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Development of Biodegradable Nonwoven Fabrics from *Alpinia purpurata* Pseudo-Stem Fibres Using Poly Lactic Acid Binder

*Razvoj biorazgradljivih vlaknovin iz vlaken, pridobljenih iz navideznega stebela rastline *Alpinia purpurata*, in polimlečne kisline kot veziva*

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Abstract

This study investigates the development of biodegradable nonwoven fabrics utilizing *Alpinia purpurata* pseudo-stem fibres, bonded with poly lactic acid (PLA) through a thermal bonding process. Given the underutilization of *Alpinia purpurata* fibres, this research explores their potential for sustainable textile applications. The fibres were extracted via decortication and blended with PLA at varying mass ratios (90/10, 80/20, 70/30), followed by comprehensive characterization. Evaluations included fabric mass per unit area, thickness, air permeability, tensile strength, elongation, wetting time, moisture regain and surface morphology. The results indicate that increasing PLA content enhances tensile strength but reduces air permeability and water absorption. Conversely, a higher proportion of *Alpinia purpurata* fibres improves breathability and moisture regain. These findings demonstrate that *Alpinia purpurata* fibres, in combination with PLA, can produce nonwoven fabrics with tunable properties, offering promising potential for environmentally friendly textile applications.

Keywords: nonwoven fabrics, *Alpinia purpurata* pseudo-stem fibres, poly lactic acid, biodegradable binder, thermal bonding method

Izvleček

Študija zajema razvoj biorazgradljivih vlaknovin z uporabo vlaken iz navideznega stebela rdečega ingverja (*Alpinia purpurata*), termično utrjenih s polimlečno kislino (PLA). Glede na slabo izkoriščenost vlaken rdečega ingverja je bila v tej raziskavi proučevana možnost uporabe teh vlaken za trajnostne tekstilije. Vlakna so bila strojno ekstrahirana iz navideznega stebela in mešana v različnih masnih razmerjih s PLA (90/10, 80/20, 70/30), čemur sta sledili termična obdelava in celovita karakterizacija.ocene so vključevale ploščinsko maso vlaknovine, debelino, zračno prepustnost, natezno



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trdnost/raztezek, čas omočenja, vsebnost vlage in morfologijo površine. Rezultati kažejo, da povečanje vsebnosti PLA izboljša natezno trdnost, vendar poslabša zračno prepustnost in absorpcijo vode. Nasprotno pa večji delež vlaken *Alpinia purpurata* izboljša zračnost in vsebnost vlage. Ugotovitve kažejo, da iz vlaken *Alpinia purpurata* v kombinaciji s PLA lahko izdelajo vlaknovine načrtovanih lastnosti, kar je velik potencial za razvoj okolju prijaznih tekstilij.

Ključne besede: netkane tkanine, polilaktid, biorazgradljivo vezivo, metoda toplotnega utrjevanja

1 Introduction

The textile industry continually seeks innovative materials that provide environmental benefits along with novel functional properties. Natural fibres have become increasingly popular due to their biodegradability and sustainable nature, aligning with global trends towards environmentally friendly products [1]. Among various natural sources, pseudo-stem fibres from plants such as *Alpinia purpurata* present a promising avenue for exploration. *Alpinia purpurata* (Figure 1a) is primarily cultivated for its rhizome [2,

3]. However, the pseudo-stem, which is considered agricultural waste, remains underutilized (Figure 1b) and represents potential as a raw material for fibre production. Previous studies have successfully utilized pseudo-stem fibres from similar species in textile applications, indicating the feasibility of this approach [4].

Previous research has shown that fibres extracted from *Alpinia purpurata* pseudo-stems possess properties suitable for textile applications [5]. Tradi-



Figure 1: a) *Alpinia purpurata* plant, b) rhizome and pseudo stem of *Alpinia purpurata*

tionally, these fibres were extracted using the water retting method, a time-consuming and labour-intensive process where plant stems are soaked in water to loosen the fibres. To improve efficiency, this study focuses on using decortication—a mechanical method that separates fibrous material from non-fibrous components—thereby enhancing the extraction process. Decorticators play a crucial role in fibre production by improving the efficiency and quality of extracted fibres. This mechanical method, widely applied to other fibres such as flax and hemp, allows for efficient fibre extraction without the need for the labour-intensive retting processes [6].

The development of nonwoven fabrics using natural fibres is an area of significant interest due to their wide range of applications, from geotextiles to hygiene products [7–9]. Nonwoven fabrics are preferred for certain applications due to their adaptability, cost-effectiveness, and high-speed manufacturing compared to traditional woven fabrics. The integration of bio-based polymers such as poly lactic acid (PLA) in nonwoven fabric production further enhances their environmental appeal, as PLA is known for its biodegradability and is derived from renewable resources [10–13].

The conversion of agricultural byproducts such as *Alpinia purpurata* pseudo-stems into useful materials aligns with sustainable development principles, particularly reduction, reuse and recycling [14]. Natural fibres from agricultural waste, such as banana stems, pineapple leaves and coconut coir, are increasingly recognized for their mechanical properties, low density and renewability [15].

Recent advancements in sustainable textile production have explored non-traditional fibrous plants, leading to the development of innovative textile products. For example, fibres from plants such as *Furcraea foetida*, *Cordyline australis*, and *Etilingera elatior* have shown potential in creating new raw material for textiles [16–18]. Similarly, *Alpinia purpurata* pseudo-stem fibres could be utilized as a sustainable raw material, thereby contributing to the reduction of environmental impacts.

The production of nonwoven fabrics, known for their versatility and cost-effectiveness, often involves thermal bonding techniques. Thermal bonding involves the application of heat to a thermoplastic component, which can exist in the form of fibres, powders, films or melts. The heat causes the thermoplastic material to become viscous or melt, enabling it to flow to fibre crossover points where bonding regions are formed and solidify upon cooling. These bonds, primarily mechanical or adhesive, arise from physical interactions at the interface between different materials. The resulting thermally bonded fabrics can be composed entirely of thermoplastic materials or blends that include non-thermoplastic fibres [19]. The binder, typically representing 5–50% of the total weight, significantly affects a fabric's properties, such as tensile strength, flexibility and biodegradability. The remaining 50–95% consists of base fibres, which are crucial in determining a fabric's final characteristics. Commonly used base fibres include natural fibres, synthetic fibres and mineral fibres. Thermal bonding is preferred for its economic and environmental benefits, and for its ability to produce recyclable and sustainable textile products [19].

The research problem centres on the utilization of *Alpinia purpurata* pseudo-stem fibres for nonwoven fabric production, a domain that has not been extensively studied. The primary challenge is determining the mechanical and physical properties of these fibres and understanding their behaviour when combined with a thermal bonding method using PLA as a binder. The hypothesis suggests that nonwoven fabrics can be developed from decorticated *Alpinia purpurata* pseudo-stem fibres that meet the functional requirements for textile applications, necessitating a thorough investigation of fibre characteristics and fabric performance [5, 20].

The general solution involves a novel approach using the thermal bonding technique to create nonwoven fabrics. Thermal bonding is widely recognized for its effectiveness in bonding fibres through heat application, eliminating the need for additional

weaving or knitting processes [19]. This method is particularly suitable for preserving the structural integrity of delicate pseudo-stem fibres, as it minimizes mechanical stress that could degrade their physical properties. The selection of PLA as a biodegradable binder further enhances the sustainability of a fabric, aligning with previous studies that highlight its role in improving fibre cohesion while maintaining biodegradability [20]. Consequently, the combination of thermal bonding and PLA offers a promising pathway for developing environmentally friendly nonwoven fabrics with potential applications in the textile industry [20].

Thermal bonding is a well-established method in nonwoven fabric production, and is particularly advantageous for blending synthetic and natural fibres [19, 21]. It involves the application of heat and pressure to bond fibre webs, often using biopolymers such as PLA as binders [19, 21]. This method is ideal for *Alpinia purpurata* fibres, as it preserves their natural properties while ensuring adequate bonding and structural integrity [20].

Although extensive research has been conducted on nonwoven fabrics derived from natural fibres such as banana and hemp, a significant gap remains in studies specifically examining *Alpinia purpurata* pseudo-stem fibres. While previous literature has highlighted the potential of various pseudo-stem fibres for nonwoven fabric applications, the unique properties and performance of *Alpinia purpurata* fibres in this context remain unexplored. This gap in research limits the understanding of how these fibres interact with biodegradable binders such as PLA during the thermal bonding process. Addressing this knowledge gap is crucial to expanding scientific insights into the feasibility, structural characteristics and sustainability of *Alpinia purpurata*-based nonwoven fabrics, thereby unlocking new opportunities for eco-friendly textile applications.

Despite the promising potential of *Alpinia purpurata* fibres, research regarding their application in nonwoven fabric production remains scarce, particularly in combination with biodegradable

binders such as PLA. To date, no scholarly studies have explored the development of nonwoven fabrics using decorticated *Alpinia purpurata* fibres, or evaluated their structural and mechanical properties. This study seeks to fill this gap by investigating the feasibility of utilizing *Alpinia purpurata* fibres in nonwoven fabric applications using the thermal bonding method.

This study aims to bridge the research gap by examining the properties of nonwoven fabrics produced from *Alpinia purpurata* pseudo-stem fibres, utilizing the thermal bonding method with PLA as a biodegradable binder. Unlike previous studies that have focused on other natural fibres such as banana and hemp, no prior research has specifically investigated *Alpinia purpurata* fibres for nonwoven applications. The novelty of this research lies in the introduction of *Alpinia purpurata* as a new natural fibre source in textile technology, thereby contributing to the development of sustainable and eco-friendly textile products.

2 Materials and methods

The production and characterization of nonwoven fabrics from *Alpinia purpurata* fibres and PLA involve several key steps, as illustrated in Figure 2. These steps include the harvesting of the stems, fibre decortication, fibre drying, PLA powder preparation and the blending of PLA with the fibres. The fabricated nonwoven fabrics were then subjected to various characterization tests to evaluate their mass per unit area, thickness, air permeability, tensile strength, wetting time and moisture regain. The process flow highlighted in Figure 2 provides a comprehensive overview of the methodology used to develop these fabrics and assess their performance characteristics.

2.1 Materials

Alpinia purpurata stems (Figure 3a) were harvested from Bogor city, West Java, Indonesia. These stems were approximately 10–12 months old and had reached a height of 1–2 meters. Polylactic acid

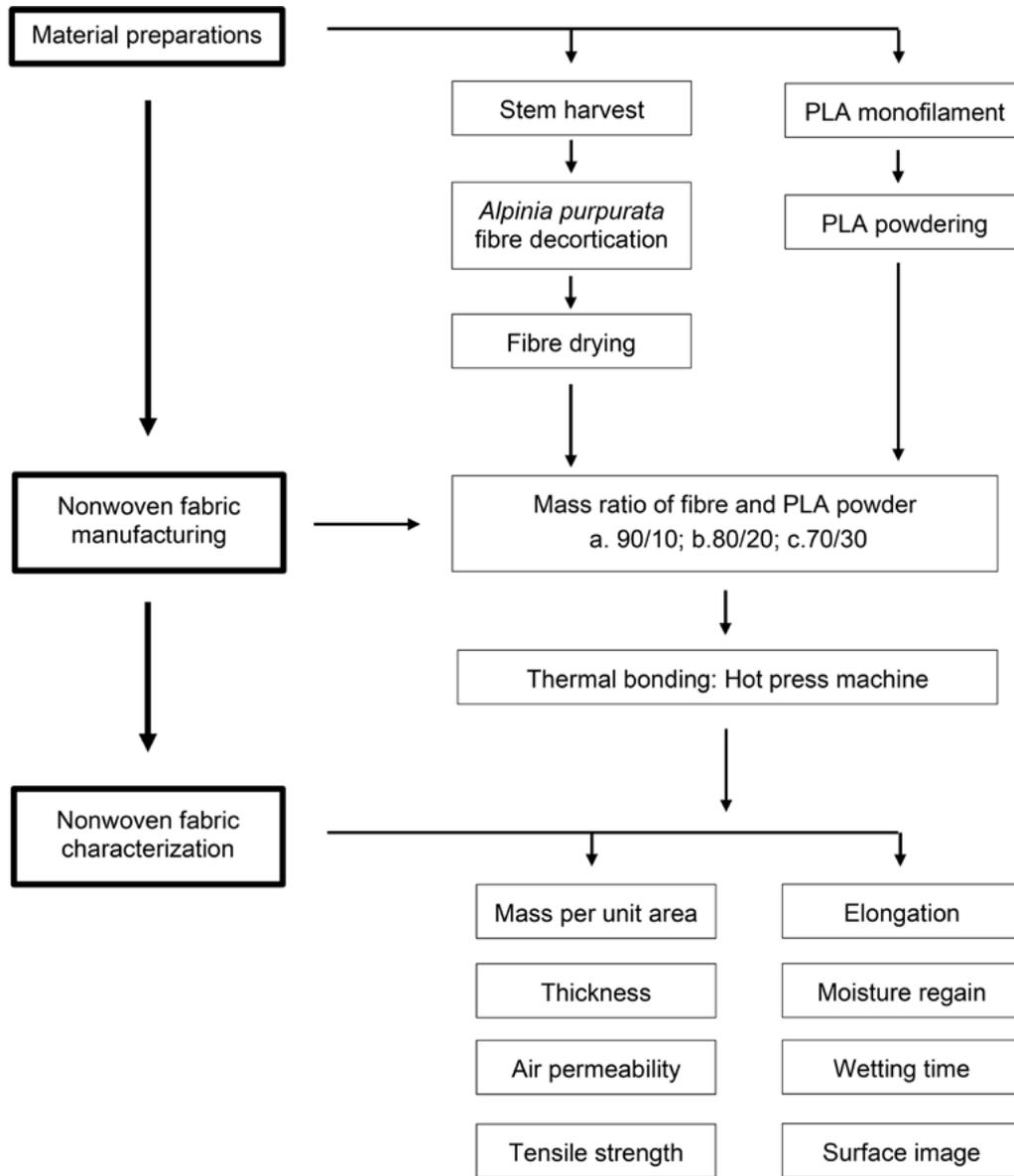


Figure 2: Process steps in the fabrication and characterization of nonwoven fabrics made from *Alpinia purpurata* fibres and PLA

(PLA) powder was used as the binding agent due to its biodegradable properties and compatibility with natural fibres. The PLA powder (Figure 3c) was derived from 100% polylactic acid monofilament fibres (Figure 3b), which were powdered using a blender.

2.2 Methods

2.2.1 Fibre extraction

Alpinia purpurata fibres were extracted from the plant's stems through the decortication process,

which involves different methods with decortication being a common mechanical process used for this purpose. Decortication helps separate valuable bast fibres from plant stems by breaking down components such as pectin, lignin, and hemicellulose [6]. This process is essential for obtaining high-quality raw materials for further processing [22].

Fibre extraction was performed using a decorticator machine, as shown in Figure 4. The minimum fibre length to be processed using the decorticator

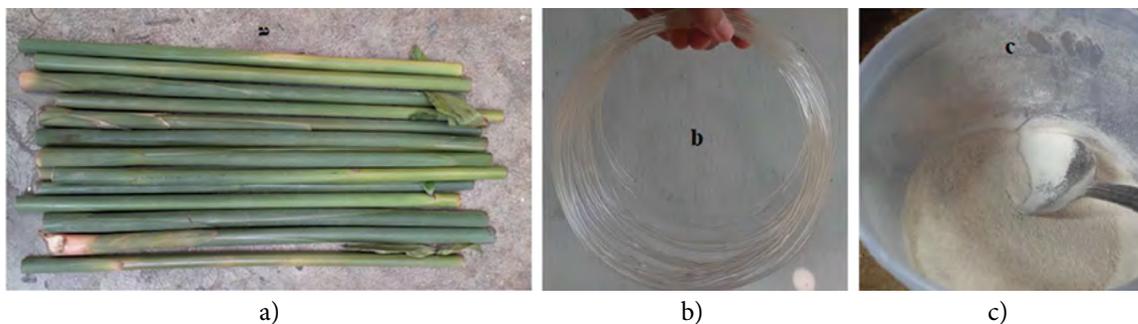


Figure 3: a) *Alpinia purpurata* pseudo stem, b) poly lactic acid monofilament, c) poly lactic acid powder

machine is 60 cm. Therefore, after harvesting, the stems were cut into 60–80 cm lengths. After decortication, the fibres were dried in the shade by aerating them and turning them upside down to ensure they dried quickly and evenly without exposure to direct sunlight. The dried fibres were then ready to be processed into nonwoven fabric.



Figure 4: Fibre extraction process using decorticator

2.2.2 Nonwoven fabric production

The nonwoven fabric was produced using a hot press machine (Figure 5a) under the following conditions: a temperature of 190°C, a pressure of 40 psi, a pressing time of 30 s and a sample size of 30 cm x 30 cm. The fabric was produced by varying the fibre composition and PLA powder content. The mass ratios of *Alpinia purpurata* fibres to PLA powder used were 90/10, 80/20 and 70/30. This study focused on the production of nonwoven fabric rather than composite materials. According to the literature [19], materials with a binder content of less

than 50% are classified as nonwoven fabrics, while those with a binder content exceeding 50% are considered composites. In this study, the binder content was maintained below 50%, ensuring that the final product was categorized as nonwoven fabric.

Nonwoven fabric production involved planning the fabric mass per area, taking into account fibre availability. PLA powder was prepared as the binding material, and the fibres and PLA powder were weighed according to predetermined weights. The fibres were sprayed with water to maintain the position of the PLA powder and prevent it from falling to the bottom layer when sprinkled. The PLA powder was evenly distributed on the bottom, middle and top layers of the fibres. This mixture was placed on a 30 cm x 30 cm baking tray (Figure 5b) lined with Teflon paper to prevent sticking to the tray and the top press plate. The temperatures of the top and bottom plates were set to 190 °C. The pressing pressure was adjusted to 40 psi, while the pressing time was set to 30 s. After pressing, the Teflon paper containing the nonwoven fabric was removed and the fabric sample was cooled at room temperature. This process was repeated for subsequent samples. Finally, the nonwoven fabric was ready for testing (Figure 6).

2.2.3 Characterization of nonwoven fabrics

Fabric mass testing: The fabric mass test complied with the Indonesian National Standard SNI ISO 3801:2010 (Testing Method for Fabric Mass per Unit Length and Area).

Fabric thickness testing: This testing adhered to the Indonesian National Standard SNI ISO 5084:2010



Figure 5: a) Hot press machine, b) preparation of *Alpinia purpurata* fibre and PLA powder in baking tray, c) pressing process

(Testing Method for Textile and Textile Product Thickness). The fabric thickness was measured using a thickness gauge tester.

Air permeability testing: Air permeability testing was conducted according to Indonesian National Standard SNI 7648:2010 (equivalent to ISO 9237 1995 - Textiles — Determination of the permeability of fabrics to air) using the Textest FX 3300 air permeability tester. Test samples with a surface area of 20 cm² were evaluated under a pressure drop of 100 Pa. The results were expressed in mm/s.

Tensile strength and elongation testing: Tensile strength and elongation testing were performed using a Tensolab tensile strength tester, following

Indonesian National Standard SNI 08-0276:2009 (Testing Method for Tensile Strength and Elongation of Fabrics). The test sample, measuring 10 cm x 20 cm, was mounted on the machine with a grip distance of 7.5 cm between two clamps. The procedure for the tensile and elongation strength test was as follows: First, the test sample was prepared. Next, the sample was mounted on the machine, ensuring a grip distance of 7.5 cm. The pulling speed was set to 300 mm/min. The machine was then operated to pull the test sample, while the test was stopped by pressing the OFF button once the pulling process was completed. The sample was released from the clamps by pressing the pressure pedal to open the clamps.

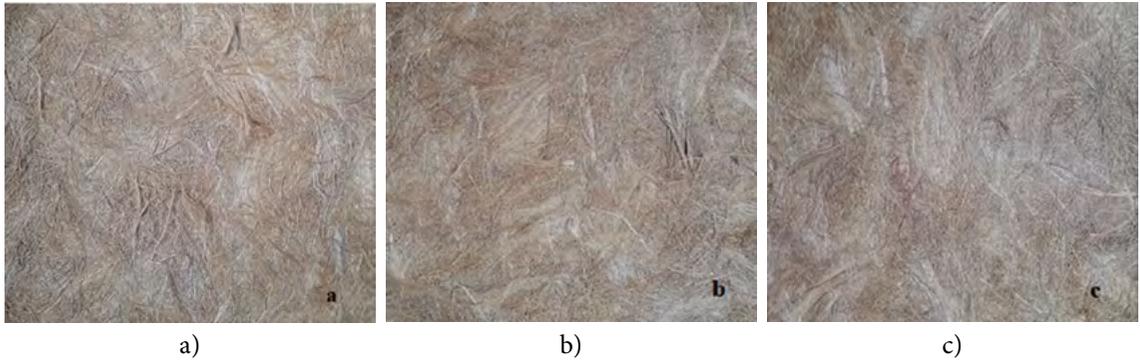


Figure 6: Experimental nonwoven fabric with different ratios of *Alpinia purpurata* fibre and PLA powder: A) 90/10, B) 80/20, C) 70/30

The results of the tensile and elongation strength test were displayed on the Tensolab software, which was connected to a computer linked to the tensile strength tester.

Moisture regain testing: Moisture regain testing followed the Indonesian National Standard SNI 8100:2015 (Testing Method for Moisture Content and

$$\text{Moisture regain (MR)} = \frac{W_1}{W_2} \times 100 (\%) \quad (1),$$

where W_1 represents the mass of water present in the material and W_2 represents the oven dry mass of material.

$$\text{Moisture regain of blended fabric} = \frac{(\%A)(Ra) + (\%B)(Rb) + \dots}{\%A + \%B + \dots} (\%) \quad (2),$$

where %A represents a percentage of fibre A in dry state in the blended fabric, %B represents a percentage of fibre B in dry state in the blended fabric, R_a represents moisture regain of fibre A (%) and R_b represents moisture regain fibre B (%).

Wetting time testing (relevant to water absorption): Water absorption testing was conducted using the water drop method, in accordance with Indonesian National Standard SNI 0279:2013 (Testing method for water absorption of textile materials). The procedure began with the preparation of the nonwoven fabric sample to be tested, which was then conditioned in a standard testing room. Next, the burette was filled with water and a stand or three-legged support was positioned beneath the burette. The fabric sample was placed on top of the support at a distance of (10 ± 1) mm from the burette. One drop of water was then released onto the surface of the stretched fabric sample and the stopwatch was started as soon as the water drop

Moisture Regain) protocol. The procedure involved heating a weighing bottle in an oven at 110°C , cooling it in a desiccator and then weighing it. The sample was subsequently heated and weighed to determine the air-dry and oven-dry weights. Actual moisture regain was determined using equation 1 and theoretical moisture regain was determined using equation 2 [23].

touched the sample. The recorded time was the duration it took for the reflection of the water drop on the fabric to disappear, known as the wetting time. If the reflection remained after 60 s, the wetting time was considered to be greater than 60 s.

Surface image: The images of nonwoven fabrics were obtained using a Phenom ProX G6 Desktop SEM at a magnification of $800\times$ and an accelerating voltage of 15 kV.

Statistical analysis: Statistical analysis was performed using one-way analysis of variance (ANOVA) to identify significant differences between the mean values of various fabric samples. The significance level was set at 0.05, followed by a post hoc test.

3 Results and discussion

3.1 Fabric mass

Figure 7 illustrates the mass per unit area (g/m^2) of three types of experimental nonwoven fabrics (A, B and C). Each fabric type exhibits similar mass values, averaging approximately 550 g/m^2 . The chart indicates that variations among the groups are minimal. This observation is further supported by the ANOVA test results, which yielded a p-value of 0.99. This p-value confirms that there is no statistically significant difference in mass per unit area among the three fabric groups (A, B and C) at a 5% significance level ($\alpha = 0.05$).

The analysis from both the bar chart and ANOVA test results suggests that the composition of *Alpinia purpurata* fibres and PLA powder as a binder (A: 90/10, B: 80/20 and C: 70/30) does not significantly impact the mass per unit area of the nonwoven fabrics. Furthermore, the predetermined target mass of approximately 550 g/m^2 was consistently achieved across all three compositions. These findings indicate that the blending process successfully maintained uniform fabric mass, regardless of the variations in the fibre-to-binder ratio. This consistency can be attributed to the fact that the mass per unit area was pre-established and the mass ratio of fibre to PLA was carefully controlled and predetermined. Additionally, the manufacturing process strictly followed established protocol, ensuring that the target mass per unit area and fibre-to-binder ratio were adhered to with minimal variation. Moreover, precise control over the amounts of fibres and PLA powder during the preparation phase likely contributed to the uniformity in the final fabric weight. The lack of significant differences in mass per unit area further suggests that the thermal bonding process applied during manufacturing did not cause any significant changes to the overall fabric weight, even with varying compositions of fibres and binder.

3.2 Fabric thickness

Figure 8 illustrates the thickness of nonwoven fabrics composed of *Alpinia purpurata* fibres and PLA

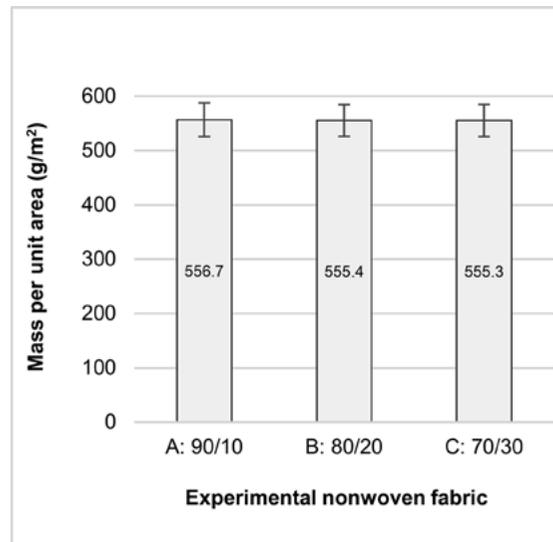


Figure 7: Mass of experimental nonwoven fabric with different ratio of *Alpinia purpurata* fibre and PLA powder: A) 90/10, B) 80/20, C) 70/30

powder. The ANOVA test results indicate that there are no statistically significant differences in fabric thickness, as the p-value is greater than the 0.05 significance level. These results suggest that variations in the composition of *Alpinia purpurata* fibres and PLA do not significantly influence the thickness of the nonwoven fabrics. Despite differences in fibre composition, the thickness measurements remain relatively consistent across all fabric types. This consistency can be attributed to the fact that the fabrication process used the same pressing pressure (40 psi) for all samples. As the pressure is uniform across all compositions, the resulting thickness is likely to be consistent, as the mechanical force applied during the pressing process is equal for all fabric types. Additionally, the thermal bonding process does not significantly alter the fabric's thickness, as it serves primarily to bond the fibres together without causing substantial compression. The pre-established target mass per unit area and the fixed fibre-to-binder ratio also play a role in maintaining consistent thickness, as these parameters guide the fabric formation without significantly influencing thickness variations.

The study demonstrates that the thickness of nonwoven fabrics composed of *Alpinia purpurata*

and PLA remains uniform, regardless of the specific blend ratios tested. This finding is particularly important for applications requiring consistent fabric thickness and provides valuable insight into the structural characteristics of nonwoven fabrics with different fibre compositions.

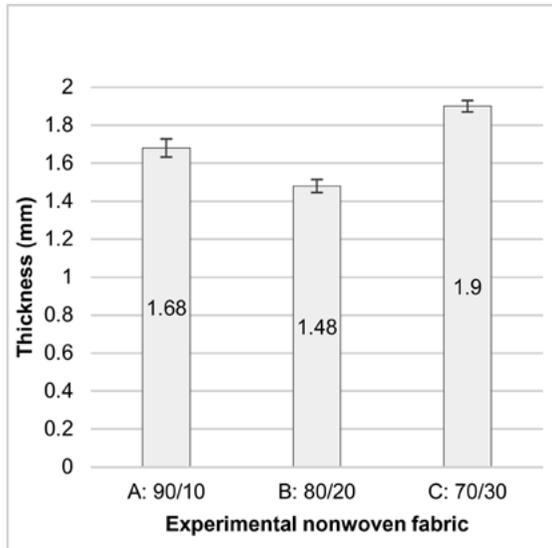


Figure 8: Thickness of experimental nonwoven fabric with different ratio of *Alpinia purpurata* fibre and PLA powder: A) 90/10, B) 80/20, C) 70/30

3.3 Air permeability

Figure 9 illustrates the air permeability of nonwoven fabrics composed of *Alpinia purpurata* fibres and PLA powder. Significant differences in air permeability were observed among the three fabric compositions, with Fabric A (90/10) showing the highest air permeability, followed by Fabric B (80/20) and Fabric C (70/30). Specifically, the mean air permeability for Fabric A was approximately 200 mm/s, around 180 mm/s for Fabric B and about 160 mm/s for Fabric C. These results suggest that fabrics with higher proportions of *Alpinia purpurata* fibres allow air to pass through more effectively.

The ANOVA test yielded an F-statistic of approximately 5.948 and a p-value of 0.0062, confirming that the differences in air permeability among the three fabric types are statistically significant at a 0.05 significance level. This indicates that the observed

variation in air permeability is due to differences in the fabric composition, particularly the relative proportions of *Alpinia purpurata* fibres and PLA powder.

These findings suggest that Fabric A, with its 90/10 composition, is the most breathable among the three, while Fabric C (70/30) is the least breathable. This trend can be attributed to the role of PLA in the fabric formation process. As the proportion of PLA increases, air permeability decreases. This is likely due to the melting of PLA during the manufacturing process, which forms a denser structure that obstructs airflow. PLA, being hydrophobic and prone to melting under heat, fills the gaps between fibres more extensively, reducing the overall porosity of the fabric and, thus, its ability to allow air to pass through.

These results underscore the significant impact of fibre composition on the breathability of nonwoven fabrics. A higher proportion of *Alpinia purpurata* fibres maintains more open spaces between fibres, facilitating air flow, while increased PLA content creates more compact and less permeable structures. These insights provide a valuable foundation for optimizing fabric compositions to achieve specific breathability characteristics tailored to particular applications, especially in textiles where air permeability is a crucial factor.

3.4 Tensile Strength

Figure 10 illustrates the tensile strength of nonwoven fabrics composed of *Alpinia purpurata* fibres and PLA powder. Significant differences in tensile strength were observed among the three fabric compositions. Specifically, Fabric C (70/30) exhibited the highest tensile strength, followed by Fabric B (80/20) and Fabric A (90/10). The mean tensile strength for Fabric C was approximately 500 N, around 400 N for Fabric B and about 300 N for Fabric A. These results suggest that fabrics with higher PLA content possess greater tensile strength.

The ANOVA test yielded a p-value of 0.000131, confirming that the differences in tensile strength

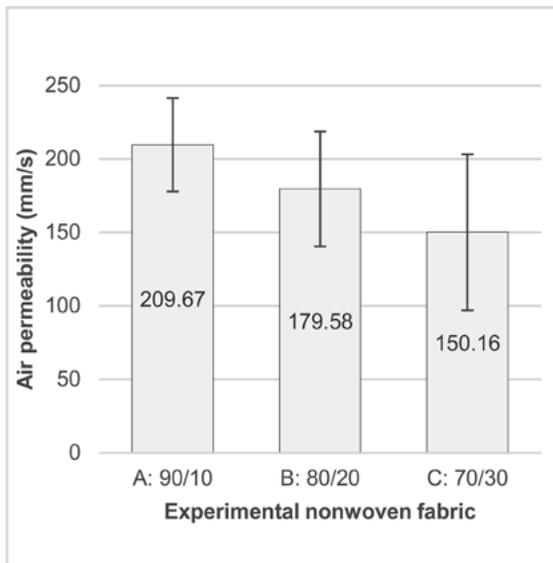


Figure 9: Air permeability of experimental nonwoven fabric with different ratio of *Alpinia purpurata* fibre and PLA powder: A) 90/10, B) 80/20, C) 70/30

among the fabric types were statistically significant at a 0.05 significance level. This indicates that the variations in fabric composition (specifically the proportion of PLA) have a meaningful impact on the fabric's mechanical properties. This trend can be attributed to the role of PLA in the fabric formation process. PLA is a thermoplastic material, meaning it melts under heat. During the manufacturing process, PLA melts and forms stronger bonds with the fibres, reinforcing the structure of the fabric. As the proportion of PLA increases, more bonding sites are available, which increases the overall strength of the fabric. This process of bonding through thermal fusion leads to improved cohesion between the fibres, resulting in a fabric that can withstand greater forces before breaking. Consequently, fabrics with higher PLA content, such as Fabric C (70/30), exhibit superior tensile strength.

These findings clearly demonstrate how the varying compositions of *Alpinia purpurata* fibres and PLA powder affect the tensile strength of the nonwoven fabrics. A higher proportion of PLA enhances tensile strength by increasing inter-fibre bonding, while an increased proportion of *Alpinia purpurata* fibres leads to lower tensile strength. This is likely due to the reduced bonding strength

between the fibres when there is less PLA present to act as a binder, making the fabric more prone to failure under stress.

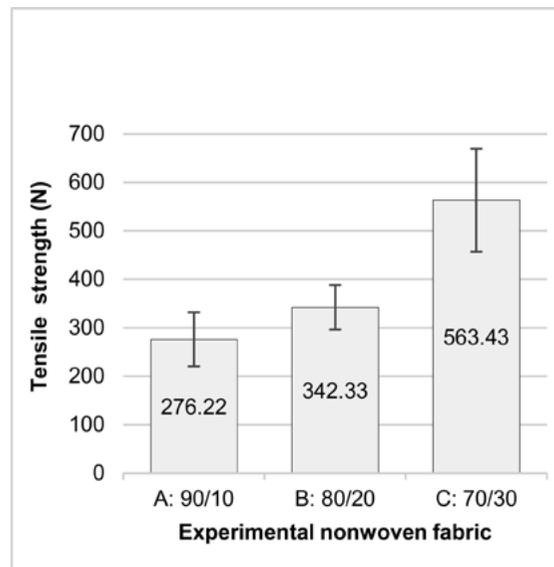


Figure 10: Tensile strength of experimental nonwoven fabric with different ratio of *Alpinia purpurata* fibre and PLA powder: A) 90/10, B) 80/20, C) 70/30

3.5 Elongation

Figure 11 illustrates the elongation of nonwoven fabrics composed of *Alpinia purpurata* fibres and PLA powder. Based on the graph and ANOVA test results, no significant differences in elongation were observed among the three fabric compositions. The mean elongation percentages for the fabrics were approximately 3.2% for Fabric A, 3.1% for Fabric B and 3.4% for Fabric C.

The ANOVA test results, with a p-value of 0.26, confirm that the differences in elongation among the fabric types are not statistically significant at a 0.05 significance level. Additionally, the post-hoc Tukey HSD test showed no significant differences between any pairs of fabric groups, reinforcing the conclusion that variations in fibre-to-PLA composition do not substantially affect elongation. This suggests that factors such as the ratio of *Alpinia purpurata* fibres to PLA powder do not significantly alter the fabric's ability to stretch under stress.

This uniformity in elongation can be attributed to the fact that elongation is largely dependent on the overall fibre network structure and the mechanical properties of the fibres themselves, rather than on the composition of the binder. PLA, being a thermoplastic polymer, provides some flexibility when bonded with the fibres. However, since the thermal bonding process is controlled and the PLA content does not vary drastically between the fabric types, the overall elongation behaviour remains relatively unchanged. The consistent fibre network created during the manufacturing process likely allows for similar stretchability across the different fabric compositions, despite variations in the fibre-to-PLA ratio.

These results indicate that the elongation properties of the fabrics remain consistent regardless of the specific ratio of fibres to PLA in the composition. This uniformity in elongation is beneficial in applications where consistent stretchability is required, such as in certain medical or protective textiles, as the fabric will perform similarly regardless of slight variations in the fibre and binder composition.

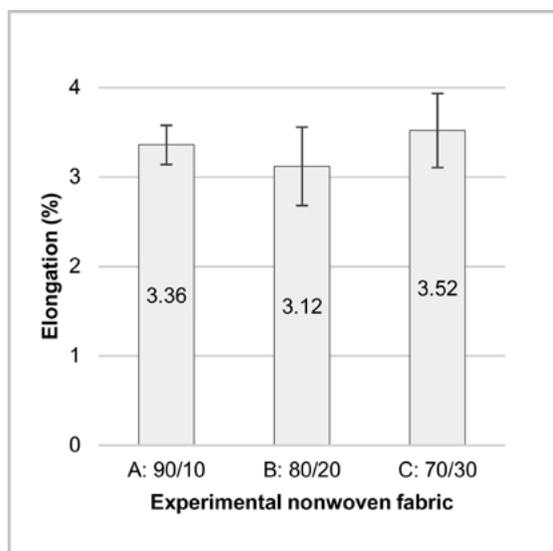


Figure 11: Elongation of experimental nonwoven fabric with different ratio of *Alpinia purpurata* fibre and PLA powder: A) 90/10, B) 80/20, C) 70/30

3.6 Wetting time

Figure 12 illustrates the wetting time of nonwoven fabrics composed of *Alpinia purpurata* fibres and PLA powder. Significant differences in wetting time were observed among the three fabric compositions. Fabric C (70/30) exhibited the longest wetting time, followed by Fabric B (80/20) and Fabric A (90/10). Specifically, the mean wetting time for Fabric C was approximately 90 s, for Fabric B around 80 s, and for Fabric A about 70 s. These results suggest that fabrics with higher PLA content require more time to wet. The ANOVA test yielded a p-value of 0.0499, confirming that the differences in wetting time among the three fabric types are statistically significant at a 0.05 significance level.

The trend observed can be attributed to the hydrophobic nature of PLA. PLA is a hydrophobic material, meaning it repels water rather than absorbing it. As the proportion of PLA in the fabric increases, the fabric's ability to absorb water decreases, leading to a longer wetting time. This resistance to wetting is particularly evident in Fabric C (70/30), which has the highest proportion of PLA and thus demonstrates the slowest water absorption. Conversely, Fabric A (90/10), with a higher proportion of *Alpinia purpurata* fibres, is more hydrophilic, allowing water to be absorbed more quickly, resulting in a shorter wetting time. The *Alpinia purpurata* fibres, being more water-absorbent than PLA, allow for quicker wetting and faster water absorption.

This study highlights the significant influence of fibre composition on the wetting properties of nonwoven fabrics. As the proportion of PLA increases, the fabric becomes more hydrophobic, leading to longer wetting times. On the other hand, increasing the proportion of *Alpinia purpurata* fibres enhances the fabric's hydrophilicity, resulting in shorter wetting times. These insights are valuable for optimizing fabric compositions to achieve specific wetting characteristics required for various applications.

3.7 Moisture regain

Figure 13 illustrates the moisture regain of nonwoven fabrics composed of *Alpinia purpurata* fibres

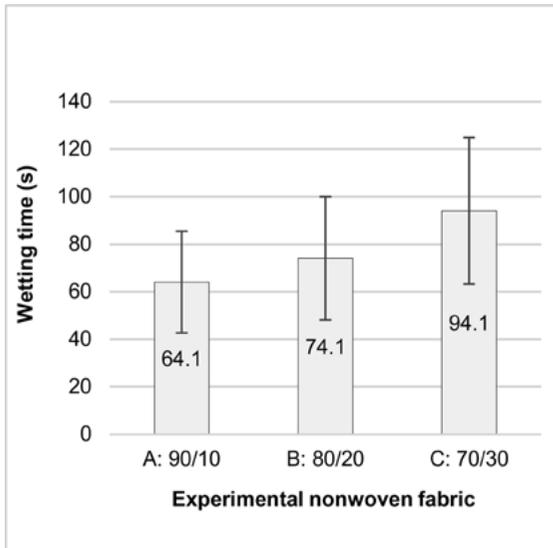


Figure 12: Wetting time of experimental nonwoven fabric with different ratio of *Alpinia purpurata* fibre and PLA powder: A) 90/10, B) 80/20, C) 70/30

and PLA powder. The moisture regain properties were analysed based on both experimental results and theoretical calculations. The graph presents laboratory-measured and theoretically calculated moisture regain values for three fabric compositions: Fabric A (90/10), Fabric B (80/20) and Fabric C (70/30). The results show strong correlation between experimental and theoretical values, particularly for Fabrics A and B. Fabric A, with the highest proportion of *Alpinia purpurata* fibres, exhibited the highest moisture regain, while Fabric C, with the highest PLA content, demonstrated the lowest moisture regain.

The theoretical calculations were performed using a formula that accounts for the individual moisture regain properties of *Alpinia purpurata* (11.97%) and PLA (0.4%), weighted by their respective proportions in the fabric. The close correlation between theoretical and experimental results for Fabrics A and B validates the reliability of this formula in predicting the moisture regain behaviour of these blended fabrics.

However, a slight discrepancy was observed in Fabric C, where the laboratory-measured moisture regain was marginally lower than the theoretical

prediction. This variation can be attributed to several factors, such as experimental uncertainties, differences in fibre interactions at higher PLA concentrations or potential variations in measurement conditions. For example, PLA, being hydrophobic, may not interact as effectively with water as *Alpinia purpurata* fibres, leading to slightly less moisture absorption than expected in the fabric with a higher PLA ratio. Additionally, the high PLA content may result in a less open structure and fewer spaces for water absorption.

Despite this minor deviation, the overall trend remains clear: fabrics with higher *Alpinia purpurata* content show greater moisture regain, while those with higher PLA content exhibit lower moisture regain. This is due to the higher water-absorbing capacity of *Alpinia purpurata* fibres compared to PLA, which resists water absorption due to its hydrophobic nature. Therefore, fabrics with a higher proportion of *Alpinia purpurata* fibres tend to absorb more moisture.

These findings highlight the significant influence of fibre composition on the moisture regain properties of nonwoven fabrics. The strong correlation between theoretical and experimental data provides a solid framework for predicting the moisture regain characteristics of these materials.

3.8 Surface image

Figure 14 presents SEM images of the experimental nonwoven fabric at 800× magnification, captured from two distinct locations. In Figure 13a, the fibres and the PLA binder, which has melted and re-solidified on the fibres, are visible. Initially in powder form, the PLA melts and subsequently bonds the fibres together. Due to the low binder content—comprising 10% PLA and 90% fibres—the presence of PLA melt is minimal in Figure 14a.

In contrast, Figure 14b exhibits a slightly greater amount of PLA melt compared to Figure 13a, corresponding to an increased PLA composition of 20%, while the fibres remain discernible. Finally, Figure 14c shows a substantial increase in PLA melt, nearly

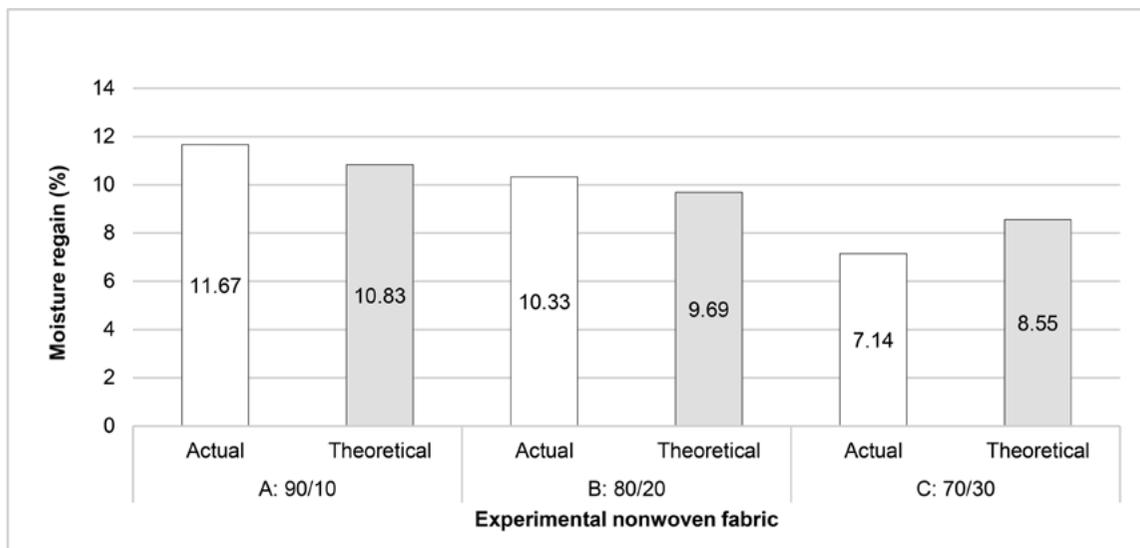


Figure 13: Moisture regain of experimental nonwoven fabric with different ratio of *Alpinia purpurata* fibre and PLA powder: A) 90/10, B) 80/20, C) 70/30

covering the entire surface at 800 \times magnification, with only a small fraction of the fibres remaining visible. This is attributed to the highest PLA content among the samples, at 30%.

This progression demonstrates that as the PLA binder content increases, fibre bonding becomes more extensive, leading to a more pronounced PLA melt. These observations align with the tensile strength test results, which indicate that the melting PLA binds the fibres and solidifies upon cooling. Consequently, fabrics with higher PLA content exhibit stronger fibre bonding, resulting in enhanced tensile strength.

3.9 Limitations

This study serves as a preliminary investigation, as no prior research has explored the use of *Alpinia purpurata* fibres in nonwoven fabric production. Due to the limited availability of fibres from the decortication process, only a limited quantity of nonwoven fabric was produced, which constrained the range of characterization tests that could be conducted. Additionally, the available laboratory equipment limited the scope of testing to physical and mechanical characterization.

3.10 Future research recommendation

This study provides initial insights into the potential of *Alpinia purpurata* fibres for nonwoven fabric applications using thermal bonding with PLA. However, further research is required to enhance the understanding of fibre properties and material performance. Future studies should focus on comprehensive chemical characterization, including differential scanning calorimetry (DSC) to assess thermal transitions, thermogravimetric analysis (TGA) to evaluate thermal stability and degradation, and Fourier transform infrared spectroscopy (FTIR) to analyse chemical interactions between *Alpinia purpurata* fibres and PLA. Additionally, extended mechanical and structural performance tests, such as compression and recovery tests, stiffness and fabric handle evaluation, and durability tests (tear strength, burst strength and abrasion resistance), are essential to assess fabric resilience and long-term usability. Porosity and fluid management properties, including water permeability testing and analysis of porosity, pore size and distribution, should also be investigated to evaluate liquid absorption, transport characteristics, filtration potential and breathability. These future investigations will provide a more

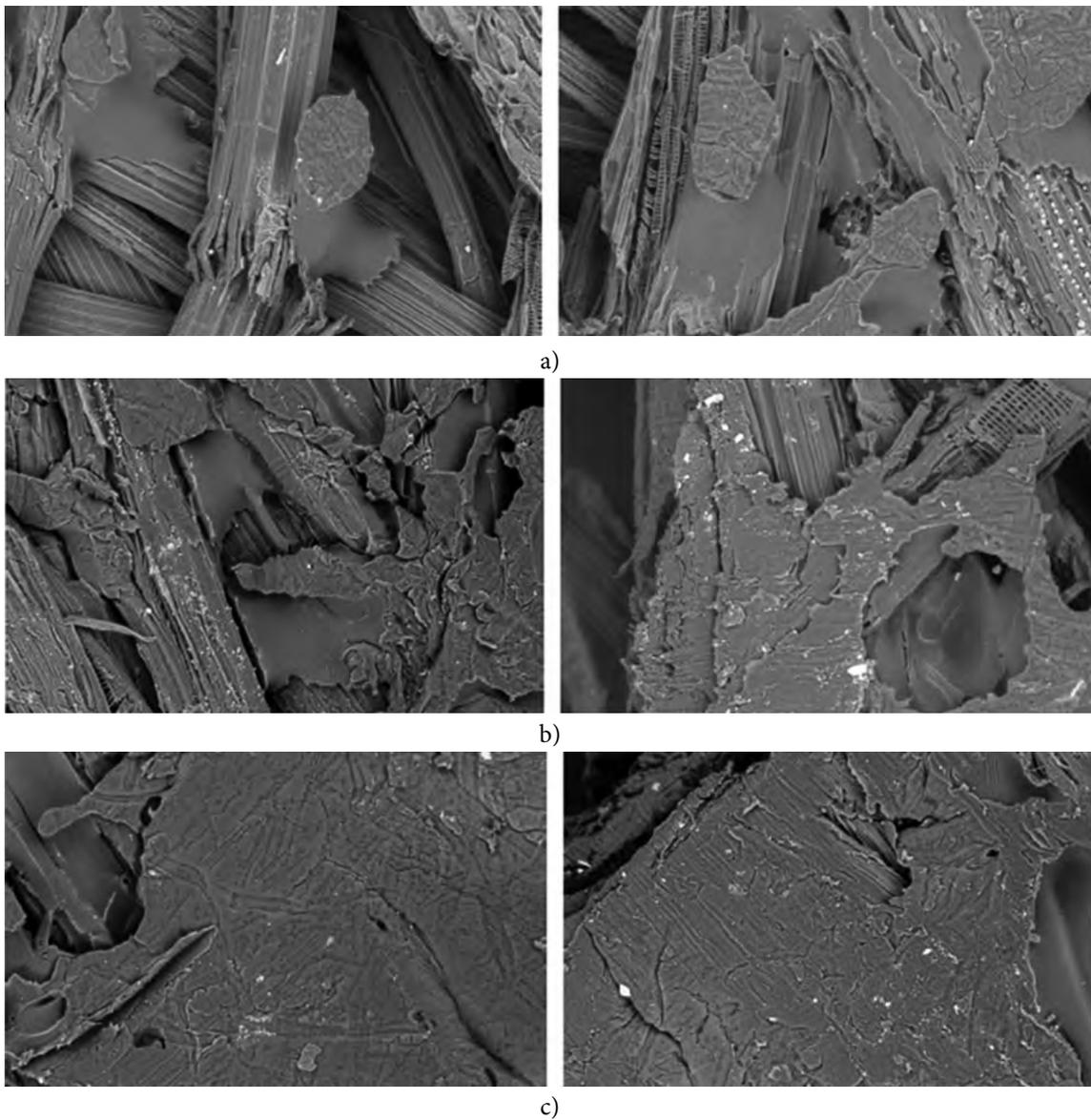


Figure 14: Experimental nonwoven fabric with three different fibre and binder compositions at 800x magnification, shown at two different locations: (a) 90/10, (b) 80/20 and (c) 70/30

comprehensive understanding of the structural, chemical and mechanical properties of *Alpinia purpurata*-based nonwoven fabrics, further establishing their suitability for sustainable textile applications.

4 Conclusion

This study explored the development of biodegradable nonwoven fabrics using *Alpinia purpurata* pseudo-stem fibres and poly lactic acid (PLA) as

a binder using the thermal bonding method. The findings demonstrate that the fibre-to-binder ratio significantly influences fabric properties, with higher PLA content enhancing tensile strength but reducing air permeability and water absorption, while a greater proportion of *Alpinia purpurata* fibres improves breathability and moisture regain. The successful integration of these natural fibres into nonwoven fabric structures highlights their potential for sustainable textile applications. However,

limitations such as the lack of chemical and thermal analyses, indicate the need for further research. Future studies should focus on optimizing processing conditions, evaluating long-term environmental impact and exploring industrial feasibility to fully harness the benefits of *Alpinia purpurata*-based nonwoven fabrics. This research provides a foundation for advancing eco-friendly textile materials while contributing to the broader goal of sustainability in the textile industry.

Data availability statement: Since 4 November 2025, the research data have been available at <https://doi.org/10.5281/zenodo.17518726>.

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Recent Advances in Textile Functionalization Using Essential Oil-Based-Microcapsules with Antimicrobial Properties

Nedavni napredek funkcionalizacije tekstilij z mikrokapsulami na osnovi protimikrobnih eteričnih olj

Scientific review/Pregledni znanstveni članek

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Abstract

Antimicrobial textiles are functionalized textiles designed to inhibit or terminate the growth of microorganisms. In light of the increasing emphasis on eco-friendly processes, the application of essential oils presents a viable alternative to synthetic drugs (antibiotics). The aim of this study was to evaluate recent advances in microencapsulation methods of essential oils with antimicrobial activity that can be applied on medical textile for dermal use by employing the PRISMA methodology. Essential oils have been microencapsulated using various methods: coacervation, spray-drying, emulsion method and *in situ* polymerization. Among these, coacervation is still extensively utilized, though associated scale-up challenges persist. Many essential oils have demonstrated antibacterial properties against Gram-positive (*Staphylococcus aureus*, *Bacillus subtilis*) and Gram-negative (*Pseudomonas aeruginosa*, *Escherichia coli*, *Klebsiella pneumoniae*) bacteria, as well as antifungal activity (*Candida albicans*). The growth inhibition of these microorganisms was assessed in the presence of the following essential oils and their active substances with the highest biological-antimicrobial activity: cinnamon (transcinnamaldehyde), lime (α -terpineol, terpineol, and limonene), tea tree (terpinen-4-ol), rosemary (1,8-cineole and α -pinene), peppermint (l-menthol, menthone, methyl acetate and limonene), lavender (linalool and linalyl acetate), thyme (carvacrol) and clove (eugenol). The findings indicate that functionalized textile with microcapsules exhibits enhanced antibacterial activity against Gram-positive bacteria compared to Gram-negative bacteria (*Escherichia coli*), which could be attributed to the bacteria's thick wall. However, there is a notable lack of data regarding cytotoxicity and the sensory evaluation of functionalized textile. The potential utilization of essential oils was explored in the development of eco-friendlier functionalized textile with antimicrobial



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properties. However, additional research is required to maximize the antimicrobial activity of microcapsules to overcome challenges in the scale-up to pilot process, and to improve the immobilization in textiles.

Keywords: antimicrobial properties, sustainability, essential oils, microcapsules, textile functionalization

Izvlaček

Protimikrobne tekstilije so funkcionalizirani materiali, zasnovani za zaviranje ali preprečevanje rasti mikroorganizmov. Ker si prizadevamo za uporabo okolju prijaznih tehnologij, je uporaba eteričnih olj mogoča kot alternativa sintetičnim zdravilom, kot so antibiotiki. Namen raziskave je bil oceniti razvoj metod mikroenkapsuliranja eteričnih olj s protimikrobnim delovanjem, ki jih je mogoče s pomočjo metodologije PRISMA uporabiti pri pripravi medicinskih tekstilij za dermalno uporabo. Eterična olja so bila mikrokapsulirana z različnimi tehnikami, vključno s koacervacijo, sušenjem z razprševanjem, emulzijsko metodo in polimerizacijo in situ. Med omenjenimi metodami je koacervacija še vedno najpogosteje uporabljena kljub izzivom, povezanim z razširitvijo procesa na industrijsko raven. Posamezna eterična olja izkazujejo širokospektralno protibakterijsko delovanje proti grampozitivnim (*Staphylococcus aureus*, *Bacillus subtilis*) in gramnegativnim bakterijam (*Pseudomonas aeruginosa*, *Escherichia coli*, *Klebsiella pneumoniae*) ter protiglivično učinkovitost proti *Candida albicans*. Najvišjo biološko-protimikrobno aktivnost so pokazale aktivne snovi eteričnih olj cimeta (*trans*-cinamaldehyd), limete (*α*-terpineol, terpineol, limonen), čajevca (*terpinen-4-ol*), rožmarina (*1,8*-cineol, *α*-pinen), poprove mete (*L*-mentol, menton, metil acetat, limonen), sivke (*linalol*, *linalil acetat*), timijana (*karvakrol*) in klinčkov (*evgenol*). Ugotovljeno je bilo, da mikrokapsulirane funkcionalizirane tekstilije izkazujejo učinkovitejše protibakterijsko delovanje proti grampozitivnim bakterijam kot proti gramnegativnim, kar je mogoče pripisati razliki v strukturi celične stene mikroorganizmov. Kljub spodbudnim rezultatom pa so podatki o citotoksičnosti in senzoričnih lastnostih protimikrobnih tekstilij še vedno omejeni. Potrebne so nadaljnje raziskave za povečanje protimikrobne učinkovitosti mikrokapsul, optimiziranje postopkov industrijske izdelave in izboljšanje vezave mikrokapsul na tekstilna vlakna.

Ključne besede: protimikrobne lastnosti, trajnost, eterična olja, mikrokapsule, funkcionalizacija tekstilij

1 Introduction

Antimicrobial resistance (AMR) is one of the major global public health threats of the 21st century, and is characterized by the reduction in the efficacy of antibiotics [1]. AMR has been exacerbated by COVID-19 pandemic, due to the over prescription of antimicrobial agents by physicians and the easy availability of over-the-counter (OTC) antibiotics in pharmacies and drug stores [2]. According to the CDC's July 2024 Report on Antimicrobial Resistance Threats, AMR increased by 20% during the COVID-19 pandemic relative to the pre-pandemic period [2]. Globally, bacterial infections on the skin and subcutaneous tissues rank as the sixth leading infectious syndrome contributing to the mortality associated with AMR [3].

Natural products, particularly essential oils (EOs), are potential candidates to combat AMR due to their antioxidant and pro-oxidant properties [4]. EOs are plant extracts derived from various parts such as petals and flowers, grasses, seeds, leaves, stems, roots and rhizomes, woods and resins [5]. According to the European Pharmacopoeia (Ph. Eur.) and to the Association Française de Normalisation, an essential oil is defined as a "product obtained from a natural raw materials of plant origin, either through distillation using water or steam, a mechanical process from the epicarp of *Citrus sp.* fruits or through dry distillation [6,7]. The essential oil is separated by physical means from the aqueous phase. EOs are multicomponent systems contain-

ing a variety of volatile, lipophilic and odoriferous chemical compounds, including terpenes, alcohols, sesquiterpenes, amides, phenols, acids, ketones, aldehydes, esters, ethers and oxides [8]. EOs have been extensively investigated for their biological activities [9], including antibacterial properties. Active substances, with natural antimicrobial properties are derived from thyme (*Thymus vulgaris*), oregano (*Origanum compactum*), clove (*Eugenia caryophyllata*), mint (*Mentha piperita*), sage (*Salvia officinalis*), lavender (*Lavandula angustifolia*) and others (Figure 1).



Figure 1: Species from which essential oils with antimicrobial properties can be extracted: a) *Eugenia caryophyllata* (<https://www.pioneerherbal.com>), b) *Thymus vulgaris* (<https://plants.ces.ncsu.edu>), c) *Salvia officinalis* (<https://www.greensmile.cy>), d) *Origanum compactum* (<https://aliksir.com>), e) *Mentha piperita* (<https://www.la-saponaria.com>) and f) *Lavandula angustifolia* (<https://www.seedscape.net.au>)

Due to their fragrance, EOs are widely explored in the textile industry and employed as natural antibacterial agents [10, 11]. Antibacterial activity has been demonstrated against various bacterial strains, including *Escherichia coli*, *Shigella dysenteria*, *Listeria monocytogenes*, *Bacillus cereus*, *Salmonella typhimurium* and *Staphylococcus aureus* [12]. EOs are thus broadly used in research and development laboratories to design value-added textiles with cosmetic and medical applications. Three groups of antimicrobial textiles can be distinguished: antibacterial textiles that inhibit bacteria growth, antifungal textiles that prevent fungal mycelium and spore germination, and antiviral textiles that modify the virus surface structure [13]. Although commercial antimicrobial products have been developed, the most efficient compounds (silver nanoparticles, triclosan and quaternary ammonium compounds) are regulated under Regulation 528/2012 [14].

While the shift towards sustainability is still in its early stages, consumers increasingly prefer eco-friendly choices. In light of this trend and the looming threat of AMR, the application of EOs can be considered an alternative to synthetic drugs (antibiotics), as it was the case in ancient times. The earliest references to the use of sandalwood and cinnamon essential oils date back to ancient Hindu scriptures called Vedas [15]. The Egyptians used plants for medicinal purposes, surgery, food preservation, mummification and healing practices or massages [16]. A graphical illustration is presented in Figure 2.

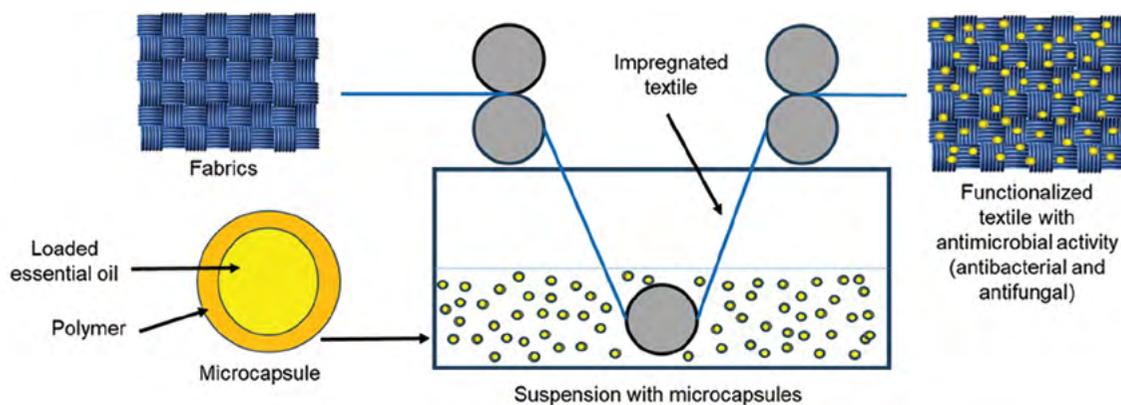


Figure 2: Graphical illustration of medical textile functionalization with microcapsules

However, the main disadvantage of EOs is their susceptibility to environmental conditions (oxygen, light, temperature and humidity), making them prone to decomposition and easy volatilization [17]. These drawbacks can be mitigated through technological and/or formulation modification in the microencapsulation process.

The potential use of microencapsulation technology for encapsulating EOs in medical textile has been previously discussed [18]. Nevertheless, not all microencapsulation methods are suitable for textile applications. Commonly used techniques in textile functionalization are:

- physical: spray-drying and solvent evaporation,
- physico-chemical: simple and complex coacervation and molecular inclusion, and
- chemical: *in situ* polymerization, photopolymerization and interfacial polymerization.

This study addresses recent developments in microencapsulation methods for EOs, types of EOs with antimicrobial activity, textile functionalization methods with microcapsules and tested microorganism strains. The focus is on summarizing the antimicrobial activity of various EOs, the production of microcapsules, and their use in creating eco-friendly, biocompatible, and nontoxic functional antimicrobial textiles with biological, aromatherapeutic and antioxidant properties.

2 Methodology

A comprehensive literature search was conducted using the Scilit database, focusing on the keywords “essential oil”, “antimicrobial activity”, “fabrics” and “antibacterial activity”. The selection criteria included studies published between 2014 and 2024, and was limited to articles in English. Both peer-reviewed journal articles and ‘grey’ literature, such as conference papers, were included. Eligible studies were required to report antimicrobial efficiency testing, microencapsulation methods and textile functionalization techniques with a clear research purpose. For purposes of screening and selection,

the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) was followed. Evaluation was performed based on ‘title and abstract’, followed by qualitative content analysis by two reviewers. Any discrepancies between the reviewers were resolved by triple-checking the articles and through discussion with a third reviewer. After selecting eligible articles, obtained results and cited studies were screened for inclusion. Data extracted from the included studies encompassed microencapsulation techniques, types of essential oils, microorganism strains, types of textile/fabrics and functionalization methods. Due to absence of a standardized quality tool for the assessment of studies involving functionalized textiles with antimicrobial activity, articles with clearly presented relevant data were considered for evaluation.

3 Results

3.1 Results from the qualitative literature search

The following parameters were included in the prior advanced tool search: publication period (2014–2024) and English language. All journal articles that had results on antimicrobial activity of microcapsules and a lack data on antimicrobial activity of functionalized textile alongside textile functionalization were excluded. Book chapters, preprints and review articles were also excluded. A total of 84 studies were identified from the Scilit database with three duplicates. The screening of the title and abstract led to the exclusion of fifteen articles, while eight more were excluded after full-text screening. The final number of relevant studies was 16. The full selection process and outcomes are summarized in Figure 3.

3.2 Characteristics of included studies

Details of included studies and their outcomes are presented in Table 1. Five studies reported [19–21, 24, 32] that their microcapsules were obtained through coacervation, two using the spray-drying process [28, 34], seven using the emulsion method [23, 25–27,

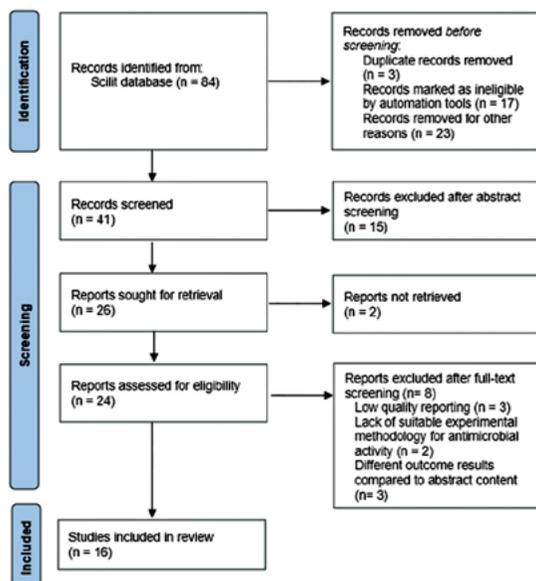


Figure 3: Qualitative literature search results

29–31] and one using the *in situ* polymerization method [33], while one article [22] did not provide data regarding the microencapsulation method. In one study [31], microcapsules with thyme essential oil were obtained as a commercial product. Essential oils from cinnamon [19, 27] and clove [29, 34] were each reported in three studies. Lime [20, 24] and tea tree [21, 22] essential oils were each reported in two studies. Thyme [31], ginseng [30], peppermint [32], eucalyptus [26] and sandalwood [26], and rosemary [28] essential oil were each reported once. The majority of the textile functionalization methods (Table 1) included padding (N = 4), pad-dry-cure (N = 4), pad-dry method (N = 2), printing, finishing, *in situ* procedure and exhaustion process (N = 1, each), while one study covered the fibre spinning method. The most commonly tested bacteria were *Staphylococcus aureus* (Gram positive) and *Escherichia coli* (Gram negative). Additionally, antibacterial efficiency against the microorganisms *Klebsiella pneumoniae*, *Staphylococcus epidermis*, *Bacillus cereus* and *Salmonella typhimurium* was assessed. In one article, antifungal activity against *Candida albicans* was evaluated. Cotton fabrics (N = 9) were predominantly investigated, followed by viscose fibres, cellulosic fibres, nylon-polyurethane fabrics, linen fabrics, PLA

fabrics and polyester fabrics (N = 1, each). Research studies that elucidated both microencapsulation, followed by textile functionalization and extensive characterization (washing durability, sensory evaluation, biocompatibility study and cytotoxicity effects), are limited.

4 Discussion

Results from the systematic review suggest that functionalized textile with essential oil-based microcapsules possess antimicrobial activity. This is further confirmed by different previously conducted literature-scientific reviews that are not part of this systematic review [18, 35–37]. Based on the review analysis, the coacervation method, one of the oldest methods, is widely explored in microencapsulation studies. However, the commercialization of coacervation is hindered by high-costs and a time-intensive multistep manufacturing process (polymer hydration, emulsification, coacervation, shell hardening and drying). The reviewed articles did not provide explicit data regarding advances in industrially feasible and scalable coacervation methods. Therefore, further studies are required to design an industrially scalable coacervation process following up on the work performed by Tang [38].

Considering technological advances, eco-friendlier trends and the optimization of resources, Sharma and Chakraborty [34] optimized process parameters in the spray-drying method using the Design of Experiments approach (DoE), employing the Box-Behnken and Central composite design. This research methodology adds value and should encourage researches to employ DoE in their studies. Beşen [22] suggested that optimization in technological and formulation parameters should be carried out to achieve equally high antibacterial activity against strains, which could be further achieved by using the DoE approach.

Although polyester fibre made of poly(ethylene terephthalate) holds the highest market share (> 50%) in the textile industry, the reviewed data showed that

Table 1: Summary of textile functionalization using microcapsules with antimicrobial activity

Microencapsulation technique	Wall material(s)	Essential oil	Microorganism strains	Functionalization method	Type of fabrics	Ref.
Coacervation	Chitosan	Cinnamon	<i>Escherichia coli</i> and <i>Staphylococcus aureus</i>	Padding	Cellulosic fibres surface	[19]
Coacervation	Alginate and gelatine	Lime	<i>Staphylococcus aureus</i> , <i>Escherichia coli</i> , <i>Klebsiella pneumoniae</i> and <i>Staphylococcus epidermidis</i>	Pad-dry-cure	Cotton fabrics	[20]
Coacervation	Poly(vinyl)-alcohol, gum Arabic and β -cyclodextrin; ethyl-cellulose	Tea tree	<i>Escherichia coli</i> and <i>Staphylococcus aureus</i>	Padding	Cotton fabrics	[21]
No data	Ethyl Cellulose	Tea tree	<i>Escherichia coli</i> and <i>Staphylococcus aureus</i>	Padding	Cotton fabrics	[22]
Emulsion	β -cyclodextrin	Lavender, thyme and clove	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	Exhaustion	Knitted polyester fabrics	[23]
Complex coacervation	Chitosan and gum Arabic	Lime oil	<i>Escherichia coli</i> , <i>Staphylococcus aureus</i> , <i>Bacillus cereus</i> and <i>Salmonella typhimurium</i>	Dipping	Cotton fabrics	[24]
Emulsion	Chitosan and β -cyclodextrin	Cinnamon, lavender, thyme and savory	<i>Escherichia coli</i> and <i>Staphylococcus aureus</i>	<i>In situ</i> procedure	PLA fabric	[25]
Emulsion	Chitosan	Eucalyptus; Sandalwood	<i>Escherichia coli</i> and <i>Staphylococcus aureus</i>	Pad-dry-cure	Cotton fabrics	[26]
Emulsion	Chitosan	Cinnamon + propolis	<i>Escherichia coli</i> and <i>Staphylococcus aureus</i>	Padding	Knitted cotton textile	[27]
Spray-drying	Chitosan-gelatine complex	Rosemary	<i>Escherichia coli</i> and <i>Staphylococcus aureus</i>	Pad dry method	Linon fabric	[28]
Spray-drying	Chitosan-gelatine complex	Rosemary	<i>Escherichia coli</i> and <i>Staphylococcus aureus</i>	Pad dry method	Linon fabric	[28]
Emulsion	Chitosan	Clove	<i>Escherichia coli</i> and <i>Staphylococcus aureus</i>	Pad-dry-cure	Cellulosic fabric	[29]
Emulsion	Melamine-formaldehyde prepolymer	Ginseng oil	<i>Staphylococcus aureus</i> , <i>Klebsiella pneumoniae</i>	Pad-dry-cure	Nylon-polyurethane fabric	[30]
Simple coacervation	Arabic gum	Peppermint oil	<i>Escherichia coli</i>	Finishing process	100% cotton denim fabric	[32]
<i>In situ</i> polymerization method	Melamine-formaldehyde polymer	Lavender, rosemary and sage	<i>Escherichia coli</i> and <i>Staphylococcus aureus</i>	Printing	100% cotton woven fabric	[33]
Spray-drying	Chitosan	Clove oil	<i>Bacillus sp.</i> and <i>Escherichia coli</i>	Pad-dry method	Cotton fabrics	[34]

majority of functionalized textile are cotton fabrics. Cotton fabric is preferred to synthetic fabric as it is biodegradable and naturally occurring. The functionalization of such fabrics with bio-based, green and renewable antibacterial molecules will help improve environmental sustainability.

It is evident from the reviewed articles that *Escherichia coli*, as Gram-negative bacteria, and *Staphylococcus aureus*, as Gram-positive bacteria, were mainly evaluated. Research has proven that functionalized textiles with EO-based-microcapsules exhibit antibacterial activity against *Staphylococcus aureus*. However, the lower inhibition of *Escherichia coli* could be observed in certain studies. This can be attributed to *Escherichia coli*'s thick cell wall, which hinders the penetration of antibacterial compounds.

Despite extensive research on the antimicrobial potential of EOs as a green alternative to antibiotics in engineered-textile, their toxicological effects are still insufficiently investigated. This research area is crucial for the commercialization of EOs-based-functionalized textile, and for meeting requirements for permitted daily exposure contained in the EMA Guidelines (2014) [39] on setting health-based exposure limits for use in risk identification in the manufacture of different medicinal products in shared facilities. Affygitly Solutions' catalogue includes monographs for lavender, peppermint and coconut oil, suggesting that the industrial scale-up process of microencapsulation and functionalization methods of textiles are challenging from technological, economical, toxicological and health-based perspectives.

The technological limitations of applied microencapsulation techniques in textile functionalization are mainly attributed to one critical quality attribute (CQA): the particle size distribution of microcapsules. In functionalized-medical textiles, this CQA is directly correlated with a patient's acceptance. More attention must thus be paid to sensory evaluations, which currently lack extensive results. Since EOs are multicomponent systems, the quantitative analysis of assay poses another challenge in commercializing EOs-based-textiles.

5 Conclusion

The microencapsulation of volatile EOs is widely investigated as a promising technique for designing textile with functional properties. Their application in fabric functionalization to produce medical textiles has been intensively explored due to eco-orientated consumerism. This study highlighted the use of essential oils such as cinnamon, lime, peppermint, thyme, lavender, clove and tea tree.

Coacervation is the most commonly employed method for essential oil microencapsulation in textile functionalization, followed by emulsion and spray-drying techniques. Published results indicate durable antimicrobial efficacy against both typical Gram-positive and Gram-negative bacteria, with higher efficacy observed against Gram-positive (*Staphylococcus aureus*) bacteria. One commonly employed textile functionalization method is the pad-dry-cure method.

Functionalized textiles embedded with microcapsules containing essential oils represent a significant potential for applications in medical treatments. Specifically, in the context of dermal wound healing, such textiles can serve as effective agents for the prevention or inhibition of infections and inflammation. Additionally, microcapsules exhibiting antifungal efficacy may be incorporated into athletic socks to reduce the incidence of fungal infections. Furthermore, medical textiles designed with immobilized microcapsules endowed with antimicrobial properties hold promise for the development of advanced military apparel, offering protection against microbial proliferation and the associated risks of infection.

The gaps that remain in the broad and diverse disciplines conducting research on antimicrobial textile with essential oil-based microcapsules must be narrowed over time. Further research arises from identified gaps in the field of textile functionalization, and is highlighted below:

1. The sensory evaluation and dermatological testing of medical textiles with immobilized

microcapsules must be performed in future research studies. If needed, further optimization on the particle size distribution or the overall technological process should be carried out. Such studies would increase the scientific worth of antimicrobial textiles. Dermatological testing should be performed in future studies to assess whether a product causes irritation and inflammation when in contact with the skin.

2. Toxicological studies of essential oils are extremely limited. Scientific-based toxicological studies of essential oils with proven antimicrobial activity must be performed. This would be a prerequisite in setting the dosage in antimicrobial textiles.
3. Studies focusing on release kinetics, mechanism of release, EO concentration and microencapsulation optimization, as well as the functionalization process, optimization and transdermal delivery, are not focused on evaluating the overall benefit of such technological development and the “therapeutic” benefit of value-added textile.
4. Performing stability studies of microcapsules and functionalized textile using microcapsules to set the shelf-life of finished products (functionalized textile). Until now, no literature has been identified that investigates for how long microcapsules maintain their antimicrobial efficacy.

Microcapsule textile functionalization is undoubtedly a challenging task for scientists but is expected to receive more attention in future. To overcome current knowledge gaps, an interdisciplinary approach in research groups is essential for the commercialization of antimicrobial textiles with essential oil-based microcapsules.

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Conflict of Interest: The authors declare no conflict of interest.

Data availability statement: All data analysed in this review were obtained directly from publicly accessible Scilit database using their readily available filters under advanced search.

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An Investigation into the Comparative Performance of Different Splicing Methods under Various Splicing Parameters

Primerjava učinkovitosti različnih metod spajanja koncev predivne preje v odvisnosti od različnih parametrov spajanja

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Abstract

End splicing is necessary to ensure continuity in the production of yarn from staple fibres. This process is essential for maintaining the integrity and quality of yarns during manufacturing and subsequent usage in textile products. For this purpose, the influence of various splicing variables on yarn splicing efficiency was analysed, and several splicing methods were compared. The article focuses on identifying optimal splicing parameters to improve the performance of spliced yarns. The research investigates several splicing variables such as overlap length, blast duration and splicing time for the pneumatic splicing method, and untwisting time, drafting and retwisting time for the mechanical splicing method to join the yarn (100 tex) ends. The performance of the yarns was assessed based on retained splice elongation (RSE) and retained splice strength (RSS). Statistical analysis was performed to determine the significance of variations in splicing variables. The results indicated that both RSE and RSS increased when the value of the splicing variables (parameters) increased for each method. The research found that variations in splicing variables significantly impact the characteristics of the spliced yarn. The study contributes significant insights into optimizing splicing techniques to improve yarn performance in the spinning industry.

Keywords: ring spun yarn, splicing parameter, pneumatic splicing, mechanical splicing, yarn characteristics

Izvleček

Pri proizvodnji preje iz kratkih vlaken je treba za zagotavljanje neprekinjenosti preje spojiti konca pretrgane preje. Postopek je nujen za ohranjanje celovitosti in kakovosti preje med proizvodnjo in nadaljnjo uporabo v tekstilnih izdelkih. Namen raziskave je bil analizirati različne vplivne parametre na učinkovitost spajanja preje. Primerjanih je bilo več metod spajanja. Članek se osredinja na prepoznavanje optimalnih parametrov spajanja za izboljšanje



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kakovosti spojenih prej, kot so dolžina prekrivanja, trajanje pihanja in čas spajanja za pnevmatsko metodo spajanja in čas odvijanja, napenjanja in ponovnega sukanja za mehansko metodo spajanja za spajanje koncev preje s finočo 100 tex. Učinkovitost spajanja je bila ocenjena na podlagi ohranjenega raztezka (RSE) in trdnosti (RSS) spoja. S statistično analizo je bil ugotovljen vpliv parametrov spajanja. Pokazalo se je, da sta se pri ob zvišanju vrednosti parametrov spajanja pri obeh metodah spajanja povečala RSE in RSS. V raziskavi je bilo dokazano, da obravnavani parametri spajanja pomembno vplivajo na lastnosti spojene preje. Raziskava podaja pomemben vpogled v optimizacijo tehnik spajanja v predilnicah za izboljšanje kakovosti prej iz kratkih vlaken.

Ključne besede: prstanska preja, parameter spajanja, pnevmatsko spajanje, mehansko spajanje, značilnosti preje

1 Introduction

Yarn splicing is a crucial process in the textile industry that is used to produce continuous lengths of yarn by joining the yarn ends. This process is essential for maintaining the integrity and quality of yarns during manufacturing and subsequent usage in textile products. In yarn manufacturing, the splicing of yarn is critical to joining the yarn ends for producing continuous lengths of yarn, which are necessary for fabric production and other applications [1]. Splicing is a perfect method for joining the yarn ends, and splice strength has a significant impact on the quality of spun yarns during warping, winding, weaving, and knitting [2]. The efficiency of yarn splicing has a significant impact on the final yarn quality as well as the finished products produced from this yarn [1, 3]. The splicing of yarn is a method used to connect two ends of yarn by interlocking the fibre to make it significantly similar in appearance and required characteristics relative to the main yarn [1]. To achieve the desired spliced yarn quality, different methods are applied, such as pneumatic, mechanical, electrostatic, and pneumo-mechanical methods [4, 5].

Mechanical splicing represents the physical intermingling of the fibres of yarn utilizing mechanical operations. Pneumatic splicing uses compressed air to bind the fibres of yarn. The pneumatic splicing technique is the most widely utilized compared to mechanical splicing [6]. The integration of water in the pneumatic splicing technique can improve performance by increasing fibre cohesion [5].

Some researchers have investigated the characteristics of spliced yarn in terms of splicing parameters, splicing methods, and yarn parameters, and found different results. Cheng et al. (2000) investigated spliced yarn strength under several conditions and found that the length and count of yarn have a significant impact on spliced yarn strength [7]. Cheng & Lam (2000) investigated spliced yarn properties under various splicing situations and found different results based on splicing conditions [8]. Nawaz et al. (2005) discussed the influence of splicing parameters on blended yarn characteristics and identified significant variations in terms of the properties of spliced yarn [9]. Hassen et al. (2008) examined the appearance and characteristics of cotton/ elastane spliced yarn and found that yarn count has a significant impact on the appearance and properties of spliced yarn [6]. Webb et al. (2009) investigated the impact of various variables on the appearance of yarn (spliced) utilizing the Taguchi analysis method and identified a significant impact on the appearance of yarn (spliced) [10].

Ünal et al. (2010) investigated the effects of splicing parameters, fibre and yarn properties on the tenacity and elongation of spliced yarns. In this study, artificial neural networks and response surface models were used to analyse spliced yarn tenacity and elongation as dependent variables. As independent variables, fibre properties together with the machine settings, such as opening air, splicing air, splicing time, yarn twist and yarn count, were

chosen [11]. In the second part of their study, Ünal et al. (2010) investigated the retained spliced diameter as it relates to splicing parameters and fibre and yarn properties [12]. Ünal et al. attempted to identify optimum splicing settings to obtain maximum tenacity and elongation after the splicing of the yarns that have different fibre properties, yarn counts and yarn twists [13].

Webb et al. (2010) investigated the implementation of simulation and visualization methods in spliced yarn development and found that the model applies to spliced yarn to determine the required results [14]. Boubaker et al. (2010) tried to develop a model (descriptive) for the longitudinal construction of spliced yarns and found that this model helps determine yarn structure [15]. Jaouachi et al. (2010) discussed the assessment of spliced yarn performance utilizing fuzzy theory and found that fuzzy theory is more suited for prediction than regression theory [16]. Baykaldi et al. (2011) examined the effect of various parameters (specifications) on the quality of elastane/cotton blended spliced yarn and found a significant impact on spliced yarn properties [17]. Moqet et al. (2013) discussed the influence of splicing specifications on spliced blended yarn (cotton/flax) and found that retained elongation, strength and appearance are affected by various parameters [18]. Uyanik (2019) attempted to identify the optimum splicing method for yarn count and fibre types, and found that a twin splicer is optimal for acrylic and cotton but not good for regenerated fibres (cellulose) [19].

Hossan et al. (2021) examined the splice strength of yarn manufactured from several types of cotton and found significant variations in characteristics between yarns [2]. Uyanik (2022) aimed to identify the optimum splicing method for cotton yarns and viscose yarns in terms of different yarn counts. For this purpose, three different methods – air splicing, wet splicing and twin splicing – were compared [20]. Ji & Wang (2023) attempted to develop a prediction model for spliced yarn and found that the model provides a basic formula for the relationship between

splicing, fibre and yarn properties [21]. Hamdi et al. (2023) investigated the mechanical characteristics of elastic yarn (dual-core) splice and found that the preparation parameter has less of an impact than the joining parameter [22]. Fahmida et al. (2024) investigated the impact of mingling chambers (60z and 92z2 types made of copper) on yarn splice strength and appearance using air and wet splicing methods. Their study found that both the type of mingling chamber and the splicing medium significantly impact the quality of the yarn joint. The findings contribute to the understanding of how equipment configuration and process parameters impact splice performance, offering insights for optimizing yarn joining techniques in textile manufacturing [23]. Although there are some studies that have investigated the elongation, strength and appearance of spliced yarn based on fibre types and characteristics, yarn types, the linear density of yarn, the splicing method and the utilization of different theories and software, no works have been found where several parameters have been used within the same methods to join yarn ends through splicing. There is still a lack of information in literature regarding the investigation of spliced yarn performance based on various splicing variables within the same method of splicing. This study explored the comparative performance of different methods under several splicing parameters. The purpose was to systematically investigate how these parameters affect the key properties of the spliced yarn. In addition, most studies have been conducted on middle and fine yarns. However, this study was carried out using coarse yarn, which is commonly used in denim production.

2 Materials and methods

During this research, 100 tex cotton yarn (carded) was produced using a ring spinning machine to investigate the variables impacting spliced yarn characteristics.

1.1 Raw materials

For this study, 100% cotton (roller-gin Turkish cotton) was sourced from a local supplier to produce 100 tex yarns. The specifications of the cotton fibre

are presented in Table 1. The cotton was tested using Uster HVI 1000 equipment. Ten test results were recorded, and the average result was taken for analysis.

Table 1: Properties of cotton fibre

SCI ^{a)}	Mic ^{b)} ($\mu\text{g}/\text{cm}$)	MI ^{c)}	UHML ^{d)} (mm)	UI ^{e)} (%)	SFI ^{f)}	Strength (cN/tex)	Elongation (%)	Moisture (%)	Trash count (g ⁻¹)	Trash area (%)
142.89	1.77	0.90	29.75	84.37	6.68	32.95	6.16	7.52	147.67	3.89

^{a)} Spinning consistency index, ^{b)} Micronaire ($1.77 \mu\text{g}/\text{cm} = 4.50 \mu\text{g}/\text{inch}$), ^{c)} Maturity index, ^{d)} Upper half mean length, ^{e)} Uniformity index, ^{f)} Short fiber index

1.2 Spinning process

With this collected cotton fibre, carded yarn was manufactured using a traditional ring spinning

machine. The parameters (specifications) of the production of several machines are presented in Table 2.

Table 2: Parameters of yarn production

Machine name	Brand name	Delivery material	Speed
Blowroom	Marzoli	card mat: 7.30 ktex	600 kg/h
Carding machine	Marzoli C601	sliver: 7.37 ktex	139 m/min
1 st draw-frame	Rieter-SB D-50	1 st sliver: 5.9 ktex	6 doubling: 750 m/min
2 nd draw-frame	Rieter-RSB D-50	2 nd sliver: 5.9 ktex	7 doubling: 750 m/min
Roving frame	Marzoli FTD-2	roving: 1.15 ktex	flyer speed: 1000 m ⁻¹
Ring frame	Marzoli-MPTN-1	Count of yarn: 100 tex, TPI: 9.7 ^{a)}	spindle speed: 6400 m ⁻¹

^{a)} turns per inch; 1 TPI = 0.3937 cm^{-1}

2.3 Winding process

After yarn production, the winding process was performed on a winding machine (SAVIO POLAR IDLS). During winding, three different splicing methods were employed to join broken yarn ends. These methods include mechanical (twin) splicing, pneumatic splicing without water and pneumatic splicing with water. Figures 1 and 2 show the mechanical splicer and pneumatic splicer, respectively.

2.4 Testing setup and specific process parameters

The specific process parameters, including untwisting time (U), re-twisting time (R), and drafting (D), which adjust the splice diameter, were investigated as process parameters for the mechanical method (Figure 1). The range of untwisting and re-twisting time is 1 to 7 (7 is the highest strength), while the range of drafting (which balances the diameter of the splice) is 0 to 4 (diameters decrease from four to zero). Also investigated

were the duration of the blast (the ends preparation blast- T_1), overlap length (the end of the overlap-L), and the duration of the splicing blast (T_2) for the pneumatic methods (Figure 2). The range of the T_1 and T_2 is 1 to 12 (12 is the largest blast), and the range of the overlap length is 1 to 12 (12 is the maximum overlap). Based on previous studies and operational experience, the most commonly applied values were selected. In this context, T_1 was evaluated at two levels (2 and 3), L was evaluated at two levels (9 and 10) and T_2 was evaluated at three levels (6, 7 and 8) for pneumatic splicing with and without water, while U was evaluated at three levels (5, 6 and 7), D was evaluated at two levels (2 and 3) and R was evaluated at three levels (4, 5 and 6) for mechanical splicing. To reduce bias and improve the reliability of results, a structured randomization strategy was applied. The randomization process was designed using a random number generator via a Microsoft Excel function. Each experimental condition (i.e. a combination of T_1 , L and T_2 , water application

for the pneumatic method, and U, D and R for the mechanical method) was first coded and listed. Random numbers were then assigned to each sample and the list was sorted based on these values to determine the testing order. This ensured that the sequence of experiments did not follow a systematic or ordered pattern that could influence the results. A total of thirty-six samples were produced based on various variables for

the pneumatic method, which is presented in Table 3, and a total of ten samples were produced based on multiple variables for the mechanical method, which is presented in Table 4. The other parameters of the winding machine for all splicing techniques were the same, while the winding machine speed was 950 m/min and the air pressure was 6 bar for the pneumatic method.

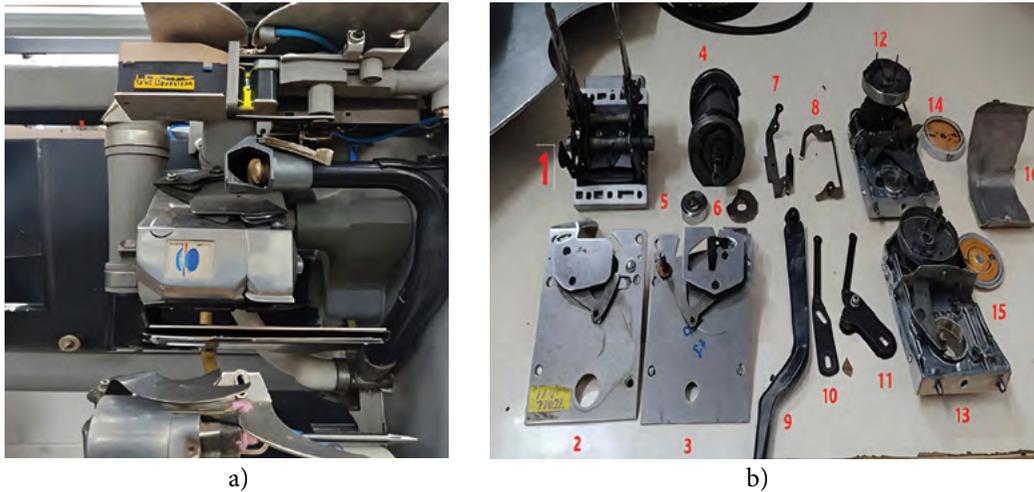


Figure 1: Mechanical splicer: a) splicer, b) splicer parts

Legend: 1 – yarn holding pliers, 2, 3 – cover, 4 – movement cam, 5 – bearing, 6 – flange, 7, 8 – fork opening device (collets), 9 – splice guide arm (lever), 10 – yarn breaking arm (lever), 11 – yarn tension adjustment (lever), 12, 13 – splice general body, 14, 15 – disc, 16 – dust prevention cover

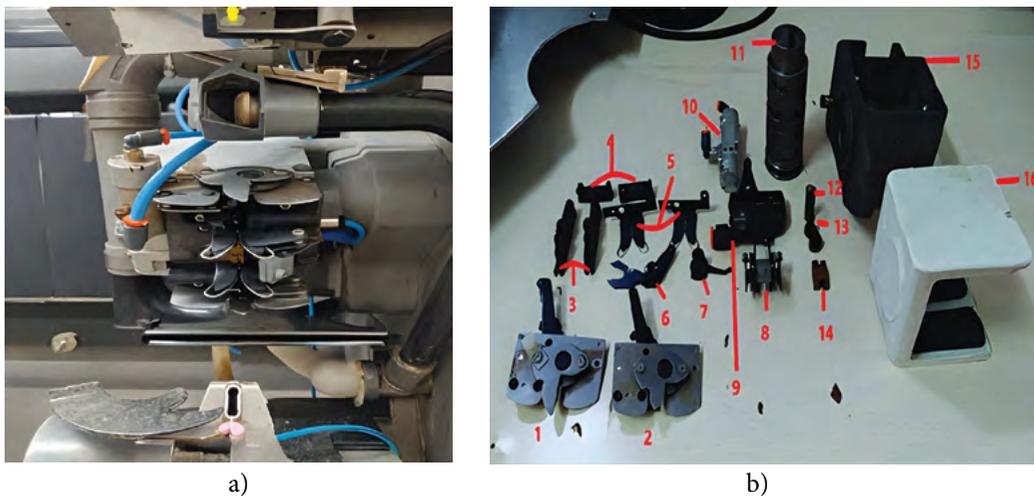


Figure 2: Pneumatic splicer: a) splicer, b) splicer parts

Legend: 1 – upper scissor group, 2 – lower scissor group, 3 – opener, 4 – opener scissor group, 5 – yarn guide, 6 – end lever, 7 – end retraction lever, 8 – chamber cover, 9 – valve, 10 – water tank, 11 – actuating cam, 12 – piston spring, 13 – splice piston rod, 14 – prism, 15 – body, 16 – carter

Table 3: Samples produced by the pneumatic method based on several variables

Serial no.	Sample code	Duration of blast, T_1 (ms)	Overlap length, L (mm)	Splicing blast, T_2 (ms)	Water application (1 or 2 times)
1	3-10-8	3	10	8	
2	3-10-7	3	10	7	
3	3-10-6	3	10	6	
4	3-9-8	3	9	8	
5	3-9-7	3	9	7	
6	3-9-6	3	9	6	
7	2-10-8	2	10	8	
8	2-10-7	2	10	7	
9	2-10-6	2	10	6	
10	2-9-8	2	9	8	
11	2-9-7	2	9	7	
12	2-9-6	2	9	6	
13	3-10-8- W_1	3	10	8	1
14	3-10-7- W_1	3	10	7	
15	3-10-6- W_1	3	10	6	
16	3-9-8- W_1	3	9	8	
17	3-9-7- W_1	3	9	7	
18	3-9-6- W_1	3	9	6	
19	2-9-8- W_1	2	9	8	
20	2-9-7- W_1	2	9	7	
21	2-9-6- W_1	2	9	6	
22	2-10-8- W_1	2	10	8	
23	2-10-7- W_1	2	10	7	
24	2-10-6- W_1	2	10	6	
25	3-10-8- W_2	3	10	8	2
26	3-10-7- W_2	3	10	7	
27	3-10-6- W_2	3	10	6	
28	3-9-8- W_2	3	9	8	
29	3-9-7- W_2	3	9	7	
30	3-9-6- W_2	3	9	6	
31	2-9-8- W_2	2	9	8	
32	2-9-7- W_2	2	9	7	
33	2-9-6- W_2	2	9	6	
34	2-10-8- W_2	2	10	8	
35	2-10-7- W_2	2	10	7	
36	2-10-6- W_2	2	10	6	

Finally, the properties of manufactured yarns, such as strength and elongation, appearance, retained splice elongation (RSE) and retained splice strength (RSS), were investigated. The elongation at break and strength of yarns were tested using

an Uster Tensorapid-3 according to the ISO 2062, DIN 53 834 and ASTM D-1578 standards. Ten test results were taken and the mean value was calculated for analysis. For visual analysis, photographs of every spliced place were taken after splicing. Testing

conditions (temperature: $20 \pm 2^\circ\text{C}$, relative humidity: $65 \pm 2\%$) were continuously monitored and maintained using a controlled lab setup according to the ASTM D1776 standards. All yarns used were from the same production lot to ensure consistency in raw material properties.

The RSE and RSS were calculated using the following equations [17, 22, 24].

$$RSS = \frac{\text{Spliced yarn strengt}}{\text{Strenath of parent yarn}} \times 100 \quad (1)$$

$$RSE = \frac{\text{Spliced yarn elongation}}{\text{Elongation of parent yarn}} \times 100 \quad (2)$$

For visual analysis, photographs of each spliced place were taken using an ultra-wide camera –13mm f/2.2 (Apple iPhone 14 Promax).

Table 4: Samples produced using the mechanical method based on several variables

Serial no.	Sample code	Untwisting time-U (milliseconds)	Drafting-D	Re-twisting time-R (milliseconds)
1	7-3-5	7	3	5
2	6-3-5	6	3	5
3	5-3-5	5	3	5
4	7-2-5	7	2	5
5	6-2-5	6	2	5
6	5-2-5	5	2	5
7	6-3-4	6	3	4
8	6-2-4	6	2	4
9	6-3-6	6	3	6
10	6-2-6	6	2	6

Furthermore, analysis of variance (one-way ANOVA) with a post-hoc test was applied as a statistical analysis to investigate the significant variation in terms of the characteristics of several yarns with SPSS 25.0 within the same splicing method and for different splicing methods. It was performed at a 95.0 percent confidence level or a 0.050 significance level, which shows that if the p-value is less than 0.05, the difference (properties) will be statistically significant [25–27].

3 Results and discussion

3.1 Results

The appearance of the yarns joined with the splicer is as important as their strength. For visual analysis, photographs of each spliced place were taken. When the photographs are examined, the hairiness of the yarns varies at the joints according to the selected process parameters and splicer. In the case of visual analysis, as shown in Figures 3 to 5, it can be generally observed that the splice appearance produced by the pneumatic method without the use of water exhibits a very hairy structure. This is primarily due to the incomplete twisting of fibres under the influence of pressurized air. When the pneumatic method is applied with water, the spliced yarns display a less hairy appearance than those produced without water. This improvement is attributed to the role of water in promoting fibre adhesion, thereby helping to prevent fibre separation from the yarn cross-section during the application of pressure.

Furthermore, spliced yarns prepared using the mechanical method exhibit the lowest hairiness among the three methods. With a mechanical (twin) splicer, the yarn ends are opened between two rotating disks, and then twist is given between the disks as it closely resembles the twisting process used in ring yarn spinning. The contact between the discs and the fibres ensures the effective re-twisting of the yarn ends. Moreover, there is no air pressure and thus the separation of short fibres is prevented. Similar results were also reported in earlier studies [19]. Conversely, when each splicing method was assessed independently, it was determined that the selected splice parameters did not result in a notable difference in splice appearance. This suggests that the splicing technique itself, rather than the specific parameters applied, played a determining role in the visual outcome of the splice.

The test results for strength, elongation at break, RSS and RSE are presented in Table 5. The strength of the parent yarn before splicing was 17.85 cN/tex with a CV of 6.2%, while the elongation at break of

the parent yarn before splicing was 7.65% with a CV of 5.2%, taking into account ten measurements.

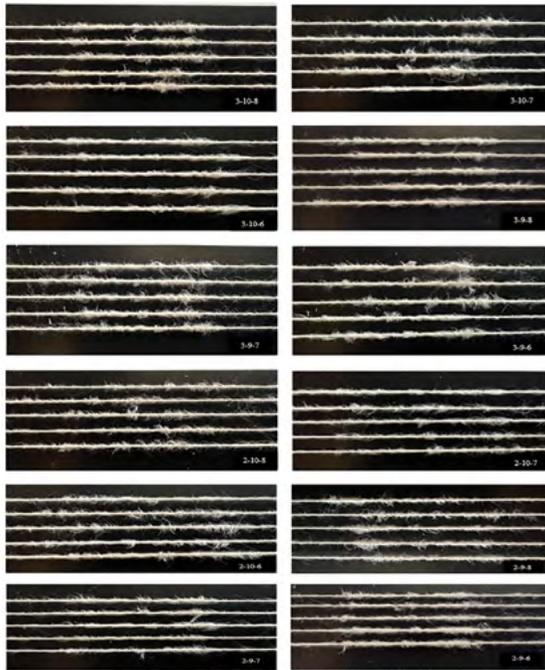


Figure 3: Appearance of spliced yarn-6x (pneumatic method without water)

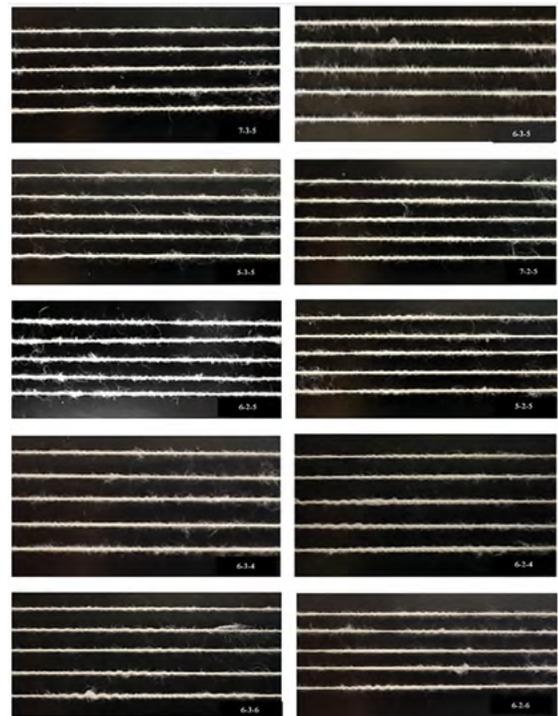


Figure 5: Appearance of spliced yarn-6x (mechanical method)

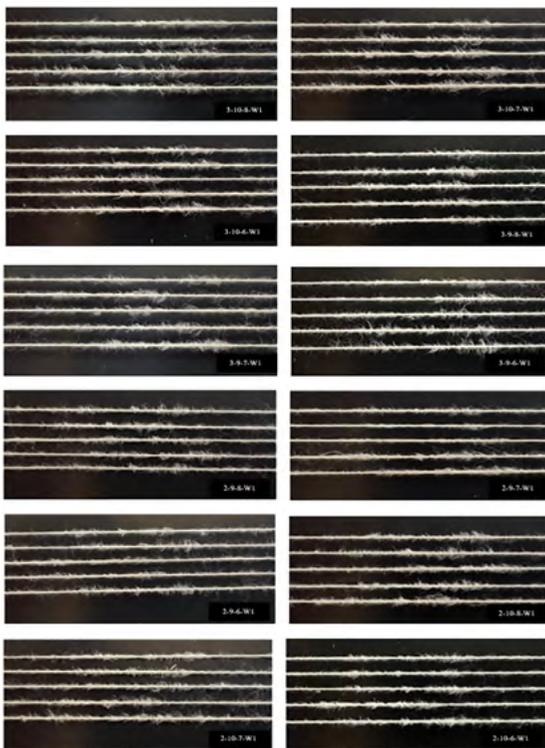


Figure 4: Appearance of spliced yarn-6x (pneumatic method with water)

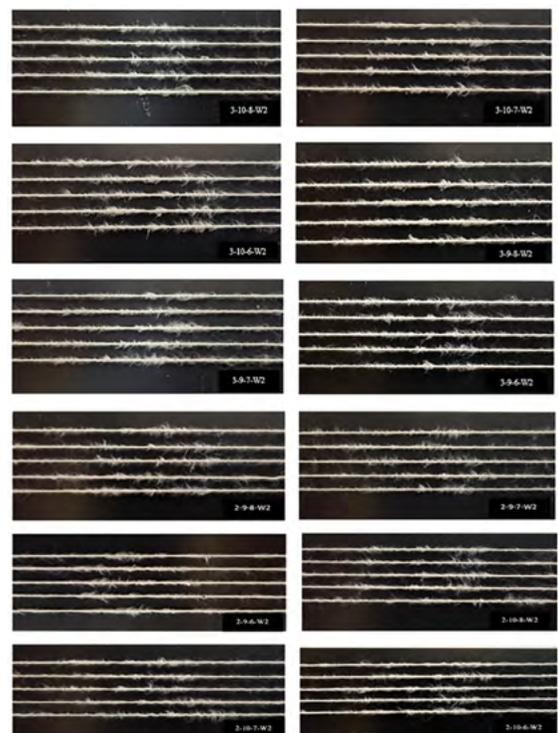


Table 5: Test results of spliced yarn

Splicing method	Sample code	Elongation (%)	Strength (cN/tex)	RSE ^{a)} (%)	RSS ^{b)} (%)
Pneumatic splicing method without water	3-10-8	4.54	4.38	59.35	24.56
	3-10-7	4.82	4.12	63.01	23.08
	3-10-6	5.05	4.72	66.01	26.43
	2-10-8	5.18	7.41	67.71	41.54
	2-10-7	5.27	6.69	68.89	37.47
	2-10-6	5.41	7.45	70.72	41.76
	3-9-8	4.33	4.49	56.60	25.16
	3-9-7	5.17	5.33	67.58	29.83
	3-9-6	3.82	3.99	49.93	22.36
	2-9-8	5.18	5.10	67.71	28.57
	2-9-7	4.78	4.69	62.48	26.26
2-9-6	4.09	3.71	53.46	20.77	
Pneumatic splicing method with water	3-10-8-W ₁	5.07	6.54	66.27	36.65
	3-10-7-W ₁	4.97	6.34	64.97	35.49
	3-10-6-W ₁	4.72	5.26	61.70	29.45
	3-9-8-W ₁	5.16	6.79	67.45	38.02
	3-9-7-W ₁	4.93	6.16	64.44	34.50
	3-9-6-W ₁	4.53	5.83	59.22	32.64
	2-9-8-W ₁	4.99	5.92	65.23	33.18
	2-9-7-W ₁	4.82	5.32	63.01	29.78
	2-9-6-W ₁	4.85	5.18	63.40	29.01
	2-10-8-W ₁	5.45	6.49	71.24	36.37
	2-10-7-W ₁	4.94	6.58	64.58	36.87
	2-10-6-W ₁	4.71	5.08	61.57	28.46
	3-10-8-W ₂	7	6.26	91.50	35.05
	3-10-7-W ₂	4.85	5.93	63.40	33.24
	3-10-6-W ₂	5.69	6.48	74.38	36.32
	3-9-8-W ₂	5.44	6.85	71.11	38.35
	3-9-7-W ₂	4.87	6.56	63.66	36.76
	3-9-6-W ₂	5.03	6.61	65.75	37.03
	2-9-8-W₂	5.45	7.48	71.24	41.92
	2-9-7-W ₂	5.22	7.02	68.24	39.34
2-9-6-W ₂	5.02	6.46	65.62	36.21	
2-10-8-W ₂	4.78	5.84	62.48	32.69	
2-10-7-W ₂	5.42	6.74	70.85	37.74	
2-10-6-W ₂	4.79	5.35	62.61	30.00	
Mechanical (twin) splicing method	7-3-5	6.06	11.72	79.22	65.65
	6-3-5	5.21	9.40	68.09	52.63
	5-3-5	4.95	8.97	64.68	50.27
	7-2-5	6.06	10.73	79.18	60.11
	6-2-5	5.41	10.83	70.73	60.66
	5-2-5	4.49	9.00	58.64	50.44
	6-3-4	5.30	10.60	69.29	59.39
	6-2-4	4.99	9.61	65.19	53.84
	6-3-6	4.87	9.77	63.69	54.72
6-2-6	5.22	10.67	68.22	59.78	

^{a)} Retained splice elongation; ^{b)} Retained splice strength

3.2 Discussion of RSS and RSE

3.2.1 Evaluating RSS and RSE

RSS and RSE are the most important elements in investigating the properties of spliced yarn [22]. While T_1 changed from 3 to 2, RSS and RSE generally increased, as shown in Figure 6. On the other hand, as the T_2 value increased from 6 to 8, there was a gen-

eral increase in RSS and RSE values. When the end preparation (blast duration- T_1) is short, the fibres are opened without being damaged. However, the long blast duration (T_2) for splicing ensures that the fibres intermingle well, creating a strong joint. In previous studies, it was found that splice strength improved with an increase in the joining air duration [6, 10].

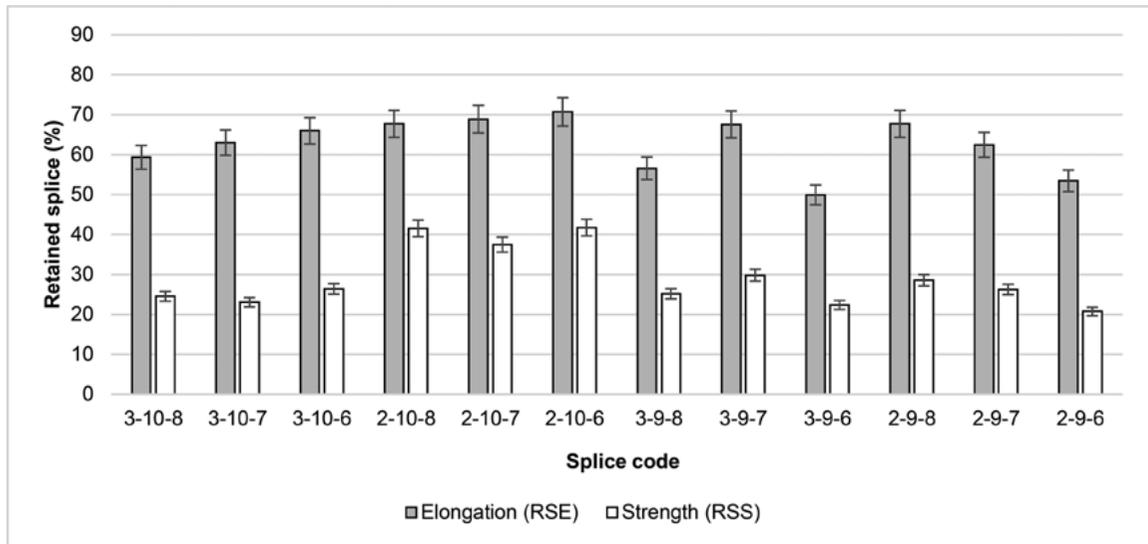


Figure 6: RSS and RSE of several yarns prepared using the pneumatic method without water

Increasing overlap length (L) from 9 to 10 generally increased RSS and RSE values. L refers to the length of the yarn ends that overlap before they

are joined together. A high overlap length ensures a strong and durable splice. Similar results have been found in previous studies [7, 8].

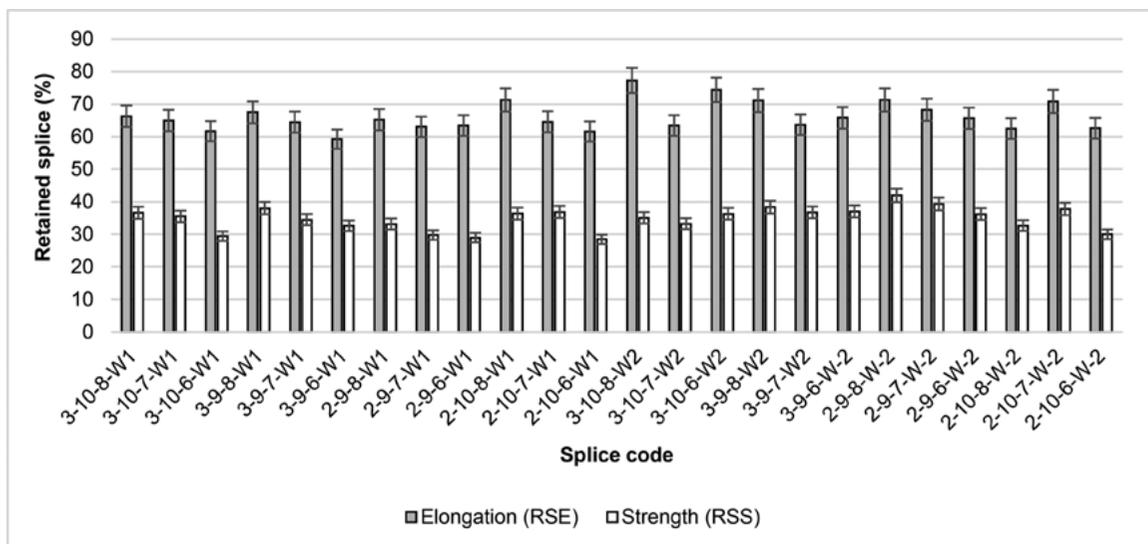


Figure 7: RSS and RSE of several yarns prepared using the pneumatic method with water

The results showed that applying water twice in the wet splicer generally improved the RSS and RSE values (Figure 7). The presence of water helps to improve the adhesion of fibres during the splicing process. Enhanced adhesion ensures that fibres remain well-integrated within the yarn structure [19].

Within the observed range, T_1 did not generally result in a significant change in RSS and RSE values; the variation in T_2 had a more pronounced effect.

RSS and RSE were found to increase in most of the samples when T_2 was increased in the pneumatic splicing method with water. A previous study [22] emphasized that joining parameters are more impactful than preparation parameters. Similarly, in this study, T_2 was found to be more effective than T_1 . Increasing overlap length (L) from 9 to 10 generally decreased RSS while increasing RSE values.

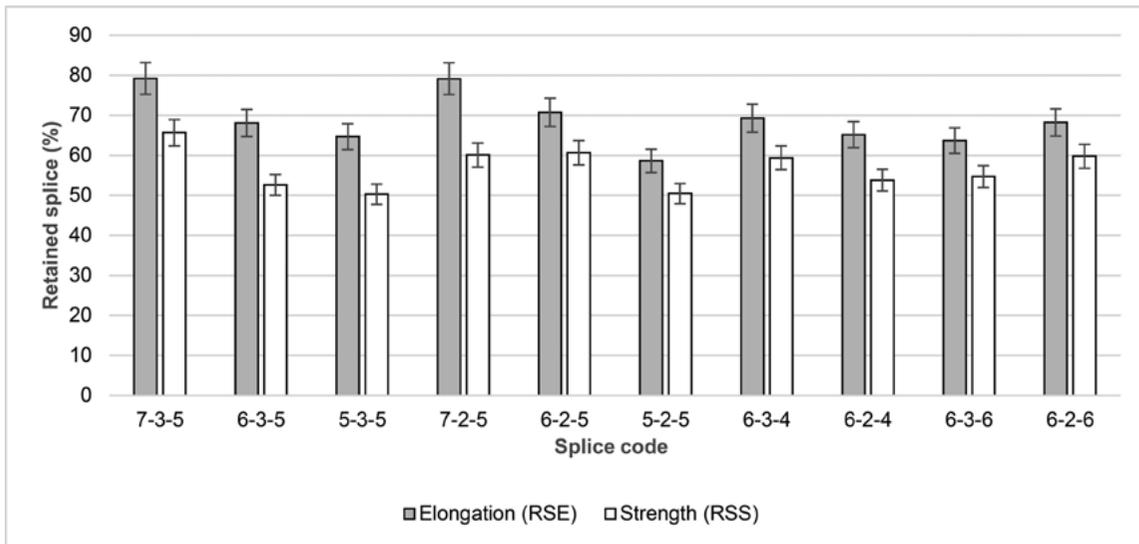


Figure 8: RSS and RSE of several yarns prepared using the mechanical (twin) method

In the mechanical method, increasing the U, D and R values generally increased the RSS and RSE values (Figure 8). Proper drafting (D) ensures that the diameter of the spliced section matches that of the original yarn, maintaining yarn consistency.

3.2.2 Comparison of splicing methods

For comparison purposes, the average RSS and RSE values across all variables were calculated for each method and are presented in Figure 9. It was found that the pneumatic method without water resulted in low RSS and RSE values. This is attributed to the incomplete twisting of fibres in coarse yarns, caused by the impact of pressurized air. In the case of the

pneumatic method with water, the spliced yarns exhibited better results than the pneumatic method without water. This improvement is attributed to the presence of water, which enhances fibre adhesion and helps prevent fibre separation from the yarn cross-section under pressure, thereby resulting in higher RSE and RSS values. Spliced yarns produced using the mechanical method exhibited higher RSE and RSS values than the other two methods. This can be attributed to the lower likelihood of short fibre separation in the absence of air pressure and the ability of the twin discs to effectively twist the yarn ends through direct contact. Similar results have been found in previous studies [19, 20].

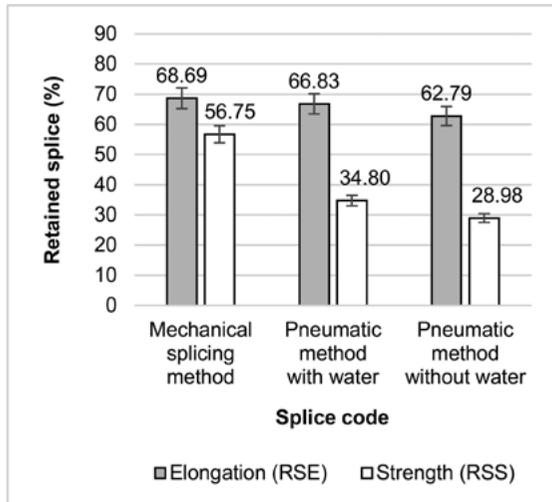


Figure 9: RSS and RSE of several yarns prepared by different methods

In the case of statistical analysis, the spliced yarn property (RSE or RSS) is the dependent variable, while the parameters (variables) of each splicing method are independent variables. For the homogeneity test (Levene’s test), it was found the ‘P’ value of RSS and RSE was 0.084 and 0.079, both of which are greater than 0.05, which indicates the data are normally distributed. In the case of the post-hoc test, the Tukey test was performed. It was found that the ‘P’ value of spliced yarn property (RSE or RSS) was less than 0.050 for one-way ANOVA and the post-hoc test, which indicates there is a significant variation in spliced yarn properties (RSE or RSS) prepared using different variables for each method, as presented in Tables 6 and 7.

Table 6: Statistical analysis for RSS and RSE (one-way ANOVA)

Method	Dependent variable	Type III sum of squares	df	Mean square	F	Sig.
Pneumatic method without water	RSS	6399.766	10	581.799	24046.237	.000
Pneumatic method with water		6568.366	24	591.274	23016.254	.000
Mechanical (Twin) method		6101.153	12	562.362	21037.341	.000
Pneumatic method without water	RSE	5371.828	10	488.348	10226.374	.000
Pneumatic method with water		5534.153	24	490.258	10986.421	.000
Mechanical (Twin) method		5212.921	12	469.453	10101.289	.000

Table 7: Multiple comparison (post-hoc test)

Tukey HSD					
Dependent variable	(I) Method	(J) Method	Mean Difference (I-J)	Std. error	Sig.
RSS	Pneumatic method without water	Pneumatic method with water	4.04250	2.30192	.044
	Pneumatic method with water	Mechanical (Twin) method	1.86300	2.45058	.042
	Mechanical (Twin) method	Pneumatic method without water	5.90550	2.78776	.038
RSE	Pneumatic method without water	Pneumatic method with water	5.81250*	1.79894	.007
	Pneumatic method with water	Mechanical (Twin) method	21.9531*	1.91511	.000
	Mechanical (Twin) method	Pneumatic method without water	27.76567*	2.17862	.000

4 Conclusion

The splice structure is highly complex, especially when working with staple fibres. It is worth noting that understanding the intricacies of splice structures,

particularly within the intricate context of yarn fibre structures, poses a formidable challenge.

The optimal values of splicing parameters are

crucial for enhancing yarn performance. This study focused on the impact of different splicing variables on yarn properties using pneumatic and mechanical (twin) splicing methods. The performance of the spliced yarns was evaluated based on RSE and RSS by comparing them to the original yarn. Additionally, spliced yarn images were also taken. The key findings of the study are summarized below:

- The results showed that applying water twice in the wet splicer generally improved the RSS and RSE values for the pneumatic splicing method. As mentioned in previous studies, the presence of water reduces the likelihood of fibres separating from the yarn's cross-section. This is crucial when pressures are applied during the splicing process, as it maintains the integrity of the splice. The combination of water and air generates substantial torque within the air chamber, facilitating superior intermingling. Moreover, water acts as a lubricant, enhancing inter-fibre cohesion, further contributing to the overall quality of the splice [6, 19, 24].
- Similar to a previous study [19], the mechanical method yielded better results than the other two methods in terms of both RSS and RSE values, as well as yarn appearance.
- In the pneumatic method, optimal strength results were achieved when the blast duration was 2 ms, the overlap length was 10 mm and the splicing blast was 6 ms. On the other hand, no significant difference was observed between the splice appearances.
- In the pneumatic method with water, optimal strength results were achieved when the blast duration was 2 ms, the overlap length was 9 mm, the splicing blast was 8 ms and the water was applied twice. However, no notable difference was observed between the wet splice appearances.
- In the mechanical method, optimal strength results and better yarn appearance were achieved when the untwisting time was 7 ms, the drafting was 3 and the re-twisting time was 5 ms. However, no significant difference was observed between the wet splice appearances.
- The two main splice characteristics are appearance and strength. Although RSS is suitable for objective assessment, splice appearance is more difficult to assess. Specifically, a splice with an RSS exceeding 80% was considered acceptable for production purposes [22, 24]. An increase in yarn linear density causes a drop in the RSS because the splicer is designed for splicing fine yarns [6, 7]. In this study, a yarn count commonly used in denim (100 tex) was selected. It was observed that the RSS values were generally low due to the coarse nature of the yarn used in the study. Among the three methods, the mechanical splicer yielded the highest RSS value (65.65%). This study recommends the use of a mechanical splicer for coarse cotton yarns, both in terms of strength and splice appearance. Similar studies stated that the twin (mechanical) splicing mechanism is the most suitable for cotton fibres, with twin splicing being the best option for coarse yarns [19, 20].
- This research provides valuable insights into the optimization of splicing techniques to improve yarn performance in the spinning industry. By adjusting splicing variables, manufacturers can achieve improved yarn quality and durability, enhancing the overall quality and efficiency of the production process. This research focused on specific splicing parameters and methods for coarse cotton yarn. Further research could explore various fibre types and additional splicing techniques to validate and extend these outcomes.

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The Application of an Intelligent System in Digital Weave Design: Optimising Light Intensity and Font Selection for Enhanced Fabric Creation

Uporaba inteligentnega sistema pri digitalnem oblikovanju tkanine: optimizacija osvetljenosti in izbira pisave

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Abstract

The increasing demand for creative and aesthetically pleasing fabric designs has been facilitated significantly by advances in software engineering, enabling textile designers to meet these challenges more effectively. Complex designs that were once difficult or nearly impossible to produce are now readily available with the aid of specialized software. However, the use of such software necessitates a high level of skill and experience, and there is limited literature on its performance under varying environmental conditions. This research focuses on the application of digital weaving software to identify best practices for font selection and considers the impact of light intensity on image capture. The statistical analysis reveals a strong linear correlation between light intensity and variation in unbroken floats. The study's findings recommend specific font styles for writing text on fabric selvedge and suggest an optimal light intensity range for camera-based image capture, which is crucial for subsequent software processing. These insights are expected to assist textile technologists in creating fabric selvedge with woven text more efficiently.

Keywords: digital weaving, optimization, intricate designs, Jacquard, intelligent systems

Izvleček

Zadovoljevanje naraščajočega povpraševanja po kreativnih in estetsko privlačnih vzorcih tkanin je znatno olajšano z napredkom v razvoju programske opreme, ki tekstilnim oblikovalcem in tehnologom omogoča učinkovito spopadanje s temi izzivi. Zapleteni vzorci, ki jih je bilo nekoč težko ali skoraj nemogoče izdelati, so sedaj z uporabo specializirane programske opreme zlahka izvedljivi. Uporaba tovrstne programske opreme zahteva visoko raven znanja in izkušenj, literature o njenem delovanju v različnih okoljskih razmerah pa je malo. Ta



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raziskava se osredinja na uporabo programske opreme za digitalno tkanje, za prepoznavanje najboljših praks pri izbiri pisave, in upošteva tudi vpliv intenzivnosti svetlobe na zajem slike. Statistična analiza razkriva visoko linearno korelacijo med intenzivnostjo svetlobe in variacijo flotirajočih niti. Rezultati raziskave so priporočila za izbor določenih slogov pisav za vstavljanje besedila na rob tkanine in predlogi optimalnega razpona intenzivnosti osvetlitve za zajem slike s kamero, kar je ključnega pomena za nadaljnjo obdelavo s programsko opremo. Pričakovati je, da bodo ti vpogledi pomagali tekstilnim oblikovalcem in tehnologom pri učinkovitejšem ustvarjanju robov tkanine s tkanim besedilom.

Ključne besede: digitalno tkanje, optimizacija, zapleteni dizajni, žakard, inteligentni sistemi

1 Introduction

A Jacquard loom is a type of weaving machine capable of producing intricate and artistic fabric designs. Jacquard weaving has a long-standing tradition and historical significance. Before 1804, Jacquard fabrics were made by hand. It was in that year that Joseph Jacquard introduced punch cards to automate the Jacquard loom. The early versions of the loom were referred to as “treadle looms,” later evolving into “pattern looms,” and eventually becoming known as “draw looms” [1]. Modern electronic Jacquard weaving machines are widely used in the textile industry. These machines have electronic selection systems that allow them to harness control to generate specified designs [2, 3]. Significant advances in Jacquard technology have occurred over the past few decades [4]. Modern Jacquard machines have transitioned to electronic forms with computer controls, and Jacquard weaving now widely utilizes network communication [5, 6]. Additionally, the hook count in computerized Jacquard machines has increased to 20,000, significantly expanding patterning capabilities [7]. The latest approach in computer art design is digital picture design, with Jacquard fabric now regarded as a “high-grade” material featuring intricate colours and textures. The design and techniques for digital Jacquard fabrics are inspired by computer-generated images and colour modes, allowing the creation of advanced Jacquard fabric designs that surpass traditional free-hand patterns [8]. In contemporary Jacquard weaving, the variability of the colour of the yarn is limited to electronic Jacquard technology,

making it challenging to achieve a wide range of weave colours. To reproduce pictorial images with minimal yarn variation, a CMYK (cyan, magenta, yellow and black) colour system is used to define artwork colours, with primary colour data applied to weave structures. These weave colours display a wide spectrum of brightness, hue, and chroma variations, closely mimicking the effect of pigment mixing [9].

Currently, there is limited literature on the performance of widely used Jacquard software. While the potential for design creation is great, translating these designs into woven fabric presents several challenges. These challenges include managing the number of colours in a design, selecting the appropriate design to achieve the desired appearance and configuring machine settings for computer-aided manufacturing. An essential technical parameter in Jacquard weaving is the control of unbroken floats. In textile terminology, a float refers to the length of yarn on the surface of a woven fabric between two consecutive intersections of yarns woven at right angles, and it is a critical factor in determining a fabric’s weave-ability. This research specifically examines the process of floatation editing, emphasizing the importance of managing float length, particularly at the edges and borders of design motifs. Proper floatation control is critical for maintaining the sharpness and aesthetic quality of woven text and intricate patterns. At the borders of these motifs, where float length control becomes particularly challenging, the precision of floatation directly impacts the visibility and readability of the

woven fabric. This study, therefore, addresses the intricate process of floatation editing to ensure that the design remains visually intact, even in its most detailed parts. This research focuses on selecting font styles to print text for Jacquard weave patterns on the fabric selvage, and examines the impact of sunlight on the designs through image processing techniques for colour reduction and weave assignment. The findings of this research will assist Jacquard designers in effectively incorporating text into designs and developing new patterns using camera-based methods. Future research should explore the integration of advanced AI algorithms to further enhance design precision and automation in Jacquard weaving.

2 Methodology

Research results were analysed using both subjective and objective methods. The subjective evaluation involved visual inspection during the float-breaking process, along with feedback from respondents gathered through a survey. The objective analysis focused on quantifying the number of broken and unbroken floats. This study did not involve the physical production of woven fabric. Instead, the weaving process was simulated using digital images to evaluate the occurrence of unbroken floats under varying light intensities and times of day. Table 2 provides details of the unbroken floats for the selected fonts of the 225 font styles studied. To determine the most visible font for digital weaving, the pre-installed Microsoft Paint application, available on all Microsoft operating systems, was used. A total of 225 different font styles from the Microsoft Word application were selected

for evaluation. Fonts were categorised as “Good” if they retained clarity, “Satisfactory” if they showed slight degradation and “Compromised” if they became hard to read due to excessive float breaking. The “The quick brown fox jumps over the lazy dog” was used for all font styles. The image size was set to 744 pixels in width and 120 pixels in height before copying the text from Word to Paint, as illustrated in Figure 1. The images were then saved in Portable Network Graphic (PNG) files. ScotWeave, software developed by ScotCad Textiles Ltd., UK, was used to convert these image files into a format readable by the Bonas Jacquard machine. The image files were opened in the artwork module of ScotWeave, where the colours were reduced to grayscale and then further limited to only two colours. The processed artwork was then opened in the Jacquard designer module, where yarns were defined, and 5-end satin and sateen weaves were added to the colour Jacquard module.

The float length was set to six (6) in the float breaking tool within the Jacquard designer module. The number of floats was measured on both sides (face and back) of the fabric and in both weaving directions (warp and weft). This process was repeated four times to minimize the number of floats as much as possible. Finally, the output from the Jacquard designer module was exported in Bitmap format for fabric weaving. The Bitmap format was chosen as an intermediate step due to its compatibility with image processing tools and lossless quality, enabling precise design adjustments. After optimizing the design, it was converted to the Jacquard-specific format required for the loom, ensuring compatibility while maintaining design integrity.



Figure 1: Microsoft paint with copied font style from Microsoft Word

2.1 Optimization of light conditions for Jacquard weaving

Referring to Figures 2 and 3, images were captured from two locations at the National Textile University (NTU), Pakistan: the main entrance (UME) and the medical centre (UMC), during morning and evening hours. The images were taken using an Android smartphone equipped with a 48MP AI quad-camera. Sunlight intensity, measured in lux, was recorded using the Lux Light Meter application developed by Micro Inc., available in the Google Play Store. To optimise light conditions for Jacquard weaving, the Jacquard inscription “The quick brown fox jumps over the lazy dog” was simulated using the collected lighting data. The images captured under varying light intensities were processed to assess their effect on the clarity and readability of the text in the simulated Jacquard weave. The impact of light intensity on the unbroken floats and overall fabric design was observed. The float-breaking process followed a specific sequence: first breaking the warp float on the face side of the fabric, followed by the weft float on the face side, then the warp float on the backside and finally the weft float on the backside. The results were used to determine the optimal lighting conditions for accurate image capture, which is crucial for subsequent software processing in Jacquard weaving. To analyse the impact of lighting on fabric quality, images were captured at various times of the day, starting from the morning, with light intensity measured using the Lux Light Meter application. The time of day was recorded to assess how varying light conditions influenced the occurrence of unbroken floats. While camera angles were considered during image capture, their impact on the results was minimal and did not significantly affect the fabric quality. The primary focus was on how light intensity changes throughout the day correlated with the visual clarity of the woven fabric. Twelve images were taken at one-hour intervals, starting at 5 am (Pakistan Standard Time). Detailed timings and corresponding light intensities are provided in Table 1. The camera angles were set at 76.0 (x, y), 77.0 (x, v) and 83.0 (x, y) for image capture.

The process of converting these images for computer-aided design followed the same procedure as described in the methodology section, except that the number of colours was reasonably reduced to preserve image quality. Additionally, the intelligent system known as “The PictureJaq Feature” within ScotWeave was used to apply weaves to the colours, ensuring a smooth integration of the design with the weaving process while maintaining optimal visual detail. The reduction of colours and application of weaves were necessary to maintain image clarity and achieve a high-quality woven output suitable for manufacturing.

Table 1: Time and light intensity measurements at two locations of the NTU

Ser. no.	University main hall		University medical center	
	Time (24 h)	Intensity (lux)	Time (24 h)	Intensity (lux)
1	6:15	7	6:22	61
2	7:15	1750	7:22	1840
3	8:15	4500	8:22	5439
4	9:15	7421	9:22	7621
5	10:18	35500	10:23	27621
6	11:18	45335	11:23	35200
7	12:18	34300	12:25	27220
8	13:20	21520	13:25	23500
9	15:15	16070	15:25	13528
10	16:15	2100	16:25	2200
11	17:15	105	17:12	200
12	17:43	2	17:45	0

3 Results and discussion

3.1 Results

The results of the study were analysed to evaluate the impact of different font styles and light intensity conditions on the number of unbroken floats in the Jacquard weave patterns. Both subjective and objective analyses were performed to assess the visual quality and quantification of floatation across



a)



b)

Figure 2: Images taken in the early morning of (a) UME and (b) UMC



a)



b)

Figure 3: Images taken in the late evening of (a) UME and (b) UMC

different fonts and lighting scenarios. Additionally, a supplementary Excel file (.xlsx) is available, which contains comprehensive data for all 225 fonts. When the float-breaking function was applied in the software, new floats emerged from newly formed interlacement points from the breaking of previous floats. This process was repeated for four iterations, with the first ten fonts, arranged alphabetically, selected for further analysis. The results are summarized in Table 3. In this table, green cells indicate that the font style's visual appearance remains clear as the floats are broken, yellow cells denote satisfactory visibility, and red cells indicate that visibility and readability fall below acceptable levels for the human eye.

Although the camera angle parameter was considered during image capture, its direct impact on the number of unbroken floats was minimal, and therefore, it is not included in the results presented in Tables 4 and 5. It was observed that breaking floats over four iterations had minimal impact on the visual quality of most font styles, except for Bancroft Condensed, whose quality degraded from “good” to “satisfactory”. Figure 4 represents examples of font styles with an increased difficulty level of readability. The subjective survey identified the five top font styles with the most visually appealing appearance.

Arial Black, Berlin Sans FB Demi, Cambria, Franklin Gothic Demi and Segoe UI Black.

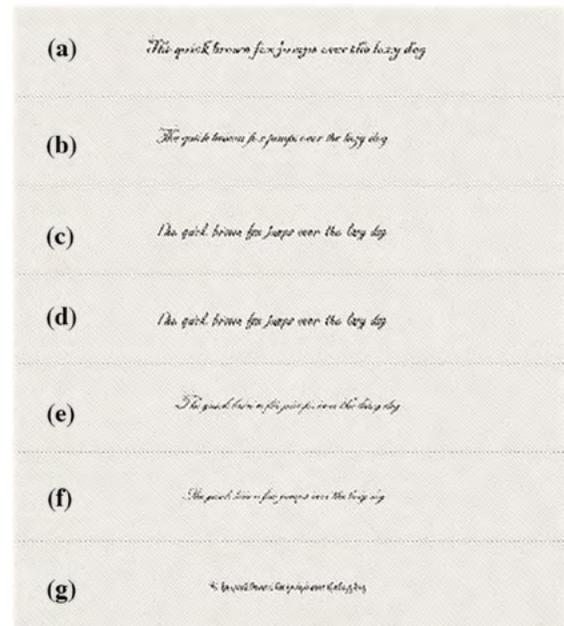


Figure 4: Examples of font styles with an increased difficulty in level of readability: (a) Blackader ITC, (b) Edwardian script ITC, (c) Freestyle script, (d) French script MT, (e) Kunstler script, (f) Palace script MT and (g) Parchment

Table 2: Details of number of unbroken floats of selected fonts

Ser. no.	Font name	No. of unbroken floats			
		Face of fabric		Back of fabric	
		Warp	Weft	Warp	Weft
1	Courier	0	0	0	0
2	Fixedly	0	0	0	0
3	MS Outlook	0	0	0	0
4	MS serif	0	0	0	0
5	Small fonts	0	24	0	0
6	System	0	0	0	0
7	Terminal	0	0	0	0

Table 3: No. of unbroken floats from the first ten (10) font styles after four iterations

Ser. no.	Font style	No. of unbroken floats															
		Face of fabric								Back of fabric							
		Warp				Weft				Warp				Weft			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	Agency	6	0	*	*	0	*	*	*	5	0	*	*	10	0	*	*
2	Algerian	14	1	0	*	29	1	0	*	50	2	0	*	39	2	0	*
3	Arial black	14	3	*	*	11	*	*	*	6	*	*	*	27	1	*	*
4	Arial Narrow	4	0	*	*	9	*	9	0	2	0	*	*	13	0	*	*
5	Arial rounded MT Bold	13	1	0	*	10	0	*	*	3	1	0	*	40	0	*	*
6	Baskerville Old face	5	0	*	*	21	0	*	*	45	5	0	*	6	0	*	*
7	Arial Unicode MS	5	0	*	*	18	0	*	*	3	0	*	*	13	1	0	*
8	Bancroft	3	0	*	*	31	0	*	*	1	0	*	*	12	0	*	*
9	Bancroft condensed	3	0	*	*	5	0	*	*	1	0	*	*	9	0	*	*
10	Bancroft light	2	0	*	*	17	0	*	*	1	0	*	*	8	0	*	*

* Not affected

To explore the relationship between camera angles, light intensity and the visual appearance of woven fabric, the results related to the number of unbroken floats at the university’s main entrance (UME) and the University Medical Center (UMC) are presented in Tables 4 and 5. These tables provide information regarding how different lighting conditions and their corresponding effects on fabric quality are influenced by the time of day. Figures 5 and 6 illustrate the initial

(morning) time data, specifically from the first attempt to weave the warp on the face side of the fabric. These figures highlight the correlation between the time of day and light intensity, showcasing how these variables influence the occurrence of unbroken floats and, ultimately, the visual clarity of the woven fabric. This information is crucial for understanding how environmental factors, such as lighting and positioning, impact the quality of textile designs.

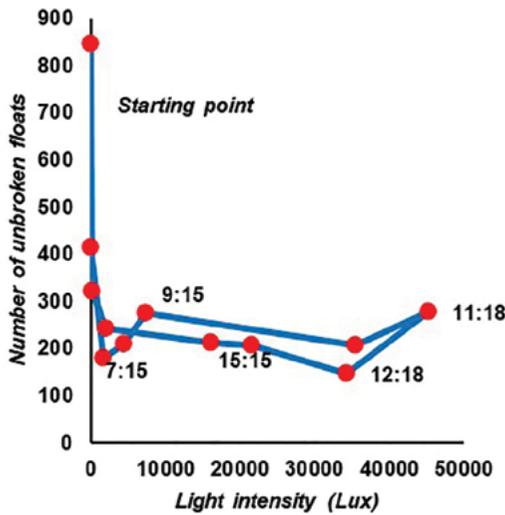


Figure 5: Graphical representation showing how many continuous floats there are at the university's main entrance (UME) as the sun rises and sets

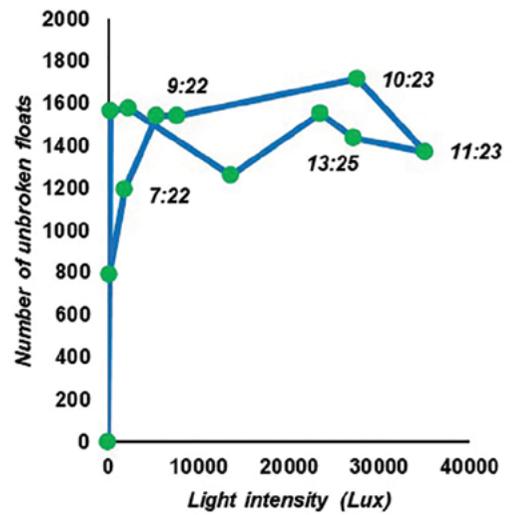


Figure 6: Graphical representation showing how many continuous floats there are at the University's Medical Center (UMC) as the sun rises and sets

Table 4: No. of unbroken floats at the University Main Entrance (UME) after four iterations

Ser. no.	Main entrance		No. of unbroken floats															
			Face of fabric								Back of fabric							
	Time (24 h)	Intensity (lux)	Warp				Weft				Weft				Weft			
			1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	6:15	7	416	1	*	*	0	*	*	*	0	*	*	*	783	22	*	*
2	7:15	1750	180	1	*	*	0	*	*	*	405	*	*	*	285	5	*	*
3	8:15	4500	209	0	*	*	26	*	*	*	0	*	*	*	199	6	1	*
4	9:15	7421	275	1	*	*	5	*	*	*	917	*	*	*	287	13	1	*
5	10:18	35500	206	1	*	*	0	*	*	*	38	*	*	*	269	9	1	*
6	11:18	45335	278	0	*	*	225	*	*	*	0	*	*	*	314	8	*	*
7	12:18	34300	148	0	*	*	81	1	*	*	223	*	*	*	251	10	0	*
8	13:20	21520	206	1	*	*	329	*	*	*	0	*	*	*	313	8	*	*
9	15:15	16070	214	0	*	*	380	1	*	*	424	*	*	*	399	13	*	*
10	16:15	2100	242	0	*	*	0	*	*	*	349	*	*	*	297	9	0	*
11	17:15	105	322	0	*	*	49	*	*	*	0	*	*	*	436	13	1	*
12	17:43	2	847	5	*	*	0	*	*	*	0	*	*	*	1127	12	*	*

*Not affected

Table 5: Number of unbroken floats on the University Medical Center (UMC) picture after four iterations

Ser. no.	Medical center		No. of unbroken floats															
			Face of fabric								Back of fabric							
	Time (24 h)	Intensity (lux)	Warp				Weft				Warp				Weft			
			1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	6:22	61	790	3	*	*	0	*	*	*	6	*	*	*	694	27	0	*
2	7:22	1840	1196	4	*	*	0	*	*	*	239	*	*	*	1120	48	0	*
3	8:22	5439	1542	14	*	*	0	*	*	*	0	*	*	*	1556	54	2	*
4	9:22	7621	1542	10	*	*	0	*	*	*	87	*	*	*	1948	50	2	*
5	10:23	27621	1717	10	*	*	0	*	*	*	8	*	*	*	1782	98	4	0
6	11:23	35200	1374	4	*	*	0	*	*	*	650	*	*	*	1733	90	3	0
7	12:25	27220	1439	7	*	*	27	*	*	*	94	*	*	*	2152	99	5	*
8	13:25	23500	1553	3	*	*	11	1	*	*	322	*	*	*	2220	96	6	*
9	15:25	13528	1262	6	*	*	0	*	*	*	480	1	*	*	1790	87	4	*
10	16:25	2200	1581	9	*	*	9	*	*	*	737	*	*	*	2165	98	3	*
11	17:12	200	1567	7	*	*	4	*	*	*	257	*	*	*	1411	38	*	*
12	17.45	0	0	*	*	*	0	*	*	*	0	*	*	*	0	*	*	*

*Not affected

3.2 Discussion

The objective evaluations in Table 2 indicate that seven font styles had zero unbroken floats from the outset, and thus did not require any float-breaking process. These fonts included Courier, Fixedly, MS Outlook, MS Serif, Small Fonts, System and Terminal. Although the number of unbroken floats for most font styles remained within acceptable limits, several were difficult to read. One contributing factor to poor visibility was their relatively small text size. Furthermore, many of these fonts were thin or italic, increasing the complexity of the interlacements during weaving. Examples of such challenging fonts are shown in Figure 4. As a result, these font styles were excluded from the first phase of the study. It was observed that after breaking the warp float on the fabric's face side, the floats on the warp of the backside and the weft floats on the face side became less significant. The primary focus for breaking floats was the weft direction on the backside of the fabric, largely due to the directional choice when applying

the float breaking function. If the function was applied in the weft direction first, the results could be reversed.

During the initial phases of float breaking, it was relatively easy to reduce a significant number of unbroken floats because many remained unbroken, as seen in Figure 7. However, after several iterations (in this case four), the number of unbroken floats began to increase. This is due to the emergence of new floats at newly created intersection points, which occurs because the original floats were broken. This indicates that float breaking becomes progressively more complex as fewer unbroken floats remain, requiring more strategic intervention. The blue rectangle in the Figure 7(a) is intended to illustrate the warp floats on the 14th warp, and while it currently encloses 10 weave points, this does not impact the interpretation of the results or the methodology applied. The focus of the figure is to visually convey the float-breaking process rather than the exact count of weave points in the rectangle.

The red rectangle of size five (5) drawn on the third warp in Figure 7(b) represents a scenario where the float-breaking algorithm identifies floats just below the defined threshold of six (6). This is due to the algorithm's inherent flexibility, which prioritizes the structural integrity and aesthetic consistency of the design. While the floating point is set to six (6), the software dynamically adjusts to handle cases where shorter floats need to be highlighted for improved weave stability.

As shown in Figures 5 and 6, it was observed that the number of unbroken floats was at its lowest in the early morning (7:15 am) and gradually increased as the sun rose, reaching its peak around noon (11:18 am). The maximum light intensity recorded during the day was 45,335 lux. As the sun began to set, the number of unbroken floats decreased along with the light intensity, continuing until afternoon (3:15 pm). A similar pattern of increasing unbroken floats with rising sunlight, followed by a decrease as the sun set, was also observed at the University Medical Center. These results are consistent with previous studies [10–15], indicating that light intensity and camera angle significantly affect image quality, leading to variations in results when using the same software and processing methods. The ongoing research aims to find solutions to minimize the impact of environmental factors, such as light and camera angle, to optimize the performance of digital image processing software. At this stage, a survey was conducted to assess which lighting conditions produced the most visually appealing fabric appearance. Forty percent of the respondents preferred a light intensity range of 2000–5000 lux, suggesting that this range offers optimal conditions for visual clarity and readability in woven fabric designs. This preference highlights the importance of controlled lighting in achieving consistent results in digital weaving processes.

3.3 Statistical analysis of the data

Statistical analysis performed based on the results using the light intensity and unbroken floats data for the UME and UMC are given in Figure 8. Analysis

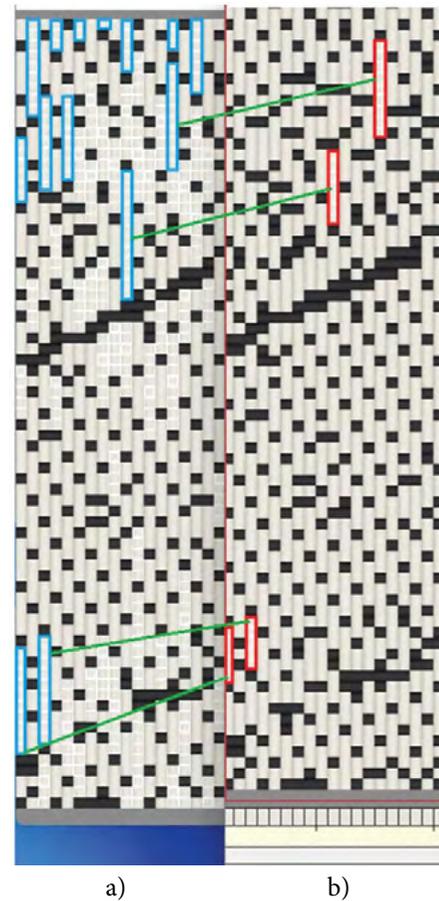


Figure 7: Float breaking: a) unbroken floats are shown by the blue rectangle and white-bordered blocks; b) the red rectangles remaining unbroken floats are shown after the float-breaking function is applied

was performed against each result and outcomes were recorded. During the analysis, a Pearson correlation coefficient (r) between light intensity and the number of unbroken floats in the warp and weft directions was calculated using the formula below to determine how strongly the light intensity influence the fabric quality.

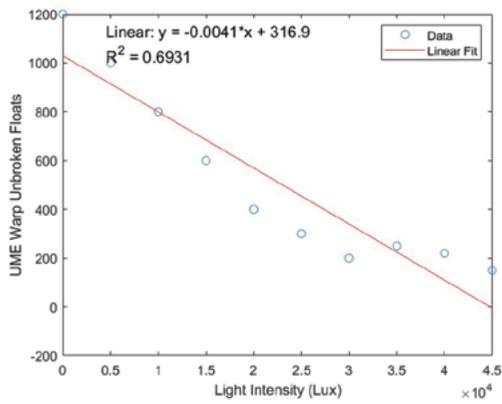
$$r = \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{\sqrt{(n\Sigma^2 - (\Sigma x)^2)[n\Sigma^2 - (\Sigma y)^2]}} \quad (1)$$

where x represents the light intensity, y represents the number of unbroken floats and n represents the number of data pairs.

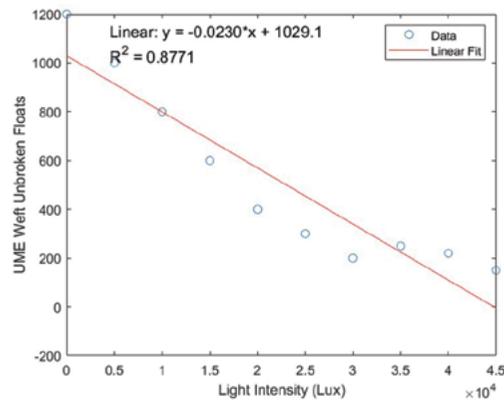
A linear regression analysis was performed to model the relationship between the light intensity and unbroken floats, which helps in predicting how the changes in light intensity could affect the unbroken floats. High intensity light seems to reduce unbroken floats until noon, after which the trend might reverse as the light intensity decreases.

Figure 8 presents a linear regression analysis of unbroken floats against light intensity for UME warp, UME weft, UMC warp and UMC weft. The R^2 values indicate how well the linear models fit the data. UME warp (a) has an R^2 of 0.6931, showing a moderate negative correlation, meaning light

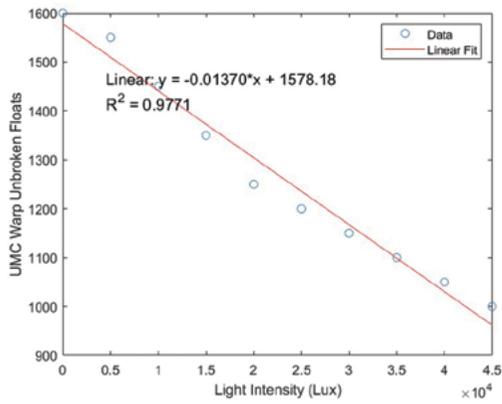
intensity explains about 69% of the variation in unbroken floats. UME weft (b) has a stronger negative correlation with an R^2 of 0.8771. UMC warp (c) has an even stronger negative correlation, with an R^2 of 0.9771, while UMC weft (d) has the strongest positive correlation, with an R^2 of 0.9877, suggesting that light intensity has a major impact on UMC weft performance. These results indicate that UMC fabrics, particularly weft, are more significantly affected by light intensity than UME fabrics, with the positive relationship for UMC weft contrasting with the negative trends observed in the other cases.



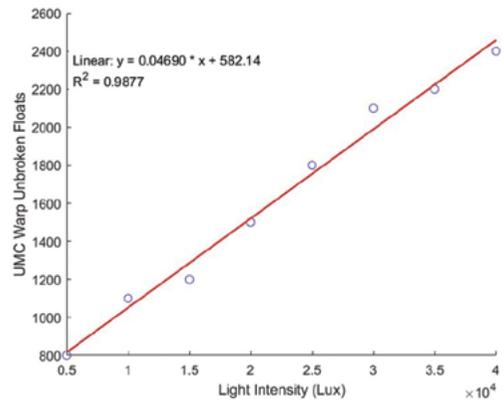
a)



b)



c)



d)

Figure 8: Linear regression of unbroken floats against light intensity for (a) UME warp, (b) UME weft, (c) UMC warp and (d) UMC weft

4 Conclusion

This study highlights the delicate balance between technical weaving requirements and aesthetic preferences in fabric design, particularly in the context of woven text on fabric selvages. Careful consideration of light intensity and image processing techniques is essential for achieving high-quality and visually appealing results. The recommended light intensity range of 2,200 lux to 55,000 lux provides an optimal setting for capturing images for digital weaving, contributing to more effective colour reduction and fabric design optimization. The variation in unbroken floats is strongly influenced by light intensity, meaning that environmental factors such as light intensity play a significant role in the optimisation of woven fabric design. These insights are valuable for textile designers and manufacturers aiming to enhance the clarity and aesthetic appeal of woven designs. Future research should focus on refining digital weaving processes by further exploring the impact of environmental factors, such as light intensity and camera angles, to enhance the precision and consistency of woven fabric designs.

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Application of the Aramis Optical 3D Deformations Measuring System in Dynamic Anthropometry

Uporaba optičnega 3-D merilnega sistema Aramis v dinamični antropometriji

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Abstract

This paper presents a study on the possible application of the Aramis optical 3D measuring system for analysing dynamic deformations of the human body in motion. A methodology for the use of Aramis in the field of dynamic anthropometry is presented for the first time in this study. Five body movements were analysed on three female test subjects. Based on the surface deformation results, a set of ten characteristic body measurements, relevant for garment design and construction, were identified, analysed and compared to reference values obtained using laser 3D body scanning technology. Changes in measurement dimensions during particular movements were determined in relation to initial measurements in a static standing position, where the greatest body measure deformation recorded was a 37% increase in back width during arm-forward movement and a 23% elongation of the posterior lower body length during forward bending. A comparative analysis of the results indicated a high level of precision of measurements obtained using the Aramis system, which achieved mean absolute errors of less than 3 mm and relative errors of less than 3%, thus emphasising the ability to monitor and analyse surface deformations of the body throughout entire movements and not just in final body positions, as is the case with the use of 3D body scanning technology. The proposed measurement methodology from this study offers valuable data for the development of garment model design, material selection and clothing pattern construction according to the requirements of dynamic anthropometry.

Keywords: dynamic deformations, Aramis optical 3D measurement system, body in motion, dynamic anthropometry, 3D body scanning

Izvleček

Članek predstavlja raziskavo o možnostih uporabe optičnega 3-D merilnega sistema Aramis za analizo dinamičnih deformacij človeškega telesa v gibanju. V tej raziskavi je prvič predstavljena metodologija za uporabo sistema Aramis na področju dinamične antropometrije. Analiziranih je bilo pet telesnih gibov pri treh preiskovankah. Na podlagi rezultatov površinskih deformacij je bil določen niz desetih značilnih telesnih mer, pomembnih za



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načrtovanje in izdelavo oblačil, analiziran in primerjan z referenčnimi vrednostmi, pridobljenimi z lasersko 3-D tehnologijo skeniranja telesa. Spremembe merjenih dimenzij pri posameznem gibanju so bile določene glede na začetno meritev v statičnem vzravnem položaju, kjer sta 37-odstotno povečanje širine hrbta med premikanjem rok naprej in 23-odstotno podaljšanje zadnje dolžine spodnjega dela telesa med upogibanjem naprej bili največji opaženi deformaciji telesne mere. Primerjalna analiza rezultatov je pokazala visoko natančnost meritev, pridobljenih z uporabo sistema Aramis, pri čemer so bile dosežene povprečne absolutne napake pod 3 mm in relativne napake pod 3 %, kar poudarja sposobnost spremljanja in analize površinskih deformacij telesa skozi celotno gibanje in ne le v končnih položajih telesa, kot je to pri uporabi tehnologije 3-D skeniranja telesa. V tej raziskavi predlagana metodologija merjenja ponuja dragocene podatke za razvoj oblikovanja modelov oblačil, izbiro materialov in konstrukcijo krojev oblačil v skladu z zahtevami dinamične antropometrije.

Ključne besede: dinamične deformacije, optični 3-D merilni sistem Aramis, telo v gibanju, dinamična antropometrija, 3-D skeniranje telesa

1 Introduction

Dynamic anthropometry research is most often applied in the development of functional garment models for special purposes, in the context of defining parameters for garment patterns adjustments in the construction process [1]. This most often involves the development of protective and sports garment models. In that regard, case studies are usually conducted on the target subject or smaller samples of specific groups, depending on the purpose of the garment, in which body movements and deformations are analysed in positions specific to performing the targeted activity. The method for determining measurements, the number of analysed positions and the characteristic measures per individual position vary in different studies [2–6]. Choi and Ashdown analysed changes in lower body circumference dimensions in three standard positions on a sample of female subjects and applied the results to the design of women's trousers [7, 8]. Xiao and Ashdown also analysed changes in the lower body, but over a larger range of motion and with a much larger set of characteristic measures to analyse changes in the surface areas of the lower extremities [9]. As part of the investigation and development of a diving suit, Petrak et al. analysed dimensional changes in the upper body, with an emphasis on the shoulder girdle and upper back in diving-specific positions, such as

open-arm, over-arm and under-arm positions [10].

The methodology for determining body measurements in dynamic anthropometry is still not clearly defined, neither in terms of body positions specific to a particular activity, nor in terms of defining characteristic measures and methods of body measurement. Determining body measurements in different positions is an extremely time-consuming process, in which the results largely depend on the expertise and training of the person performing the measurement. There are also certain issues in connection with maintaining the body in the target position during the measurement process, given that measurement using the conventional method lasts a certain period of time, during which the subject must stand still and remain in the given position without additional movements and shifts, which is challenging especially with more demanding body positions. For this reason, very few studies can be found in literature that use the conventional measurement method to determine body measurements in different positions. One of the most significant and extensive studies using the conventional measurement method was conducted by Avandanei et al. The study included a sample of 400 subjects who were measured in four specific working positions for body measurement characteristics in clothing

construction. Comfort values for the construction of work overalls were defined based on the results, i.e. the differences and relationships between the values of measurements in the standard standing and specific body positions, which the authors defined as a dynamic effect [11].

In the field of dynamic anthropometry, 3D body scanners are used to measure the body in various positions, specific to a particular activity, with the aim of determining the differences in body measurements between the standard upright position and various specific body positions [1]. In terms of locomotion biomechanics, body positions used for 3D body scanning in the field of dynamic anthropometry represent characteristic body positions that are part of the kinematic chain of a particular movement described by the phases of changing the position of a particular body segment. Currently, the measurement of the body in different positions is exclusively interactive, by positioning measurement points on the scanned model and measuring distances or determining the circumference obtained by cross-sectioning the body with planes through given points. Markers positioned on the test subject's body at characteristic anthropometric points are most often used in the scanning process in order to enable the precise determination of measurements [2–6]. It is evident from our literary review that differences in the approach to investigating dimensional changes of the body in various positions depend on the application of the results. Although specific body positions, such as the sitting position, are covered by the standard [12] and some are frequently repeated in different studies, such as lunges, squats and maximum upper limb reaches, the sets of characteristic measures for analysis in a particular position and the methods for determining the value of a particular measure differ primarily with regard to the targeted application.

Significant progress in the application of dynamic anthropometry study results was made by researchers from the Hohenstein Institute in Germany. As part of their research, Morlock and

Klepster introduced the terminology of functional measurements, referring precisely to body measurements in specific positions identified using a 3D scanner. They conducted a fairly extensive study of changes in body measurements in different positions, specific to a particular physical activity, on a sample of 93 subjects, and analysed the results and differences in characteristic measurements from the aspect of clothing sizes and body shapes defined by the German standard SizeGERMAN. Significant changes in body dimensions were found in all analysed positions. In particular, changes in back body area dimensions, in the forward bending position can be highlighted. Considering the relatively small initial value of the hip depth in the upright position, a significant increase of up to 21.5% in the posterior back length and up to 39.7% in the hip depth was determined. By linking the dimensional changes of the body in motion with the existing standard, they developed a sizing system that also takes into account the functional measurements of the body in specific positions, thus ensuring the applicability of the research results in practice [13, 14].

3D body scanning in characteristic positions does not actually provide a fully realistic representation of the body in dynamic conditions. Since the body must remain still during the scanning process, the activity of the locomotor system is focused on maintaining the body's balance and position, rather than on performing movements, which due to different muscle activity, also leads to different body deformations [15]. In this regard, the intensive development of the field of dynamic anthropometry over the last ten years has been contributed to by the development of fast stereophotographic 3D body scanning systems that enable the recording of a series of images of a body in motion over a certain period of time, for which the term 4D scanning has been introduced in literature. 4D scanning technology enables comprehensive research in the field of dynamic anthropometry and the analysis of movement dynamics and changes of the body in full motion [15–19]. 4D scanning systems are primarily

based on imaging using structured light technology and depth sensors, where upon completion of the imaging, most often using the triangulation method and/or the light cross-section technique, a continuous 3D surface mesh of the scanned body in motion is generated, on which it is possible to conduct analysis and the measurement of body dimensions in any phase of movement. Measurements determined using 4D scanning, according to Klepster et al., are called dynamic body measurements. They used photogrammetric technology and the “Little Alice” 3D scanner from 3Dcopsystems to analyse dynamic body measurements. The scanning system uses 38 cameras to capture images at a speed of three frames per second. The results showed adequate scanning accuracy for analysing changes in body measurements and the surface geometry of body parts in motion, suitable for application in clothing design and the construction process. The method showed limitations in terms of movement recording time length and the number of recorded frames, since an excessive number of recorded frames leads to an overload of the system when reconstructing the model [15].

The methodology of recording with a 4D body scanner, as well as sets of characteristic measures and methods of measurement on a scanned body model in motion, are still not clearly defined. The application of 4D scanning technology in the field of computer garment design is in the initial phase, and has been reduced to testing the possibilities and precision of individual systems and identifying different methods for monitoring changes in body dimensions during motion.

Uriel et al. conducted a study of changes in body dimensions during movement using the MOVE4D 4D scanner [19]. On a sample of 10 subjects, eight body measurements were analysed in four different movements. In order to determine body measurements during movement, a method was developed based on parametric curves, which determine the position of each measurement in the initial body position and facilitate the tracking of the dimension throughout the entire sequence of movement execution [20].

As an alternative to 4D scanning, this study proposes the use of an optical 3D measurement system for dynamic deformation analysis, which has a verified application and is widely used in the fields of mechanical engineering, construction and other manufacturing industries, but has not yet been applied or tested in the field of dynamic anthropometry.

2 Experimental

This paper presents a study on the possibilities of using the Aramis optical 3D measurement system for dynamic analysis of deformations on the human body in motion. The Aramis system, made by the German company GOM GmbH, is an optical system for 3D deformation analysis based on the stereophotogrammetry method, in which the three-dimensional deformations of the recorded object are reconstructed based on two or more images from different positions [21]. The recording and measurement methodology involves the preparation of a test object in terms of creating a contrasting stochastic dot pattern, based on which the coordinates of the surface points are determined and displacements and deformations on the recorded object surface are monitored during motion. Data processing was conducted using GOM Inspect Suite 2020 and ZEISS Inspect Correlate (v. 2023) software, which offer a wide range of tools that enable the precise determination of various parameters of linear and surface deformations, comparable to the parameters used in the development and analysis of 3D simulations and computer garment prototypes. In this regard, a methodology for recording the human body according to the requirements of the measurement system was defined. The research was conducted on five movements in which body deformations in the kinematic chain and changes in body measurements in the final position of the body, relevant for the construction and design of clothing, were analysed. For comparative analysis and verification of the results provided by the Aramis system, the results of body measurements in characteristic positions

using a laser 3D body scanner were used. In order to facilitate the comparison of measurement results between the two applied measurement systems, all measurements were performed on the same day, on a sample of three female test subjects, with precisely positioned markers on the body anthropometric points that define each observed measure.

2.1 Defining body movements and positions for dynamic anthropometric analysis

Five body positions were selected for the research (Figure 1), where the movements, i.e. kinematic chains of bringing the body to a certain characteristic position, were precisely defined (Figure 2). The first kinematic chain (KL1) defined the movements of spread-arm (P1) and forward-arm (P2) for recording in the posterior plane. Initially, the subject stood in an upright standing position with a hip-width gap and arms extended alongside the body with palms facing back. With a slow movement from the shoulders and rotation in the posterior plane, the outstretched arms were brought into the spread-arm position with palms facing down (position P1). In this position, the subject paused for two seconds, after which, with a slow movement from the shoulders

and rotation in the transverse plane, the outstretched arms were brought into the forward-arm position (position P2) with a two-second hold.

The second kinematic chain (KL2) defined the movements of spread-arm (P1) and arm extension (P3) for recording in the posterior plane. The subject stood in an upright standing position with a hip-width gap and arms extended alongside the body with palms facing back. With a slow movement from the shoulder and rotation in the posterior plane, the extended arms were brought into the spread-arm position with palms facing down (position P1). In this position, the subject paused for two seconds, after which the rotation in the posterior plane continued with a slow movement from the shoulder to the extension position (position P3), with a two-second hold.

The third kinematic chain (KL3) defined the arm extension (P3) movements for recording in the sagittal plane. The subject stood in the forward-arm position (P2) with the hip-width distance between the feet. With a slow movement from the shoulders and rotation in the sagittal plane, the arms were brought from the forward into the extension position (position P3), with a two-second hold.

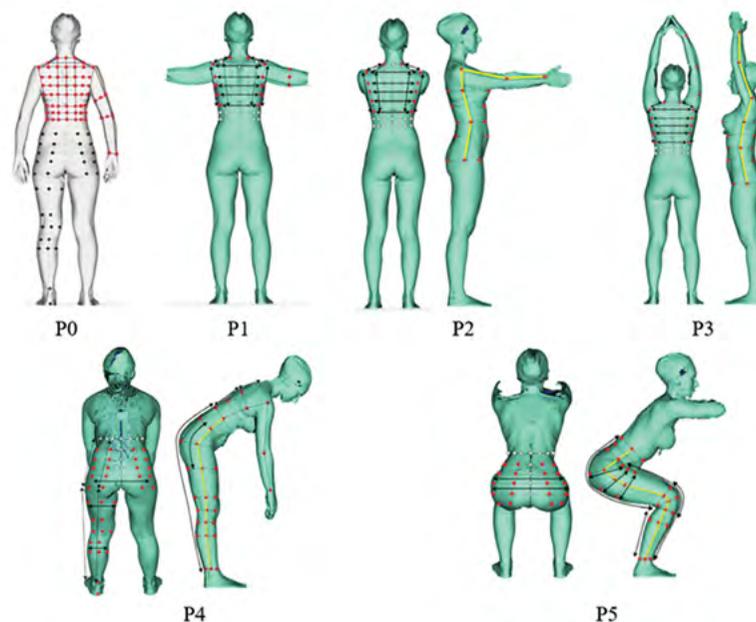


Figure 1: Characteristic positions selected for the analysis of changes in body dimensions

The fourth kinematic chain (KL4) defined the forward bending movement (P4) for recording in the posterior and sagittal planes. The subject stood in the forward-arm position (P2) with the hip-width distance between the feet. By slowly bending the spine and torso forward, the body was first brought into a forward bending position with the arms reaching the knee height, where it was held for two seconds, after which the torso was brought into

maximum flexion (position P4) in which the subject was held for two seconds.

The fifth kinematic chain (KL5) defined the squatting movement (P5) for recording in the posterior and sagittal planes. The subject stood in the forward-arm position (P2) with the hip-width distance between the feet. By slowly lowering the torso and bending the knees, the body was brought into a squatting position (position P5) with a two-second hold.

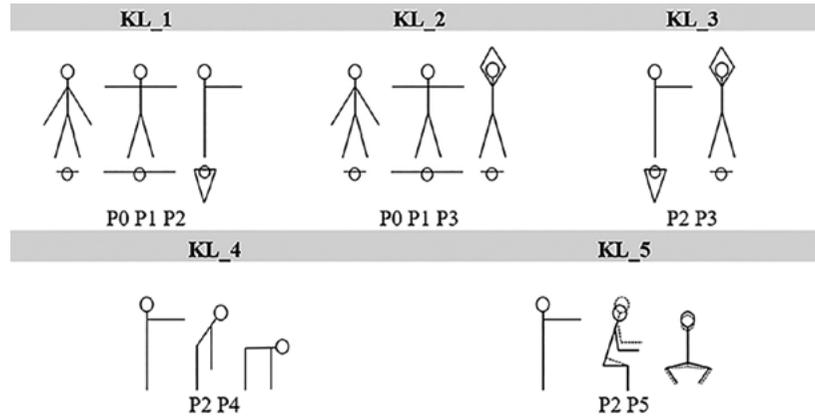


Figure 2: Schematic representations of the five defined kinematic chains

2.2. Recording of the body in motion using the Aramis 3D measurement system for dynamic deformation analysis

Using the optical 3D measurement system for dynamic deformation analysis Aramis, five predefined movements (Figure 2) were recorded on three subjects (I1, I2 and I3). The final positions of each movement correspond to the previously defined characteristic body positions P1 to P5, Figure 1.

2.2.1 Preparation of test subjects

According to the previously described methodology of the measurement system, a stochastic dot pattern was manually applied to the bodies of the test subjects wearing sports underwear using a black body paint. Black and white circular markers were placed at the positions of the anthropometric points to ensure the precise positioning and monitoring of the anthropometric points during the surface measurement and deformation analysis (Figure 3).

2.2.2 Creation of 3D surfaces and definition of surface geometry parameters for body deformation analysis

The processing of recorded results and the 3D analysis of body surface geometry deformations during motion were carried out using the GOM Inspect Suite 2020 and ZEISS Inspect Correlate (v. 2023) software. The processing of the recorded results included the creation of the body 3D surface and segmentation of the surface parts, depending on the movement and the targeted body zones for further analysis (Figure 4), and the adjustment of the coordinate system for each segment of the surface (Figures 5 and 6). Given that the continuity of the stochastic pattern was interrupted on parts where the body surface was covered with clothing, and as due to markers that differed in size from the rest of the pattern, additional facets were created in order to obtain a better quality of testing geometry (Figure 4) when creating the measuring 3D surfaces for testing.



Figure 3: Preparation of test subjects for the body motion recording using the Aramis system

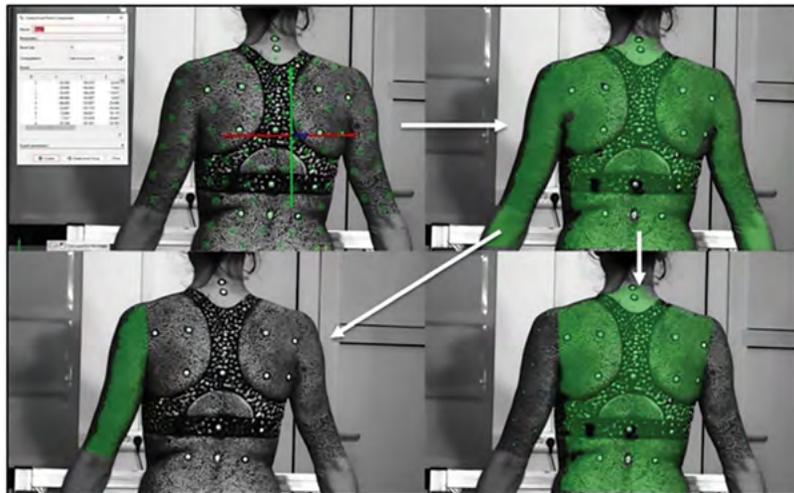


Figure 4: Recorded data processing – creating surface components for the analysis

The created surface geometries of the recorded bodies were defined by a local coordinate system at each point of the geometry. Deformations in the x direction were always calculated as local coordinates that move with the material. Therefore, the program calculated the stress in the moving coordinate system, not the global coordinate system. The z direction was used as the thickness direction. The local x direction was the result of the product of the intersection of the normal plane vector and the global y axis, while the local y direction was the result of the product of the local z and x axes (Figure 5) [21].

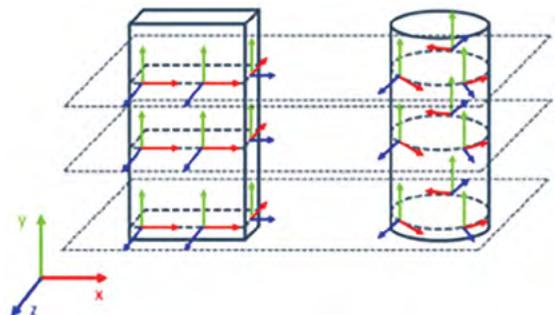


Figure 5: Positioning the local coordinate system on the surface of a recorded object in the Aramis system [21]

Due to the complexity of the human body, especially regarding the position of the upper and lower extremities, it was not possible to position the coordinate system in a way that the tensors were oriented in the desired direction across the entire single measurement geometry. Therefore, for each movement, parts of the measurement geometry were segmented depending on the initial position of the body, while the direction of the coordinate system was adjusted depending on the segment being analysed (Figure 6).

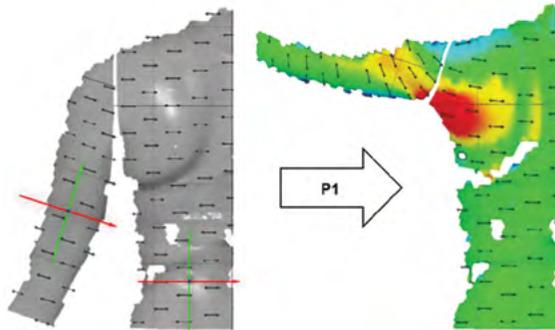


Figure 6: Adjustment of the coordinate system on segmented surface geometry in the initial position – KL1

When analysing longitudinal deformations in the arm-extension movement (KL3, P3), due to the initial arms position, the measurement surface was divided into a body and arm segment, while the coordinate system on the arm surface segment was adjusted so that the x direction still followed the transverse dimension and the y direction followed the longitudinal dimension (Figure 7).

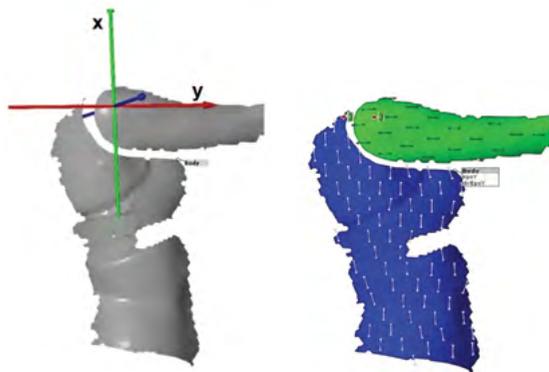


Figure 7: Adjustment of the coordinate system on segmented surface geometry in the initial position – KL3

When recording movements KL4 and KL5, greater deficiencies in the measurement surfaces were observed on the lower parts of the body due to the coverage of the hips and buttocks area by underwear (Figure 8).

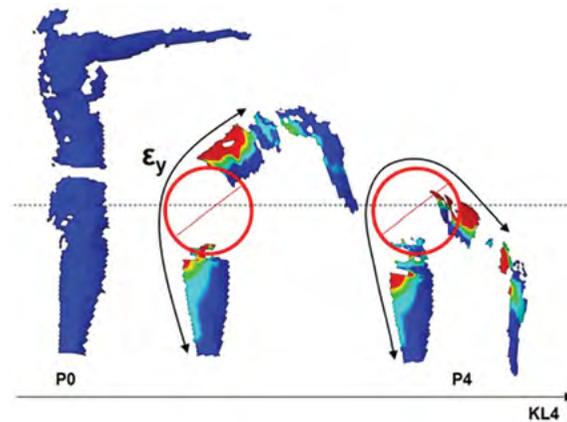


Figure 8: Longitudinal body deformation (ϵ_y) by phases of the kinematic chain KL4 of body moving into the forward bending position (P4) – test subject I1 in the sagittal view

Since the most significant changes were expected on the lower body area in the movements of bending the body forward (P4) and lowering into a squat (P5), the study included the recording and analysis of test subjects dressed in tight overalls, constructed according to the body measurements and characteristics of the particular test subjects (Figure 9).

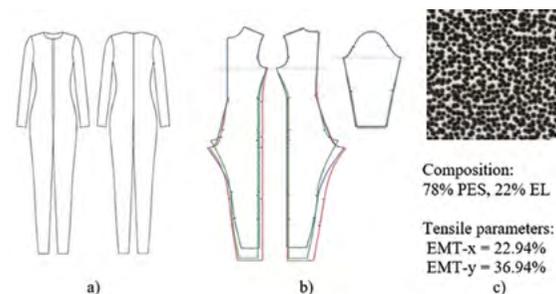


Figure 9: Model of a tight jumpsuit: a) model sketch, b) pattern adjusted to the measurements of three test subjects, c) sample of dot-printed knitted material with presented fibre composition and tensile properties parameters

The overalls were made of knitted material with a high content of elastane fibres. Since the model fit closely to the body, deformations of the body surface were reflected on the surface of the garment, which was used in this part of the research to obtain more complete and high-quality geometry surfaces for analysis. A stochastic dot pattern defined by the Aramis system methodology was applied on the knit using the digital printing technique, Figure 9c.

2.3 Analysis of deformations and changes in body measurements depending on body motion

For the analysis and more precise monitoring of the body surface geometry and segments deformations in each movement, networks of transversal and sagittal sections on the lines of characteristic body circumferences and measurements were created, enabling a link between research results and garment design and development process (Figure 10). The positions of the sections and curves on each test subject body were determined based on the measurements obtained by the 3D scan. A network of curves was defined by transverse sections at the shoulder blade height, the back width at armpit level, the chest circumference, the waist circumference and two auxiliary sections. Sections along the sagittal

plane were defined at the mid-back line, the back width line at armpit level and three auxiliary sections dividing the back width into quarters (Figure 10).

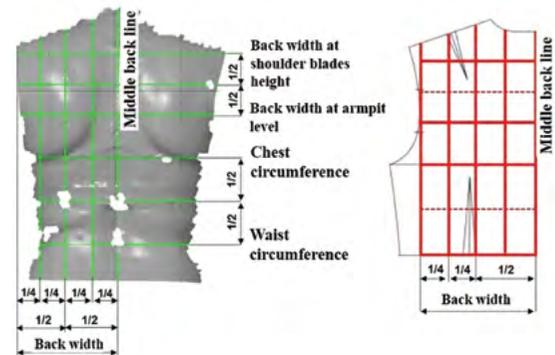


Figure 10: Characteristic cross-sections for upper body analysis in positions P1 to P3 (a) and link with garment construction measurements (b)

In each of the five defined kinematic chains, deformations in the transverse and longitudinal directions of the body surface were analysed, and the zones of the greatest deformations in each position were determined. Further analysis investigated the changes in body measurements affected by the deformation zones, and the dimensions of the targeted body curves and their segments, i.e. changes in body measurements in the defined movements (Figure 11).

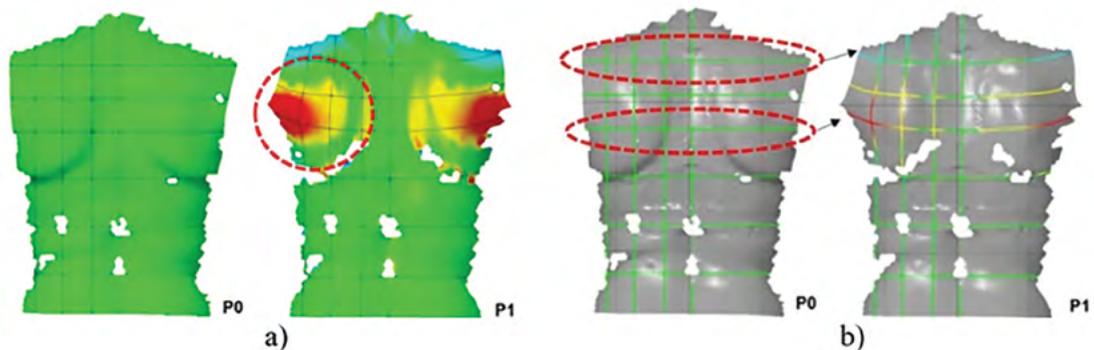


Figure 11: Analysis of body deformations in the transverse (x) direction in position P1: a) analysis of surface segments, b) analysis of curves on characteristic sections

The deformations of the lower body surface were analysed in the frontal and sagittal planes (Figure

12). A network of curves was determined by transverse sections at the lines of the chest, waist, hips,

thighs, knees and lower legs circumferences, longitudinal sections at the mid-body corresponding to the lateral suture line, and sagittal sections dividing the hips width into quarters.

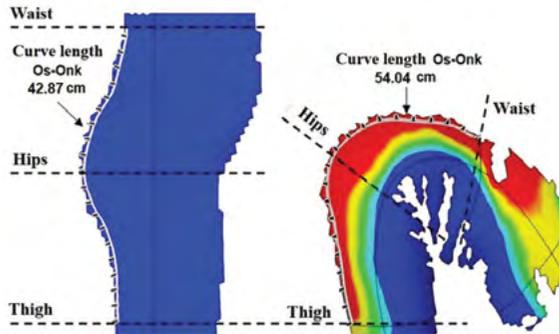


Figure 12: Analysis of the posterior body curve length in the P4 position

2.3.1 Definition of a set of body measurements for the analysis of dimensional changes depending on a characteristic position

Based on the identified zones of greatest body deformation using the Aramis system, a set of 10 body measurements relevant for the design and construction of clothing was defined, which are located in the areas covered by deformations in a particular movement (Table 1). Changes in relation to the standard upright body position were analysed on a defined set of body measurements, and a comparative analysis of the determined results was conducted with the results of measurements of the subjects on scanned 3D body models in characteristic positions, as a verification of the applicability of the optical 3D measurement system for deformation analysis.

Table 1: Set of body measurements for analysing changes in characteristic body positions

No.	Measurement	Positions
1.	ŠI1 – back width measured across the shoulder blades height line	P1, P2, P3
2.	ŠI2 – back width measured at armpit level	
3.	BDps – lateral length of the upper body measured between the armpit height and the waist circumference	P3
4.	SŠb – back hip width	P4, P5
5.	Šnk – thigh width	
6.	SDgk – the length of the back body curve between the chest and the knee circumferences	
7.	SDgs – the length of the back body curve between the chest and the waist circumferences	
8.	SDsb – the length of the back body curve between the waist and the hip circumferences	
9.	SDbnk – the length of the back body curve between the hips and thigh circumferences	
10.	SDnkk – the length of the back body curve between the hips and knees circumferences	

2.4 Research and analysis of changes in body measurements in characteristic body positions using a 3D body scanner

Using the Vitus Smart laser 3D body scanner, subjects I1, I2 and I3 were scanned in five characteristic body positions P1 to P5. Interactive measurements on scanned 3D models determined the values of 10 given body measurements, according to anthropometric points highlighted with markers positioned on test subjects' bodies. Dimensional changes were analysed in relation to the standard upright body position.

3 Results and discussion

The results show the identified zones of greatest body deformation in five defined movements and a comparative analysis of the results of the identified differences in body measurements in relation to the results of measurements on scanned 3D body models in each characteristic position.

An analysis of body surface deformations during arm movements revealed significant transverse deformations in the back area. Figures 12 to 14 show transverse (x) and longitudinal (y) deformations by phases of kinematic chains of recorded arm movements, using the example of subject I1. If we look at

the sections network of characteristic body lines, the zone of maximum deformation extends around the line of the back width at the armpit level. Looking at the transverse sections, in position P1, the deforma-

tion appears and increases from the back line, where there is almost no deformation, towards the lateral lines with maximum deformation in the area of the second quarter of the back width (Figure 13).

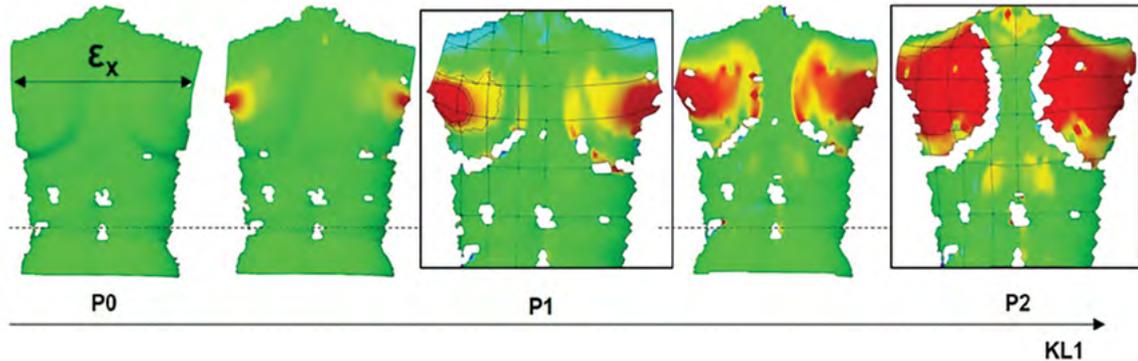


Figure 13: Transverse body deformation (ϵ_x) by phases of the kinematic chain KL1, which includes the spread-arm position (P1) and forward-arm position (P2) – test subject I1 in posterior view

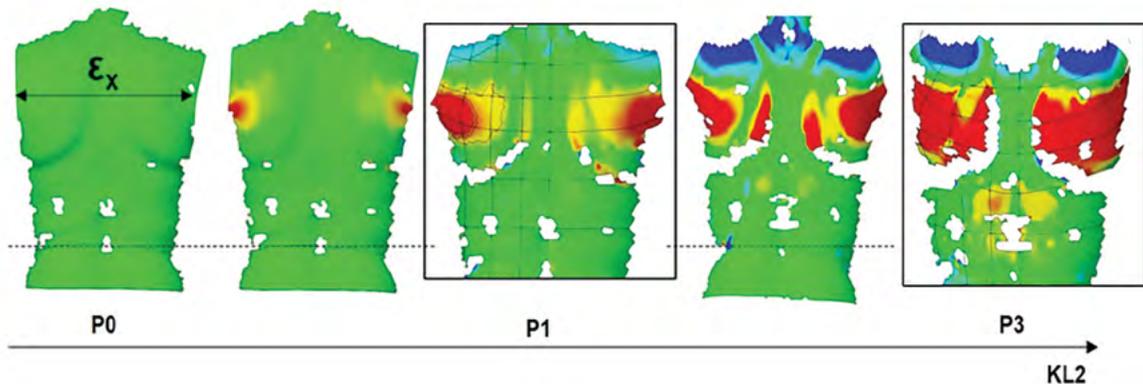


Figure 14: Transverse body deformation (ϵ_x) by phases of the kinematic chain KL2, which includes the spread-arm position (P1) and extension-arm position (P3) – test subject I1 in posterior view

In the forward-arm position (P2), transverse deformations extended across the entire surface of the back, from shoulder height to chest circumference (Figure 13). In the extension-arm position (P3), the deformation in the back area was slightly smaller compared to P2 (Figure 14). In addition to transverse deformations, in the extension-arm position P3, viewed in the sagittal plane, significant longitudinal (y) deformations of the lateral body part were observed, and were especially pronounced in the armpit area (Figure 15). In the kinematic

chain KL3, surface breaks were visible on parts of the body around the chest circumference line due to the coverage of this body part by clothing. Therefore, when determining the overall dimensions of the curves on the lateral body, missing parts of the curve were measured as the distance between the edge points of the curve on the upper and lower parts of the surface.

Figure 16 shows the longitudinal (y) deformations by phases of the recorded kinematic chains KL4 and KL5, using the example of test subject I1.

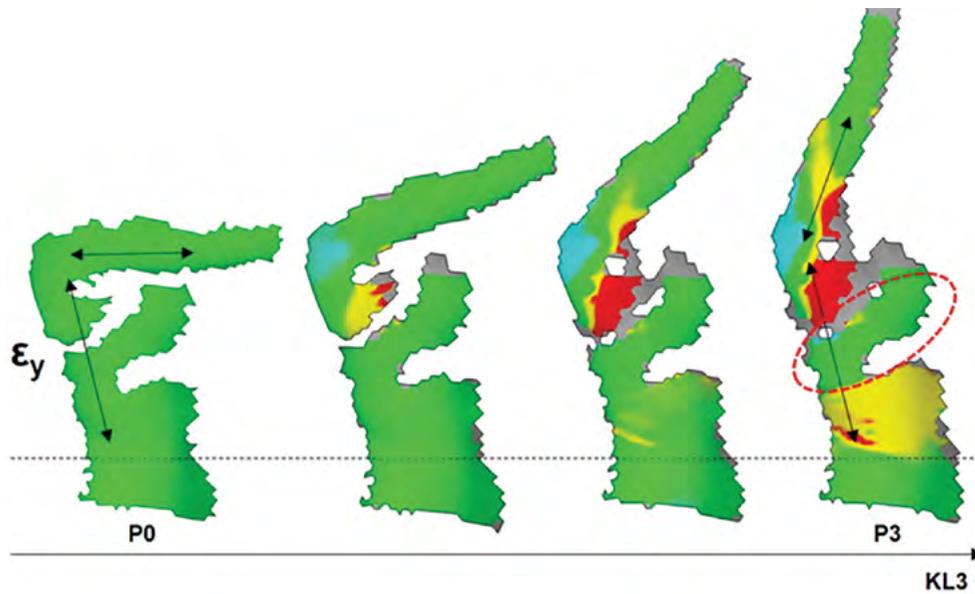


Figure 15: Longitudinal body deformation (ϵ_y) by phases of the kinematic chain KL3, which includes the forward-arm position (P2) and extension-arm position (P3) – test subject I1 in sagittal view

An analysis of surface deformations in the movement of bending the body into the forward bending position (P4) revealed significant deformations in the longitudinal (y) direction on the back of the body, in the length from the chest to the knee circumference and in the back length of the leg from

the hip to the thigh circumference. An analysis of surface deformations in the movement of lowering the body into the squat position (P5) revealed significant longitudinal deformations in the length from the waist to the upper thigh circumference and the transverse deformation zone in the hip area.

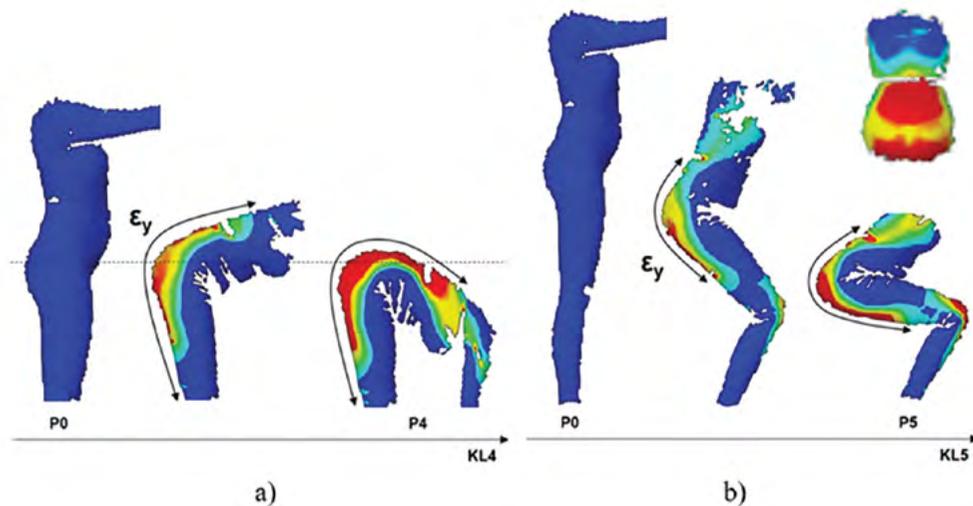


Figure 16: a) Longitudinal body deformation (ϵ_y) by phases of the kinematic chain KL4 of body bending in the forward bending position (P4), b) Longitudinal (ϵ_y) and transverse (ϵ_x) body deformation by phases of the kinematic chain KL5 of body lowering in squat position (P5) – test subject I1 in sagittal view wearing tight overall

3.1 Analysis of the body measurement results and dimensional changes determined by the Aramis system in relation to the data obtained by 3D body scanning

The results of the research and analysis of dynamic body anthropometry determined using the Aramis 3D dynamic deformation analysis system and the 3D body scanner are presented below. The determined values and changes in body measurements for the three subjects in the final positions P1, P2 and P3 are shown in Table 2. For both applied measurement systems, the determined changes in dimensions are shown as differences in the length of the curve in relation to the initial position and as elongation expressed in percentages.

In positions P1 and P3, a negative dimensional change was observed in the body measurement of the back width at the height of the shoulder blades (ŠI1), i.e. a decrease in the value of the measurement

compared to the initial position. The negative changes measured in the three subjects ranged from -1.2 to -2.7 cm. The most pronounced negative changes, from -6.42% to -7.54% compared to the initial length, were identified on test subject I3. The measure of the back width at the armpits level (ŠI2) increased significantly in all subjects when the arm position changed. The most significant changes in the ŠI2 measurement were identified in the forward-arm position (P2), with an extension of 31.64% to 36.52% compared to the initial position (Tables 2 and 3). In position P3, a significant increase in the value of the ŠI2 measurement was observed in subject I2, where an extension of 36.66% was measured compared to the measurement in the standard position. In subjects I1 and I3, the ŠI2 measurement in position P3 was smaller compared to the maximum change in the forward arm position (P2), while in subject I2 the largest deformation was identified precisely in position P3.

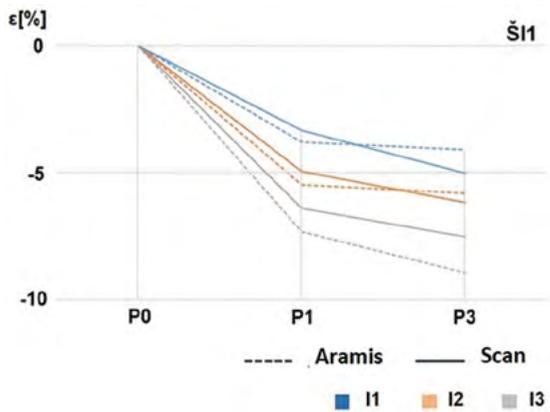
Table 2: Body measurements of the upper body in positions P1, P2 and P3, determined on 3D body models in motion obtained by the Aramis system and by interactive measurement on scanned 3D body models

System	Position	Measurement ^{a)}	Subject								
			I1			I2			I3		
			Measure [cm]	Δ ^{b)} [cm]	ϵ ^{c)} [%]	Measure [cm]	Δ ^{b)} [cm]	ϵ ^{c)} [%]	Measure [cm]	Δ ^{b)} [cm]	ϵ ^{c)} [%]
Aramis	P1	ŠI1	33.98	-1.34	-3.79	29.80	-1.73	-5.49	32.58	-2.58	-7.34
		ŠI2	41.07	5.83	16.54	35.43	4.51	14.59	38.22	4.31	12.71
	P2	ŠI1	40.73	5.41	15.32	36.65	5.12	16.23	40.58	5.42	15.41
		ŠI2	47.12	11.88	33.71	42.34	11.42	36.93	44.42	10.51	30.99
	P3	ŠI1	33.88	-1.44	-4.08	29.69	-1.84	-5.83	32.01	-3.15	-8.96
		ŠI2	45.30	10.06	28.55	43.21	12.29	39.75	43.47	9.56	28.19
		BDps	21.80	2.82	14.86	22.35	2.77	14.15	22.87	1.74	8.23
3D body scanning	P1	ŠI1	34.6	-1.2	-3.35	30.8	-1.6	-4.94	33.5	-2.3	-6.42
		ŠI2	40.3	4.9	13.84	34.8	3.7	11.90	38.4	3.9	11.30
	P2	ŠI1	41.6	5.8	16.20	37.3	4.9	15.12	41.9	6.1	17.04
		ŠI2	46.6	11.2	31.64	42.1	11.0	35.37	47.1	12.6	36.52
	P3	ŠI1	34.0	-1.8	-5.03	30.4	-2.0	-6.17	33.1	-2.7	-7.54
		ŠI2	44.3	8.9	25.14	42.5	11.4	36.66	43.6	9.1	26.38
		BDps	20.6	1.1	5.64	22.8	2.7	13.43	23.0	1.6	7.48

^{a)} See legend in Table 1; ^{b)} differences in the length of the curve in relation to the initial position; ^{c)} elongation.

Figures 17 and 18 show a comparison of the identified changes in body measurements in characteristic positions P1, P2 and P3, determined on 3D

models of bodies in motion using the Aramis system and scanned 3D body models.



Legend: I1 – first test subject, I2 – second test subject, I3 – third test subject

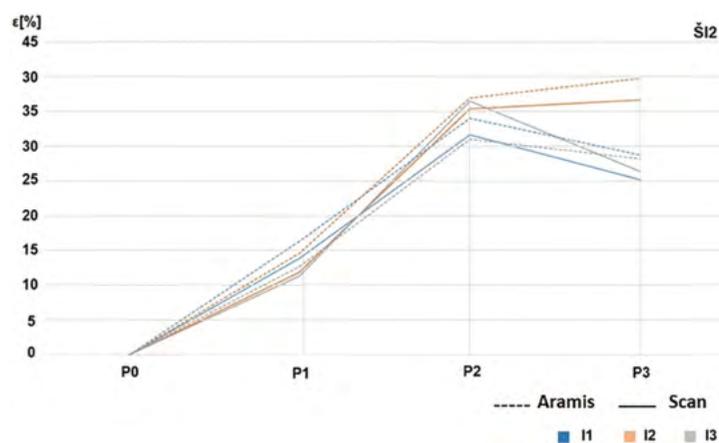
Figure 17: Analysis of dimensional changes in the body measurement of back width at the height of the shoulder blades (ŠI1), in positions P1 and P3, determined using the Aramis system and 3D body scanning

In the forward bending position (P4), all three subjects had a similar value of the back body line extension, measured along the vertical curve at a quarter of the back width, from the height of the chest circumference to the upper thigh circumference (Table 3). Differences of 12.9 to 13.5 cm were identified compared to the measurement in the standard upright position, i.e. an elongation of the measurement of 22.84% to 23.60%.

The results of the curve segments dimensional

analysis in P5 position were divided into the upper part from the chest to the waist circumference, the lower part from the waist to the hips circumference and the upper leg part from the hips circumference to the middle of the thighs. In the squatting position (P5), an increase from 13.86% to 15.91%, compared to the initial value, was determined on the measurement of the hips width in the posterior plane. In the measurement of the posterior body line, measured from the waist circumference to the upper thigh circumference, an elongation of 20.91% to 22.16% was determined, which is a slightly lower value compared to the elongation in the P4 position.

Figure 19 shows a comparison of the dimensional changes in body measurements in the characteristic position P4, determined on 3D body models in motion analysed using the Aramis system and scanned 3D body models. For all analysed measurements, minor deviations were identified between the results of the measurements on 3D models using two different systems. Although the measurements of scanned 3D models were performed interactively, where the precision of the person performing the measurement had a major impact on the accuracy of the results, markers positioned at characteristic anthropometric points on the subjects' bodies during the scanning ensured a high level of measurement precision, as is evident from the comparison of the results.



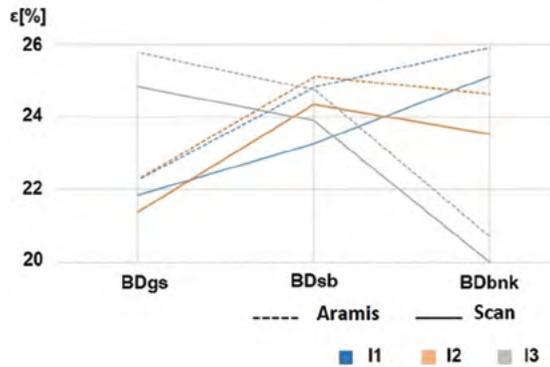
Legend: I1 – first test subject, I2 – second test subject, I3 – third test subject

Figure 18: Analysis of the dimensional changes in the body measurement of back width at the armpit level (ŠI2), in positions P1, P2 and P3, determined using the Aramis system and 3D body scanning

Table 3: Body measurements in positions P4 and P5, determined on 3D body models in motion obtained by the Aramis system and by interactive measurement on scanned 3D body models

System	Position	Measurement ^{a)}	Subject								
			I1			I2			I3		
			Measure [cm]	Δ ^{b)} [cm]	ϵ ^{c)} [%]	Measure [cm]	Δ ^{b)} [cm]	ϵ ^{c)} [%]	Measure [cm]	Δ ^{b)} [cm]	ϵ ^{c)} [%]
Aramis	P4	SŠb	37.06	3.37	9.91	38.49	4.52	13.31	40.36	4.56	12.74
		SDgnk	72.47	14.29	24.56	70.45	13.70	24.14	69.76	13.38	23.73
		SDgs	18.73	3.42	22.34	19.86	3.63	22.37	19.64	4.02	25.73
		SDsb	26.15	5.20	24.82	24.62	4.94	25.10	28.09	5.57	24.73
		SDbnk	27.59	5.67	25.87	25.97	5.13	24.61	22.03	3.79	20.78
	P5	SŠb	38.13	4.72	14.13	39.48	5.45	16.02	40.81	5.01	13.99
		Šnk	19.09	2.26	13.43	18.60	1.39	8.08	20.17	2.45	13.83
		SDgnk	52.07	9.09	21.15	48.95	8.02	19.59	49.24	8.67	21.37
		SDsb	25.37	4.36	20.75	24.21	4.03	19.97	26.75	4.84	22.09
		SDbnk	26.70	4.73	21.53	24.74	3.99	19.23	22.49	3.83	20.53
3D body scanning	P4	SŠb	37.4	3.5	10.32	39.2	4.7	13.62	40.6	4.5	12.47
		SDgnk	70.7	13.5	23.60	68.5	12.9	23.20	65.4	12.2	22.93
		SDgs	18.4	3.3	21.85	19.3	3.4	21.38	19.1	3.8	24.84
		SDsb	24.9	4.7	23.27	24.0	4.7	24.35	22.8	4.4	23.91
		SDbnk	27.4	5.5	25.11	25.2	4.8	23.53	23.4	3.9	20.00
	P5	SŠb	38.6	4.7	13.86	40.0	5.5	15.91	41.3	5.2	14.40
		Šnk	19.5	2.4	14.04	19.4	1.5	8.38	20.5	2.3	12.64
		SDsnk	51.4	9.3	22.09	48.0	8.3	20.91	46.3	8.4	22.16
		SDsb	24.5	4.3	21.29	23.5	4.2	21.76	22.7	4.3	23.36
		SDbnk	26.9	5.0	22.83	24.5	4.1	20.10	23.6	4.1	21.03

^{a)} See legend in Table 1; ^{b)} differences in the length of the curve in relation to the initial position; ^{c)} elongation.



Legend: I1 – first test subject, I2 – second test subject, I3 – third test subject

Figure 19: Analysis of dimensional changes by segments in the measurement of posterior body length, from chest to thigh circumference, in the P4 position, determined using the Aramis system and 3D body scanning

Although the study involved subjects with comparable anthropometric characteristics, the results revealed notable differences in body surface deformations, particularly in the scapular, waist and knee areas. These variations suggest that body shape characteristics, such as shoulder width, spinal curvature or fat distribution, directly influence the value and distribution of dynamic strain. The results revealed that the test subject with a more pronounced lumbar curve showed a 26% elongation in posterior lower body length during forward bending, compared to 22% and 21% of elongation on the other two test subjects. Similarly, the test subject with narrower shoulders exhibited reduced back width expansion in the arm-forward position (31% vs. 37%), indicating implications for additional garment pattern modelling. These findings support the use of the Aramis system for anthropometric analysis in the process of developing garment designs that accommodate body

measurement changes in motion, thus achieving high functionality and fit. Future work should incorporate a wider range of body types to formalize the link between static morphology and dynamic deformation, enabling more precise fit customization.

4 Conclusion

The results demonstrate that the Aramis system ensures the reliable and detailed measurement of body deformation during movement, offering multiple avenues for practical application. Monitoring deformation throughout the entire movement performance and the possibility of visualizing and analysing segments of the body surface affected by deformation, as a measurement method, represent a great advantage potential compared to 3D scanning of the body in characteristic positions and determining linear changes in body measurements. By analysing the deformations of the body in motion, where the deformations of the surface geometry are analysed in a specific direction (x/y), depending on the body segment being observed, the obtained data are applicable in the process of garment design and construction, given the possibility of linking the direction of deformation with the structure and direction of the thread system on the textile material. This is particularly important when designing functional garments, particularly sportswear, protective and workwear clothing, where the Aramis data support the development of patterns that reflect actual body deformation under motion. Data regarding deformations and dimensional changes of the body surface by zones can be used to adjust the garment construction pattern with the aim of achieving greater functionality of the model in dynamic conditions of movement, and can also be used for the selection of materials in production process, considering the parameters of material tensile properties. For example, based on the established high-stress zones identified in the armpit, lower back and knee areas, garment construction can be further modified to incorporate

textile material of targeted stretch on strategic garment zones. Moreover, the method facilitates virtual fit assessments within CAD systems for garment 3D simulations, thereby reducing the need for physical prototypes and shortening development cycles. Looking forward, this approach holds promise for mass-customization workflows, where user-specific motion data can enhance garment personalization. In the fashion and e-commerce sectors, improved fit prediction based on dynamic morphology may reduce return rates and enhance customer satisfaction. Future work will aim to validate the method on a broader range of body types and incorporate more complex motion sequences, such as jumping and running, and to integrate deformation data into methods and algorithms for garment pattern modifications and digital human modelling systems.

Data availability statement: All research results related to the measurements of the subjects are listed in the Manuscript. Other data, namely scanned models on which measurements were performed, cannot be provided in the repository due to the protection of personal data and the consent given by each individual subject to the use of measurement data, but not the distribution of complete 3D models, which is in accordance with the code of ethics and Personal Data Protection.

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Application of ANOVA and AHP in Assessing the Quality of Roving Cotton-Polyester Siro Yarn

Uporaba analize variance (ANOVA) in analitičnega hierarhičnega procesa (AHP) pri ocenjevanju kakovosti bombažno-poliestrške siropreje

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Abstract

Siro spinning, an evolution of ring spinning, optimizes parameters, such as roving strand distance and twist multiplier, thereby enhancing yarn quality according to numerous studies. Experts have differing opinions on the benefits of roving distances for yarn quality. However, the effect of roving distance on the roving blending technique in the ring frame has not been fully investigated. An integrated analysis of variance (ANOVA) and the analytical hierarchy process (AHP) based methodology are presented in this work to close the research gap between yarn quality attributes and roving strand distance in the context of roving blending. For this purpose, five yarn samples of 19.68 tex were developed using different roving distances, specifically 2 mm, 4 mm, 6 mm, 8 mm and 10 mm, within the drafting zone using a 50/50 cotton-polyester roving blending technique in a ring frame. Subsequently, the quality metrics of the yarn were studied, including variation concerning yarn mass ($CV_{VM}\%$), the imperfection index (IPI_{γ}) value, hairiness (HI), the count strength product (CSP_{LS}) value, elongation at break ($\epsilon_{br}\%$) and the total quality index (TQI_{YQ}). The results revealed that yarn sample B, made using a distance of 4 mm, resulted in good yarn quality. An ANOVA demonstrated that roving distance had no significant effect on HI , $\epsilon_{br}\%$ or TQI_{YQ} . However, AHP assisted in determining the ideal roving strand distance among various options. The study's findings provide practical suggestions for determining the ideal roving strand distance for better blended yarn quality.

Keywords: siro spinning, cotton-polyester roving blended yarn, analysis of variance, analytical hierarchy process

Izveček

Številne raziskave so pokazale, da se pri siropredenju, ki je nadgradnja prstanskega predenja, z optimizacijo parametrov, kot sta razdalja med stenjema v raztezalni coni in faktor zasuka, lahko bistveno izboljša kakovost preje. Strokovna mnenja o vplivu razdalje med stenjema na kakovost preje so različna, vpliv te razdalje na učinkovitost mešanja obeh stenjev v prstanskem predilniku pa do sedaj še ni bil celovito raziskan. V tej raziskavi je



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predstavljena integrirana metodologija, ki temelji na analizi variance (ANOVA) in analitičnem hierarhičnem procesu (AHP), njen namen pa je bil zapolniti raziskovalno vrzel med atributi kakovosti preje in razdaljo med stenjema glede na mešanje stenjev pri predenju. Za ta namen je bilo izdelanih pet vzorcev preje z dolžinsko maso 19,68 tex pri različnih razdaljah med stenjema v raztezalni coni (2 mm, 4 mm, 6 mm, 8 mm in 10 mm) z uporabo mešanice bombaž/poliester v razmerju 50/50. Proučeni so bili izbrani kazalniki kakovosti preje: variacija mase preje (CV_{vm} %), indeks nepopolnosti (IPIY), lasavost (HI), produkt finosti in trdnosti (CSPLS), raztezek pri pretrgu (Ebr %) in skupni indeks kakovosti (TQIYQ). Pokazalo se je, da je najboljšo kakovost dosegla preja vzorca B, izdelana pri razdalji med stenjema 4 mm. Analiza ANOVA je pokazala, da razdalja med stenjema ni imela statistično pomembnega vpliva na lasavost preje (HI), raztezek pri pretrgu (Ebr %) ali skupni indeks kakovosti (TQIYQ). Metoda AHP pa je omogočila določitev optimalne razdalje med stenjema med preizkušenimi možnostmi. Ugotovitve iz raziskave ponujajo praktične smernice za določanje optimalne razdalje med stenjema v raztezalni coni pri predenju, kar pripomore k izboljšanju kakovosti mešane bombažno-poliestrške siropreje. Ključne besede: predenje siro, preja iz mešanice bombaža in poliestra, analiza variance (ANOVA), analitični hierarhični proces (AHP)

1 Introduction

In the textile sector, backward linkage begins with yarn manufacturing or spinning, which transforms fibres into yarns [1–2]. Several yarn manufacturing methods are useful for this transformation, including ring spinning, open-end spinning such as rotor spinning, and air vortex spinning. Because of its adaptability, ring spinning is especially widely used. There have been numerous technical improvements made to this spinning technique in recent years, but the fundamental technology behind it has stayed virtually the same. There have been some improvements to ring spinning in recent decades in terms of yarn quality and production rates. As a result, unique and efficient spinning technologies such as compact spinning, siro spinning and solo spinning have emerged [3]. The International Wool Secretariat (IWS) and the Division of Textile Industry Laboratories of the Australian CSIRO created the relatively new and extensively utilized technique of siro spinning in 1975–1976. Two rovings are drawn in parallel in the drafting zone, emerge from the front roller through twisting, and are then combined in siro spinning [4].

The roving strand distance, spindle speed, traveller, twist multiplier, drafting method and other

factors all had an impact on the quality of siro spun yarn. Siro spinning has been studied for a variety of process parameters. Many researchers have made important contributions to overcome the difficulties related to these qualities.

Numerous studies have been conducted on siro spinning in literature taking into account various process parameters, such as the twist multiplier (TM) and roving spacing etc., as indicated in Table 1. Those studies concentrated on the use of natural-based textile yarn. Today, however, studies focus on the use of man-made fibre-based yarn, especially for advancing functional and sustainable properties rather than conventional textile usage. For example, Zachariah et al. found that yarns for ballistic and woven aramid fabric play a crucial role in providing exceptional strength and protection [5]. The yarn is meticulously crafted to maintain consistent quality and performance. Designed to endure extreme conditions, it provides reliable protection while remaining lightweight and strong. Aramid yarn ensures comfort and mobility without compromising on safety. The main aim of using aramid yarn is to obtain high tensile strength, heat resistance and abrasion resistance, which enables the resulting yarn

to be suitable for the applications of ballistic vests, helmets and other protective gear [6]. Khan et al. carried out another study in which researchers developed a sustainable blending approach employing cotton, banana, and Tencel fibres in siro spinning, resulting in fabrics with 6.61% and 12% higher tear and tensile strength, respectively, than conventional woven fabrics. Another significance of their study is that all the raw materials are obtained from waste cotton and banana fibres [7]. Moreover, yarns, especially micro and nano-sized variants, possess distinctive characteristics that are advantageous for micro electromechanical systems (MEMS). These specialty yarns are designed to fulfil the specific requirements of MEMS applications, necessitating narrow diameters, great strength and, when required, electrical conductivity. They can function as structural elements, offering support and stability to fragile MEMS structures. Moreover, these yarns can serve as electrical connectors or sensing components, enhancing a system's overall usefulness. The production procedure for these yarns is meticulously regulated to guarantee uniformity and dependability in MEMS devices. The adaptability of these yarns facilitates their incorporation into intricate geometries, fostering inventive designs that improve both performance and usefulness. The appropriate yarn can markedly enhance the durability, reliability and efficiency of sensors, actuators or other MEMS components. The potential of micro/nano yarns in MEMS has been examined in various studies, with an emphasis on the essential function of specific yarns in guaranteeing optimal performance in MEMS devices, particularly for mechanical strength, electrical characteristics and integration capabilities. Yarns manufactured from fibres with diameters of micrometers or nanometers are known as micro/nano yarns. They are often developed via electrospinning, melt spinning or advanced twisting, resulting in fine, flexible and lightweight structures [8–10].

Despite the fact that functional yarns for advanced applications and siro spinning have made great progress, there are still a number of unanswered

questions. Few in-depth studies have investigated how siro technology, which combines natural and synthetic fibres, might improve sustainability and performance in a range of industrial contexts. Optimizing process parameters, such as roving spacing and twist multiplier, to enhance the mechanical properties of specific yarns, especially for MEMS devices, requires additional research. Moreover, in order for these advanced yarns to be commercially viable, further research into their scalability and environmental impact is necessary. Furthermore, further research is needed to fully understand how roving distance effects the roving blending process, as there is limited existing literature on the topic. In order to optimize the siro spinning process, it is essential to understand the intricate relationship between roving distance and blending efficiency. To learn more about the effects of roving distance variations on fibre alignment, blending uniformity and yarn qualities, further research is needed. These findings have the potential to enhance the performance of yarns used in niche applications such as MEMS and high-tech protective clothing. To elucidate the matter further, research has examined the impact of process parameters on the mechanical and functional qualities of yarn during manufacture. Improving yarn quality for new textile applications can benefit greatly from the more in-depth study of these issues [8, 11].

To close the present gap in research, this study applied the combined use of various roving spacing with a combined approach of using the analytic hierarchy process (AHP) and one-way ANOVA to produce good-quality siro spun yarn in the case of roving blending. The following research questions are required to find the optimum outcome of this current study:

- How does roving distance affect roving blending for both natural and synthetic fibres?
- Do varying roving distances have a significant impact on essential quality indicators such as mass variation, imperfection index, hairiness, strength, elongation and overall quality index?

- Which statistical analysis is most suitable for finding the optimum roving distance?
To address the research issues stated above, the following objectives have been developed:
- To determine the impact of different roving distances in the case of roving blended cotton-polyester (50/50) siro yarn.
- To evaluate the significant impact of roving distances from the different yarn quality metrics such as CV_{vm}%, IPIY, HI, CSPLS, Ebr% and TQIYQ using one-way ANOVA.
- To identify the optimum roving distance from different options for producing good quality yarn using the AHP method.

Table 1: Overview of prior research studies

No.	Author	Objective	Materials	Methodology	Key findings
1.	Subramaniam et al. [12]	To identify the impact of processing parameters such as spacing between top and bottom aprons, twist multiplier (TM) and the speed of the spindles on produced blended yarn properties such as tensile strength elongation, and evenness.	100% cotton	Central composite rotatable design (CCRD).	Reduced break draft in the ring frame and closer apron spacing improved all but one of the investigated attributes.
2.	Cheng et al. [13]	To determine the effect of TM and spacing among the strands of rovings on produced cotton siro yarn quality.	100% cotton	Empirical data	Increased strand spacing increases the tenacity of 36.9 tex siro spun yarn, peaking at 9 mm for 28.1 and 18.5 tex yarns, while yarn hairiness decreases gradually.
3.	Liu WY et al. [14]	To study how filament-roving strand-spacing influences siro yarn properties.	50 % wool/50 % polyester	Empirical data	Yarn qualities include evenness, tensile strength and breaking elongation, yarn hairiness, as well as ideal strand spacing for different spinning methods.
4.	Soltani P et al. [15]	To ascertain how the structural and mechanical characteristics of siro yarns are influenced by the TM and the spacing of the roving strands.	100% lyocell	ANOVA	Lower hairiness and higher mean fibre standing, fibre migrating factor, broken fibre proportion and strand spacing of 8 mm increase in toughness. A statistical investigation also demonstrated that yarn durability is affected by TM and roving strand spacings.
5.	Liu SQ et al. [16]	To determine how siro yarn manufacturing variables affect cotton- flax blended yarn.	55% flax/45% cotton. Flock blending carried out in a blow room.	ANOVA	The specification of the traveller and spacing between two strands greatly affected the yarn's HI and CV _m %. A heavier traveller and more space resulted in lower hairiness with higher unevenness values, where 8 mm roving strands were suitable for high-quality yarn.
6.	Sundaresan et al. [17]	To establish how the siro compact yarn's strand spacing influences the fabric's characteristics.	100% cotton	Regression analysis	Higher overall yarn quality was reported when roving strands were spaced 8 mm apart and there was 24 mbar of negative pressure. Siro compact yarn on the fabric's properties.

7.	Wang et al. [18]	To investigate elastic-conductive composite yarns' tensile response on the strand spacing.	Core spun using rayon and filament	Least significant difference (LSD) method and ANOVA	The findings showed that the breaking strength and length at yarn break increase with increased spacing up to a value of 14.0 mm, after which they decrease, and the mean values were deemed substantially different.
8.	Temel E et al. [19]	To examine both polyester and combined polyester-cotton siro yarn's spinnability.	100% polyester and cotton-polyester blended yarn	ANOVA	The quality of the yarn was significantly affected by the types of fibres, count of yarns, twist multiplier and spacing between strands.
9.	Ute et al. [20]	To create a statistical approach to forecast siro yarn evenness.	100% cotton	Linear regression	The study assessed cotton blends from Turkish spinning mills using AFIS, identifying yarn production parameters as independent variables, and manufacturing siro spun yarns under standardized conditions.

2 Experimental part

2.1 Materials

The primary components of this experiment were fibres of cotton and polyester. Table 2 illustrates the fibres' characteristics, obtained from a high-volume instrument (HVI) according to ASTM D7642 [21].

Table 2: Attributes of fibres

Attributes of fibres	Cotton fibre	Polyester fibre
Fibre length (mm)	29.2	38
Fibre fineness (den) ^{a)}	1.6	1.4
Strength (N/tex)	282.52	309.02
Short fibre content (%)	9.2	-

^{a)} 1 den = 0.9 dtex

2.2 Methods

2.2.1 Research outline

The research work was conducted following the diagram depicted in Figure 1.

2.2.2 Working procedure

In this study, 19.68 tex siro spun yarns made of 50% polyester and 50% cotton were produced. Roving

blending was performed in the ring-spinning frame with a 50/50 blend ratio. During this experiment, three samples were prepared with five different roving strand distances: 2 mm, 4 mm, 6 mm, 8 mm and 10 mm. The working procedure is described below: First, carded slivers of cotton and polyester fibre were collected from the carding portion. The slivers were then fed individually into the breaker and finisher draw frames, resulting in individually drawn slivers of cotton and polyester. Individual slivers of cotton and polyester were fed to the simplex machine to produce the required roving hank at a 50:50 blend ratio. After that, 437.40 tex roving of cotton and 407.24 tex roving of polyester were fed into the ring frame to produce siro spun cotton and polyester blended yarn. In this experiment, five samples were produced, as shown in Table 3, while the other process parameters of the various machines remained constant, as indicated in Table 4.

Table 3: Data matrix for the experiment

Samples	Roving strand distance (mm)
I	2
II	4
III	6
IV	8
V	10

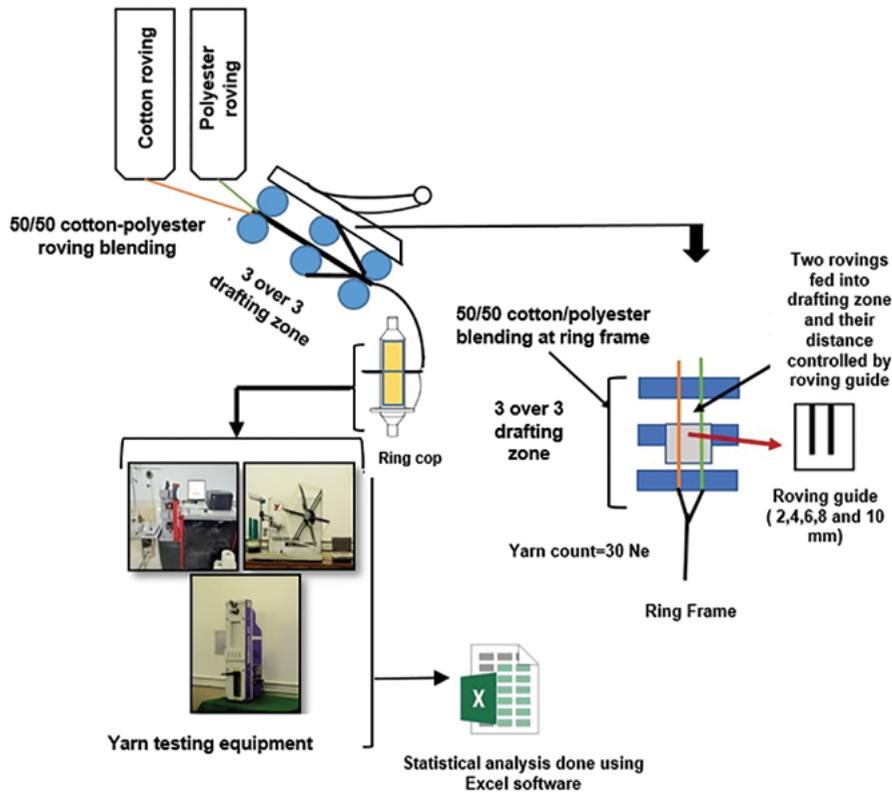


Figure 1: Approach for this study

Table 4: Technical parameters of various machines

Name of the equipment	Model	Origin	Name of the equipment's parameters	Values of each parameter
Carding	Rieter C-70	CH	Turns of the carding cylinder (m^{-1})	750
			Sliver count (ktex/Ne)	10/0.1
Drawframe	Rieter SB-D22 (Breaker), Rieter RSB D30 (Finisher)	CH	Speed of the delivery roller (m/min)	700 (breaker), 600 (finisher)
			Sliver count (ktex/Ne)	9.09/0.11
Simplex	FXM4-5-HY/L	CN	Twist of roving ($cm^{-1}/inch^{-1}$)	7.87/1.1
			Roving count (tex/Ne)	437/1.35 (cotton); 407/1.45 (polyester)
			Roller gauge (mm)	37.5 mm \times 48.5 mm \times 49.5 mm
			Spacer size (mm)	6.5
			Flyer speed (m^{-1})	1000
Ring frame	G-32	CH	Spindle gauge (mm)	70
			Roller gauge (mm)	44 \times 60
			Spindle speed (m^{-1})	14.800
			Twist of yarn ($cm^{-1}/inch^{-1}$)	7.229/18.34
			Spacer size in (mm)	2.5
			Yarn fineness (tex)	19.86
			Roving distance (mm)	2, 4, 6, 8, 10

The quality parameters of five yarn samples, including variation concerning yarn mass (CV_{vm}%), the imperfection index (IPIY) value, hairiness (HI), the count strength product (CSPLS) value and elongation at break (E_{br})%, were tested using a Uster tester-5, Wrap reel, Lea strength testers and Uster Tens-orapid, following the standard test methods given in Table 5. Testing equipment details are given in Table 6. Finally, test results were analysed to determine the impact of five levels of roving strand distances on the quality of siro spun yarns. The total quality index (TQI) can be calculated using Equation 1.

Table 5: Test standards

Parameters	Test method	Reference
Yarn count	ASTM D 1907	[22]
Evenness, imperfection and hairiness values of yarn	ASTM D1425M-14	[23]
Bundle yarn strength	ASTM D 1578	[23]
Tenacity (cN/tex)	ASTM D 2256	[24]

Table 6: List of testing equipment

Machine name	Model	Manufacturer	Country
HVI	HVI 1000	USTER	CH
USTER evenness tester	UT-5	Zellewger USTER	CH
Wrap reel	Ele Warp XT	MAG	IN
Lea strength tester	Me Stretch XT	MAG	IN

$$\text{Total Quality Index} = \frac{\text{Tenacity} \times \text{Elongation}}{\text{Mass variation}} \quad (1)$$

In Equation 1, tenacity (cN/tex) represents the strength of a single yarn, mass variation (CV_m%) quantifies the percentage variation in yarn mass and elongation (%) defines the highest extension before breaking.

2.3 Evaluation using statistical methods

2.3.1 ANOVA technique for analysing variance

When comparing the mean values of three or more groups, a one-way analysis of variance (ANOVA) is employed to determine if there are significant differences among the groups' means. This statistical technique assesses whether the means vary significantly from one another. The ANOVA yields an F-statistic, which represents the ratio of the differences between the group means to the difference within each group. This F-statistic is crucial in deciding whether to accept or reject the null hypothesis. A statistical table provides the F-critical value, which is compared with the F-value obtained from the test results. If the calculated F-value exceeds the F-critical value, the null hypothesis can be rejected. Additionally, the null hypothesis, which posits that all groups have the same mean, should be rejected if the one-way ANOVA produces a P value lower than 0.05 [26–28]. Yarn quality indicators, such as the coefficient of variation of yarn mass (CV_{vm}%), imperfection index (IPIY), hairiness index (HI), count strength product (CSPLS) and elongation at break (E_{br}%), were evaluated using this approach to determine the impact of varying roving distances.

2.3.2 Briefly about the analytic hierarchy process (AHP)

The Satty-developed AHP is a widely used decision-making tool for determining the most usable alternatives among all the alternatives. It was used to choose the highest quality yarn sample form with five different roving strand distances. According to this technique, the consistency ratio (CR) is obtained from the ratio between the consistency index (CI) to the random index (RI) in a matrix of the same size. Equations 2 and 3 were also used to calculate the CI and CR [29-30]. Figure 2 depicts a statistical model for a problem analysis. Various criteria have been developed using the Satty scale, as shown in Table 7 where the inputs from industry experts are very crucial. A pair-wise matrix for AHP analysis is presented in Table 8.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2) \quad CR = \frac{CI}{RI} \quad (3)$$

where n represents the number of items, λ max represents the consistency vector and CI represents the consistency index.

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

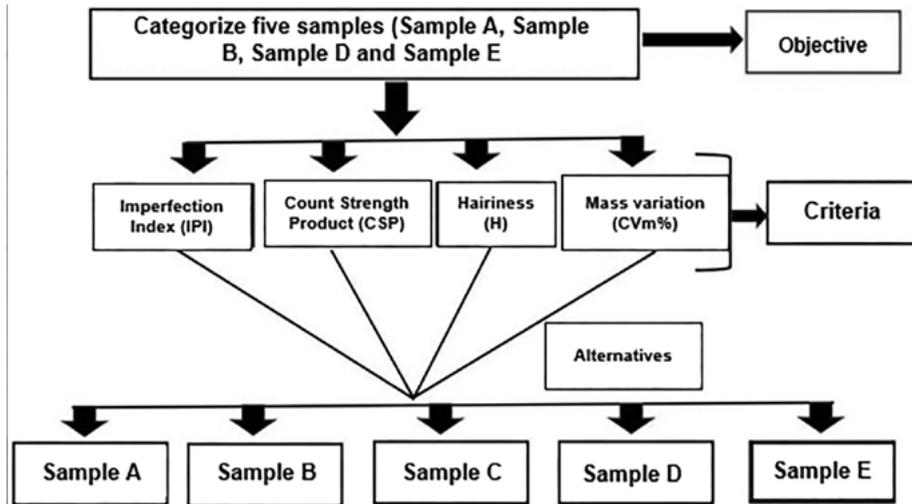


Figure 2: Methodology for problem analysis

Table 7: Scale for comparing two things in AHP [29–30]

Priority or inclination degree	Explanation in words
1	Equal weight is given to the two components
3	One factor is moderately significant to the other
5	One factor is highly significant to the other
7	One factor is very significant to the other
9	One factor is extremely significant to other
2, 4, 6, 8	Values positioned intermediately

Table 8: Pair-wise matrix

Yarn characteristics	IPI _Y	CSP _{LS}	HI	CV _{vm} %
IPI _Y	1	3	5	5
CSP _{LS}	1/3	1	3	3
HI	1/5	1/3	1	2
CV _{vm} %	1/5	1/3	1/2	1

3 Results and discussion

In this study, five yarn samples of 30 Ne were prepared using different types of roving strand distances in a ring frame machine. Test results from different samples against various distances are summarized in Table 9. In order to minimize random errors, each experiment was carried out three times using a total of five samples. When examining the data using standard deviation (±0.5) and coefficient of variation (CV: 1.5–2%), there was little difference between runs.

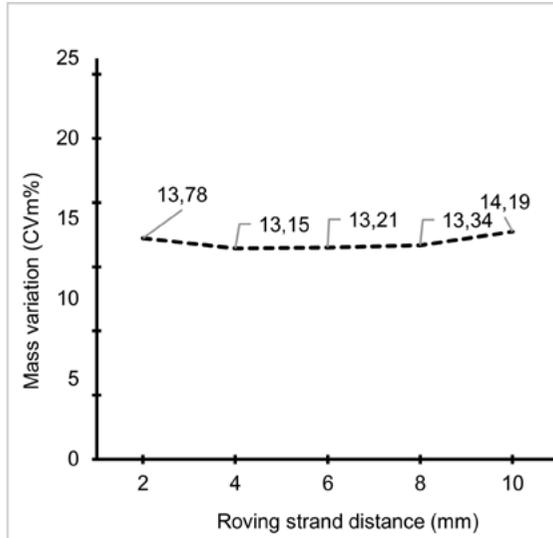
3.1 Graphical representation

3.1.1 Effect of different levels of roving distance on CV_{vm} % of siro spun yarn

The impact of spacing on yarn evenness is demonstrated in Figure 3, which shows the mass variation (CVm%) of yarn produced at five various roving strand distances.

Table 9: Uster test results for 30 Ne cotton/polyester roving blended yarn

Sample	CV _{vm} %	IPI _y	HI	CSP _{LS}	E _{LB} %	Total qualityindex (TQI _{vq})
I	13.78	278	5.84	2846	6.55	8.01
II	13.15	240	4.65	2955	7.12	9.57
III	13.21	257	5.15	2928	6.91	9.01
IV	13.34	268	5.46	2890	6.83	8.47
V	14.19	310	6.47	2733	6.65	7.72

Figure 3: CV_{vm} % of siro spun yarn at different roving distances

It can be concluded from the above figure that the values of mass variation were higher for samples made from 2 mm and 10 mm distances compared to other samples. The 2 mm gap between rovings was insufficient to spread out the fibres in the drafting zone, resulting in the higher mass variation of the yarn. After that, the mass variation in the drafting zone was reduced for a distance of 4 mm and then progressively increased as the roving strand distance rose. A distance of 4 mm provided a good result because the narrow space between two rovings in the drafting zone improves the controlling of fibres during drafting, resulting in a lower mass variation (CV_{vm} %).

These findings support previous studies showing that too small or large strand spacing causes slippage and poor fibre control, which deteriorates the yarn structure [13, 19]. Additionally, the current research's findings are in line with previous research

that found that yarn evenness was enhanced by moderate strand spacing and decreased by higher spacing [13, 14].

3.1.2 Effect of different levels of roving distance on IPI_y of siro spun yarn

The imperfection index (IPI) values of yarn are shown in Figure 4. These values are determined by adding the neps (+200%), thick areas (+50%) and thin places (-50%) per kilometre [31]. The figure illustrates the variation in yarn imperfections with varying roving strand spacing.

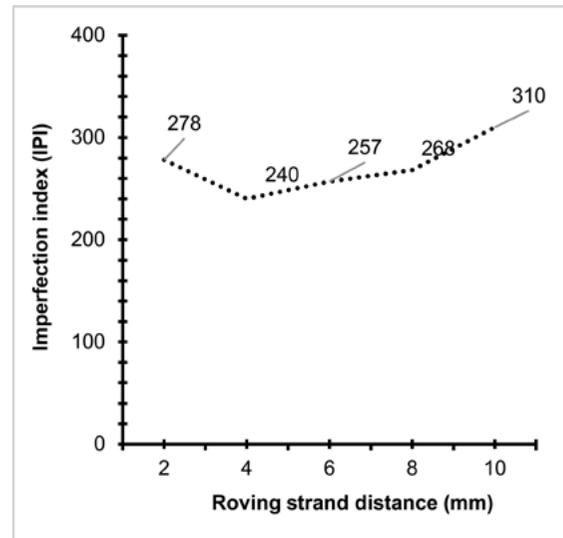


Figure 4: IPI value of siro spun yarn at different roving distances

Yarn samples with roving strand intervals of 4 mm, 6 mm and 8 mm showed a gradual increase in IPI, showing that imperfections increase with roving spacing.

This pattern can be explained by the spinning triangle's expansion at longer distances, which lessens

the drafting rollers' ability to regulate edge fibres, and increases fibre migration and nep generation. [17].

Moreover, the blending efficiency between cotton and polyester fibres declines with increasing roving spacing, especially in the ring frame drafting zone, resulting in a weaker fibre network and more imperfections. Conversely, roving distances of less than 4 mm cause the yarn sample's imperfection values to increase. A shorter distance causes an issue for fibre spreading during drafting and also helps to promote fibre entanglement. These results are consistent with other studies that showed that yarn structure is adversely affected by both extremely tiny and very large strand spacings, mostly as a result of ineffective fibre control or ineffective blending dynamics in the drafting zone [17].

3.1.3 Effect of different levels of roving distance on hairiness (HI) of siro spun yarn

Figure 5 depicts the hairiness values of siro spun yarns with varied roving spacing. The yarn's hairiness is primarily the protruding fibres at the yarn surface. Hairiness has a big impact on fabric performance and is a key component in evaluating yarn quality [32]. The hairiness value is also affected by twist level.

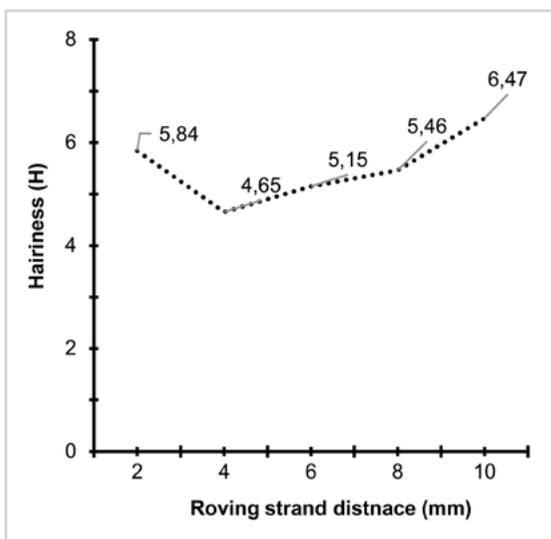


Figure 5: Hairiness (HI) of siro spun yarn at different roving distances

The findings show that increased roving distance is associated with higher hairiness scores. Remarkably, yarn samples spun at distances of 4 mm, 6 mm and 8 mm showed less hairiness than those made at distances of less than 4 mm or more than 8 mm. This shows that both insufficient and excessive strand spacing compromise the yarn's structural integrity by lowering the converging point in the spinning triangle which produces more protruding fibres [17]. When blending varying lengths of fibre, shorter fibres consistently tend to cause slippage between the nipping and convergence points, which further adds to the hairiness of the yarn.

The results, however, differ from earlier research that indicated a decrease in hairiness with strand spacing at distances greater than 8 mm. However, as strand spacing increased from 8 mm to 12 mm, a slight rise in hairiness was noted, most likely as a result of uneven fibre movement and a loss of control at greater distances. This finding emphasizes the need to control roving strand spacing in maintaining yarn smoothness and fibre cohesiveness, which has not been thoroughly addressed in previous research [13]. This study contributes to the understanding of how strand spacing influences hairiness by focusing on the combined effect of roving distance and fibre cohesion in cotton-polyester blends. The findings suggest that the spacing between rovings influences not just the yarn structure but also the cohesive strength of cotton and polyester fibres during blending, an attribute that has received less attention than hairiness.

3.1.4 Effect of different levels of roving distance on strength (CSP_{LS}) of siro spun yarn

The CSP_{LS} of siro yarn is shown in Figure 6 at varying roving distances. This figure indicates that yarn samples taken at distances of 4 mm, 6 mm and 8 mm showed greater strength than samples taken at distances of 2 mm and 10 mm.

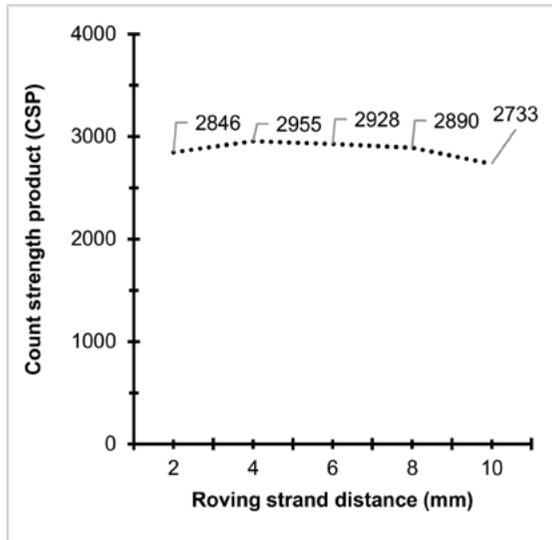


Figure 6: Strength of siro spun yarn at different roving distances

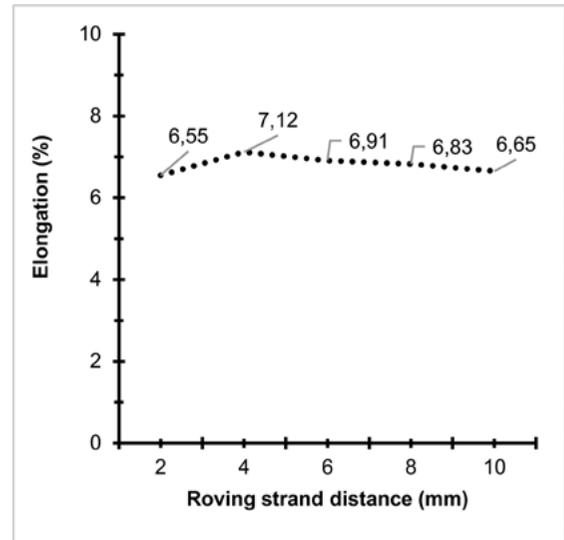


Figure 7: Elongation at break (E_{LB}) % of siro spun yarn at different roving distances

The yarn strength gradually decreased when increasing roving spacing. Higher spacing is also related to a higher amount of imperfection in the yarn samples, resulting in inferior yarn strength. Increased strand spacing, which results in longer strands, may induce increased fibre slippage in strands above the convergence point. This slippage may result in weaker areas and a possible decrease in the strength of the yarn [12]. Roving spacing of less than 4 mm interrupts fibre processing in the drafting zone, resulting in increased yarn imperfections and decreased strength. Yarn quality is further deteriorated when the spacing exceeds 8 mm because it reduces the drafting roller's control over individual fibres. Furthermore, whereas prior research reported higher tenacity at 8 mm strand spacing, the current study demonstrates that distances greater than 8 mm reduce yarn strength due to a lack of fibre cohesion and control inside the drafting zone.

3.1.5 Effect of different levels of roving distance on elongation at the break (E_{LB}) % of siro spun yarn

The elongation values of siro spun yarn at different roving distances are presented in Figure 7.

The overall extensibility and performance of the end product are determined by the right breaking elongation of the strands, which is crucial when turning yarn into fabric. A load is distributed between the individual fibres that make up yarn and the arrangement of the fibres inside the yarn's structure, while fibre extension affects the yarn's breaking elongation. The data shown above in Figure 7 indicates that there was no significant change in elongation percentage among the five samples, indicating that roving strand distance did not affect the elongation property of the yarn. When compared to samples taken at distances of 2 and 10 mm, yarn samples taken at 4 mm, 6 mm and 8 mm had good elongation properties. Poorer elongation property results from poorer fibre integration within the yarn structure caused by roving distances greater than 10 mm and less than 4 mm. These two distances also have an impact on the yarn's spinning triangle, which makes twisting the yarn inappropriate because of the inadequate insertion of the fibres therein. These results align with earlier research that found that greater strand spacing typically leads to a loss in breaking elongation because of increased fibre slippage and irregular fibre arrangement.

3.1.6 Effect of different levels of roving distance on total quality index (TQI_{YQ}) of siro spun yarn

Figure 8 depicts varied TQI_{YQ} values for different yarn samples at various roving distances.

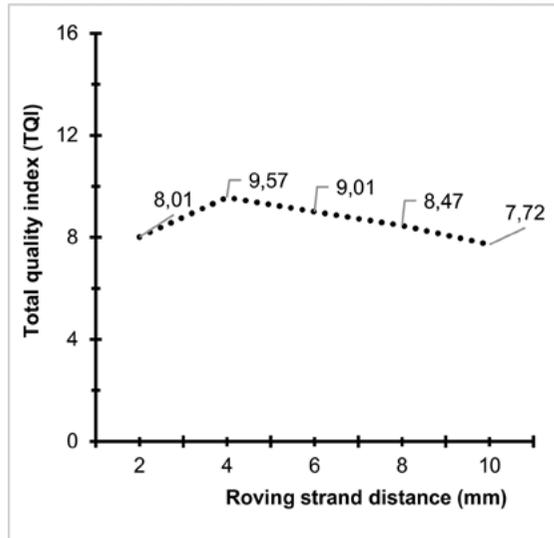


Figure 8: Total quality index (TQI_{YQ}) of siro spun yarn at different roving distances

Yarn tenacity, elongation at break and evenness are important characteristics for determining the quality of yarn. It is simpler to compare a single descriptive number than several. The total quality index gives the overall quality idea of the yarn samples. Higher TQI_{YQ} values suggest that multiplication values of strength and elongation were higher, but mass variation was lower. Yarn samples made from 4, 6, and 8 mm had greater TQI values than those made from 2 and 10 mm. Distances of less than 2 mm and greater than 10 mm affect yarn quality factors, such as elongation at break and mass variation, resulting in lower TQI_{YQ} values for the yarn.

3.2 Statistical analysis

3.2.1 ANOVA with a single-way test

In the case of ANOVA with a single-way test, the null hypothesis was “There is no correlation between yarn quality characteristics and roving strand distances”. On the other hand, the alternative hypothesis was “There is a correlation between yarn

quality characteristics and roving strand distances”. The test results of several samples from Table 8 were utilized to calculate the one-way ANOVA analysis. A summary of the results is presented in Table 10. This statistical analysis was done using Excel software.

Table 10: Results of one-way ANOVA for different yarn samples

Yarn Quality Parameters	F-statistics	P value	F-critical
$CV_{vm}(\%)$	27.83	0.007	5.32
IPI_Y	504.56	0.000	
HI	0.112	0.754	
CSP_{LS}	5402.64	0.000	
$E_{LB} \%$	0.3280	0.528	
TQI_{YQ}	3.094	0.1165	

The ANOVA results in Table 9 indicate that the values of F-statistics are significant because, in terms of mass variation, imperfection index and count strength product, F-statistics values are higher than F-critical values for a 0.05 significance obtained from the table [33], indicating the acceptance of alternative hypothesis and the rejection of the null hypothesis. P values for $CV_{vm} \%$, IPI_Y and CSP_{LS} are always less than alpha 0.05, which denotes a 95% confidence level [34]. Thus, based on this analysis, it can be concluded that the quality of yarn is greatly impacted by varying roving strand spacing in terms of quality parameters such as $CV_{vm} \%$, IPI_Y and CSP_{LS} . The F-statistical values are less than the F-critical values, however, because the values of the hairiness elongation% and total quality index of the various yarn samples did not change significantly. P values greater than the alpha value of 0.05 were identified for hairiness, elongation and overall quality index. The various roving distances thus have little to no effect on these quality parameters.

3.2.2 Analytic hierarchy process (AHP)

Based on the input from industry experts, four criteria were chosen. Excel software was used to determine the weighting of the criteria. First, the

CI and CR were calculated. The CR was presented in Table 11 following verification. The random consistency index value is 0.89 for the four number of elements. The acquired value of the consistency ratio was 0.0389, which was acceptable because it is less than 0.1 [35]. Finally, the weights assigned to the three options were calculated. When calculating

weights, the lowest imperfection index (IPI), lowest mass variation, lowest hairiness and highest count strength product (CSP) were considered for each alternative shown in Table 12. During this calculation, the quality parameters of yarn from different samples shown in Table 8 were used. Following that, Table 12 displayed the final performance value.

Table 11: Determination of CI and CR

CI and CR				
Criteria's	Average consistency vector (λ_{max})	Consistency index (CI) ($CI = \frac{\lambda_{max} - n}{n - 1}$)	Consistency ratio (CR) ($CR = \frac{\text{Consistency index}}{\text{Random consistency index}}$)	Consistency ratio (CR) [24–25]
IPI _Y	4.104	0.034	0.0389	Because a CR of 0.0389 < 0.1, it is acceptable
CSP _{LS}				
HI				
CV _{vm} %				

Table 12: Calculation of weights for various alternatives

Weightage calculation for different alternatives					Alternatives criteria weight	Performancescore
Criteria weightage	0.533	0.243	0.115	0.079		
Alternatives	IPI _Y	CSP _{LS}	HI	CV _{vm} (%)		
I	0.46	0.23	0.09	0.075	0.86	5
II	0.53	0.24	0.12	0.079	0.97	1
III	0.50	0.24	0.10	0.079	0.92	2
IV	0.48	0.24	0.10	0.078	0.89	3
V	0.41	0.22	0.08	0.073	0.79	4

The statistical analysis of five-roving spacing's is presented in Table 12, which displays the ranking in significance of the various choices. Sample II, obtained from a 4 mm roving distance, had the highest weightage, showing that this distance is ideal for creating high-quality yarn in the roving blending process, with a score of one. As shown in Table 12, the statistical analysis places the alternatives in the following performance order: II > III > IV > I > V. Samples A and E, which were produced with different roving spacing, had lower scores. This occurred at a lower and higher distance, which causes issues with

fibre processing during drafting and also affects the spinning triangle's convergence point, which has a major impact on the parameters affecting yarn quality.

4 Conclusion

This study identified and analysed the relationship between roving strand distance with the quality of siro yarn. It can be concluded that sample A made from a 4 mm distance showed better yarn quality than the others. This happened because minimum distance reduced the fibre slippage in the strands

above the convergence point as a result increased inter-fibre cohesion. Additionally, this distance helps to preserve the inter-fibre cohesiveness between two different fibre types of roving blending technique and is appropriate for improved fibre processing in the drafting zone of a ring frame machine. In comparison to Sample II, Sample I's yarn quality attributes were of lesser quality due to its production using a 2 mm roving strand spacing. A 2 mm spacing also disturbed the spinning triangle and inhibited the fibre processing in the drafting zone. Furthermore, extending the roving distance beyond acceptable levels reduced yarn quality because higher lengths compromised fibre-to-fibre cohesion, resulting in lower yarn quality. In an ANOVA analysis, variable roving strand spacing had a substantial impact on yarn quality measures such as $CV_{vm}\%$, IPIY and CSPLS. However, the hairiness, elongation at the break, and overall quality index were not significantly affected by these disparities in distance. Furthermore, the analytic hierarchy process (AHP) method identified 4 mm as the optimal roving strand distance for producing high-quality siro yarn, as it had the highest criteria weight compared to other samples. Thus, while Sample II stood out favourably, Samples III and IV were seen as viable options worth considering within the context of this study.

5 Future research directions

Siro spinning must explore several essential domains to improve yarn performance and optimize processes. The impact of roving distance on different yarn blends and fibre compositions warrants significant attention. Examining the effects of varying roving distances on the structural integrity and functional properties of blends, including natural and synthetic fibres, is essential for the progression of yarn technology. Broadening the analysis to include a wider variety of yarn counts and qualities would yield insights into the optimization of spinning parameters for various textile applications [36]. Additionally,

examining the relationships between roving distance and other spinning variables, such as twist multiplier, tension and draft, provides a means to optimize the overall spinning process. This may result in more uniform yarns exhibiting improved mechanical and functional characteristics, particularly for specialized uses such as protective textiles and MEMS devices. Long-term studies evaluating the durability, abrasion resistance and overall performance of yarns produced with different roving distances are essential for predicting their behaviour in practical applications, particularly in demanding fields such as ballistic protection and advanced sensors [8]. Moreover, integrating advanced technologies, including machine learning and artificial intelligence, into the siro spinning process has the potential to enhance efficiency and quality control significantly. Utilizing predictive models to ascertain optimal roving distances and other process parameters enables manufacturers to improve product consistency, minimize waste and optimize material utilization. These innovations may facilitate large-scale production of high-performance yarns suitable for various advanced applications, such as wearable electronics, smart textiles and MEMS-based systems [8].

Furthermore, some other studies emphasize the necessity for a more comprehensive understanding of the intricate relationships between processing parameters and yarn properties [37–38]. Future research should focus on integrating computational models with experimental data to enhance the efficiency and sustainability of yarn manufacturing processes. The integration of textile engineering and data-driven technologies is crucial for addressing the increasing requirements of next-generation textile applications.

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A Content Analysis of GRI Standards in XTEKS Listed Companies Sustainability Reporting

Vsebinska analiza standardov GRI za celovito poročanje o trajnostnem razvoju podjetij, ki kotirajo na borzi XTEKS

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Abstract

The aim of this study was to examine the most recent sustainability reports of companies listed on the BIST Textile and Leather Index (XTEKS) and to discuss their sustainability practices. In this context, the sustainability reports of the six companies registered with XTEKS that publish sustainability reports were examined in accordance with the Global Reporting Initiative (GRI) standards. The results revealed that the most frequently mentioned GRI keywords pertain to production, water, shareholder, water, effluent, education and performance. Although the sampled companies provide disclosures on environmental, social and economic issues, the quality of the information is found to be lacking. The general findings reveal significant gaps in the sustainability disclosures and practices of Turkish textile companies, indicating substantial room for improvement to meet international standards and enhance effective engagement with stakeholders. This study is significant, as it represents one of the pioneering efforts to provide a conceptual framework while raising awareness of sustainability reporting. Keywords: textile industry, XTEKS, sustainability reporting, GRI standards

Izveček

Namen raziskave je bil proučiti najnovejša poročila o trajnostnem poslovanju podjetij na carigrasjski borzi, uvrščenih v indeks BIST Textile and Leather (XTEKS), in oceniti njihove trajnostne prakse. V ta namen so bila pregledana trajnostna poročila šestih podjetij, vpisanih v XTEKS, ki objavljajo trajnostna poročila v skladu s standardi Global Reporting Initiative (GRI). Analiza je pokazala, da se najpogosteje omenjene ključne besede GRI nanašajo na proizvodnjo, vodo, delničarje, vodo, odpadne vode, izobraževanje in uspešnost. Čeprav vzorčena podjetja razkrivajo informacije o okoljskih, družbenih in gospodarskih vprašanjih, je bilo ugotovljeno, da je kakovost informacij pomanjkljiva. Splošne ugotovitve razkrivajo precejšnje vrzeli v razkritih trajnostnih informacij in praksah turških tekstilnih podjetij, kar kaže na precejšnje možnosti za izboljšave, da bi izpolnili mednarodne standarde in okrepili učinkovito sodelovanje z deležniki. Ta študija je pomembna, ker je eno od pionirskih prizadevanj, ki zagotavlja konceptualni okvir in hkrati povečuje ozaveščenost o trajnostnem poročanju.

Ključne besede: tekstilna industrija, XTEKS, trajnostno poročanje, standardi GRI



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1 Introduction

The Industrial Revolution and the advent of mass production led to the careless consumption of resources. Emerging in this process, as it became evident that irreversible burdens were being imposed on the environment, was the concept of sustainability, which has become increasingly valuable for protecting resources and making them available to future generations. Sustainability is defined as a participatory process in agriculture, tourism, architecture, business and economics that ensures the prudent use of all social, cultural, scientific, natural and human resources within society [1]. In addition to global warming and climate change, the scarcity of natural resources, driven by a growing population, flow shop manufacturing and consumption, has brought sustainability practices to the forefront. Heightened competition within the corporate sphere and a global emphasis on the UNDP's Sustainable Development Goals (SDGs) has enhanced participation in sustainability practices. Today, there is a belief that a company's sole purpose is not to make profit, but also to implement socially responsible projects that will benefit society and the environment, and contribute to sustainability. Corporate sustainability (CS) refers to a strategic framework aimed at creating shareholder value through the effective utilization of opportunities and the management of risks associated with economic, environmental and social dynamics [2].

The textile industry is responsible for producing 8–10% of global greenhouse gas emissions throughout the entire lifecycle, while it also contributes to numerous environmental challenges, such as excessive water use, harmful chemicals and waste generation [3]. Recognising the importance of sustainability in textiles, the Turkish Clothing Manufacturers' Association (TGSD) published *Horizon 2030* to inform businesses in the sector about global and sectoral trends, and strategic targets and support programmes for the Turkish textile industry [4]. According to *Horizon 2030*, the impacts of sustain-

ability for businesses will primarily manifest through changes in resource consumption, production technologies, supply chain, brands and standards. With a growing population, pressure on natural resources will also increase. In the textile industry, raw materials such as cotton and linen are preferred due to their perceived health benefits. While agricultural areas account for 70% of global water consumption [5], cotton production accounts for approximately 3% of the world's annual water resources [6, 4]. As a matter of fact, water consumption continues to be a significant aspect of the textile production process, and 17–20% of industrial dirty water wastes come from washing, dyeing and printing processes. While creating stress on natural resources, artificial fertilisers, pesticides and pesticides create soil pollution. The effect of this situation in textiles has manifested itself as a decrease in the share of cotton in raw material use and an increase in the use of recycled inputs. As the share of smart and functional garment use increases, innovation will become as valuable as design. In addition, the 'Better Cotton Standard', which is an environmentally friendly and sustainable standard without reducing cotton production yield, has been introduced [7]. Advancements in the field of technology and innovation necessitate the use of more technology at every stage in the textile industry. In product development processes, the relationships between manufacturers, suppliers and brands/retailers, as well as the internal management and decision-making processes of each entity, will become increasingly technology-driven and digitally based. In production and transportation, the importance of carbon footprints will rise, and suppliers with smaller footprints will be preferred. Short-distance supplier countries that will cause less carbon emissions will be preferred. The share of railway transportation in logistics is expected to increase. The Higg Index was developed to improve efficiency and to assess environmental and social sustainability at every stage of the supply chain [8]. Consumer preferences and habits will diversify, while regional and local brands will grow faster. Brands will make

compliance with sustainability a priority, which in turn will strengthen their position and diversify their sales channels. They will be responsible for the stages of design, material selection, production, distribution, exhibition, sales, consumption, waste management and recycling. In response to the growing need for sustainability, it is estimated that there will be an increase in the number of relevant regulations and standards. It will become a necessity for businesses to have BCI, BSCI, SA 800, OHSAS 18000 and similar social compliance standards and various certificates [4].

Businesses publish sustainability reports to conduct more effective risk analysis, utilize natural resources efficiently, enhance brand loyalty and gain the confidence of investors. The textile industry is among the sectors that have a particularly detrimental impact on the environment and the balance of ecosystems, with destructive effects on natural resources. Surprisingly, even though available studies address many issues, the issue of sustainability has not been given due consideration. The growing awareness of sustainability has heightened stakeholders' demands for non-financial information. Stakeholders are increasingly vocal in demanding that external reports include not only financial indicators but also criteria related to environmental and social factors. This inclusion enables a more comprehensive evaluation of a company's managerial efficiency, and its commitment to environmental stewardship and social responsibility within the context of its operations. However, it is still difficult for businesses to align their activities with economic, environmental and social dimensions, and to reflect these aspects in their sustainability reporting or identify appropriate tools for this purpose. The Global Reporting Initiative (GRI) Standards serve as a critical resource for companies publishing corporate sustainability reports, enabling them to comprehensively understand and disclose their economic, environmental, and social impacts. Over the past decade, numerous businesses across various sectors have adopted the GRI Standards to guide their

operations. While some have introduced numerous initiatives aligned with truly global objectives, their practical application remains geographically uneven due to the underrepresentation of certain regions. On the other hand, even companies that voluntarily publish these reports may refrain from disclosing significant CS information to relevant stakeholders. In line with this information, the primary research question of this study was to determine which GRI Standards are currently included in the sustainability reporting disclosed by Turkish textile companies. Accordingly, the study concentrates on the sustainability reports of companies listed under the Textile Leather Index (XTEKS) registered on the Istanbul Stock Exchange (BIST). In this study, the economic, social and environmental performance of the six companies listed in the XTEKS that publish sustainability reports were analysed in accordance with the Global Reporting Initiative (GRI) Standards. The study provides important data regarding the localisation process and challenges of international reporting standards in developing countries such as Turkey, and contributes to existing literature in this field. It provides guidance for improving sustainability reporting by identifying the frequency of use of GRI keywords and highlighting gaps in reporting processes.

1.1 Literature review

Sustainability emerged as a critical concept with the realization that environmental degradation could eventually lead to the destruction of life. It then began to be addressed from different perspectives. The equivalent of the concept of sustainability at the business level is referred to as corporate sustainability. Corporate sustainability is a concept that recognises the importance of corporate growth and profitability, and also requires businesses to pursue societal goals related to environmental protection, social justice and equality [9]. Since the early 1990s, with the introduction of environmental reporting, companies have increasingly begun to publish sustainability reports that encompass economic, social

and environmental parameters [10]. Businesses publish sustainability reports to enhance brand value, strengthen competitiveness, improve social and ecological performance, and inform stakeholders in accordance with the principles of transparency and accountability. Stakeholders are increasingly concerned with assessing not only profits but also the processes that generate them, as these processes, encompassing innovation, production and the safety of both workers and consumers, are shaped by a company's values regarding the environment, financial resources and human capital [11]. For example, in 1996 Nike faced consumer backlash, boycotts and long-term reputational damage due to poor working conditions and the use of child labour in its factories in Pakistan [12].

The studies in literature relating to the Turkish textile sector have primarily focused on technical aspects such as production technologies, waste/wastewater management and recycling, as well as on measuring competitiveness and productivity levels. Nart et al. [2] examined the impact of green human resource management, environmental performance and organizational commitment on corporate sustainability (CS) within the textile and fashion industry. The findings confirm that green human resource management positively affects corporate sustainability, with environmental performance mediating this relationship. However, organizational commitment does not exhibit a mediating effect in this context. Köse and Aydın [13] examined consumers' perceptions and knowledge levels regarding sustainability and sustainable fashion, their clothing purchase and disposal behaviours, their evaluations of sustainable fashion retailers and their purchase intentions. Consumers are aware of their responsibility, alongside retailers, in mitigating the negative impacts of fast fashion. Additionally, due to the lack of information regarding the scope of sustainability initiatives and the companies engaged in these activities within the industry, effective communication channels should be emphasised. Consumers are increasingly receptive to sustainable fashion retailing,

and sustainability practices positively influence the image and positioning strategies of fashion retailers. To convert these positive perceptions into purchases, it is crucial to focus on communication activities, the use of sustainable and recycled materials, maintaining quality, and ensuring that design and pricing are appropriate.

According to Özdoğan et al. [14], demonstrating that products are safe and environmentally friendly through honest labelling, in line with the growing global awareness of health and environmental issues, is believed to create a distinct advantage in the eyes of consumers. Environmental labelling criteria should consider all stages of a product's lifecycle, from raw material selection to design, production, distribution, consumption and ultimately its recyclability after use. Baydar et al. [15] compared the contribution of Eco T-shirts made from organic cotton to global warming, acidification, water and terrestrial eutrophication, and photochemical ozone formation with that of conventional T-shirts. Although Eco T-shirts demonstrate clear superiority in environmental performance across all analysed categories, both products significantly contribute to global warming. The imperative to utilize sustainable raw materials throughout all stages of the textile product life cycle was emphasised. Atalay Onur [16] stated that environmental concerns, along with social and political changes, have led to the questioning of the linear economy model within the fashion industry. It was emphasized that the industry cannot continue with current practices that threaten the world's limited resources, and underscores the need to transition towards a circular economy and the slow fashion movement. The reuse of waste materials, the enhancement of creativity through the limitation of resources, the application of traditional craftsmanship techniques and the promotion of collective production are expected to positively contribute to the industry.

The Global Reporting Initiative (GRI) has developed sustainability reporting guidelines that offer companies a systematic approach to reporting

their performance across social, environmental and economic dimensions of sustainability [17]. The GRI seeks to establish a voluntary reporting framework that enhances sustainability reporting practices to match the rigor, comparability, auditability and general acceptance of financial reporting [18]. Various researchers have analysed sustainability reports disclosed by different sectors in accordance with the GRI standards [19–23]. Saygılı et al. [24] analysed the economic, environmental and social sustainability disclosures of 34 companies according to the GRI standards. They found that companies frequently provide disclosures on topics related to employees, water, products, markets, suppliers, education, economy, energy and waste. Lehenchuk et al. [25] investigated the impact of sustainability reporting on the financial performance of 48 Turkish companies operating in the food, beverage, tobacco, textile, apparel and leather sectors listed on the Istanbul Stock Exchange. They concluded that companies' sustainability reporting has no impact or almost no impact on financial performance. This finding, which contradicts the majority of recent studies, suggests that there is a need for improvement in the reporting system in Turkey. This study presents one of the first in-depth analyses of the sustainability reports published by Turkish textile companies listed on XTEKS, utilizing the GRI standards.

The GRI provides guidance to businesses on what to report and how to report it. This facilitates an increase in demand for consulting and other services aimed at assisting companies in complying with emerging regulations. The GRI Standards emphasize that reporting should be accurate, balanced, transparent, comparable and reliable. Nevertheless, the quality of published sustainability reports varies significantly from one report to another, with some companies opting to provide disclosures based on their preferred criteria rather than adhering to reporting guidelines. In general, as long as reporting remains voluntary, addressing transparency outside the scope of mandatory requirements and close monitoring processes can be challenging. For these

reasons, compliance with sustainability reporting standards is a critical issue that warrants further empirical investigation. Furthermore, it can be stated that there is an insufficient number of studies conducted on this subject in Turkey, despite its growing prominence at the international level in recent years. The absence of existing studies specifically investigating the factors driving corporate sustainability reporting in the textile sector, combined with the sector's importance in the social, economic and environmental spheres, constitutes one of the key motivations behind this study. Our study may raise awareness among authors of sustainability reports and encourage them to write impartially about their organisations' sustainability performance. It may also contribute to the advancement of both managerial and academic knowledge and awareness regarding the more effective application of the GRI Standards. Moreover, given the limited number of studies examining sustainability practices specific to the textile industry, this study is expected to contribute to filling this gap in literature. In this context, by analysing how GRI Standards are applied by Turkish textile enterprises, it provides a valuable insight into how these standards are interpreted and used in the local context.

2 Material and methods

The Global Reporting Initiative (GRI) was established in Boston, USA, in 1997 in response to the public outcry over the environmental damage caused by the Exxon Valdez oil spill. Its origins can be traced back to the non-profit organizations CERES (the Coalition for Environmentally Responsible Economies) and the Tellus Institute. The GRI recognises that businesses, governments and other organisations need to address climate change, human rights, the impact of business on corruption and many other critical sustainability issues, and is an independent international organisation that helps people to understand and communicate. Initially aimed at creating a framework for holding companies accountable

to principles of responsible environmental conduct, the GRI was subsequently broadened to address social, economic, environmental and governance concerns. In 2016, GRI shifted to establishing the first global standards for sustainability reporting, known as the GRI Standards. The GRI Standards, which have been updated over time, have become an important resource for many organisations trying to publish corporate sustainability reports. Figure 1 shows the chronology of GRI's history.

The GRI Standards empower an organization

to publicly communicate its foremost effects on the economy, environment and society, encompassing effects on human rights, along with detailing an organization's strategies for managing these effects [26]. The GRI provides guidance to companies by developing sustainability reporting guidelines to increase the capacity of businesses to report on the environmental, social and economic dimensions of their activities, as well as their products and services. This fosters transparency regarding an organization's effects and amplifies organizational accountability.



Figure 1: Chronology of GRI's history

The GRI Standards consist of three interrelated parts (Figure 2). They consist of 'universal standards' that apply to all organisations, 'sector standards' that apply to specific sectors and 'topic standards' that include items with disclosures that focus on specific topics. The topic standards are categorized into three

series: Economic (GRI 200), Environmental (GRI 300), and Social (GRI 400). Each topic-specific standard contains disclosures pertinent to its respective area and is intended to be used in conjunction with GRI 103: Management Approach, which outlines the management approach for a topic.



Figure 2: GRI Standards

In this study, the latest sustainability reports of Turkish textile enterprises in the BIST Textile Leather Index (XTEKS) were analysed within the framework of the GRI Standards. The research question addressed is “Which GRI Standards are currently utilized in the sustainability reports disclosed by Turkish textile enterprises?”. The sustainability reports of the companies were analysed through content or document analysis, a methodology commonly employed in prior research examining such reports [27, 28]. Content analysis is a type of text analysis that examines the messages or features of a text by determining the frequency of concepts such as words or phrases [29]. Document analysis is a technique to present valid, reliable, and repeatable results from data [30]. To provide a basis for the content analysis, keywords were extracted from the GRI topic-specific standards related to economic, social and environmental issues. The sample was selected from companies listed in the Textile Leather Index (XTEKS) of the Istanbul Stock Exchange (BIST). As of 2024, there were 22 Turkish textile enterprises traded within the scope of the Textile Leather Index (XTEKS) registered on the Istanbul Stock Exchange (BIST). In line with the objectives of our study, we selected the top three publicly listed companies on the basis of size (market capitalization), representing approximately half of the sector’s total market value, along with companies that publish sustainability reports. Thus, the sample for this study consisted of six companies. Size according to market capitalization has also been used in previous studies by Guthrie and Parker [31], Hackston and Milne [32] and Kamal and Deegan [27], among others. When the published reports were analysed, it was seen that the statements in the report seem to have come from a template. Thus, it was deemed that the reports obtained encompass the sustainability reports of textile enterprises in Turkey. Although our sample size may seem limited, since the purpose of our study is to analyse current reporting practices, we believe that the sample is sufficiently representative of the current state of the sector in the field of sustainability reporting. Moreover, the market share and pioneering

roles in sustainability of the six companies registered with the XTEKS enhance the representativeness of this sample in a meaningful way. In this study, the sustainability reporting of the selected companies was analysed through content analysis, which was employed to evaluate a specific methodological standard in the sustainability reports of companies and to ensure consistency with previous studies in this field. However, it should be noted that additional research utilizing surveys and case studies could be conducted to examine these companies’ sustainability practices more comprehensively. It is possible to obtain in-depth data by incorporating methods such as surveys and case studies. While this would have expanded the scope of the research, it was not feasible within the time, cost and resource constraints of the study. Future research is recommended to address these limitations and integrate the two methods to evaluate sustainability practices from a broader perspective. On the other hand, this limitation of the study does not diminish the validity of the chosen method. Indeed, content analysis is a frequently employed and effective method in literature for identifying general trends and key themes in sustainability reports.

3 Results and discussion

Companies disclose their sustainability reports by associating their activities with economic, environmental and social dimensions, driven by both legal obligations and the need to remain competitive in the marketplace. These reports have increasingly been used by informed consumers as a criterion for evaluating companies’ financial performance when making investment decisions. In this study, the sustainability reports of six companies listed in the XTEKS were analysed through content analysis, and the frequency of the usage of GRI keywords was determined. First, the keywords within the descriptions of each of the seven economic, seven environmental and 17 social topic-specific standards were identified. In other words, relevant keywords were identified for each of the 31

topic-specific standards. Subsequently, to prevent double counting, a frequency analysis of the keywords presented in Figure 3 was performed using the word-based NVivo software. According to the results, the italicised keywords stand out as the most frequently used words. For instance, the frequency of the keywords “production” and “energy” was six, with each word repeated more than 500 times. The frequencies of shareholder, water, effluent, education and performance were five (observed between 400 and 499 times). The frequencies of economic, R&D, climate/climate change, material, governance and operations and suppliers at risk were three. The frequencies of investment, market, standard, reporting, recycled input, energy reduction, waste water, supplier, occupational health, job security, career development, participation and selecting new suppliers using social criteria were two. The frequencies of other keywords and phrases included in the analysis were one. On the other hand, it was determined that the selected keywords such as monopoly, drainage, red list species, trained security personnel, political contributions, cases of non-compliance, incidents of non-compliance concerning product information labelling and complaints concerning and losses of customer data were not included in the analysed reports.

The analysis results indicate that six companies out of 22 companies listed in the XTEKS have currently published sustainability reports. Two of these six companies have declared that they prepared their reports in accordance with the GRI Standards. The most frequently emphasized GRI keywords are related to production and energy, followed by shareholder, water, effluent, education and performance. Significant variations were observed among companies in their disclosures related to economic, environmental and social sustainability issues. The sampled companies provided explanations related to keywords concerning economic issues; however, only a few addressed topics such as anti-poverty initiatives and anti-competitive behaviour. It was observed that the companies provide disclosures on environmental topics, including key issues such as energy, water and effluent. The sustain-

ability reports of the companies include disclosures on social sustainability topics such as employment, education, governance, and occupational health and safety. Finally, some companies have provided disclosures related to key terms such as employee diversity, discrimination, negative social impacts on the supply chain, and labelling. However, they made no disclosures regarding collective bargaining, incidents of violations involving rights of indigenous people, political contributions, customer health, safety and privacy, or socio-economic compliance.

Our findings indicate that the relative size of a company has an impact on its sustainability activities and the disclosures provided in its reports. The larger the enterprise, the more information it tends to disclose, possibly due to greater pressure from the international community. It appears that Turkish textile companies provide information on their sustainability practices to establish/maintain legitimacy and/or meet the expectations of stakeholders. Adopting a sustainability reporting framework represents a significant step for a business. However, the mere act of producing a report does not automatically ensure greater transparency and accountability. Our findings indicate that sustainability disclosures fall short in supporting key values such as transparency, accountability, fairness, and responsibility. Certainly, it will take time for businesses to modify their internal mechanisms before providing the relevant disclosures. Initially, businesses may make ‘symbolic’ disclosures about their social and environmental performance, but if social pressures persist, real (or significant) changes in processes and practices are eventually expected and relevant disclosures will follow. Sustainability reporting, driven by increasing pressures and evolving stakeholder expectations, is expected to become a widespread practice across organizations of all sizes and industries. Considering the employment, GDP share and export figures generated by the textile sector in the local and international context, disclosure of social and environmental information by regulatory bodies should become mandatory. Governance practices related to social and environmental issues

should constitute an integral part of an organization's broader corporate governance practices. The fact that only six out of the 22 businesses within XTEKS

publish sustainability reports indicates that awareness of sustainability and reporting practices in the sector are not yet sufficiently widespread.

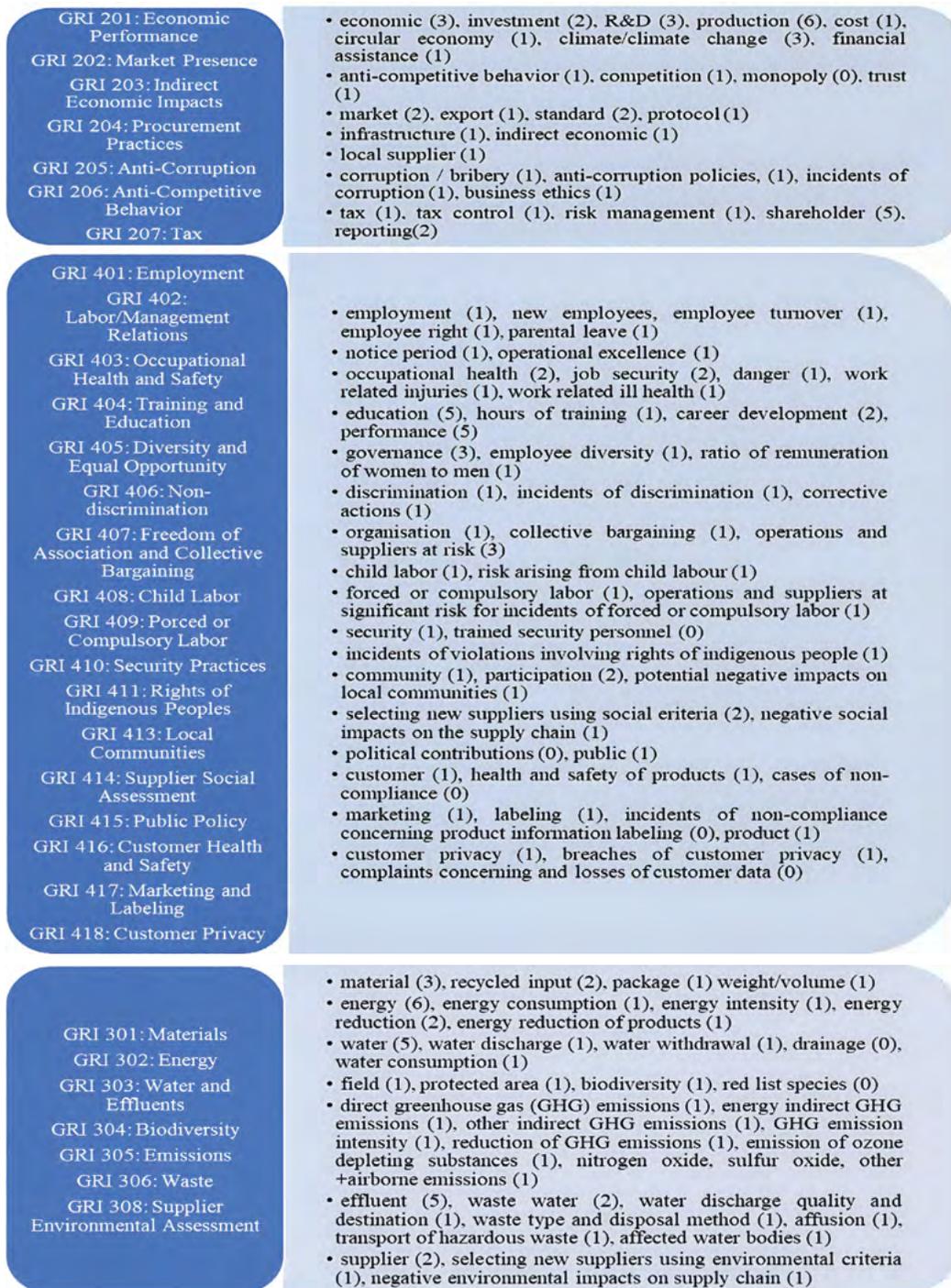


Figure 3: The frequency of GRI topic-specific keywords used in the sustainability reporting of companies listed in XTEKS [Each level on the XTEKS scale represents the total number of words as follows: 0–99 = (1), 100–199 = (2), 200–299 = (3), 300–399 = (4), 400–499 = (5), 500–599 = (6).]

4 Conclusion

Since sustainability reports are considered within the scope of a company's sustainability, they encompass not only environmental aspects but also include evaluations from social, economic and governance perspectives [33]. Given the significant impact of sustainability practices on development, policies and strategies related to this issue have begun to be discussed across all sectors. It appears inevitable that in the near future, businesses will be required to disclose their activities in sustainability reports by linking them to economic, environmental and social dimensions. This is expected to increase the quality and quantity of production by switching to sustainability practices in the textile sector. From this perspective, the textile industry should be shaped by conscious steps such as transitioning to a circular economy, aiming for zero waste, utilizing recyclable materials, and incorporating innovation and digital tools. While the share of cotton in the use of fibre in raw material consumption decreases, the use of recycled inputs is expected to increase. With increasing innovation in the industry, there will be a focus on convertible and smart garment designs, more efficient production systems and personalized manufacturing options. In the supply chain, a low carbon footprint will become increasingly important, while regional and local brands are expected to grow more rapidly, and new regulations and standards will be implemented. Meanwhile, Europe's targets to reduce carbon emissions by 55% by 2030 and to achieve carbon neutrality by 2050 will necessitate the development of new business strategies.

The aim of this study was to conduct an in-depth examination of the most recent sustainability reports of Turkish textile companies listed in the BIST Textile Leather Index (XTEKS). Through content analysis, the sustainability reports of six companies were analysed within the framework of the GRI Standards. The results indicate that the most emphasized GRI keywords are energy, production, shareholder, water, effluent, education and performance. Although the

frequency of GRI keyword usage varies, the companies in question provided disclosures on economic, social and environmental issues. Some of the sampled companies have provided disclosures on key terms such as anti-poverty initiatives, anti-competitive behaviour, employee diversity, discrimination, negative social impacts on the supply chain, and labelling. However, it was observed that there were no disclosures related to collective bargaining, incidents of violations involving rights of indigenous people, political contributions, customer health, safety and privacy, or socio-economic compliance. Our findings support a positive relationship between the content of sustainability disclosures and the relative size of a company. Turkish textile companies publish sustainability reports to establish their legitimacy and meet the expectations of their stakeholders. The adoption of a sustainability reporting framework does not necessarily ensure greater transparency and accountability for an organization. The examined reports reveal that the sustainability disclosures fall short in supporting fundamental values such as transparency, accountability, fairness and responsibility. The study reinforces the necessity for more transparent and effective sustainability reporting frameworks to enhance corporate practices and drive progress toward sustainability goals.

Through their published sustainability reports, companies enable corporate governance bodies, capital providers and other stakeholders to assess their corporate sustainability profiles. In such an environment, companies' decision-making and strategy formulation are driven not only by profit generation but also by efforts to achieve sustainability. Therefore, sustainability reporting should be established as a relatively effective tool for conveying information to create a greater impact on stakeholders and attract more shareholders who may take an interest in the social and environmental programmes undertaken by the business. Indeed, within the framework of the Capital Markets Board's Sustainability Principles Compliance Framework, publicly traded companies listed on the Istanbul Stock Exchange (BIST) are

expected to disclose their environmental, social and governance (ESG) activities. In addition to sustainability reports, the compliance report, which is mandated to be disclosed under the ‘comply or explain’ principle, enhances the transparency of company practices and attracts investors. The initial compliance reports were published in 2022, covering data from 2021. According to the most recent Sustainable Development Report published in 2024, Turkey ranks 72nd out of 167 countries worldwide. This further highlights the increasing need for companies to enhance their sustainability reporting and practices to achieve sustainability goals. Additionally, the study revealed that six out of the 22 companies listed in the XTEKS, representing approximately 27%, have published sustainability reports. The absence of legal requirements, the focus on profit and the perceived lack of importance of social and environmental information are the primary factors underlying the limited reporting of social and environmental information in sustainability reports. On the other hand, the sampled companies do not observe full compliance with the GRI standards. It was observed that while businesses make reasonable efforts to disclose their activities, the voluntary nature of reporting prevents a comprehensive reflection of their actual circumstances. In Turkey, it is essential to improve the sustainability reporting system, enhance its quality, examine the published reports and encourage companies to engage in reporting practices.

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