULLAH, M., WIDIASA, I.N. Study on ultrafiltration of hospital wastewater treatment effluent. In *IOP Conference Series: Materials Science and Engineering (Vol. 1053, No. 1, p. 012120)*. IOP Publishing, 2021, doi: 10.1088/1757-899X/1053/1/012120.
54. UROŠEVIĆ, T., POVRENOVIĆ, D., VUKOSAVLJEVIĆ, P., UROŠEVIĆ, I., STEVANOVIĆ, S. Recent developments in microfiltration and ultrafiltration of fruit juices. *Food and Bioproducts Processing*, 2017, **106**, 147–161, doi: 10.1016/j.fbp.2017.09.009.
55. SINGH, V., JAIN, P.K., DAS, C. Performance of spiral wound ultrafiltration membrane module for with and without permeate recycle: experimental and theoretical consideration. *Desalination*, **322**, 94–103, doi: 10.1016/j.desal.2013.05.012.
56. RITSON, J.P. GRAHAM, N.J.D. TEMPLETON, M.R. CLARK, J.M. GOUGH, R. FREEMAN, C. The impact of climate change on the treatability of dissolved organic matter (DOM) in upland water supplies: a UK perspective. *Science of the Total Environment*, 2014, **473-474**, 714–731, doi: 10.1016/j.scitotenv.2013.12.095.
57. CESCON, Anna. JIANG, Jia-Qian. Filtration process and alternative filter media material in water treatment. *Water*, 2020, **12(12)**, 1–20, doi: 10.3390/w12123377.
58. LAVENDER, P. Filter media: treating chemical wastewaters. *Filtration and Separation*, 2008, **45**(4), 16–18, ddoi: 10.1016/S0015-1882(08)70087-9.
59. MORITA, A.K.M., REALI, M.A.P. Fiber filter built with polypropylene fibers applied to water clarification. *Water Supply*, 2019, **19(4)**, 1036–1043, doi: 10.2166/ws.2018.150.
60. LOGSDON, G.S. HORSLEY, M.B. FREEMAN, S.D.N. NEEMANN, J.J., BUDD, G.C. Filtration processes – a distinguished history and a promising future. *Journal of American Water Works Association*, 2006, **98**(3), 150–162, doi: 10.1002/j.1551-8833.2006.tb07613.x.
61. BARBUSIŃSKI, K, FILIPEK, K. Water and wastewater treatment: selected topics. *Clean Technologies*, 2022, **4**(1), 91–96, doi: 10.3390/cleantechnol4010007.
62. MAO, H., FAN, W., CAO, H., CHEN, X., QIU, M., VERWEIJ, H., & FAN, Y. Self-cleaning performance of in-situ ultrasound generated by quartz-based piezoelectric membrane. *Separation and Purification Technology*, 2022, **282**(Part B), 1-10, doi: 10.1016/j.seppur.2021.120031.

63. Pharmaceutical membrane filtration market research report by product (accessories, filters, and systems), material, technique, application, region (Americas, Asia-Pacific, and Europe, Middle East & Africa) - global forecast to 2027 - cumulative impact of covid-19 [online]. Research and Markets [accessed 16. 5. 2022]. Available on World Wide Web: <https://www.researchandmarkets.com/reports/5311221/pharmaceutical-membrane-filtration-market accessed on 16/05/2022>.
64. TYLE, P. Filtration in the pharmaceutical industry. *Journal of Pharmaceutical Sciences*, 1987, **76**(2), 185, doi: 10.1002/jps.2600760223.
65. WHO Director-General's opening remarks at the media briefing on COVID-19 - 11 March 2020 [online]. WHO [accessed 16. 5. 2022]. Available on World Wide Web: <https://www.who.int/director-general/speeches/detail/who-director-general-s-opening-remarks-at-the-media-briefing-on-covid-19---11-march-2020>.
66. Pharmaceutical filtration market size, COVID-19. Impact analysis, regional outlook, application development potential, price trends, competitive market share & forecast, 2022 – 2028 [online]. Global Market Insight [accessed 17. 5. 2022]. Available on World Wide Web: <https://www.gminsights.com/industry-analysis/pharmaceutical-filtration-market accessed on 17/05/2022>.

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