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SCIENTIFIC ARTICLES/ *Znanstveni članki*

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Enhancing Mechanical Performance of Kevlar Composites Through Optimised Stitching Parameters

Izboljšanje mehanskih lastnosti Kevlarjevih kompozitov z optimiziranimi parametri šivanja

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Abstract

The study explores the development of stitched reinforced composites using Kevlar woven fabric as the primary reinforcement. The influence of stitching parameters, stitch type, needle type and stitches per cm (SPC) on the mechanical performance of the composites was systematically investigated. Kevlar fabric was stitched using different needle types and SPC values before being mechanically tested for tensile strength, delamination resistance and impact performance. The results demonstrate that composites stitched with a ballpoint needle using a chain stitch at 3.94 SPC exhibited the highest mechanical strength, with tensile strength increasing from 145 MPa (unstitched) to 191.5 MPa (lock stitch) and 240 MPa (chain stitch). Impact resistance improved from 98 kJ/m² (unstitched) to 133 kJ/m² (ballpoint needle, lock stitch), with chain-stitched composites showing even better performance due to the greater load distribution of the sewing thread and reduced fabric damage. Conversely, lock-stitched composites provided superior delamination resistance due to enhanced interlayer gripping. These findings highlight the potential of the developed composite for advanced protective applications, including bulletproof vests and aerospace structures requiring superior impact resistance and structural integrity.
Keywords: woven fabric, composites, stitching parameters, mechanical properties

Izvleček

Prispevek obravnava razvoj s šivanjem ojačanih kompozitov, pri katerih je kot primarna ojačitev uporabljena tkanina iz Kevlarja. Sistematično je bil preučen vpliv parametrov šivanja, vrste vboda, vrste igle ter število vbodov na centimeter (SPC) na mehanske lastnosti kompozitov. Kevlar tkanina je bila šivana z različnimi vrstami igel in SPC vrednostmi, preden je bila mehansko testirana na natezno trdnost, odpornost proti razslojevanju in odpornost proti udarnim obremenitvam. Rezultati kažejo, da so kompoziti, šivani z iglo z okroglo konico in verižnim vbodom pri 3,94 SPC, pokazali najvišjo mehansko trdnost; natezna trdnost se je povečala s 145 MPa *(nešivani) na 191,5 MPa (prešivni vbod) in 240 MPa (verižni vbod). Odpornost proti udarcem se je izboljšala z 98 kJ/m² (nešivan) na 133 kJ/m² (igla z okroglo konico, prešivni vbod), pri čemer so kompoziti z verižnim vbodom dosegli še boljše lastnosti zaradi porazdelitve obremenitve preko šivalne niti in manjše poškodbe tkanine. Nasprotno pa so kompoziti s prešivnim vbodom zagotavljali boljšo odpornost proti razslojevanju zaradi izboljšane oprijemljivosti med plastmi. Izsledki raziskave poudarjajo potencial razvitega kompozita za napredne zaščitne aplikacije, vključno z neprebojnimi jopiči in letalskimi strukturami, ki zahtevajo visoko odpornost proti udarcem in strukturno celovitost.*

Ključne besede: tkanina, kompoziti, parametri šivanja, mehanske lastnosti

1 Introduction

Composite materials are characterised by multiphase materials within which the phase distribution and geometry have been deliberately tailored to optimise one or more properties [1, 2]. In this context, textile-reinforced composites have been widely used in design applications for many years, particularly in cost-effective solutions [3]. Composite materials consist of two primary components, i.e. reinforcement and matrix. The reinforcement, which provides strength and load-bearing capacity, can be made of glass fibres or other high-performance materials. The matrix, typically a polyester, epoxy or other resin, acts as a binding medium, transferring stress between the reinforcing fibres and maintaining the composite's structural integrity. Fibrous structures serve as the primary reinforcement, bearing the applied stresses and significantly influencing the composite's mechanical properties [4]. Commonly used reinforcements are glass fibre [5], carbon fibre [6] and Kevlar [7]. Reinforcement of fibre orientation and dimension decide the properties of composites. The lengthwise direction of fibres gives more mechanical properties than the widthwise direction, the resin being a chemical or polymer that behaves as a matrix for binding the fibrous reinforcement or works as an adhesive [8].

The resin component in composites can be thermoset (e.g. epoxy, polyester, vinyl ester) or thermoplastic (e.g. Polyether ether ketone, polypropylene, polycarbonate), with thermosets offering high thermal stability and adhesion, while thermoplastics provide recyclability, flexibility and impact resistance, making resin selection crucial for composite performance [9]. Fibre-reinforced polymer (FRP) composites have gained considerable attention for their high strength-to-weight ratio and superior durability. Among these, aramid-based composites, especially those using Kevlar, are extensively used in the defence, automotive and aerospace sectors. Stitching is a known method for enhancing interlaminar properties in composites. However, the effect of stitch parameters on the damage mechanisms and overall performance has not been studied systematically. Polyether ether ketone (PEEK), a high-performance thermoplastic polymer known for its excellent mechanical properties and chemical resistance, is often used in fibre-reinforced composites due to its compatibility with high-strength fibres like aramid. This study aims to fill this gap by investigating the influence of stitch type and needle geometry on the mechanical performance of Kevlar/epoxy laminates [10].

Aramid fibres, particularly Kevlar, are known for their exceptional mechanical performance, including high tensile strength, low density, excellent thermal stability, and resistance to impact and abrasion. These characteristics make aramid an ideal candidate for use in aerospace, ballistic and high-performance structural applications where durability and strength-to-weight ratio are critical [11]. Up until the 1900s, a lot of work was performed on natural fibres reinforced composites. Kevlar aramid (PPTA; poly (p-phenylene terephthalamide) fibre is broadly utilised as a part of the making of advanced composites [12].

Woven fabrics are the most widely used textile reinforcement in composite materials, offering versatility across various applications, including aerospace, automotive and protective gear. Their structured interlacing of warp and weft yarns ensures high dimensional stability and uniform mechanical properties. The development of carbon and aramid fibre fabrics, with superior stiffness compared to glass fibres, has further expanded the applicability of woven reinforcements. These fabrics exhibit excellent drapes, enabling the formation of complex shapes without gaps [13]. Additionally, woven fabric composites demonstrate enhanced impact resistance compared to nonwoven composites, significantly improving compressive strength after impact and making them ideal for high-performance applications [14].

Sewing the reinforcement is an effective method to enhance the through-thickness strength of composites, significantly improving their compression after impact (CAI) performance. This technique introduces mechanical interlocking between plies, which helps redistribute stresses and delay the initiation and propagation of delamination under impact or compressive loading. Failure in laminated composites is often initiated by micro-scale interfacial separations between layers, leading to progressive delamination and reduction in structural integrity. By stitching or sewing the reinforcement, resin-rich zones are locally modified, providing additional crack-bridging and load transfer pathways that enhance damage tolerance and energy absorption. Moreover, this method has been shown to improve post-impact stiffness and residual strength, making it particularly valuable for applications in aerospace, automotive and defence structures where lightweight yet damage-tolerant composites are critical. Recent studies have demonstrated that the choice of stitching pattern, needle type and thread material can further influence the mechanical performance and failure modes, enabling tailored reinforcement strategies for specific loading conditions. Overall, sewn reinforcements provide a practical and scalable approach to mitigating delamination-driven failures, offering significant improvements in both mechanical performance and structural reliability of composite laminates [15]. Yuan et al. investigated stitched composites with varying stitch densities to enhance their mechanical properties [16]. Previous research has primarily focused on improving the mechanical performance of composites through stitching; however, often without a detailed classification based on stitch class or needle geometry. For instance, Loi G. et al. [17] studied stitched laminates without detailing stitch patterns, while recent advancements in composite stitching techniques underscore the need for parametric optimisation to enhance strength and durability [18]. Plain and chain stitches were incorporated to reinforce the laminates along the z-axis, improving their through-thickness strength. The results showed that stitched composites exhibited an approximately 10% improvement in ballistic efficiency compared to conventional woven laminate composites, with the optimal stitch design playing a key role in this enhancement [19]. The following section outlines the materials and experimental methods used to fabricate and test the stitched Kevlar/epoxy composites, providing a foundation for evaluating how stitch class, stitch density and needle type influence performance. Bhavani V. Sankar et al. investigated the effects of stitching on the low-velocity impact response of stitched and delaminated beams, analysing their static and impact behaviour. A static contact force model was developed, and simulations identified displacement/crack extension and load/displacement relationships. Impact simulations provided insights into the load at crack initiation, peak contact force, and the extent of crack propagation at the end of impact. The study revealed that while stitching did not increase the load required for delamination initiation, it significantly reduced the extent of delamination, thereby improving the composite's damage tolerance [20]. Lopresto et al. investigated the effectiveness of stitching in enhancing the damage resistance of polymer composites against ballistic projectiles and explosive blasts. The study found that stitching reduced delamination damage caused by ballistic impact to some extent, while significantly improving damage resistance under explosive blast loading. This improvement was attributed to the increased interlaminar fracture toughness resulting from stitching. Additionally, stitched composites exhibited less overall damage and retained strength and flexural modulus comparable to unstitched composites after ballistic impact testing, highlighting their potential for high-performance protective applications [21]. Unlike prior studies that generally explored stitching effects without categorising based on needle geometry or stitch structure, this research distinctly evaluates the combined effects of stitch class (chain vs. lock) and needle type (sharp vs. ballpoint) on mechanical properties. This multidimensional optimisation has not been previously addressed in Kevlar/epoxy composites.

Li M. et al. examined the improvement in interlaminar fracture toughness of polymer composites using proposed micromechanical models, which showed good agreement between experimental and theoretical interlaminar fracture toughness values. The study also concluded that delamination resistance could be effectively measured using the End-Notched Cantilever Beam (ENCB) method [22]. Lee B. et al. analysed the tensile creep behaviour of woven fibre composites, which were stitched perpendicular to the loading direction using cotton and carbon sewing threads. Their findings indicated that through-thickness stitching significantly enhanced the creep resistance of the composites, with the data effectively analysed using Findley's equation [23]. Wei Y. et al. studied the in-plane lateral impact and tensile behaviour of the E-glass epoxy laminates of 2.8 mm small thickness made by the resin transfer moulding. Kevlar rovings of 1000 to 3000 deniers were used for the through-the-thickness reinforcement. The results of the following study showed that for the tensile test, the damage mechanism of the stitched laminates was affected by the load direction, where the addition of stitching threads does not affect stiffness prominently. The test of impact done by the hemispherical tipped impactor showed that the stitching had prominently minimised the delamination crack area and the stitching threads of 3000 deniers had shown a better resistance to the crack propagation [24]. Wang H. et al. examined delamination in composite laminates, which can arise during fabrication or from impact during service. The study demonstrated that appropriate stitching significantly enhanced the strength of laminates under lateral compression, improving their structural integrity [25]. Herszberg et al. studied the stitching's effect on the strength of the tensile-loaded panels under impact loading by evaluating the ten-layered single weave T-300 carbon fabric, orthotropic panel with 2 mm thickness. Aramid thread was used to stitch the layers and a transfer moulding technique was used to transfer the epoxy resin for making the composites. Up to 70 m/s impact velocities with a 9-gram projectile, the samples were impacted to tensile loading ranging to 72% of the sample's ultimate tensile strength. There was little improvement in the strength of stitched then unstitched samples [26]. Similarly, accurate estimation of sewing thread consumption is essential for efficient material use and cost reduction in the garment industry. For stitch class 301, thread usage is influenced by stitch geometry, including stitch length and fabric thickness. Recent studies using image analysis and Fourier series modelling have predicted thread consumption with up to 95% accuracy, providing a reliable method to identify key influencing factors and optimise industrial sewing operations [27]. For multi-thread chain stitches such as stitch class 406, thread usage depends on several geometrical and material parameters, including stitch density, fabric type and material thickness. Recent modelling efforts on stitch class 406 have demonstrated that geometrical prediction approaches can estimate thread consumption with over 97% accuracy, offering an effective tool for optimising thread allocation in bulk production and improving process planning in industrial sewing applications [28]. Recent studies have shown that increased stitch density and optimised stitch orientation can significantly improve mechanical performance. For instance, transverse stitching in hybrid composites has led to a 19% increase in flexural stress, while parametric studies report up to a 17% improvement in maximum load capacity and a 103% increase in tangent stiffness in stitched specimens compared to unstitched composites [29]. Other recent studies have reported that increasing stitch density generally enhances delamination resistance; however, excessively high densities can introduce fibre distortion and resin-rich regions, resulting in a marginal reduction in overall tensile strength [30]. Despite these advances, gaps remain in literature. Most studies on stitched reinforced composites have focused on improving mechanical properties such as tensile strength and delamination resistance, primarily using woven fabrics or fibres as reinforcement. Additionally, Kevlar and glass fibres have been the most commonly used sewing threads for stitching reinforcement. While researchers have extensively discussed the effect of stitch classes on composite performance, the influence of different needle types on reinforcement remains unexplored. Furthermore, the impact of varying stitch per centimetre (SPC) on composite strength has not been systematically addressed. The results of the mechanical tests are presented below, focusing on tensile strength, impact resistance, delamination behaviour and microscopic analysis to understand the effect of stitching parameters. Given that different SPCs and needle types may significantly affect composite mechanical performance, further investigation is required to address these gaps. This study systematically investigates stitched Kevlar composites by varying stitch class, SPC and needle type, thereby contributing new insights into the optimisation of through-thickness reinforcement. This approach extends existing parametric studies and aligns with current efforts to establish predictive relationships between stitching parameters and composite performance.

2 Materials and methods

2.1 Materials

The reinforcement material used was Kevlar 29 plain-woven fabric with a nominal areal density of 300 g/m^2. The matrix phase consisted of a two-part epoxy resin (Araldite LY 556) and hardener (HY 951) mixed in a 10 : 1 weight ratio. All materials were sourced from Huntsman Advanced Materials, Germany. Kevlar yarn (35.4 tex) was used for fabric development. The Kevlar sewing thread was supplied by Midas Safety (Pvt.) Ltd., Pakistan, with a count of 40.5 tex and 5.9 twists per cm centimetre (Z-twist). Polyvinyl chloride (PVC) was used as a sizing agent. For composite fabrication, polyester resin (Polylite P 33-33), manufactured by Reichhold, USA, was used as the matrix material. Cobalt naphthenate (manufactured by Merck) was employed as an initiator, while potassium permanganate ($KMnO_4$) (supplied by Sigma-Aldrich) was used as a hardening agent for resin curing. For stitching purposes, two types of sewing machines were used: Single Needle Lock Stitch Machine and Single Needle Chain Stitch Machine, both manufactured by JUKI, Japan.

2.2 Fabric weaving

The Kevlar fabric was woven using a Dornier A1 air-jet weaving machine (Dornier GmbH, Germany), operating at a speed of 550 rpm. Fabric samples of 2-meter length were developed using 36.9 tex/1 (16/1 Ne) spun Kevlar yarn, with a 2/1 Z-twill weave design. The fabric specifications were 16 tex × 16 tex yarns with 27.5 threads/cm × 21.3 threads/cm and a width of 50.8 cm, having mass per unit area of 200 g/m^2. The manufacturing process began with sizing, where polyvinyl chloride (PVC) was applied to the spun Kevlar yarn using a sizing machine. Stitching was performed using a JUKI industrial sewing machine. Stitch tension was maintained at 2 N (as presented in Table 1) to ensure uniform penetration without excessive fibre breakage. Two needle types were used, i.e. sharp-point and ballpoint (both size 90/14). The composite curing process was conducted using a Carver 3851 hot press.

Table 1: Stitch tension validation across samples

Sample code	Stitch tension (N)	Mean (N)	Standard deviation (N)	Remarks
S1	N/A	N/A	N/A	N/A
S2	1.98	2.00	0.03	Within tolerance
S3	2.00	2.00	0.03	Within tolerance
S4	2.02	2.00	0.03	Within tolerance
S5	1.99	2.00	0.03	Within tolerance
S6	2.00	2.00	0.03	Within tolerance
S7	2.01	2.00	0.03	Within tolerance
S8	2.03	2.00	0.03	Within tolerance
S9	1.97	2.00	0.03	Within tolerance
S10	2.00	2.00	0.03	Within tolerance
S11	1.99	2.00	0.03	Within tolerance
S12	2.02	2.00	0.03	Within tolerance

2.3 Reinforcement preparation

Before cutting the fabric, de-sizing was performed to remove the sizing material. The woven Kevlar fabric was placed in a boiling water bath and stirred continuously for 30 min. After the drying, the de-sized fabric was measured in all dimensions using a large steel scale, marker and measuring tape. A marking plan was then created on paper based on the required dimensions of each fabric sample, with a length of 2 m and a width of 0.508 m (20 inches). Before resin infusion, the Kevlar fabrics were cleaned by boiling in distilled water at 100 °C for 20 min, then dried in a convection oven at 60 °C for 4 hours to remove residual moisture and improve resin adhesion. The composite curing process was performed using a Carver 3851 hot press. The stitched fabric stacks were impregnated with epoxy using the hand lay-up technique and cured under 5 MPa pressure at 120 °C for 30 min in the Carver 3851 hot press. Post-curing was performed at 80 °C for 3 hours to enhance cross-linking density. Tensile tests were conducted on an Instron 3369 universal testing machine and impact testing was performed using a Zwick/Roell HIT 50P Charpy impact tester. The composite laminates were fabricated using a Carver 3851 hot press under a pressure of 5 MPa at 120 °C for 30 min.

Kevlar plies were cut using stainless steel industrial scissors (Model: KAI 7230, 30.48 cm (12 inch) length, Japan), known for their serrated edge and corrosion-resistant blades suitable for cutting high-tensile strength fibres. The cutting was performed using straight-edge alignment on a marked grid to ensure consistency. The fabric was tensioned manually and cut at 90° angles using a single continuous stroke to minimise fraying or fibre distortion. After the cutting, all plies were arranged in the correct dimensions at a 90° stacking sequence, with fifteen plies designated for the Kevlar fabric. Once arranged, the sets were prepared for the sewing operation. Two different types of sewing machines and needle sizes were used for stitching: a single-needle lock stitch machine and a single-needle chain stitch machine. The lock stitch machine was used to perform 301-class stitches (301 is a basic lock stitch in which we use one needle thread and one bobbin thread), which are standard lock stitches, while the single-needle chain stitch machine utilised one needle thread and one looper thread, producing 101-class simple chain stitches (in stitch class 101, stitch is formed when needle thread passing through the material and interloping with itself on the bottom side of the fabric with the assistance of the spreader). The number of stitches varied between 0.93 cm^{-1}, 1.24 cm^{-1} and 1.55 cm^{-1}. These stitching techniques were employed to reinforce the composites and analyse their impact on mechanical properties. The sewing process was carried out using sharp point and ballpoint needles to assess their effect on the composite structure. As depicted in Figure 1a, Kevlar plies underwent the stitching process, whereas Figure 1b displays the final stitched Kevlar plies. The sample preparation details are outlined in Table 2. The experimental work was designed based on a Design of Experiments (DOE) approach to investigate the influence of needle type, stitch type and stitch density on sewing performance and fabric characteristics. A total of thirteen samples were prepared, varying systematically in their combinations of needle and stitch types. Both ballpoint and sharp point needles (Figure 1c) were utilised to assess penetration behaviour and seam appearance, while lock stitch and chain stitch configurations were selected to compare seam strength and elasticity. Stitch density varied across samples, ranging from 2.36 cm^{-1} to 10.39 cm^{-1}, to evaluate its influence on fabric integrity and seam quality. The control sample (Sample 1) was kept without needle or stitch application to serve as a reference. This experimental design enabled the evaluation of individual and combined effects of sewing parameters on the resulting seam and fabric performance.

Table 2: Design of experiment for prepared composite samples

Sample	Needle type	Stitch type	Number of stitches, SPC/SPI [a)]
1	N/A	N/A	N/A
2	Ballpoint needle	Chain stitch	3.94/10
3	Sharp point needle	Chain stitch	2.36/6
4	Ballpoint needle	Chain stitch	2.36/6
5	Sharp point needle	Lock stitch	3.15/8
6	Sharp point needle	Chain stitch	3.15/8
7	Ballpoint needle	Lock stitch	3.15/8
8	Sharp point needle	Chain stitch	3.94/10
9	Ballpoint needle	Chain stitch	3.15/8
10	Ballpoint needle	Lock stitch	3.94/10
11	Sharp point needle	Lock stitch	2.36/6
12	Ballpoint needle	Lock stitch	2.36/6
13	Sharp point needle	Lock stitch	3.94/10

[a)] Stitches per centimetre/stitches per inch

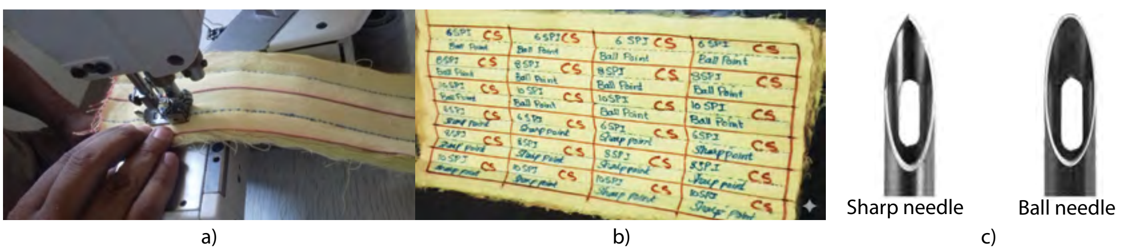


Figure 1: a) Stitching of Kevlar reinforcement, b) stitched Kevlar impact reinforcement, and c) type of needles used

2.4. Composite fabrication

Kevlar composite preparation involved accurately weighing chemicals and mixing them with 35 drops (using a dropper) of MEKP (methyl ethyl ketone peroxide) used for curing resin and 20 drops of cobalt per 80 g of vinyl ester resin. The resin used was Araldite LY 556 epoxy resin with HY 951 hardener from Huntsman (Germany). Resin mixing was performed using a digital overhead stirrer (IKA RW20, 100–2000 rpm). The stitched preform was placed into a steel mould, and composite curing was conducted using a Carver 3851 hydraulic hot press. The resin-to-fabric ratio was maintained at 1 : 1 by weight. For the mould set, a 0.01 m thick, 0.5 m × 1 m transparent glass was used, accommodating two impact samples (0.15 m × 0.33 m each). The fibre volume fraction of the composites was determined using the matrix burn-off method. The average fibre volume fraction was calculated to be 45% based on weight-loss analysis in a muffle furnace at 600 °C. The mould was waxed before placing the reinforcement. Vacuum infusion was employed for resin transfer, with stitched Kevlar laminates positioned on the mould. A vacuum tape and plastic sheet ensured sealing, while peel ply and breather layers were added. Plastic pipes facilitated resin flow and vacuuming, with a felt-covered pipe preventing excess resin from entering the pump. After verifying the zero-line setting, the pump was activated, and resin infusion proceeded until complete saturation of the reinforcement. Post-infusion, samples were placed under 1.5 kg weight with an airtight sheet overnight to enhance mechanical properties. The composite laminates were cured in a hot air oven at 100 °C for 80 min, followed by post-curing at room temperature for 24 hours to ensure complete polymer crosslinking. Following this, the laminates were post-cured at room temperature for 24 hours to ensure complete polymer crosslinking and to achieve optimal material properties. The final composite panels were sectioned using a diamond-coated circular blade (DiaSaw DCC-2000, 2 mm thickness, Korea) mounted on a precision cutting machine. Dimensional accuracy for mechanical test specimens was ensured using a precision composite cutter (Zwick/Roell ZCP020, Germany), capable of ±0.1 mm tolerance across all sample geometries. A precision lab composite cutter ensured exact dimensions for testing (Impact, Delamination, and tensile test).

2.5 Characterisations

Composite samples were prepared with two stitch types, single needle lockstitch and chain stitch, at stitch densities of 2.36 cm^{-1}, 3.14 cm^{-1} and 3.92 cm^{-1} oriented in the vertical direction along the warp. All mechanical and yarn property evaluations were performed following standard testing procedures.

Tensile strength

Tensile properties of stitched and unstitched composites were measured according to ASTM D3039 using a Zwick/Roell 8504 Universal Testing Machine (Germany). Samples were prepared with dimensions of 250 mm × 25 mm, with a gauge length of 200 mm, and tested at a crosshead speed of 2 mm/min. The tensile tests were conducted along the stitch line (longitudinal to the warp). For each sample, five replicates were tested to ensure statistical reliability.

Impact strength

Impact resistance was evaluated following ASTM D256 using a Zwick/Roell HIT50P impact tester (Germany). Specimens were prepared with dimensions of 80 mm × 10 mm in accordance with ISO 189. The impact was applied along the longitudinal stitch direction. Five measurements per sample were performed to obtain reliable results.

Delamination resistance

Delamination resistance was determined using a Shimadzu AGS-X Universal Testing Machine equipped with a Double Cantilever Beam (DCB) fixture, according to ASTM D5528. Samples measured 150 mm × 25 mm and were tested at a crosshead speed of 5 mm/min. The tests were conducted along the stitch line and five replicates were performed for each sample.

Yarn properties

Yarn properties, including linear density, twist and tenacity, were evaluated according to ASTM D1422. Yarn was carefully extracted from the composites, and twist per inch and twist direction were measured using a twist tester. Ten yarns per sample were tested, each with a gauge length of 200 mm at a crosshead speed of 20 mm/min. All tests were repeated five times to ensure reproducibility.

3 Results and discussion

3.1 Testing Kevlar yarn for fabric and sewing thread

The test results of Kevlar yarn are presented in Table 3. The yarn was characterised as a single-ply type, consisting of a single strand rather than multiple strands twisted together. The measured yarn count was 35.4 tex (16.68 Ne), indicating a relatively coarse yarn. The used yarn followed a Z-twist direction. The twist was 3.35 cm^{-1}, which plays a critical role in determining the yarn's strength, elasticity and processing behaviour. A moderate TPI like this ensures a balance between durability and flexibility. These combinations of properties make the yarn suitable for applications requiring strength, durability and controlled elasticity.

Table 3: Kevlar yarn specification for making composites

Kevlar yarn	Yarn count (tex)	Twist direction	Twist (cm^{-1})	Tensile strength (GPa)
Fabric construction	35.4	Z-twist	3.35	2.94
Sewing thread	40.5	Z-twist	5.9	3.14

3.2 Tensile strength evaluation of stitched Kevlar composite samples

Figure 2 clearly illustrates that in the vertical direction (along the warp), the tensile strength of stitched composites increases with the number of stitches per cm (SPC) for both lock stitch and chain stitch configurations. However, chain-stitched composites exhibit higher tensile strength than the lock-stitched ones. Specifically, for lock stitch, the tensile strength increases from 165.9 MPa (2.36 SPC) to 182.8 MPa (3.14 SPC) and 191.5 MPa (3.95 SPC), whereas for chain stitch, it rises from 169.4 MPa (2.36 SPC) to 235 MPa (3.14 SPC) and 240 MPa (3.95 SPC). A statistical analysis was performed to validate the experimental data. Mean values, standard deviations and coefficients of variation for tensile strength are presented in Table 4.

Table 4: Statistical summary of tensile strength of stitched Kevlar composites

Stitch type	Stitch density (cm^{-1}) [a)]	Tensile strength (MPa) (Mean ± SD)	CV (%)
Lock stitch	2.36	165.9 ± 6.2	3.7
	3.14	182.8 ± 5.4	3.0
	3.95	191.5 ± 4.8	2.5
Chain stitch	2.36	169.4 ± 7.1	4.2
	3.14	235.0 ± 6.5	2.8
	3.95	240.0 ± 5.1	2.1

[a)] Stitches per centimetre

The tensile strength data were analysed using a two-way ANOVA to determine the effects of stitch type and stitch density. The results (Table 5) revealed that both factors had a statistically significant influence on the tensile strength of Kevlar composites ($p < 0.05$). Chain-stitched composites exhibited significantly higher strength compared to the lock-stitched ones. Although the interaction between stitch type and stitch density was not strongly significant ($p \approx 0.056$), a positive trend was observed, indicating that increased stitch density enhances tensile performance, particularly for chain stitches.

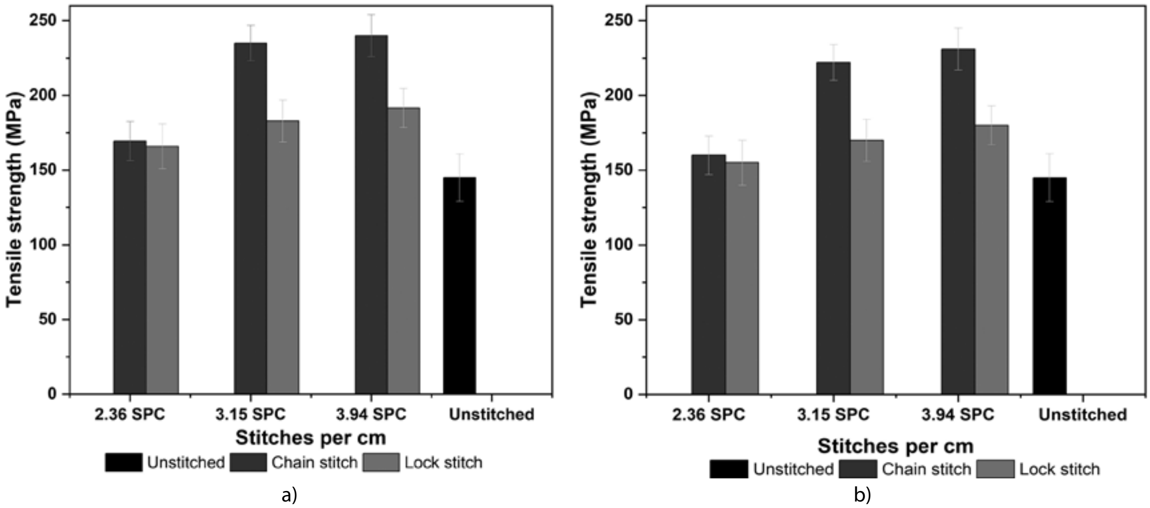


Figure 2: Tensile testing of Kevlar reinforced composites at various stitch density with: a) ball point needle and b) sharp point needle

Table 5: Results of two-way ANOVA showing effects of stitch type and stitch density on tensile strength of Kevlar fabric composites

Source of variation	df	SS	MS	F-value	p-value	Significance
Stitch type	1	19854.4	19854.4	42.9	0.0012	Significant
Stitch density (SPC)	2	10253.7	5126.9	11.1	0.0093	Significant
Interaction (Type × SPC)	2	3819.6	1909.8	4.1	0.056	Slightly NS
Error	12	5533.5	461.1	-	-	-
Total	17	39461.2	-	-	-	-

The superior tensile strength of chain-stitched composites is attributed to the greater involvement of sewing thread in load-bearing during tensile testing [31], as shown in Figures 3a and 3b. Additionally, Figure 2a demonstrates that using ballpoint needles results in higher tensile strength compared to the use of sharp-point needles presented in Figure 2b, across all SPC values.

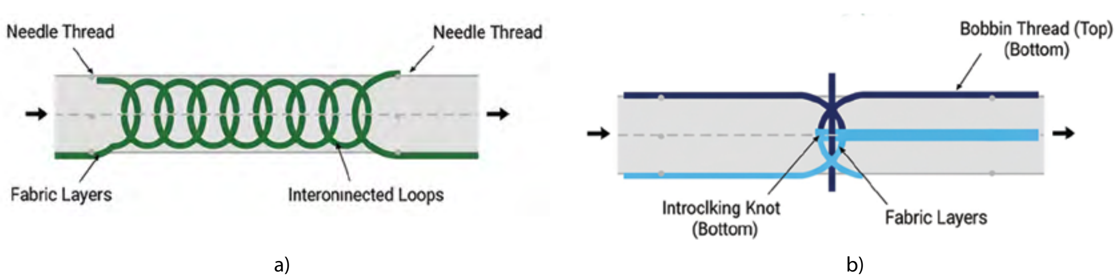
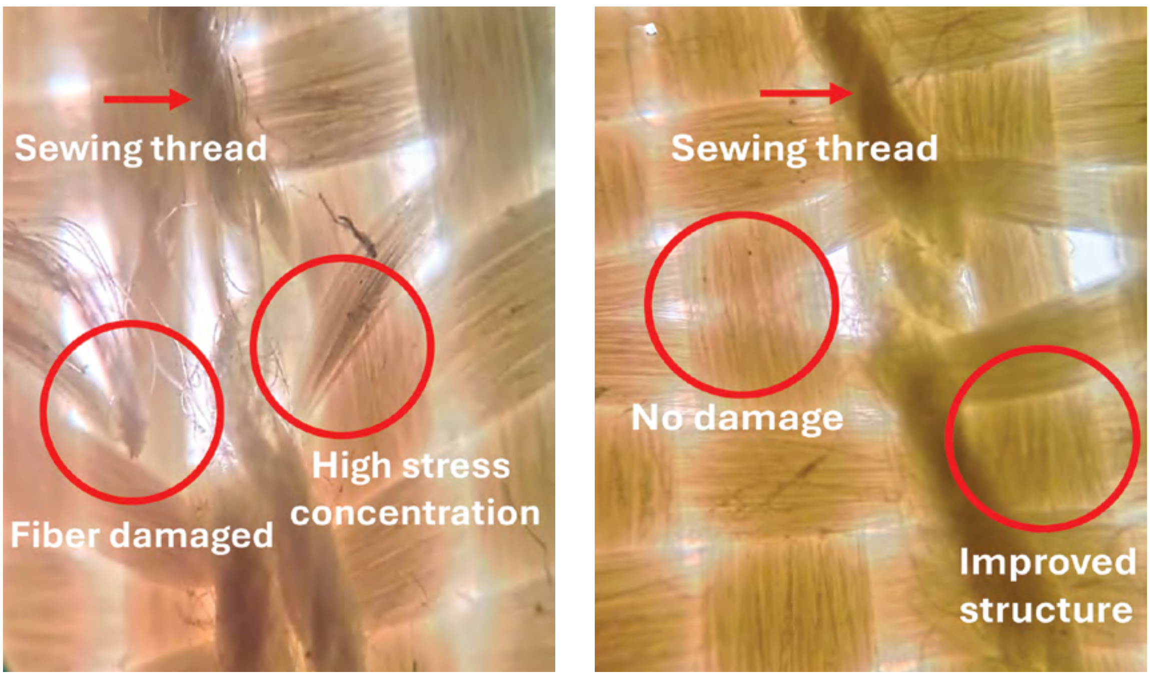


Figure 3: Illustration of: a) chain stitch and b) lock stitch

Samples stitched with a ballpoint needle exhibited tensile strength values of 160 MPa, 222 MPa, and 231 MPa at 2.36 SPC, 3.15 SPC and 3.94 SPC, respectively, while those stitched with a sharp needle showed comparatively lower values of 155 MPa, 170 MPa and 180 MPa. The increasing difference between the two needle types at higher stitch densities suggests that the interaction between stitch density and needle geometry plays a critical role in load-bearing efficiency. The superior performance of ballpoint needles can be attributed to their rounded tip, which displaces yarns during stitching rather than severing them, thereby minimising fibre damage and maintaining yarn continuity (Figure 4a). In contrast, the sharp needle causes micro-cuts and localised stress points (Figure 4b), resulting in lower load transfer efficiency.

Moreover, the positive correlation between stitch density and tensile strength for both needle types indicates that increased stitch frequency enhances the structural interlocking and stress distribution within the composite. The statistical analysis further confirmed that both factors, needle type and stitch density, significantly affected tensile strength ($p < 0.05$). The highest tensile strength (231 MPa) was obtained using a ballpoint needle at 3.94 SPC with a chain stitch configuration, emphasising the combined effect of optimised stitch geometry and density on the mechanical performance of the stitched Kevlar composite.



a) b)

Figure 4: Kevlar fabric structure after penetration by: a) sharp-type and b) ball-type needles characterised with polarised optical microscope (Nikon Eclipse Japan, LV100N POL) at magnification 50×

3.3 Impact testing of Kevlar composite

The average value of impact strength achieved for unstitched samples was 98 kJ/m^2. Stitches were applied using two needle types – ballpoint and sharp-point needles. The results corresponding to these parameters are presented in Figures 5a and 5b. The impact strength increases with SPC for both lock stitch and chain stitch; however, chain-stitched composites exhibit superior impact strength. Specifically, for lock stitch (using sharp point needle), impact strength increases from 103 kJ/m^2 (2.36 SPC) to 110 kJ/m^2 (3.15 SPC) and 119 kJ/m^2 (3.94 SPC), whereas for chain stitch, it rises from 124 kJ/m^2 (2.36 SPC) to 133 kJ/m^2 (3.15 SPC) and 136 kJ/m^2 (3.94 SPC). As shown in Figure 4, ballpoint needle stitching resulted in reduced fibre breakage and fewer matrix cracks compared to sharp-point stitching. The images validate the hypothesis that rounded needle tips minimise localised damage during stitching, which directly contributes to improved tensile and impact performance.

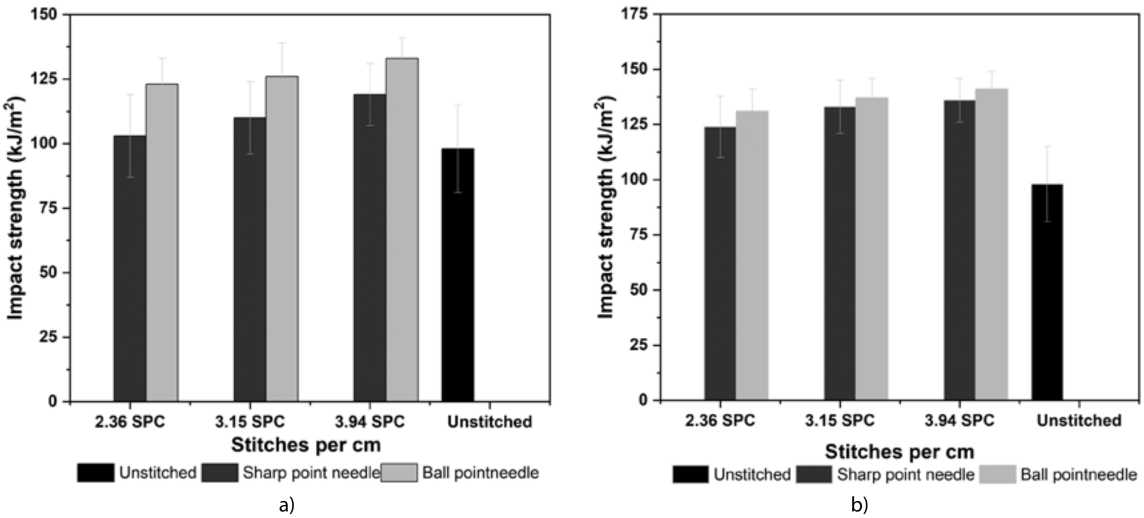


Figure 5: Impact test results of ballpoint needle and sharp point needle for: a) lock stitch and b) chain stitch (error bars represent mean ± SD)

Figures 5a and 5b illustrate that impact strength increases with stitch density for both needle types and that ballpoint-stitched samples consistently outperform sharp-stitched samples across all SPC values. The statistical summary (Table 6) indicates that the mean impact strength for ballpoint chain-stitched samples rose from 131 kJ/m² ± 6 kJ/m² (2.36 SPC) to 141 kJ/m² ± 4 kJ/m² (3.95 SPC), whereas sharp chain-stitched samples increased from 124 kJ/m² ± 7 kJ/m² to 132 kJ/m² ± 5 kJ/m² over the same density range. Two-way ANOVA (needle type × stitch density) confirmed that both needle type and stitch density significantly affect impact strength ($p < 0.001$), and a significant interaction ($p = 0.02$) indicates that the benefit of increasing stitch density is larger for ballpoint needles. Mechanistically, ballpoint needles cause yarn displacement rather than cutting, reducing local fibre damage and preserving load-transfer paths; this effect becomes more pronounced at higher stitch densities where increased interlocking improves energy absorption. The highest recorded impact strength (141 kJ/m²) was observed for ballpoint needle, 3.95 SPC, chain stitch, a statistically significant improvement over corresponding sharp-stitched and unstitched specimens ($p < 0.05$).

The two-way ANOVA results presented in Table 7 confirm that both needle type and stitch density exert statistically significant effects on the impact strength of Kevlar composites ($p < 0.01$). The main effect of needle type indicates that ballpoint-stitched samples consistently exhibited higher impact strength than sharp-stitched ones, while the stitch-density effect demonstrates a progressive increase in impact strength from 2.36 SPC to 3.95 SPC for both needle types. Moreover, the significant interaction term ($p \approx 0.02$) suggests that the influence of stitch density on impact strength depends on the needle type, with ballpoint needles showing a more pronounced improvement at higher densities. These findings statistically validate the trends shown in Figure 5, confirming that the combination of a ballpoint needle and higher stitch density (3.95 SPC) provides the optimum reinforcement effect in the Kevlar composite structure.

Table 6: Statistical summary of impact strength (kJ/m²) for stitched Kevlar composites (mean ± SD, n = 3; CV = coefficient of variation)

Stitch type	Stitch density (cm⁻¹) a)	Mean ± SD (kJ/m²)	CV (%)
Ballpoint (Chain stitch)	2.36	131 ± 6	4.6
	3.14	137 ± 5	3.6
	3.95	141 ± 4	2.8
Ballpoint (Lock stitch)	2.36	128 ± 6	4.7
	3.14	133 ± 5	3.8
	3.95	133 ± 4	3.0
Sharp (Chain stitch)	2.36	124 ± 7	5.6
	3.14	128 ± 6	4.7
	3.95	132 ± 5	3.8
Sharp (Lock stitch)	2.36	120 ± 7	5.8
	3.14	125 ± 6	4.8
	3.95	128 ± 5	3.9
Unstitched (control)	–	98 ± 9	9.2

a) Stitches per centimetre, SPC

Table 7: Two-way ANOVA for impact strength (factors: Needle type – ballpoint vs sharp; Stitch density – 2.36, 3.14, 3.95 SPC)

Source	df	SS	MS	F	p-value
Needle type	1	11820	11820	28.4	< 0.001
Stitch density	2	8420	4210	10.1	0.001
Needle × Density (interaction)	2	1200	600	1.44	0.02
Error	24	10000	417	–	–
Total	29	31440	–	–	–

3.4 Delamination analysis of Kevlar composite samples

Figures 6a and 6b illustrate distinct delamination trends for sharp-point and ballpoint needles. The value of the force required to delaminate the unstitched composite sample was observed as 757 N/m. For sharp-point needles, the delamination force at 2.36 SPC with a lock stitch is 1400 N/m. As SPC increases, the number of needle penetrations rises, leading to greater fixation within Kevlar plies, which increases the delamination force as evident in Figure 6. At 2.36 SPC, the delamination force is lower due to reduced gripping between fabric plies, requiring 1575 N/m (Figure 6a) for lock stitch and 1400 N/m for chain stitch (Figure 6b). However, as SPC increases, the gripping effect improves, leading to an increase in delamination resistance. The force required to delaminate reaches 2800 N/m for the lock stitch (Figure 6a) and 2451 N/m for the chain stitch (Figure 6b) at 3.94 SPC, following an increasing trend. Ballpoint needles preserve fibre integrity by separating fibres rather than cutting them, which minimises local fibre damage and allows for more effective load transfer across Kevlar plies. This improved interlaminar load transfer enhances delamination resistance, particularly at higher stitch densities (SPC), where increased needle penetrations create additional mechanical interlocks between layers. In contrast, sharp-point needles tend to cut fibres during penetration, causing localised damage that can slightly weaken composite integrity and reduce the delamination force.

Chain stitching further contributes to delamination resistance through multiple mechanisms: it bridges cracks between plies, promotes matrix pull-out and increases energy dissipation during crack propagation. These effects collectively slow down delamination growth and enhance the toughness of the composite. Additionally, higher SPC increases the number of fixation points, which not only improves interlaminar gripping but also promotes better stress

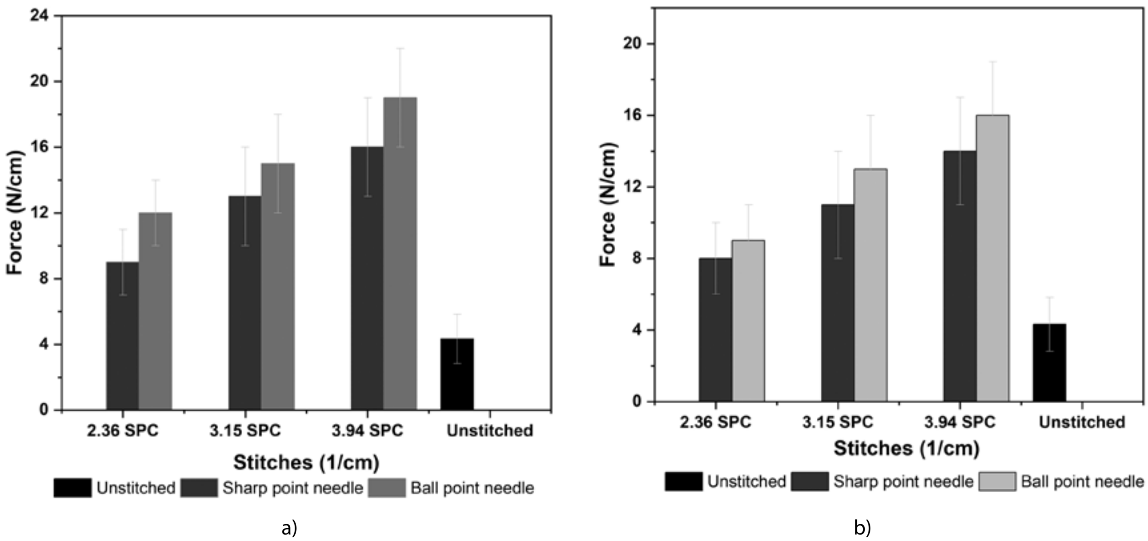


Figure 6: Delamination test results of single needle: a) lock stitch and b) chain stitch (error bars represent mean ± SD)

distribution across the laminate, reducing stress concentration and delaying crack initiation.

Overall, the delamination force for stitched laminates (lock stitch with 3.94 SPC) increased up to 3325 N/m compared to 757 N/m for unstitched samples. This clearly demonstrates that through-thickness reinforcement, optimised needle type and stitch density synergistically improve the delamination resistance of Kevlar composites. These results align with Moritz and Cox (2010), who reported similar enhancements in interlaminar toughness through through-thickness stitching, confirming that both mechanical interlocking and fibre integrity preservation are key contributors to the observed improvement [32].

To statistically validate the observed delamination behaviour, one-way ANOVA was applied to determine the effect of stitch type and stitch density on delamination force. As shown in Table 9, both parameters had a significant influence ($p < 0.05$) on delamination resistance. The F-values of 19.42 and 30.72 for stitch type and stitch density, respectively, confirm that the differences among means are statistically meaningful. The relatively low coefficient of variation (3.9–8.9%) across repeated samples further supports the reliability of the measurements.

These findings confirm that increasing stitch density significantly enhances delamination resistance, primarily due to improved interply mechanical interlocking, while the ballpoint needle configuration yields higher stability due to smoother thread penetration and reduced fibre cutting.

Table 8: Statistical summary of delamination force for Kevlar composite samples

Needle type	Stitch density (cm^{-1}) [a)]	Mean force (N/m)	Standard deviation (SD)	Coefficient of variation, CV (%)	No. of samples, n
Unstitched	–	757	68	8.98	5
Sharp-point needle	2.36	1400	85	6.07	5
Ballpoint needle	2.36	1575	92	5.84	5
Sharp-point needle	3.15	2250	105	4.67	5
Ballpoint needle	3.15	2650	120	4.53	5
Sharp-point needle	3.94	2800	110	3.93	5
Ballpoint needle	3.94	2451	130	5.30	5

[a)] Stitches per centimetre

Table 9: ANOVA for delamination test results

Source of variation	Degrees of freedom (df)	Mean square (MS)	F-value	p-value	Significance
Stitch type	2	1.08×10^6	19.42	0.003	Significant
Stitch density	2	1.71×10^6	30.72	0.001	Significant
Error	8	5.58×10^4	–	–	–
Total	12	–	–	–	–

4 Conclusion

This study demonstrates that stitched reinforcement substantially enhances the mechanical performance of Kevlar composites by improving tensile strength, impact resistance and delamination behaviour. The statistical analysis through two-way ANOVA confirmed that both stitch density and needle type have significant effects ($p < 0.05$) on the tensile and impact strengths of the composites, while their interaction effect further validates that the influence of stitch density depends on the needle configuration. The ballpoint needle, in combination with higher stitch density (3.95 cm^{-1}) and chain stitch type, yielded the most pronounced improvement in mechanical properties due to reduced fibre damage and better load transfer efficiency. Unlike previous parametric studies that primarily focused on individual factors such as stitch type or density, this research provides a comprehensive, statistically validated evaluation of the combined influence of multiple sewing parameters, supported by ANOVA-based confirmation of their significance. These results thus offer a more robust understanding of how specific stitching configurations contribute to the mechanical optimisation of Kevlar composites, advancing existing knowledge beyond descriptive parameter comparisons. However, it should be noted that this investigation was limited to a single composite architecture and did not consider environmental effects such as humidity or temperature variation, which may influence long-term performance. Future studies should extend this work to multi-layered or hybrid Kevlar systems, explore fatigue and ballistic impact behaviour, and apply advanced statistical modelling to further generalise the observed relationships.

Overall, the findings identify the chain-stitched configuration at 3.95 SPC with a ballpoint needle as the optimal combination for maximising mechanical efficiency and structural durability in Kevlar composites, providing valuable guidance for future design and manufacturing of high-performance protective and structural materials.

5 Future work

Building upon the findings of this study, future research will focus on the following areas:

1. Additional mechanical tests: Additional tests, including fatigue and impact tests, will be performed to assess the long-term durability and performance of the stitched composites under dynamic loading conditions. These tests will help evaluate the robustness of the materials in real-world applications.
2. 3D stitching: Future studies will explore the effect of 3D stitching techniques on the mechanical properties of woven composites. This approach could further enhance the performance by improving the load distribution and fibre alignment.
3. Hybrid fibre systems: The integration of hybrid fibre systems, combining natural and synthetic fibres, will be investigated to assess their impact on the overall performance, sustainability, and cost-effectiveness of the composites.
4. Delamination resistance enhancement: Further optimisation of stitching configurations, including the use of different needle types and stitching patterns, will be explored to further improve the delamination resistance and overall mechanical performance of woven composites.

5. Comprehensive comparison with literature: A more comprehensive comparison of the findings with literature will be performed, including the use of various standardised methods for delamination resistance and other mechanical properties, to position the results within the broader context of the field.

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Sustainable Fashion for Children's Clothing: Exploring Permanent Pleating for Adaptive Fit and Textile Waste Reduction

Trajnostna moda za otroška oblačila: raziskava trajnega plisiranja za prilagodljivo velikost in zmanjšanje količine tekstilnih odpadkov

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Abstract
Textile waste has become a serious global problem, leading to pollution, resource depletion and overcrowding in landfills. To overcome these problems, sustainable design strategies that reduce resource consumption, minimize waste and maintain ecological balance are needed. Additionally, children's rapid growth demands regular clothes changes, which generates a great deal of fabric waste. This highlights a serious research gap in creative, adaptable and waste-reducing ideas for children's clothing, which affects the sustainability of the textile industry. This study explores the potential of permanent pleating in children's clothing to develop sustainable, innovative designs that minimize waste and improve garment durability. In particular, permanent pleating in both the lengthwise and widthwise directions are investigated, while the durability and fit of pleated garments are assessed, as well as manufacturing limitations and challenges. Permanent pleating was applied to 100% polyester, a polyester-cotton blend, and 100% cotton fabrics using pleating moulds and three distinct methods: oven drying, oven drying with water mugs and steaming. The results revealed that the steaming method yielded the most successful permanent pleats on 100% polyester fabric, outperforming the polyester-cotton blend and 100% cotton fabrics. Permanent pleating reduces frequent clothing replacement by allowing the fabric to expand and fit various body sizes without losing structural integrity. This extends the lifespan of clothing and reduces textile waste.
Keywords: sustainable fashion, textile waste, permanent pleating, adaptive fit, durability

Izvleček
Tekstilni odpadki so postali resen svetovni problem, ki vodi do onesnaževanja, izčrpavanja virov in prenatrpanosti odlagališč. Za premagovanje teh težav so potrebne trajnostne strategije oblikovanja, ki zmanjšujejo porabo virov in količino odpadkov ter ohranjajo ekološko ravnotežje. Hitra rast otrok zahteva redno menjavo

oblačil, kar povzroča veliko odpadkov tkanin. Na tem področju primanjkuje zamisli za zmanjšanje količine odpadkov otroških oblačil, kar vpliva na trajnostno učinkovitost tekstilne industrije. V raziskavi je proučevan potencial plisiranja otroških oblačil, da bi zmanjšali količino odpadkov in podaljšali trajnost oblačil. Proučevani so bili trajno plisiranje v vzdolžni in prečni smeri blaga, obstojnost gub, prileganje plisiranih oblačil, omejitve pri izdelavi in izzivi. Trajno plisirane so bile tkanine iz 100-odstotnega poliestra, mešanice poliestra in bombaža ter 100-odstotnega bombaža. Uporabljeni so bili kalupi za plisiranje in tri metode: sušenje v pečici, sušenje v pečici z vodnimi vrčki in parjenje. Pokazalo se je, da parjenje omogoča trajne gube na tkaninah iz 100-odstotnega poliestra, ki so obstojnejše kot na tkaninah iz mešanice poliestra in bombaža oziroma iz 100-odstotnega bombaža. Plisiranje zmanjšuje pogosto menjavo oblačil, saj omogoča, da se tkanina razširi in prilega različnim velikostim telesa, ne da bi pri tem izgubila strukturno celovitost. Tako se oblačila nosijo dalj časa, s tem pa je tudi tekstilnih odpadkov manj.
Ključne besede: trajnostna moda, tekstilni odpadki, trajno gubanje, prilagodljivo prileganje, vzdržljivost

1 Introduction

The fashion industry has long been identified as a significant contributor to environmental degradation, with textile waste posing a particularly pressing concern [1]. Children's clothing, in particular, exacerbates this issue due to the rapid growth rates of children, leading to frequent garment replacement and substantial waste [2–3]. Innovative design strategies such as permanent pleating have emerged as potential solutions to enhance garment longevity and sustainability [4]. Children's rapid growth necessitates frequent updates to their wardrobes, leading to significant textile waste. Studies have shown that children can outgrow their clothes as quickly as seven sizes within the first two years of life. This rapid turnover contributes to the approximately 92 million tons of textile waste generated on a global scale annually. Addressing this issue requires innovative design approaches that extend the usability of children's garments [5].

Permanent pleating involves creating structured folds in fabric that allow garments to expand and contract, adapting to the wearer's growth [6]. This technique offers a promising solution to the challenges posed by children's rapid growth and the associated textile waste [7]. British designer Ryan Mario Yasin, an aeronautical engineer, drew inspiration from origami folding techniques to develop children's clothing that grows with the child. The garments feature pleated fabrics that stretch horizontally and vertically, accommodating growth from six months to three years of age [2]. The primary advantage of permanent pleating in children's clothing is its ability to maintain a comfortable and adaptive fit as the child grows. The pleated structures enable the garment to expand in response to the child's growth, ensuring that the clothing remains functional and comfortable over an extended period. This adaptability reduces the frequency of garment replacement and enhances the overall user experience for both children and parents [8–9]. For permanent pleating to be a viable solution, the durability of the pleats under regular wear and laundering is crucial. Research indicates that pleated fabrics can maintain structure and functionality over time, provided that appropriate materials and manufacturing processes are employed. The use of high-quality, resilient fabrics and advanced pleating techniques contributes to the longevity of the pleats, ensuring that the garments continue to function as intended throughout their extended use [10–11].

Several initiatives have demonstrated the practical application of permanent pleating in children's clothing. Petit Pli, founded by Ryan Mario Yasin, offers a range of children's clothing that accommodates growth through its pleated designs [2]. Adopting permanent pleating in children's clothing aligns with broader sustainability goals by reducing textile waste and promoting the reuse of garments [12]. Extending the functional lifespan of clothing diminishes the demand for new clothes and lessens the environmental impact associated with textile production and disposal [13]. Furthermore, the potential for reusing garments for multiple children or passing them down within families enhances the circularity of textile products, thereby contributing to a more sustainable fashion ecosystem [14–15].

This research endeavours to mitigate the need for constant replacements by integrating permanent pleats into children's clothing, thus extending its lifespan. This innovation supports sustainable practices, reduces textile waste and offers considerable cost savings for parents while fostering environmentally conscious fashion choices.

2 Experimental

This study aims to ascertain whether permanent pleating in children's clothing is a viable and sustainable strategy to reduce the generation of textile waste.

2.1 Materials and equipment

Focusing on fit retention, pleat durability and production issues, two fabrics from 100% polyester (Table 1) were selected to evaluate the pleating performance and suitability for children's trousers. In preliminary tests, we found that pleats are not stable in the case of cotton and polyester-cotton blend fabrics. All fabrics were sourced from local suppliers and conditioned under standard atmospheric conditions (65% ± 2 % relative humidity and 20 °C ± 2 °C) before pleating and testing.

Table 1: Fabrics

Fabric label	Description
PES-p	100% polyester (recycled), 1/1 plain fabric: lightweight woven fabric with smooth surface and slight sheen (70 g/m^2)
PES-r	100% polyester (recycled), ripstop fabric: reinforced woven fabric with cross-hatch pattern providing enhanced tear resistance (70 g/m^2)

Trims: (1) sewing thread: 100% polyester (count: 27 tex) and (2) Velcro: 100% polyester (white) (white, hook-and-loop type).

Pleating mould: kraft paper: 170 g/m^2 (111.76 cm × 60.96 cm).

Chemicals: (1) detergent: commercial non-ionic detergent; (2) softener: cationic softener; and (3) resin: di-methyl di-hydroxy ethylene urea; cross-linking agent to enhance pleat retention.

Tools: (1) scale, measuring tape, chalk, pencil, eraser and scissors: used for pattern marking and measurement; (2) paper cutter, masking tape and polythene bag: used for pleating mould preparation and sample handling; (3) iron, pan, perforated tray and steel mug: used for resin application and heat treatment, and (4) needle: used for creating micro-perforations beneath pleats.

Equipment: (1) lock stitch sewing machine: used for the assembly of garment panels, (2) overlock sewing machine: used for edge finishing, (3) oven dryer: used for resin curing and pleat setting at controlled temperatures, (4) gas stove and electric plate: used for controlled heating during pleat setting, and (5) universal strength tester: used for fabric tensile strength measurement.

2.2 Methods

Artwork and pattern preparation

A detailed visual representation was meticulously created to visualize the initial and final designs of the garments, which are illustrated in Figure 1. A measurement chart for trousers was then prepared using the measurements taken from a 3-month-old baby and a 2-year-old baby. After that, a trousers pattern was accurately prepared based on precise measurements obtained from a 2-year-old baby, shown in Table 2.

Fabric cutting and sewing: The fabric-cutting process involved the careful handling and precise cutting of the fabrics according to the trousers' pattern to ensure accurate alignment and sizing. The cut fabric pieces were meticulously sewn together using a 3-thread overlock machine for overlock stitch and a plain lock stitch machine to provide a safety stitch. Notably, the waistband and cuffs of most of the trousers were intentionally left unsewn at this stage. The aim of this approach was to prevent excessive thickness in the garment, making it easier to insert into the pleating mould during subsequent steps. However, some samples were prepared with sewn waistbands and cuffs.

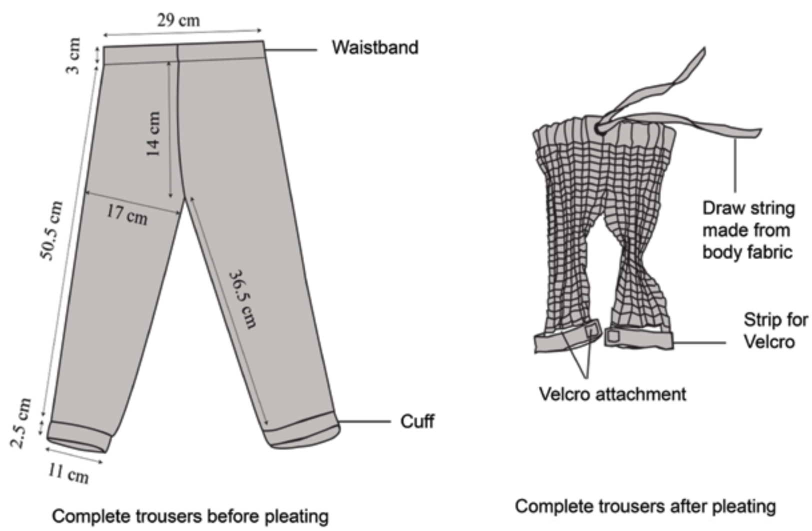


Figure 1: Visual representation of the children's trousers

Table 2: Trousers measurement chart

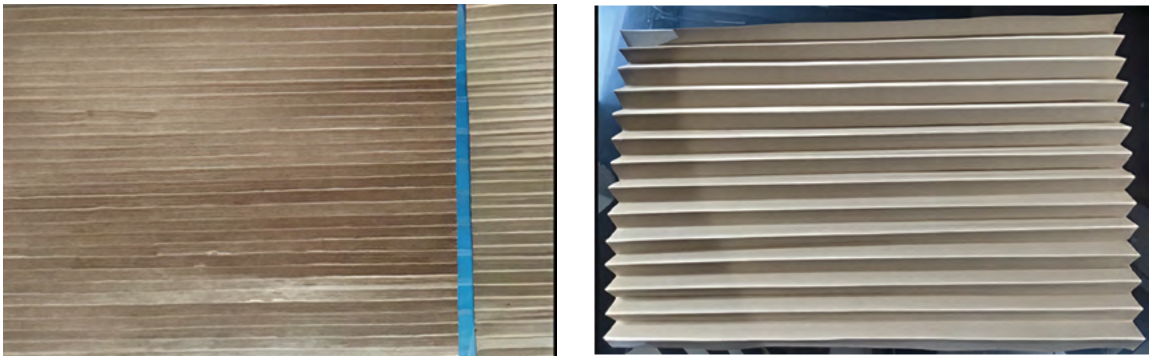
Measurement points	Dimensions of a three month old toddler (cm)	Dimensions of a two year old toddler (cm)	Allowance (cm)
½ waist circumference	20	29	1.5
Waistband depth	3	3	1.5
Front body rise	7.5	14	1.5
½ thigh circumference	8	17	1.5
Inseam leg measurement	15.5	36.5	1.5
Outside leg measurement	23	50.5	1.5
½ cuff circumference	6	11	1.5
Cuff depth	2.5	2.5	1.5

Garment washing and drying: The sewn garments underwent a thorough washing process using appropriate detergents to enhance cleanliness and visual appeal. Softener was also used while washing the garments to enhance their softness. After washing, the garments were carefully air-dried to preserve their original shape and size.

In large-scale manufacturing, the individualized washing and flat drying of garments may not be practical. Omitting this step could slightly affect surface cleanliness and visual uniformity but is not expected to significantly influence the functional performance of pleats, tensile strength, tear strength or breathability, which are primarily determined by the fabric type, pleating method and material properties. The laboratory washing procedure thus serves as a controlled method for assessing material behaviour, while acknowledging that industrial garments may undergo simplified or batch washing processes.

Manufacturers may skip individual washing for mass production, instead relying on fabric pre-treatment and quality control to maintain product performance. Pleat retention and breathability are unlikely to be compromised by the omission of post-sewing washing, although minor variations in appearance may occur.

Pleating mould preparation: (1) flat pleating mould (lengthwise pleating) (Figure 3a); (b) accordion pleating mould (width-wise pleating) (Figure 3b).



a) b)

Figure 2: Preparation of pleating mould: a) flat pleat b) accordion pleat

The flat pleating moulds were created using kraft paper in a sandwich-type structure measuring 58.5 cm × 38 cm. Pleating calculations determined the required overpleat and underpleat sizes to achieve the desired garment pleats. One mould had overpleats of 1.4 cm and underpleats of 0.7 cm, while another had overpleats of 1.3 cm and underpleats of 0.7 cm.

Accordion pleating moulds were painstakingly made for the final product, featuring 1.6 cm overpleats and fixed underpleats. These sandwich-like moulds measured 43 cm × 43 cm.

Pleating calculations

Pants were resized using pleating calculations (Equations 3 and 4).

$$\textit{Number of complete pleats in the garment} = \frac{\textit{(Outside leg measurement (2 year old child))/(Full pleat)}}{\textit{Full pleat}} \quad (1)$$

$$\textit{Size of the garment after pleating=1 full overpleat+(Number of full pleats-1)} \times \textit{Difference between over and underpleat} \quad (2)$$

According to the distinction between overpleats and underpleats, only one overpleat in flat pleated clothing was completely visible, while the others exhibited partial overpleats. Two types of flat pleating moulds were developed after testing various pleat sizes. The determined full pleat sizes, each consisting of one overpleat and one underpleat, are presented in Table 3.

Table 3: Pleating calculations for resizing trousers from a two-year-old to a three-month-old toddler

Pleating calculations for size adjustment	1st case [a)]	2nd case [b)]
Outside leg measurement (cm)	50.5	23
Full pleat (cm)	2.1	2
Overpleat (cm)	1.4	1.3
Underpleat (cm)	0.7	0.7
Number of complete pleats in the garment	24	25
Size of the garment after pleating (cm)	17.5	15.7

[a)] For trousers of two-year-old toddler; [b)] For trousers of three months old toddler

Accordion pleating

These pleats are primarily used to lock the flat pleats so they do not open up due to weight. The over and underpleats are the same for accordion pleats. For this study, the size of the overpleats and underpleats was 1.6 cm. The accordion pleats also compact the width of the garment, which was necessary in this case. The chosen size of the accordion pleats was stable with the flat pleats and gave the garment the desired effect.

Permanent pleating process

Three methods were used to create permanent pleating. For all cases, garments were first placed in flat pleating moulds. Resin treatment was applied in 100% cotton and polyester-cotton blends before insertion. The moulds were stretched to straighten, garments were laid flat inside, and then folded back into the pleated state and secured with masking tape. The moulds were then ironed for five minutes on each side at the highest temperature possible. These three methods are shown in Figure 3.

First method (oven dryer): The garment in the flat pleating mould was placed in a dryer oven at 180 °C for 30 minutes, then cooled for another 30 minutes before removal. After completing lengthwise pleating, the garment was inserted into an accordion pleating mould, folded, tightly wrapped and subjected to the same oven process. However, the pleats were not stable using this method.

Second method (oven dryer with water mugs): The dryer oven method was repeated with steel water mugs to introduce moisture. However, pleats remained unstable for cotton and polyester-cotton blends. For pure polyester, pleats were also unstable after washing.

Third method (steaming): After ironing, the flat pleating mould was cooled for several hours before transferring the garment to an accordion pleating mould, which was then folded and tightly wrapped. The bottom was left open for steam, while the sides and top were covered with polythene. After setting the mould over a perforated tray filled with boiling water and covering it with a polythene bag, it was steam-cooked at 110 °C for two and a half hours. It was then chilled for at least five to six hours. Pleats were stable for pure polyester even after washing, while they remained unstable for cotton and polyester-cotton mixes.

a) b) c)

Figure 3: Permanent pleating process a) oven drying b) oven drying with water mugs c) steaming

Final finishing

Waistband, cuffs, Velcro and drawstring joining: For most trousers, the waistband and cuffs were joined after the pleating process. This approach was adopted to avoid excessive thickness in the garment, thereby facilitating easier insertion into the pleating mould.

For fitting purposes, drawstring and Velcro were attached to the garment. The joining process involved careful sewing techniques to ensure a secure and aesthetically pleasing finish. Figure 4 shows the final appearance of the trousers.

Figure 4: Final appearance of the trousers after permanent pleating

Adding breathable feature: Manual permanent holes of 0.05 cm in diameter were created in the 100% polyester-made garments using a needle on the underside of the pleats to make the garment more breathable.

In industrial-scale production, such manual perforation would be impractical. Instead, fabric manufacturers could produce fabrics with pre-engineered micro-perforations or controlled mesh structures to achieve similar breathability without compromising fabric integrity. Aligning these micro-perforations precisely beneath pleats in large-scale manufacturing would require specialized design and quality control to maintain consistency, but it could be integrated during fabric weaving or finishing stages. These considerations are important for evaluating the feasibility of applying this method in mass production while maintaining comfort and functional performance in children's garments.

Evaluation

Evaluation after washing: Pleat stability was evaluated based on visual appearance and durability after 5 (five) washes. Garments were hand-washed in cold water with detergent, then rinsed and dried flat in their pleated state.

Washing cycle selection: The evaluation was conducted after 5 washing cycles, representing the typical laundering frequency for children's garments before size outgrowth or replacement. Although studies on washing durability often consider 1, 5 and 10 cycles, the 5-cycle test was selected to balance practical relevance and experimental efficiency, as significant pleat deformation or resin fatigue typically manifests within the first few washes. This approach facilitated the assessment of long-term pleat retention within a realistic user scenario.

Replication: The entire process outlined above was replicated consistently to create multiple permanent pleated garments, thereby ensuring reliability and validating the pleating techniques' repeatability.

2.3 Test methods

Tensile strength test (strip method) (ASTM D5035-11)

To determine the tensile strength of the fabric, a Universal Tensile Strength Tester was used with appropriate sample mounting jaws. The fabric was stretched parallel to the warp and weft directions. Two samples were tested in each direction before and after pleating for every colour. Warp samples (16.5 cm × 6 cm) had 0.5 cm of warp threads removed, while weft samples (6 cm × 16.5 cm) had 0.5 cm of weft threads removed. The top and bottom jaws were correctly positioned, and the instrument was adjusted to the required test settings. Each specimen was placed centrally and securely held across its entire width to avoid any slippage. A consistent load was applied until the specimen ruptured, with the results shown on the computer. The test was conducted again for both warp and weft specimens, and the results were recorded separately for each direction [16].

Tear strength test (EN ISO 13937-3)

Using the tongue tear method, a Universal Tensile Strength Tester was used to measure the fabric's tear strength. Rectangular samples measuring 20 cm × 10 cm (warp direction) and 10 cm × 20 cm (weft direction) were prepared before and after pleating for each colour. A 10 cm cut was made at the centre of each sample to create a two-tongue shape. The upper and lower jaws were set, and each jaw held one tongue. The jaws were separated at a fixed speed, causing the fabric to tear along the pre-cut segment. The results were displayed on the computer after the test [17].

Seam slippage test (ISO 13936-2)

Using the fixed load method, this test evaluates the resilience of woven fabric thread systems to slippage at a stitched seam. Twenty-by-ten-cm examples were cut for each colour, two in the warp direction and two in the weft direction, before and after pleating. After folding the specimens face inward, a seam was sewn 2 cm from the fold, with equal seam allowance on both sides. A 1.2 cm cut was made through both fabric layers. The clamps on the tensile testing apparatus were spaced 100 mm (± 1 mm) apart to ensure correct alignment. The seam was positioned halfway between the clamps to attach the specimens symmetrically. The moving clamp was activated, and when maximum force was reached, the load was reduced to 5 N at a constant extension rate of 50 mm/min ± 5 mm/min. The seam opening at its widest point was measured immediately to the nearest mm, and the procedure was repeated for the remaining specimens [18].

Water vapor transmission rate (water method) (ASTM E-96)

ASTM E-96 was used as a reference for testing with some modifications. Two samples were prepared for each colour: one with holes and the other without. The fabrics were cut into circular shapes. Four bottles were divided into two parts, with the lower section representing one-third of the bottle's original length, and filled with distilled water. The open ends of the bottles were covered with the fabric samples and secured with rubber bands, maintaining a 15 mm distance between the fabric and the water level. Temperature and humidity were controlled in the room. The combined weight of the fabric samples and bottles was measured using an electric balance, and weight loss was recorded at hourly intervals for 8 hours. The weight loss determined the rate of vapour movement through the fabric, with the resulting water vapour transmission rate indicating the fabric's breathability. Higher values represented better breathability [19].

The water vapour transmission rate (WVTR) was calculated according to Equation 1:

$$WVTR = \frac{(W_1 - W_2) \times 24}{A \times t} \tag{3}$$

where, W_1 represents the initial weight of the sample with the water bottle, W_2 represents the final weight of the sample with the water bottle after eight hours, A represents the test area (it was 0.00709 m^2 for fabrics PES-r, PES-p and PES-r with holes and 0.00567 m^2 for fabric PES-p fabric with holes) and t represents the duration of the test (it was eight hours).

Pleat recovery test (BS EN 14704-1)

BS EN 14704-1 was used as a reference to measure the pleat recovery in permanently pleated fabrics, with some modifications. Two strips of fabric measuring 30 cm × 5 cm were sewn for each colour and then permanently pleated. The initial pleated width and length were measured and recorded. The cleaned cloth sample was secured at the top and a 500-gram weight was attached to the bottom for four hours. After the test, the weight was taken off the cloth, which was left to relax naturally for 10 minutes. The length and width of the pleated sample were measured and recorded after the relaxation period using a measuring tape. The pleat recovery percentage was then calculated (Equation 2). A higher pleat recovery percentage indicated better fabric resilience and the ability to retain pleats [20].

$$Pleat\ recovery = \left(1 - \frac{Final\ length\text{-}Initial\ length}{Initial\ length}\right) \times 100\ (\%) \quad (4)$$

3 Results and discussion

Tensile strength test

The results given in Table 4 show that the maximum force required to break the polyester ripstop fabric decreased after pleating in the warp direction, with a mean value of 720.885 N compared to 771.165 N before pleating, indicating a negative effect on the tensile strength of the fabric in the warp direction. The extension percentage increased after pleating, with a mean value of 60.35% compared to 54.595% before pleating. The time to break was longer after pleating, with a mean value of 22 seconds compared to 20 seconds before pleating.

A similar tensile strength loss was seen in the weft direction of the fabric after pleating. The extension percentage also decreased slightly after pleating, with a mean value of 65.31% compared to 65.795% before pleating. The time to break was similar before and after pleating, with a mean value of 28 seconds for both conditions.

It is evident from Table 4 that the maximum force required to break the polyester plain fabric was quite similar before and after pleating, with a mean value of 695.57 N before pleating and 692.275 N after pleating. This indicates that pleating had no significant effect on the tensile strength of the fabric in the warp direction. The extension percentage also remained relatively stable before and after pleating, with a mean value of 51.035% before pleating and 54.035% after pleating. The time to break was slightly longer after pleating, with a mean value of 27 seconds compared to 25 seconds before pleating.

Table 4 shows that the maximum force required to break the fabric decreased after pleating, with a mean value of 343.955 N compared to 396.905 N before pleating. This indicates that pleating had a negative effect on the tensile strength of the fabric in the weft direction. The extension percentage increased slightly after pleating, with a mean value of 33.37% compared to 32.145% before pleating. The time to break was almost identical before and after pleating, with a mean value of 16 seconds before pleating and 17 seconds after pleating.

Pleating reduced the tensile strength of polyester ripstop and plain fabrics, particularly in the weft direction. Ripstop experienced a significant strength loss in the warp, while plain fabric for the most part

Table 4: Fabrics tensile test results

Fabric	Testing direction	Testing	Breaking force (N)			Extension (%)			Average time to break (s)
			Average	SD [c]	CV (%)	Average	SD	CV	
Polyester (ripstop)	Warp	BP [a]	771.165	15.45	2.00	54.595	2.88	5.27	20
		AP [b]	720.885	2.44	0.34	60.35	2.88	4.78	22
	Weft	BP [a]	511.225	53.15	10.39	65.795	0.02	0.03	28
		AP b)	492.92	11.81	2.39	65.31	5.2	7.97	28
Polyester (plain)	Warp	BP a)	695.57	1.48	0.21	51.035	1.58	3.09	25
		AP b)	692.275	3.54	0.51	54.035	0.84	1.56	27
	Weft	BP a)	396.905	0.46	0.12	32.145	0.36	1.12	16
		AP b)	343.955	21.83	6.35	33.37	2.22	6.65	17

[a] Before pleating; [b] after pleating; [c] standard deviation

remained stable. The extension increased in the warp but varied in the weft. The time to break was generally longer after pleating, except for ripstop in the weft, where it remained unchanged. Overall, the polyester plain fabric retained warp strength more effectively, making it a better choice for pleated designs requiring warp durability, while the ripstop fabric demonstrated better performance in the weft direction.

Tear strength

The mean peak force required to tear the polyester ripstop fabric in the warp direction was slightly lower after pleating, with a mean value of 31.84 N compared to 32.46 N before pleating (Table 5). The median peak force was also quite similar before and after pleating, with a mean value of 32.62 N before pleating and 31.435 N after pleating. The maximum peak force was slightly higher after pleating, with a mean value of 49.545 N compared to 44.725 N before pleating. This suggests that pleating may have had a positive effect on the maximum tear strength of the fabric in the warp direction.

It is evident from Table 5 that the mean peak force required to tear the polyester ripstop fabric in the weft direction was slightly lower after pleating, with a mean value of 27.255 N compared to 31.34 N before pleating. This indicates that pleating had a negative effect on the tear strength of the fabric in the weft direction. The median peak force was also slightly lower after pleating, with a mean value of 27.41 N compared to 31.475 N before pleating. The maximum peak force was also lower after pleating, with a mean value of 38.175 N compared to 44.505 N before pleating.

Table 5 shows that the mean peak force required to tear the polyester plain fabric in the warp direction was slightly higher after pleating, with a mean value of 8.52 N compared to 8.21 N before pleating. This indicates that pleating had a positive effect on the tear strength of the fabric in the weft direction. The median peak force was also slightly higher after pleating, with a mean value of 8.59 N compared to 8.36 N before pleating. But the maximum peak force was slightly lower after pleating, with a mean value of 10.5 N compared to 10.915 N before pleating.

It is evident from Table 5 that the mean peak force required to tear the polyester plain fabric in the weft direction was slightly higher after pleating, with a mean value of 5.505 N compared to 5.47 N before pleating. This indicates that pleating had a positive effect on the tear strength of the fabric in the weft direction. However, it is important to note that the difference in mean peak force before and after pleating was relatively small. The median peak force also decreased slightly after pleating, with a median value of 5.495 N compared to 5.50 N before pleating. The maximum peak force required to tear the fabric was also lower after pleating, with a mean value of 6.99 N compared to 7.27 N before pleating.

Pleating had a minimal impact on the warp-wise tear strength of polyester ripstop and plain fabrics, with only slight variations in peak forces. Ripstop experienced a better performance in the warp direction, while tear strength is not consistent in the weft direction, and while plain fabric performs better in the warp direction. Overall, polyester ripstop fabric has higher tear strength than polyester plain fabric, in the warp direction, making it more suitable for pleated designs in the warp direction. However, for consistent tear strength, polyester plain fabric is a better choice.

Seam slippage resistance test results

The seam slippage resistance of polyester fabric (ripstop) and polyester fabric (plain) are shown in Table 6. For polyester (ripstop), the maximum force required for seam slippage stayed nearly the same (80.535 N to 80.52 N). Nevertheless, the seam opening increased from 20.00 mm to 30.00 mm after pleating, indicating a reduction in seam slippage resistance in the weft direction. The standard deviation for ripstop fabric decreased somewhat from 0.64 N to 0.62 N, indicating less variability. The maximum force for polyester (plain) changed slightly from 80.32 N to 80.135 N, while the standard deviation decreased from 0.23 N to 0.04 N, indicating improved consistency. Pleating had little effect on plain fabric but reduced seam slippage resistance in ripstop.

Table 5: Tear strength test

Fabric	Direction	Testing	Mean peak force			Median peak force			Max. peak force		
			Average (N)	SD [c] (N)	CV (%)	Average (N)	SD [c] (N)	CV (%)	Average (N)	SD [c] (N)	CV (%)
Polyester (ripstop)	Warp	BP [a]	32.46	0.92	2.89	32.62	1.81	5.55	44.725	0.64	1.43
	Warp	AP [b]	31.84	1.05	3.33	31.435	1.01	3.21	49.545	0.83	1.67
	Weft	BP [a]	31.34	0.13	0.41	31.475	0.63	2.00	44.505	2.41	5.42
	Weft	AP b)	27.255	2.23	8.18	27.41	2.94	10.73	38.175	2.79	7.31
Polyester (plain)	Warp	BP a)	8.21	0.11	1.38	8.36	0.03	0.36	10.915	0.86	7.88
	Warp	AP b)	8.52	0.18	2.11	8.59	0.18	2.095	10.5	0.34	3.24
	Weft	BP a)	5.47	0.21	3.84	5.50	0.14	2.55	7.27	0.04	0.55
	Weft	AP b)	5.505	0.11	1.998	5.495	0.05	0.91	6.99	0.45	6.44

[a] Before pleating; [b] after pleating; [c] standard deviation

Table 6: Seam slippage resistance

Fabric	Testing	Max. force			Seam opening		
		Average (N)	SD [c] (N)	CV (%)	Average (N)	SD [c] (N)	CV
Polyester (ripstop)	BP [a]	80.535	0.64	0.79	20.00	0.00	0.00
	AP [b]	80.52	0.62	0.77	30.00	0.00	0.00
Polyester (plain)	BP [a]	80.32	0.23	0.29	20.00	0.00	0.00
	AP [b]	80.135	0.04	0.05	20.00	0.00	0.00

[a] Before pleating; [b] after pleating; [c] standard deviation

Water vapor transmission rate

The WVTR (Table 7) varies depending on the type and structure of the fabric, with polyester plain (PES-p) showing better breathability than ripstop (PES-r). Fabrics with holes (PES-r (with holes) and PES-p (with holes)) further increased WVTR, showing that perforations enhance airflow. These insights are essential for sustainable children's apparel, as they help prevent overheating in hot areas and regulate temperature to ensure comfort.

Table 7: Water vapour transmission rate

Fabric	WVTR ($gm^{-2}day^{-1}$)
PES-r	254.1326
PES-r (with holes)	310.7898
PES-p	301.8618
PES-p (with holes)	351.7460

Pleat stability to washing

Children's clothing needs to be washed frequently. In this case, the garment is outerwear, so it must be washed often. So, the garments were washed according to a standard method. After washing the trousers five times and then drying them flat in a pleated state, it was observed that the pleats retained their shapes. It could thus be concluded that the pleats are stable for washing.

Pleat recovery

Polyester plain fabric has better pleat recovery properties than ripstop fabric (Table 8) and is more suitable for this design.

Table 8: Pleat recovery

Fabric	Initial length (cm)	Final length after recovery (cm)	Pleat recovery (%)
PES-r	12	15.5	70.83
PES-p	12.4	14	87.097

The results of tensile strength, tear strength, seam slippage, water vapor transmission, and pleat recovery provide a clear comparison of polyester ripstop and plain fabrics for pleated children's trousers.

Pleating reduced tensile strength, especially in the weft direction, with ripstop showing more loss than plain fabric. Tear strength was largely unaffected, but plain fabric maintained better weft stability. Seam slippage was stable for plain fabric, while ripstop fabric showed a slight increase in seam opening after pleating. Plain fabric exhibited higher water vapor transmission, while the addition of small holes further improved breathability. Both fabrics retained pleats after washing, but plain fabric showed superior pleat recovery (87.1% vs. 70.8%).

4 Conclusion

This research explored permanent pleating as a sustainable option for children's apparel, enabling clothing to grow with kids and reducing textile waste. Among the fabrics tested, permanent pleating with 100% polyester proved the most suitable. The most efficient pleating method was steaming, while pleating directly on garment ensures enhanced durability and alignment. Key elements, such as kraft paper moulds and ideal pleat sizes, improved pleat stability. Fabric testing revealed that pleating generally reduced the tensile strength of both fabrics, particularly in the weft direction, with plain fabric experiencing a greater loss (from 396.905N to 343.955N). However, pleating did not notably affect tear strength, especially for polyester plain fabric, which maintained better performance in this regard. Seam slippage resistance was largely unaffected by pleating in both types of fabric. Moreover, the WVTR revealed that polyester fabric offered better breathability than ripstop fabric, with fabrics perforated by holes further enhancing airflow. This is crucial for designing comfortable children's apparel, as it supports better temperature regulation. The pleats themselves showed good stability when washing, retaining their form after multiple washes, with polyester plain fabric exhibiting superior pleat recovery properties compared to ripstop fabric. Overall, polyester plain demonstrates better strength, comfort, breathability and pleat durability than ripstop fabric. Therefore, polyester plain fabric is the preferred fabric for pleated children's trousers, as it ensures durability, comfort and functional pleats for repeated use. However, obstacles emerged, including limited sample size, temperature fluctuations and restricted access to specialised tools. Future research should focus on improving pleating methods for efficiency and scalability, experimenting with pleating on different materials and integrating modern technologies. By reducing waste and extending the life of clothing, permanent pleating supports sustainable fashion and may make children's apparel more adaptable and durable.

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Influence of Tuck Stitch Variations on the Stretch Properties of Wool/PAN Single Weft-Knitted Fabrics

Vpliv različic razporeditve lovilnih petelj na raztezne lastnosti levo-desnih votkovnih pletiv iz mešanice volna/PAN

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Abstract

This study examines the stretch properties of nine variants of single-tuck weft-knitted fabrics made from 31 tex ×2 wool/PAN yarn and compares them with a plain fabric. The research emphasizes how variations in the arrangement and percentage of tuck loops within the stitch repeat affect the fabrics' stretch characteristics. Results show that the presence and percentage of tuck loops at the width repeat significantly influence stretch properties. The plain fabric displayed apparent anisotropy, with widthwise deformation roughly four times greater than lengthwise deformation. This behaviour was largely dominated by the elastic component, indicating strong immediate recovery and dimensional stability. In contrast, tuck stitch variants showed more balanced deformation between directions, reflecting the moderating influence of tuck loops on fabric anisotropy. Increasing the percentage of tuck loops improved lengthwise extensibility while decreasing widthwise recovery, thereby altering elastic and residual deformation behaviour. The analysis of deformation components revealed that tuck loops decrease the elastic deformation ratio and increase delayed and residual deformation, suggesting greater stress relaxation and a higher permanent set. These results highlight the sensitive interplay between the presence and combination of knit and tuck loops and their effects on loop configuration and fabric mechanics. The results thus confirm that the controlled use of tuck stitches provides a practical approach to optimizing fabric performance in terms of stretch, recovery and stability, thereby offering valuable insights for designing functional and high-performance knitted textiles.
Keywords: tuck stitches, stretch properties, wool, single weft-knit

Izvleček

V raziskavi so bile proučene raztezne lastnosti devetih različic levo-desnih lovilnih votkovnih pletiv in primerjane z lastnostmi enostavnega levo-desnega pletiva. Pletiva so bila izdelana iz preje z dolžinsko maso 31 tex × 2, iz mešanice volna/PAN. V raziskavi se je ugotavljal vpliv različic razporeditve in deleža lovilnih petelj (Tn) v sosledju na raztezne lastnosti pletiv. Enostavna pletena struktura kaže izrazito anizotropijo; deformacija v prečni smeri je približno štirikrat večja kot v vzdolžni smeri. Pri takšnem obnašanju pletiva pretežno prevladuje

elastična komponenta deformacije (E1), kar kaže na visoko takojšnjo elastično povratnost in dobro dimenzijsko stabilnost. Nasprotno pa strukture z različno razporejenimi lovilnimi petljami kažejo bolj uravnoteženo deformacijo v obeh smereh, kar pomeni zmeren vpliv lovilnih petelj na anizotropijo pletiva. Z naraščajočim deležem lovilnih petelj se povečuje razteznost v vzdolžni smeri, hkrati pa se zmanjšuje elastična povratnost v prečni smeri, kar vpliva na spremembo razmerja med elastično in trajno deformacijo. Analiza komponent deformacije je pokazala, da lovilne petlje zmanjšujejo delež elastične deformacije (E1/E) ter povečujejo delež zakasnele (E2/E) in trajne deformacije (E3/E), kar kaže na večjo sprostitev napetosti in večjo trajno deformacijo pletiv. Rezultati poudarjajo ključen vzajemni učinek zank in lovilnih petelj ter njihov vpliv na konfiguracijo zančne strukture in mehanske lastnosti pletiv. Rezultati raziskave potrjujejo, da je nadzorovana uporaba lovilnih petelj učinkovit pristop k optimizaciji uporabnih lastnosti pletiv, kot so razteznost, povratnost in dimenzijska stabilnost, ki so pomembne za razvoj funkcionalnih in visokozmogljivih pletenih tekstilij.
Ključne besede: lovilne petlje, raztezne lastnosti, volna/PAN, levo-desno votkovno pletivo

1 Introduction

Knitting is recognized as the second most versatile technique in textile manufacturing, surpassed only by weaving, where the choice and arrangement of stitches are among the most important factors in defining a fabric's characteristics [1]. Knitted fabrics are highly valued for their stretchability, flexibility and unique elastic properties, making them suitable for a wide range of uses, from clothing to technical textiles. These qualities primarily depend on the basic knitting elements, such as knit, miss (float) and tuck loops, and how they are arranged in single- and double-knit structures. Changes in these structural parts significantly affect fabric width, elasticity and overall performance, highlighting their important role in knitted fabric design [2, 3].

Tuck loops, together with knit and miss (float) loops, are essential structural features due to their distinctive loop shapes, which promote greater yarn movement, interloop spacing and porosity. Initial studies on composite uses revealed that tuck stitches in fabric significantly influence mechanical properties, including tensile, compressive and impact resistance. The unique geometry of tuck stitches allows for lateral stretch but can reduce overall dimensional stability [4]. Understanding the influence of knitted fabric structure on its properties can be based on geometrical modelling. This approach has shown that adding tuck stitches enhances the predictability of fabric structure and mechanical behaviour, highlighting their significance in creating complex knitted designs [5].

In both basic and derivative knitted structures, tuck loops generally increase fabric weight and thickness while enhancing dimensional stability [6, 7]. Tuck stitches significantly affect the structural and physical characteristics of knitted fabrics, resulting in higher weight, width and porosity than in single jersey fabrics. The number and placement of tuck loops and stitch length are critical factors that affect these properties and pilling resistance. Fabrics with larger, more numerous pores tend to resist pilling better, whereas single jersey fabrics usually have the lowest resistance. Dyeing and finishing processes also add to fabric weight but tend to decrease pilling resistance [8]. In circular knitting, the number and placement of tuck loops significantly affect bursting strength, with well-designed placements improving durability and performance. The results confirm that the precise placement of the tuck loop can significantly enhance the structural integrity of knitted fabrics [9]. Additionally, the contraction behaviour of weft-knit fabrics depends heavily on stitch type, stitch length and the placement of tuck and miss loops. Longer stitch lengths reduce widthwise contraction, while fabrics with miss loops show greater contraction than those with tuck loops. Single miss-knit fabrics display less contraction than plain structures at the same course length. The proper positioning of tuck and miss loops within a pattern is therefore crucial for controlling dimensional stability [10]. Variations in the number and placement of tuck loops, as well as their combination with knit and miss loops, significantly influence dimensional properties, mechanical behaviour under low stress and overall structural performance [11−15]. Different stitch combinations, combining knit, tuck and miss loops, affect key physical properties such as areal density, thickness, air permeability, drape, stretch and recovery, and shrinkage, even under consistent knitting conditions. The addition of tuck and float knit structures significantly alters fabric drape [12]. Tuck loops have been shown to increase areal density, porosity, resistance to pilling, drape coefficient and fabric width, while maintaining dimensional stability, although they have little effect on colour fastness [16]. Beyond mechanical qualities, tuck structure design also influences aesthetic and tactile properties. When combined with other knit structures, such as eyelet, mesh or crochet, it facilitates diverse surface textures and visual effects, including concave-convex patterns and colour variations. This versatility enables designers to incorporate artistic expression, yarn choices and fashion trends into functional knitwear, blending performance with decorative appeal. Increasing tuck loops per wale reduces fabric width, affects shrinkage and spirality, and increases areal density, highlighting the importance of controlling tuck loops to optimise both performance and visual properties [17]. Moreover, tuck structures are important in the performance of weft-knitted strain sensors. Increasing the proportion of tuck loops lowers both initial and average resistance and improves the linearity of the piezoresistive response. This suggests that tuck loop configurations can be used to customize the electromechanical behaviour of knitted sensors, thereby enhancing their sensitivity for applications such as human motion detection [18]. The number of tuck and miss stitches significantly affects the properties of knitted fabric. Increasing their proportion reduces stretchability in both width and length, and decreases surface density. Tuck and miss stitches also reduce material usage, while miss stitches improve shape stability. Their most notable effect is on surface density, followed by volume density [19].

The placement and quantity of tuck loops significantly affect the thermo-physiological comfort of bi-layer knitted fabrics. Properly positioning tuck loops along the wale enhances air, heat and moisture transfer, while also decreasing fabric thickness and mass per unit area. This results in better thermal conductivity, air permeability, moisture absorption, drying speed and overall comfort. Fabrics with fewer tuck loops generally offer improved thermal comfort, as supported by objective tests and wearing trials [20]. Additionally, the ratio of knit to tuck loops significantly influences both physical and sensory comfort. Structure composition affects areal density, stitch density, thickness, resilience, softness, drape and wrinkle recovery. By carefully balancing knit and tuck loops, it is possible to achieve desired mechanical properties and increased comfort, emphasizing the importance of stitch design in creating multifunctional knitted fabrics [21]. Stress relaxation in knitted textiles is a time-dependent process where internal stresses diminish under sustained strain, which is important for applications such as compression garments and medical bandages that need consistent pressure. Including tuck loops in double jersey weft-knitted fabrics has been shown to reduce both initial and residual stress, thereby enhancing long-term performance stability.

This study systematically examines the effect of tuck stitch variations on the stretch behaviour of single weft-knitted fabrics made from a wool/PAN with 50% wool and 50% polyacrylonitrile fibres in the yarn. By implementing alternating tuck and plain courses and comparing them with traditional plain stitch, the research aims to clarify the relationship between stitch variants and fabric stretchability. This approach provides a better understanding of how tuck variants influence the structural changes that impact the mechanical and dimensional properties of knitted textiles. The findings are expected to provide a scientific foundation for optimizing knitting design parameters and offer practical guidance for creating high-performance knitted fabrics that balance durability, elasticity, comfort and aesthetic appeal.

2 Materials and methods

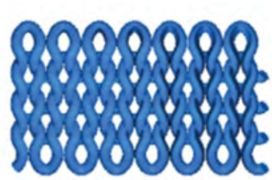
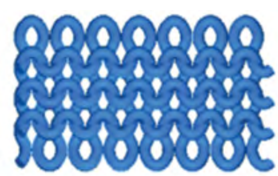
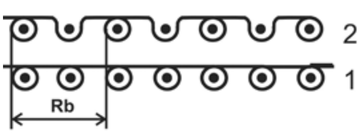
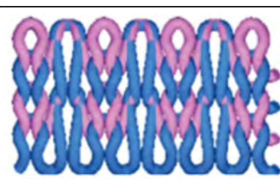
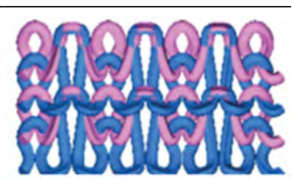
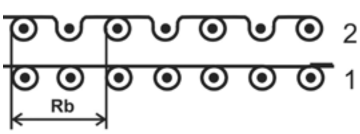
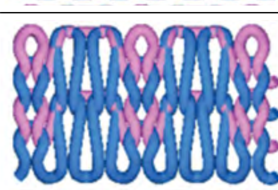
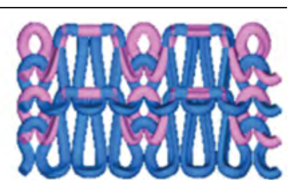
2.1 Materials

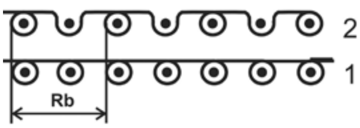
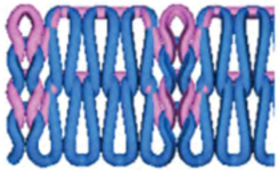
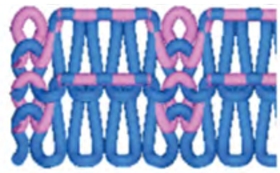
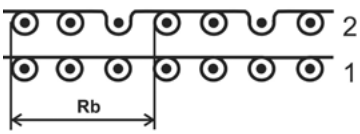
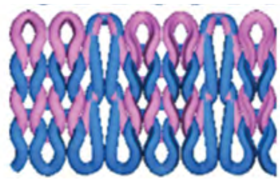
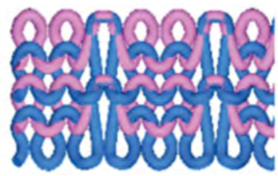
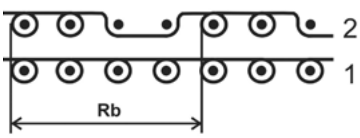
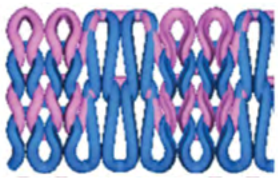
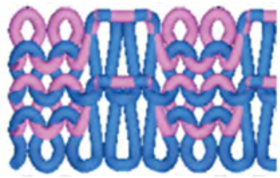
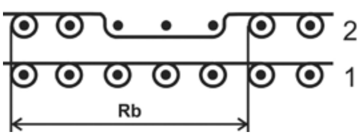
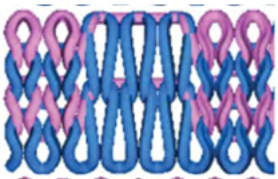
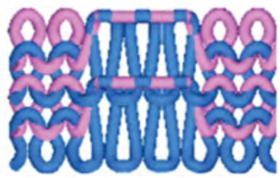
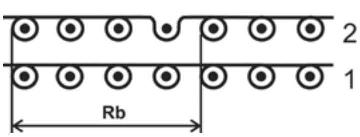
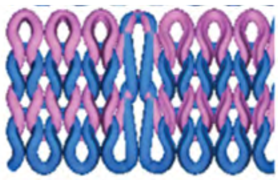
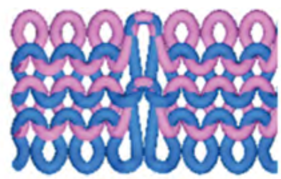
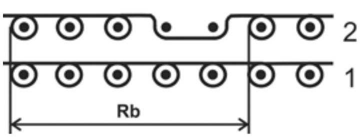
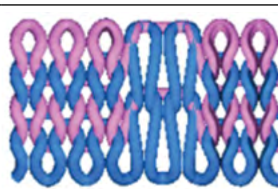
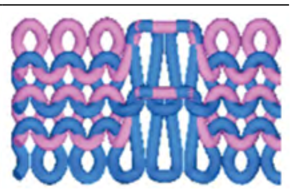
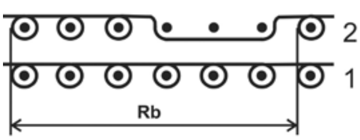
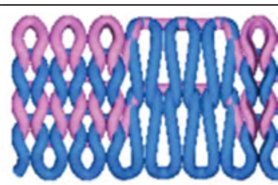
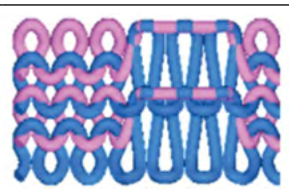
This study focuses on nine variants of single tuck fabrics (variants 2–10) and one plain fabric (variant 1) (Table 1). Each tuck stitch structure consists of one course of plain stiches (formed by the first yarn feeder), followed by one course of single tuck stitches (formed by the second yarn feeder). The knitted samples were produced on a 10-gauge flat V-bed knitting machine using a wool/PAN yarn containing 50% wool and 50% polyacrylonitrile (PAN) of 31 tex ×2. Throughout the knitting process, the stitch cam settings, yarn tension and fabric take-down were kept constant. Before knitting, the yarn was pre-treated with a 0.5% wax finish [22].

The tuck stitch index is set to one. The structure of the tuck stitch (Figure 1) consists of knit loops, which can appear as extended help loops (1) with tuck loops (2), and unextended knit loops (3). The head of the tuck loop is located on the reverse side of the fabric (the technical back). The unextended knit loops (3), which are located near the held loop with the tuck loop, usually have less height and a wider width, resembling a Ω-shape, compared to conventional knit loops, which are shown in the photo of the technical face side of the tuck stitch variant 2 (Figure 1a).

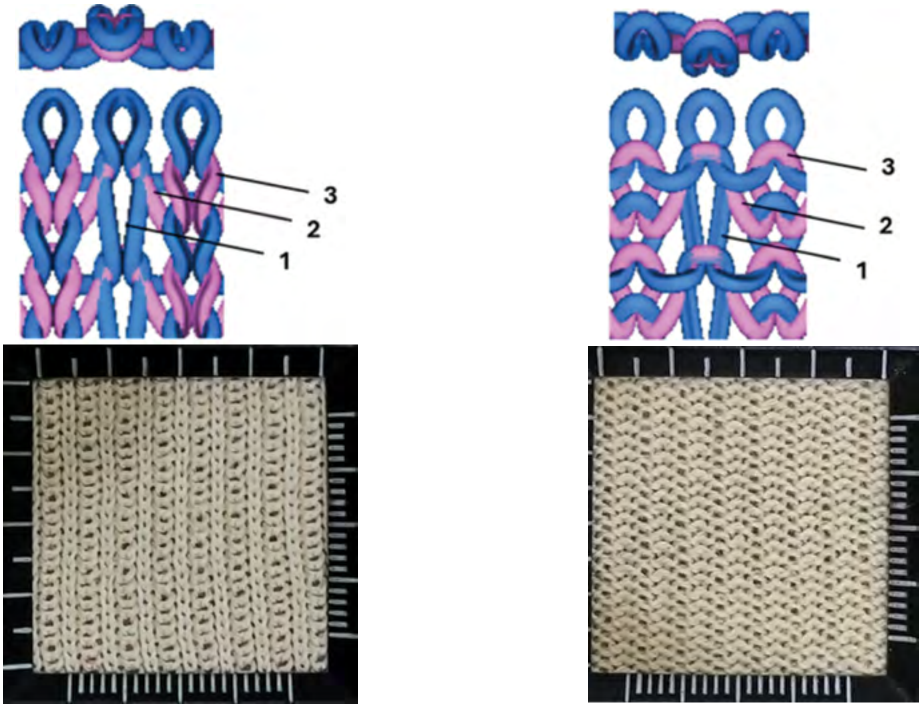
The studied variants of the single tuck stitches consist of a tuck loop produced over one, two or three adjacent needles, while various combinations of knit (m) and tuck (n) loops at the width repeat R_b define the tuck stitch variants. The number of knit (m) and tuck (n) loops in the tuck stitch structures across the fabric width can likewise be one, two or three. Different combinations of knit (m) and tuck (n) loops produced variations of the tuck stitches 2–10.

Table 1: Graphical notations and visual illustrations of the single-knitted fabrics

Variants of fabric	T_n [a)] (%)	Graphical notation of the repeat at height, R_h	Illustration of the view of the structure from the side: Technical face	Technical back
1	0			
2	50			
3	66.6			

4	75			
5	33.3			
6	50			
7	60			
8	25			
9	40			
10	50			

[a)] percentage of tuck loops



a) b)

Figure 1: Illustration and photos of the technical face of tuck stitch knitted fabric variant 2:
a) technical face, b) technical back (1 - held loop, 2 - tuck loop, 3 - knit loop)

The percentage of tuck loops within the tuck stitch repeat across the fabric width (T_n) was calculated using the following equation:

$$T_n = \frac{n}{m + n} \times 100[\%] \quad (1),$$

where m represents the number of knit loops within the tuck stitch repeat across the width R_b, and n represents the number of tuck loops within the tuck stitch repeat across the width R_b.

2.2 Methods

Relaxation conditions

Following the knitting process, the fabrics were conditioned under standard atmospheric conditions for testing, in accordance with ISO 139:2005 [23]. They were then washed in a fully automatic domestic washing machine using the wool cycle, as prescribed by ISO 6330:2021 [24].

Average stitch length

The stitch length of the knitted fabric was measured separately for plain and tuck stitches, and expressed as the average yarn length per stitch, in accordance with the EN 14970:2006 [25] and GOST 8846-87 [26] standards. Measurements were conducted over a section containing 50 wales. Each reported value represents the mean of twenty individual measurements for both the plain stitch length () and the tuck stitch length (). The overall average stitch length () was then calculated from the individual stitch lengths using the following equation:

$$l_a = \frac{l_p + l_t}{2} \text{ [mm]} \quad (2)$$

Stretch characteristics

The stretch characteristics of the single-tuck and plain stitches were measured by determining full, elastic, delayed and residual deformations, together with their contributors, according to GOST 8847-85 [27].

For determining the stretch characteristic, a "rack" relaxometer was used to conduct a "loading–unloading-rest" cycle [13, 14]. During testing, the samples were loaded with 6 N for 60 minutes. The samples were then unloaded and given a 120-minute rest period (Figure 2). Fabric specimens, each 50 mm wide and 200 mm long, were first clamped at a gauge length of 100 mm (L_0). The displayed results represent the averages of five samples for each direction (in length and width).

The lengthwise and widthwise stretch characteristics were calculated using the following formula:

a) full deformation (E):

$$E = \frac{L_1 - L_0}{L_0} \times 100[\%] \quad (3),$$

where L_0 represents the initial length of the specimen, mm (L_0 = 100 mm) and L_1 represents the length of the specimen after 60 minutes of loading in mm.

b) elastic deformation (E_1):

$$E_1 = \frac{L_1 - L_2}{L_0} \times 100[\%] \quad (4),$$

where L_2 represents the length of the specimen just after unloading in mm.

c) delayed deformation (E_2):

$$E_2 = \frac{L_2 - L_3}{L_0} \times 100[\%] \quad (5),$$

where L_3 represents the length of the specimen after resting in mm.

d) residual deformation (E_3):

$$E_3 = \frac{L_3 - L_0}{L_0} \times 100[\%] \quad (6)$$

Based on the full, elastic, delayed and residual deformations, the contributions of each component to the full deformation, such as E_1/E, E_2/E, and E_3/E, was calculated.

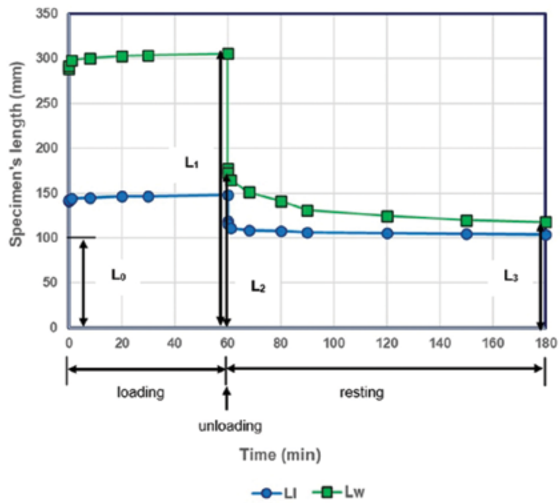


Figure 2: Specimen`s length changes of the plain (variant 1) within the cycle of "loading-unloading-resting" in both directions

Statistical analysis

The data were analysed statistically using the Student's t-test for independent samples, following the formula below:

$$t = \frac{|\overline{x_1} - \overline{x_2}|}{\sqrt{\frac{\sigma_1^2 \cdot (n_1 - 1) + \sigma_2^2 \cdot (n_2 - 1)}{n_1 + n_2 - 2} \cdot \frac{n_1 + n_2}{n_1 \cdot n_2}}} \quad (7),$$

where $\overline{x_1}$ and $\overline{x_2}$ represent the samples' mean values of the determined characteristic, σ_1 and σ_2 represent the sample's standard deviation of the determined characteristic and n_1 and n_2 represent their corresponding sample sizes ($n_1 = n_2 = 5$).

4 Results and discussion

Stitch length

The different tuck stitch variants directly influence stitch length by affecting the number of knit and tuck loops within each stitch repeat (Figure 3). Although the knitting machine's settings remained constant during production, the plain stitch length (l_p) of the fabric variants changed by up to around 5%, except for variant 8, which deviated by 10.7%. The tuck stitch length (l_t) depends on both the number and arrangement of the knit and tuck loops. When the number of knit loops (m) increases from 1 to 3 with a constant number of tuck loops (n), the tuck stitch length (l_t) increases proportionally. The relationship between the average stitch length (l_a) is linear (Figure 3), with an increase of 69.3%, when the percentage of tuck loops (T_n) reaches 75%.

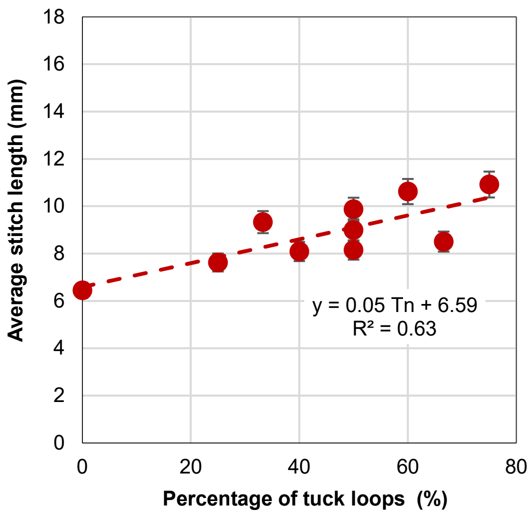


Figure 3: Dependence of average stitch length (l_a) and the percentage of tuck loops (T_n) in the tuck stitch repeat

Stretch characteristics

The results of the lengthwise and widthwise stretch characteristics of the single-tuck knitted fabrics are presented in Tables 2 and 3, respectively.

A specimen's length variations of the plain (variant 1) throughout the "loading-unloading-resting" cycle in both directions are illustrated in Figure 2.

An analysis of the stretch characteristics of the plain fabric reveals that the material exhibits significant anisotropic behaviour, with total deformation in the widthwise direction (205.8%) exceeding that in the lengthwise direction (48.0%) by a factor of four (Tables 2 and 3). In tuck stitch variants (variants 2-10), this trend is less noticeable and varies depending on the specific tuck stitch variant. In both plain fabric orientations, the elastic component (E_1) predominates, accounting for approximately 60–62% of the overall deformation, indicating the fabric's substantial capacity to revert to its original dimensions upon load removal. The delayed (E_2) component accounts for 29–32% of the total deformation, indicative of viscoelastic behaviour associated with gradual yarn relaxation. Meanwhile, the residual (E_3) component remains low at 7.5–8.6%, which confirms the fabric's good dimensional stability.

Table 2: Lengthwise stretch characteristics of knitted fabrics after washing

Fabric variants	T_n [a] (%)	m-n [b]	l_a [c] (mm)	Deformations (%) and their contributors						
				E [d]	E_1 [e]	E_2 [f]	E_3 [g]	E_1/E [h]	E_2/E [i]	E_3/E [j]
1	0	1-0	6.45 ± 0.16	48.0 ± 4.5	29.0 ± 3.9	15.4 ± 0.9	3.6 ± 1.1	0.60	0.32	0.07
2	50	1-1	8.16 ± 0.39	88.8 ± 4.1	47.6 ± 4.0	27.8 ± 1.5	13.4 ± 1.1	0.54	0.31	0.15
3	66.6	1-2	8.51 ± 0.31	80.8 ± 8.7	41.6 ± 6.3	22.0 ± 1.6	17.2 ± 3.6	0.51	0.28	0.21
4	75	1-3	10.92 ± 0.32	62.2 ± 2.9	34.0 ± 2.6	18.8 ± 1.9	9.4 ± 1.8	0.55	0.30	0.15
5	33.3	2-1	9.33 ± 0.34	69.0 ± 10.6	40.2 ± 9.1	18.8 ± 2.6	10.0 ± 3.2	0.58	0.28	0.14
6	50	2-2	9.87 ± 0.48	71.4 ± 7.8	43.2 ± 6.9	21.6 ± 1.5	6.6 ± 0.6	0.60	0.30	0.09
7	60	2-3	10.62 ± 0.06	77.8 ± 10.5	38.0 ± 5.8	25.0 ± 3.5	14.8 ± 4.1	0.49	0.32	0.19
8	25	3-1	7.63 ± 0.03	59.2 ± 6.4	26.4 ± 8.3	23.4 ± 3.3	9.4 ± 1.1	0.44	0.40	0.16
9	40	3-2	8.09 ± 0.04	69.4 ± 4.7	41.6 ± 4.3	20.2 ± 0.8	7.6 ± 2.0	0.60	0.29	0.11
10	50	3-3	9.00 ± 0.23	62.6 ± 5.4	34.8 ± 4.8	19.4 ± 2.7	8.4 ± 1.5	0.55	0.31	0.14

[a] percentage of tuck loops, [b] the number of knit and tuck loops, [c] average stitch length, [d] full deformation, [e] elastic deformation, [f] delayed deformation, [g] residual deformation, [h] contributors of elastic deformation in full, [i] contributors of delayed deformation in full, [j] contributors of residual deformation in full

Table 3: Widthwise stretch characteristics of knitted fabrics after washing

Fabric variants	T_n a) (%)	m-n b)	l_a c) (mm)	Deformations (%) and their contributors						
				E d)	E_1 e)	E_2 f)	E_3 g)	E_1/E h)	E_2/E i)	E_3/E j)
1	0	1-0	6.45 ± 0.16	205.8 ± 16.9	128.4 ± 12.3	59.6 ± 5.6	17.8 ± 2.3	0.62	0.29	0.09
2	50	1-1	8.16 ± 0.39	84.6 ± 3.4	43.0 ± 2.5	27.2 ± 1.8	14.4 ± 2.3	0.51	0.32	0.17
3	66.6	1-2	8.51 ± 0.31	99.0 ± 3.3	45.6 ± 3.5	27.4 ± 1.5	26.0 ± 1.2	0.46	0.28	0.26
4	75	1-3	10.92 ± 0.32	103.4 ± 6.9	53.6 ± 6.4	30.8 ± 2.1	19.0 ± 2.1	0.52	0.30	0.18
5	33.3	2-1	9.33 ± 0.34	142.2 ± 8.1	70.4 ± 6.8	50.0 ± 2.8	21.8 ± 1.1	0.49	0.35	0.15
6	50	2-2	9.87 ± 0.48	115.2 ± 10.4	67.6 ± 6.7	32.0 ± 4.5	15.6 ± 0.6	0.59	0.28	0.14
7	60	2-3	10.62 ± 0.06	112.6 ± 15.3	47.0 ± 7.5	29.8 ± 3.1	35.8 ± 5.0	0.42	0.27	0.32
8	25	3-1	7.63 ± 0.03	170.6 ± 9.2	92.8 ± 6.1	51.4 ± 3.2	26.4 ± 2.9	0.54	0.30	0.15
9	40	3-2	8.09 ± 0.04	130.0 ± 8.3	77.4 ± 5.1	34.0 ± 5.2	18.6 ± 1.7	0.60	0.26	0.14
10	50	3-3	9.00 ± 0.23	138.8 ± 8.0	79.2 ± 5.1	36.2 ± 4.4	23.4 ± 1.1	0.57	0.26	0.17

a) percentage of tuck loops, b) the number of knit and tuck loops, c) average stitch length, d) full deformation, e) elastic deformation, f) delayed deformation, g) residual deformation, h) contributors of elastic deformation in full, i) contributors of delayed deformation in full, j) contributors of residual deformation in full

The stretch properties of knitted fabrics are predominantly determined by the type of loop structure and the physical characteristics of the yarn [28]. Under tensile stress, deformation in plain and tuck stitches occurs through the redistribution of yarn within the constituent parts of the knit structure, including the knit and tuck loops and their components: the head, sinker loop and legs. The extent and configuration of tuck loops significantly influence a fabric's geometry and, thus, its mechanical response and elasticity.

The obtained results indicate that the presence and percentage of tuck loops significantly affect the stretch properties of the fabrics in both lengthwise and widthwise directions. Specifically, the inclusion of tuck loops led to increased elongation in the lengthwise direction (Figure 4 a–c) and a corresponding reduction in widthwise stretch compared to plain knitted structures (Figure 4 d–g), as was also noted in the study [16]. The decrease in widthwise stretching as the percentage of the tuck loop in width repeat increases follows the same trend as the increase in the miss-stitch rate in single-knit fabrics [13].

The full deformation lengthwise (E_l) of tuck stitch fabrics is generally equal to or only 1.2–2.2 times higher than the widthwise full deformation (E_w) (Tables 2 and 3). Comparing the lengthwise stretch properties of tuck stitch variants (2–10) with the plain stitch fabric (variant 1) highlights several key points (Table 2 and Figure 4 a–c). Tuck stitch fabrics show higher full (E), elastic (E_1), delayed (E_2) and residual (E_3) deformations in the lengthwise direction compared to plain fabrics. The full lengthwise deformation (E) of tuck stitch variants ranges from 59.2% to 88.8%, compared to 48.0% for the plain stitch variant, indicating that tuck loops contribute to structural changes that enhance fabric extensibility. Elastic deformation (E_1) varies from 26.4% to 47.6% in tuck stitch fabrics, slightly exceeding the plain value of 29.0%, suggesting better immediate recovery. Delayed deformation (E_2) ranges from 19.4% to 27.8% in tuck stitches, higher than the 15.4% for the plain stitch variant, reflecting increased viscoelastic behaviour. Residual deformation (E_3) ranges from 7.6% to 17.2%, which is significantly above the 3.6% for the plain stitch variant, indicating a greater permanent set after loading.

Variants with an equal number of tuck loops showed similar levels of lengthwise delayed deformation (E_2). Specifically, variants with 50.0% tuck loops (variants 2, 6, and 10) showed that delayed deformation contributed E_2/E = 0.30–0.31 to the total deformation. The same trend has been observed for single weft-knitted fabrics with the same percentage of miss loops [13].

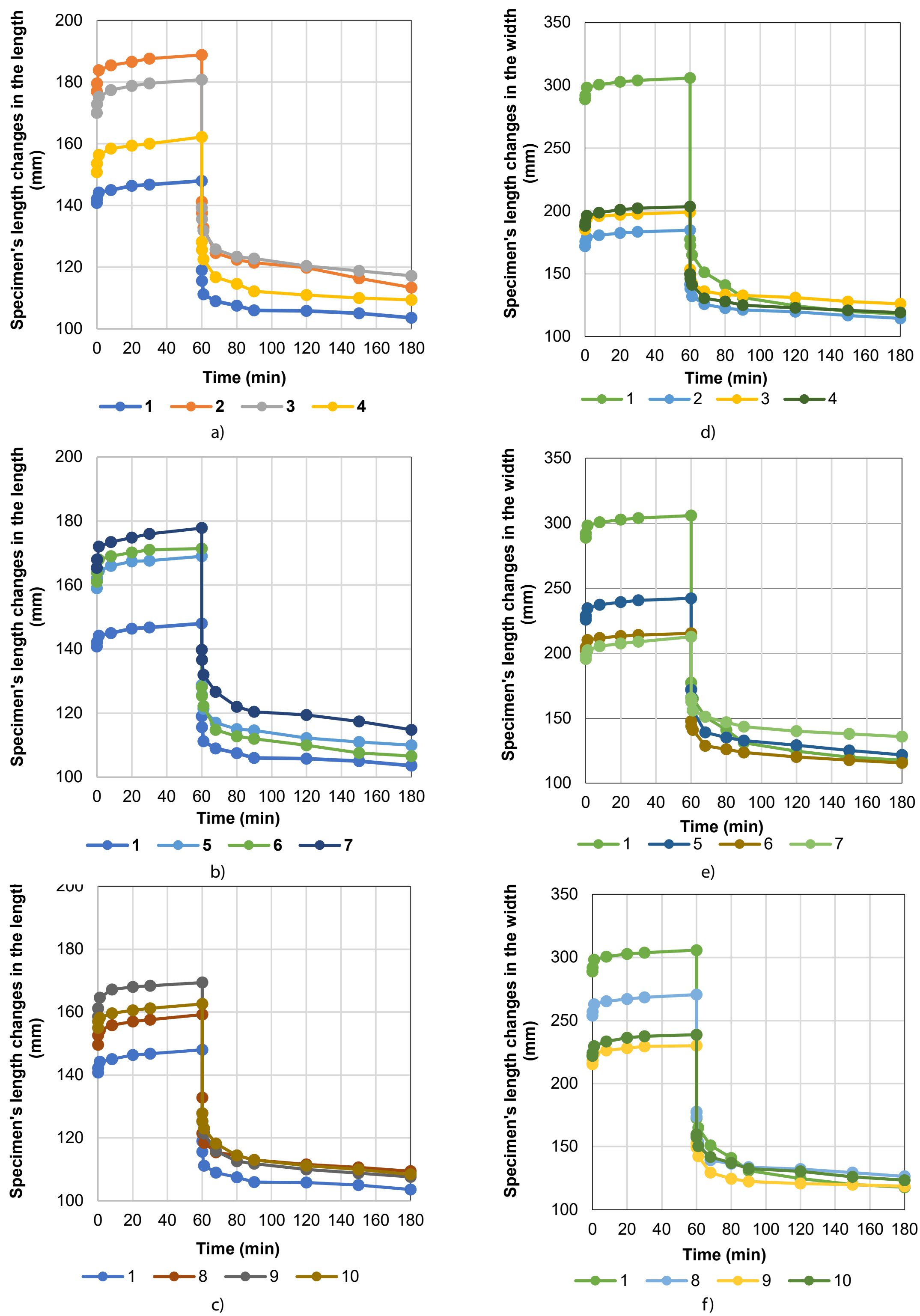


Figure 4: Specimen's length changes within the cycle of "loading-unloading-resting" for knitted fabrics in the length direction for tuck loops (n = 1, 2, 3): a) for variants 1 and 2-4 (m = 1), b) for variants 1 and 5–7 (m = 2), c) for variants 1 and 8–10 (m = 3); in the width direction for tuck loops (n = 1, 2, 3): e) for variants 1 and 2-4 (m = 1), f) for variants 1 and 5–7 (m = 2), g) for variants 1 and 8–10 (m = 3)

Conversely, the widthwise stretch properties of tuck stitch fabrics (2–10) display opposite trends. These fabrics exhibit lower full (E), elastic (E_1) and delayed (E_2) deformations in the widthwise direction than the plain stitch variant, except for the residual deformation (E_3). The full widthwise deformation (E_w) ranges from 84.6% to 170.6% across tuck stitch variations, indicating decreased overall fabric extensibility, compared to 205.8% for the plain. Elastic deformation (E_1) varies from 43.0% to 92.8% in tuck stitch fabrics, showing less immediate recovery, whereas the plain exhibits a higher value of 128.4%. Delayed deformation (E_2) ranges from 27.2% to 51.4% in tuck stitches, which is lower than the 59.6% observed in the plain stitch variant, implying lower viscoelasticity. Residual deformation (E_3) in tuck stitch fabrics ranged from 14.4% to 35.8%, encompassing the plain stitch fabric value of 17.8%.

The relationship between the widthwise full (E), elastic (E_1) and delayed (E_2) deformations, and the percentage of the tuck loops (T_n) in the stitch repeat at the width is presented in Figure 5. Figure 6 shows the lengthwise and widthwise contributions of full deformation.

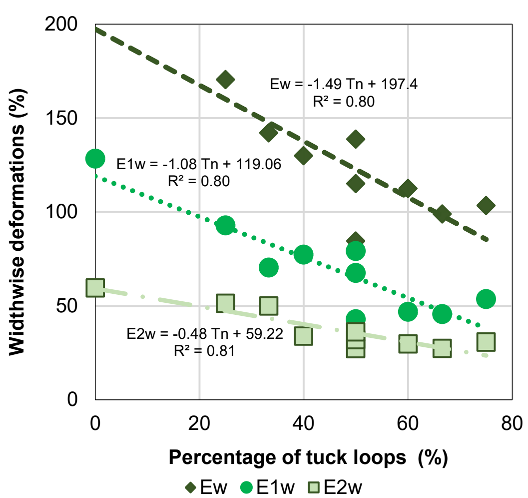


Figure 5: Relationship between the widthwise full (E), elastic (E1) and delayed (E2) deformations, and the percentage of the tuck loops (T_n) in the stitch repeat at the width

The correlation between the full widthwise (E_w), elastic (E_{1w}) and delayed (E_{2w}) deformations, and the percentage of tuck loops (T_n) per width repeat demonstrates a decreasing linear trend (Figure 5). This suggests that an increased number of tuck loops (n) diminishes a fabric's widthwise extensibility. Conversely, the relationship between lengthwise deformations and the percentage of tuck loops (T_n) per width repeat is nonlinear, indicating a more intricate structural response to tuck loop distribution.

The relative contributions of full deformation in both the lengthwise and widthwise directions are depicted in Figure 6, which shows that the deformation ratios confirm the significant influence of the introduction and distribution of tuck loops on fabric anisotropy. The presence and number of tuck loops per width repeat generally reduce the contribution of elastic deformation (E_1/E) to the total deformation in both directions compared with the plain loops, with values ranging from 0.44 to 0.60 in the lengthwise direction and from 0.42 to 0.60 in the widthwise direction, as also mentioned in the paper [16]. This reduction indicates that tuck loops limit the immediate elastic recovery of the fabric, promoting increased structural relaxation and directional dependence in deformation behaviour.

Conversely, the presence and number of tuck loops tend to increase the contribution of residual deformation (E_3/E) relative to the plain loops, with values ranging from 0.09 to 0.21 in the lengthwise direction and from 0.14 to 0.32 in the widthwise direction, reflecting greater permanent set and reduced dimensional stability.

The contribution of delayed deformation (E_2/E) ranges from 0.28 to 0.40 in the lengthwise direction and from 0.26 to 0.35 in the widthwise direction, compared with 0.32 and 0.29 for the plain stitch variant, respectively. These values indicate that tuck loops slightly enhance the viscoelastic component of deformation, allowing gradual stress relaxation and delayed recovery, which contributes to the overall flexibility and time-dependent deformation behaviour of the fabric.

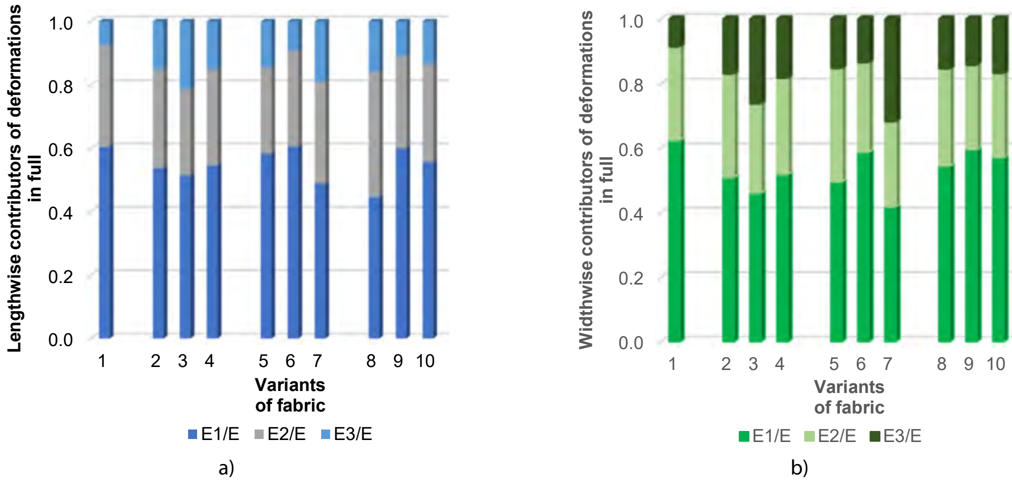


Figure 6: Contributors of elastic (E_1/E), delayed (E_2/E) and residual (E_3/E) deformations in full: a) lengthwise, b) widthwise

Tables 4 and 5 show the t–test statistical results used to determine the lengthwise and widthwise stretch characteristics of independent samples.

A statistical analysis using t-tests (Tables 4 and 5) showed greater differences in widthwise stretch characteristics than in lengthwise stretch characteristics, with a significance level of 0.001. Widthwise full (E), elastic (E_1) and delayed (E_2) deformations of the tuck stitch variants 2, 6, and 10 with 50% tuck loops at the width repeat, compared to the plain stitch fabric (variant 1), exhibit a notable difference, mainly with a significance level of 0.001.

Table 4: Statistical results for the determination of the lengthwise stretch characteristics for independent samples using the t–test

Tested parameter	Value of parameter (t) between plain and tuck stitch variants ($d_f = n_1+n_2 = 8$)			
	E	E_1	E_2	E_3
$t_{1/2}$	15.0 $^{c)}$	7.4 $^{c)}$	16.1 $^{c)}$	13.6 $^{c)}$
$t_{1/3}$	7.5 $^{c)}$	3.8 $^{b)}$	8.1 $^{c)}$	8.0 $^{c)}$
$t_{1/4}$	5.9 $^{c)}$	2.4 $^{a)}$	3.6 $^{b)}$	6.1 $^{c)}$
$t_{1/5}$	4.1 $^{b)}$	2.5 $^{a)}$	2.8 $^{a)}$	4.2 $^{b)}$
$t_{1/6}$	5.8 $^{c)}$	4.0 $^{b)}$	7.9 $^{c)}$	5.4 $^{c)}$
$t_{1/7}$	5.8 $^{c)}$	2.9 $^{a)}$	6.0 $^{c)}$	5.9 $^{c)}$
$t_{1/8}$	3.2 $^{a)}$	0.6 $^{d)}$	5.3 $^{c)}$	8.1 $^{c)}$
$t_{1/9}$	7.3 $^{c)}$	4.8 $^{b)}$	8.9 $^{c)}$	4.0 $^{b)}$
$t_{1/10}$	4.6 $^{b)}$	2.1 $^{d)}$	3.1 $^{a)}$	5.7 $^{c)}$

Legend: $^{a)}$ 0.05 level of significance; $^{b)}$ 0.01 level of significance; $^{c)}$ 0.001 level of significance; $^{d)}$ no statistically significant difference; d_f degree of freedom

Table 5: Statistical results for the determination of the widthwise stretch characteristics for independent samples using the t-test

Tested parameter	Value of parameter (t) between plain and tuck stitch variants ($d_f = n_1+n_2 = 8$)			
	E	E_1	E_2	E_3
$t_{1/2}$	15.7 $^{c)}$	15.3 $^{c)}$	12.5 $^{c)}$	2.4 $^{a)}$
$t_{1/3}$	13.9 $^{c)}$	14.5 $^{c)}$	12.5 $^{c)}$	7.1 $^{c)}$
$t_{1/4}$	12.5 $^{c)}$	12.1 $^{c)}$	10.9 $^{c)}$	0.9 $^{d)}$
$t_{1/5}$	7.6 $^{c)}$	9.2 $^{c)}$	3.5 $^{b)}$	3.5 $^{b)}$
$t_{1/6}$	10.2 $^{c)}$	9.7 $^{c)}$	8.6 $^{c)}$	2.1 $^{d)}$
$t_{1/7}$	9.1 $^{c)}$	12.6 $^{c)}$	10.5 $^{c)}$	7.4 $^{c)}$
$t_{1/8}$	4.1 $^{b)}$	5.8 $^{c)}$	2.9 $^{a)}$	5.2 $^{c)}$
$t_{1/9}$	9.0 $^{c)}$	8.6 $^{c)}$	7.5 $^{c)}$	0.6 $^{d)}$
$t_{1/10}$	8.0 $^{c)}$	8.3 $^{c)}$	7.4 $^{c)}$	4.9 $^{b)}$

Legend: $^{a)}$ 0.05 level of significance; $^{b)}$ 0.01 level of significance; $^{c)}$ 0.001 level of significance; $^{d)}$ no statistically significant difference; d_f degree of freedom

4 Conclusion

This study examined the stretch behaviour of nine variants of single-tuck weft-knitted fabrics made from 31 tex ×2 wool/PAN yarn and compared them with the plain stitch fabric. The primary aim was to determine how varying the percentage of tuck loops (T_n) within the stitch repeat influences the stretch properties of the fabrics. The analysis highlights the significant role of loop structure in governing the mechanical behaviour of plain and tuck weft-knitted fabrics.

The plain fabrics exhibited pronounced anisotropy, with widthwise deformation four times greater than lengthwise deformation. Their stretch response was dominated by the elastic component (E_1), indicating strong immediate recovery. Both delayed (E_2) and residual (E_3) deformations were relatively low, demonstrating good dimensional stability. In contrast, tuck stitch variants (2–10) exhibited more balanced deformation between lengthwise and widthwise directions, reflecting the moderating effect of tuck loops on fabric anisotropy.

The presence and proportion of tuck loops in the stitch repeat significantly impacted the stretch behaviour. Lengthwise deformations increased, enhancing fabric extensibility, while widthwise deformations generally decreased, reducing immediate recovery and diminishing the viscoelastic response. Specifically, full, elastic, delayed and residual deformations were higher in the lengthwise direction for tuck stitch fabrics than for plain fabrics, whereas widthwise deformations showed the opposite trend.

The analysis of the deformation components indicated that tuck loops lessen elastic deformation (E_1/E) and increase the residual deformation (E_3/E), suggesting a greater permanent set and reduced dimensional stability. The slight increase in the delayed component (E2/E) suggests enhanced viscoelasticity and stress relaxation. The relationship between deformation components and the percentage of tuck loops per width repeat showed a decreasing trend in widthwise extensibility and a nonlinear response in the lengthwise direction, highlighting the complex structural influence of tuck loop distribution.

Overall, the results confirm that adding and arranging tuck loops facilitates the fine-tuning of the stretch properties of knitted fabrics. By carefully controlling the percentage and placement of tuck loops, textile designers can achieve specific stretch behaviours, optimize recovery and improve dimensional stability, serving as valuable guidance for fabric development and functional textile engineering.

Data availability statement: Since December 5, 2025, the research data has been available at https://zenodo.org/records/17829260 [29].

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Dyeing on Sustainable Cotton Fabric with Mangosteen Rind: Investigating Extraction Parameters and Colour Fastness

Trajnostno barvanje bombažne tkanine z lupino mangostina (Garcinia mangostana): raziskava parametrov ekstrakcije in barvne obstojnosti

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Abstract
This study explores the sustainable dyeing of cotton fabrics using natural colorants extracted from mangosteen (*Garcinia mangostana*) rind. The extract was obtained via hot aqueous extraction and applied to cotton using varying dyeing conditions such as concentration, pH, temperature and time. Mordants (copper sulfate, iron sulfate and potassium alum) and fixatives (sodium chloride, potassium alum and acetic acid) were evaluated for enhancing colour strength and wash fastness. Copper sulfate improved dye uptake, while potassium alum best minimized colour fading. Optimal dyeing was achieved at pH 7 and 80 °C, for 30 min, balancing efficiency, cost, energy and acceptable colour quality. The dyed fabrics showed higher moisture content and stiffness, with minimal impact on air permeability and crease recovery. These results highlight mangosteen rinds promise as a sustainable, eco-friendly dye for cotton textiles.
Keywords: mangosteen rind, natural dyeing, cotton fabric, mordant, colour fastness

Izvleček
Raziskano je bilo trajnostno barvanje bombažnih tkanin z uporabo naravnih barvil, ekstrahiranih iz lupine mangostina. Izvleček, ki je bil pridobljen z ekstrakcijo mletih lupin z vročo vodo, je bil uporabljen za barvanje bombažne tkanine pri različnih koncentracijah, vrednostih pH, temperaturah in časih barvanja. Ocenjeni so bili učinki različnih čimž (bakrovega in železovega sulfata ter kalijevega aluminijevega sulfata) in fiksirnih sredstev (natrijevega klorida, kalijevega aluminijevega sulfata in ocetne kisline) za izboljšanje globine obarvanja in obstojnosti pri pranju. Bakrov sulfat je izboljšal absorpcijo barvila, medtem ko je kalijev aluminijev sulfat najbolj zmanjšal bledenje barve. Optimalno barvanje je bilo doseženo pri pogojih pH 7, 80 °C, 30 min, pri čemer so bili uravnoteženi učinkovitost, stroški, energija in sprejemljiva kakovost barve. Barvane tkanine so vsebovale več zračne vlage in bile bolj toge, minimalno sta se jim poslabšali zračna prepustnost in mečkavost.

Ti rezultati kažejo na možnost uporabe lupine mangostina kot trajnostnega in okolju prijaznega barvila za bombažne tekstilije.
Ključne besede: lupina mangostina, barvanje z naravnimi barvili, bombažna tkanina, čimža, barvna obstojnost

1 Introduction

The increasing demand for sustainable and eco-conscious practices in the textile industry has prompted renewed interest in the application of natural dyes. Unlike synthetic dyes, which are derived from petroleum-based sources and pose significant environmental and health concerns including wastewater pollution, toxicity and bioaccumulation, natural dyes offer a biodegradable, non-toxic and renewable alternative [1, 2]. However, despite their environmental advantages, natural dyes often face limitations such as low colour fastness, limited colour range and inconsistent dyeing performance, especially on cellulosic fibres such as cotton. Addressing these drawbacks remains a key focus in natural dye research [3, 4]. Plant-based colorants, particularly those derived from fruit peels, leaves and barks, have shown promising results due to their abundance of chromophoric compounds such as anthocyanins, flavonoids, tannins and xanthones [5, 6]. Among these, mangosteen (*Garcinia mangostana*) rind, a byproduct of the fruit industry, has been reported to contain high levels of xanthones and polyphenols that exhibit strong UV absorbance and vibrant coloration [7–10]. Mangosteen dyes are mainly composed of prenylated xanthones, particularly α-mangostin, γ-mangostin and garcinones, which possess a xanthone core with phenolic hydroxyl and prenyl side groups [11]. These structural features contribute to their yellow-orange colour, antioxidant activity and strong affinity for fibres in natural dyeing applications [12–14].

Previous studies have explored its potential as a natural antioxidant and antimicrobial agent, but its application as a textile dye remains relatively underexplored. Recent works have investigated the use of fruit waste in dyeing textiles. For instance,

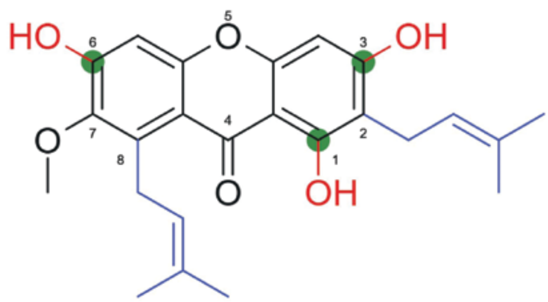


Figure 1: Chemical composition of mangosteen (Garcinia mangostana) pericarp (α-mangostin) [14]

Satyanarayana and Chandra (2021) reported that pomegranate rind extract could yield satisfactory colour strength on cotton when combined with mordants like alum and iron [15]. Similarly, Haddar et al. (2018) demonstrated that anthocyanin-rich extracts from red cabbage showed enhanced dyeability on silk and cotton under acidic conditions, although fastness properties were moderate without mordanting [16]. In a study by Prabhu and Teli (2014), tamarind seed and peel extracts were applied to cotton fabrics, with iron sulfate yielding the highest wash fastness among tested mordants [17].

These prior studies collectively underscore the importance of optimizing dyeing parameters such as pH, temperature, dye concentration and time, as well as the critical role of mordants in improving dye-fibre interactions and colour durability. Mordants, particularly metal salts, can form coordination complexes with natural dye molecules, enhancing their affinity to cellulose fibres [18–20]. Additionally, fixative agents such as alum and acetic acid have been employed to further stabilize dye-fibre bonds and improve fastness to washing and rubbing [21, 22]. Additional recent studies have emphasized the molecular mechanisms of dye–mordant interactions and the role of bio-based mordants (e.g., tannins and citric acid) in improving fastness and colour uniformity on cotton fabrics [23‑25]. Furthermore, several eco-friendly coloration processes, including ultrasonic- and microwave-assisted dyeing, have been proposed to enhance dye uptake efficiency while reducing energy and water consumption [26‑28]. These developments provide broader scientific context and reinforce the relevance of sustainable natural dye research.

Building upon such works, this study focuses on the extraction and application of natural dyes from mangosteen rind on cotton fabric. Using hot aqueous extraction, the study systematically investigates the effects of dyeing conditions including pH, temperature, concentration and time on colour development. The role of different mordants and post-dyeing fixatives is also evaluated in terms of their impact on colour strength, colour difference and wash fastness. Furthermore, changes in key fabric properties such as moisture regain, stiffness, air permeability and crease recovery are assessed to determine the practical implications of MGSR dyeing. This research contributes to the growing field of natural dye technology by identifying mangosteen rind as a potential sustainable dye source and proposing optimized methods for its effective use in cotton textile applications.

2 Experimental

2.1 Materials

Plain-woven 100% cotton fabric (120 g/m^2, purchased from Viet Thang Corporation, Vicotex) was used as the dyeing substrate. Mangosteen rinds (*Garcinia mangostana*) were collected from local markets in Ho Chi Minh city, Vietnam, cleaned, air-dried and ground into powder (Figure 1). Analytical-grade chemicals, including copper sulfate pentahydrate ($CuSO_4·5H_2O$), iron sulfate heptahydrate ($FeSO_4·7H_2O$), potassium aluminium sulfate dodecahydrate ($KAl(SO_4)_2·12H_2O$), sodium chloride (NaCl) and acetic acid (CH_3COOH), were obtained from A.R. Chemicals, India. Distilled water was used throughout all procedures. The natural dye was extracted by boiling 100 g of MGSR powder in 1000 mL of distilled water at 90 °C for 60 min. The solution was filtered and stored in dark bottles at 4 °C for later use.

Figure 2: Fruit (left) and rind powder (right) of mangosteen (adapted and redrawn from xaxafruit.vn)

2.2 Dyeing process, mordanting and fixation

Cotton fabric samples (10 cm ′ 10 cm) were pre-scoured and dyed using the exhaust method with a liquor ratio of 1:20. The effects of dye concentration (20–100% v/v), dyeing pH (3‑7), temperature (40–100 °C) and time (30–120 min) were studied. The temperature was increased from room temperature to the desired level at a heating rate of approximately 2 °C/min, and maintained for the required dyeing duration. The pH was adjusted using acetic acid or sodium carbonate. Mordanting was performed using pre-, meta- and post-mordanting techniques with $CuSO_4·5H_2O$, $FeSO_4·7H_2O$ and $KAl(SO_4)_2·12H_2O$ at concentrations of 0.5–2.0% (w/v). Each mordanting process was conducted at 80 °C for 30 min under continuous stirring to ensure uniform treatment. For fixation, dyed fabrics were treated with 5% NaCl, 5% $KAl(SO_4)_2·12\ H_2O$ or 5% CH_3COOH for 20 min at room temperature, then thoroughly rinsed with distilled water and dried at dried at 60 °C for 2 h in a hot-air oven before testing.

2.3 Evaluation methods

Colour strength (*K*/*S*) and colour difference (*ΔE*) values were calculated based on the spectrophotometric measurements performed using a Datacolor spectrophotometer. The UV-vis spectral analysis of dye extracts and dye-mordant interactions were conducted using a Yoke UV1200 UV-vis spectrophotometer to characterize the functional groups and absorption behaviour of the colorants. Washing fastness tests were carried out at 40 °C ± 2 °C using a Miele washer (Germany), and the results were evaluated according to ISO 105-C06 after one, two and four wash cycles, using grayscale ratings. In addition, the physical properties of the fabrics, including moisture regain (ISO 139), air permeability (ISO 9237), stiffness (ASTM D1388) and crease recovery (AATCC 66), were measured to assess structural and performance changes after dyeing.

3 Results and discussion

3.1 UV-vis spectral analysis of MGSR extract

The UV-vis spectra in Figure 3 show the absorbance behaviour of MGSR extract and its interaction with cotton fabric, both with and without copper sulfate as a mordant. The MGSR extract (NNO) exhibits a strong absorbance peak at around 300–320 nm, attributed to phenolic or flavonoid compounds, which are common in natural plant extracts. When MGSR is applied to cotton fabric (NNOF), the absorbance intensity decreases slightly, suggesting the partial adsorption or interaction of dye molecules with the fibre surface. When mordanting with copper sulfate mordant (NCUF), a noticeable increase in absorbance is observed in the same region, indicating the formation of coordination complexes between copper ions and MGSR constituents, which enhances dye uptake and stability on the fabric.

Beyond 320 nm, all three curves show a gradual decrease in absorbance, consistent with the typical behaviour of natural dyes, where main chromophoric absorption occurs in the UV range. Overall, the results demonstrate that mordanting with copper sulfate significantly enhances the interaction of MGSR extract with cotton fibres through chelation, thereby enhancing dye fixation and colour strength.

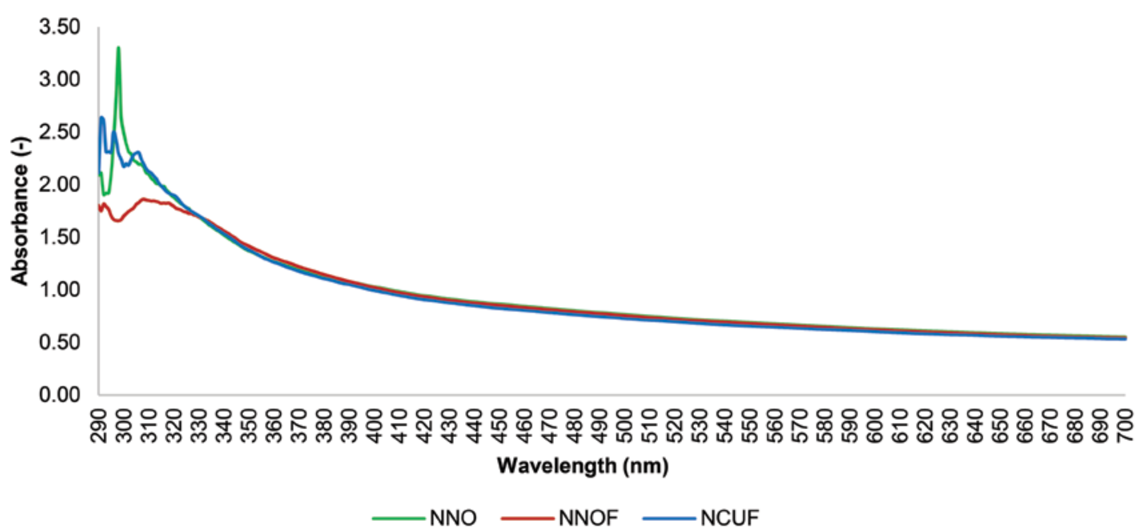


Figure 3: UV-vis spectra of MGSR extract (NNO), MGSR with cotton fabric (NNOF) and MGSR with cotton fabric and copper sulfate mordant (NCUF)

Figure 4 presents the UV-vis spectra of MGSR extract in the absence (NNO) and presence of different mordants: copper sulfate (NCU), potassium aluminium sulfate (NKA) and iron sulfate (NFE). The spectra reveal distinct variations in absorbance intensity and band shape, indicating that mordants significantly influence the optical properties of the extract. In the absence of mordant (NNO), the extract shows a broad absorption peak around 305–320 nm, characteristic of phenolic or xanthone compounds present in mangosteen rind. When copper sulfate (NCU), is added the absorbance intensity increases noticeably within this region, suggesting enhanced electronic transitions due to complexation between copper ions and active dye constituents, which improves chromophore stability. In contrast, the spectrum with potassium aluminium sulfate (NKA) displays a slightly lower absorbance, implying weaker coordination or limited complex formation. The spectrum with iron sulfate (NFE) shows a moderately broad band with intermediate intensity, indicating a different mode of interaction, likely involving hydroxyl or carbonyl coordination. Overall, copper sulfate proves to be the most effective mordant in enhancing the UV-vis absorbance of the MGSR extract, which can contribute to improved dye fixation and colour strength on textiles.

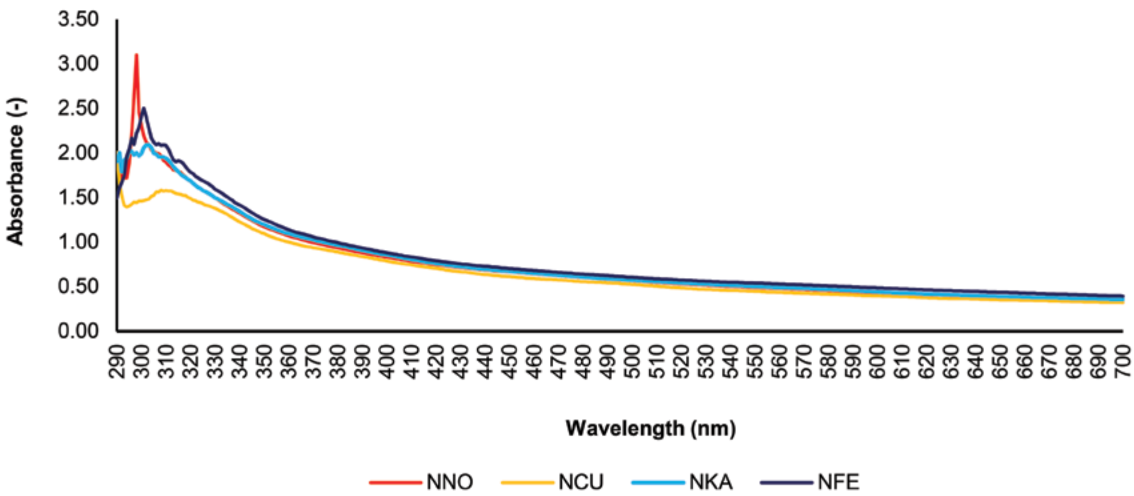


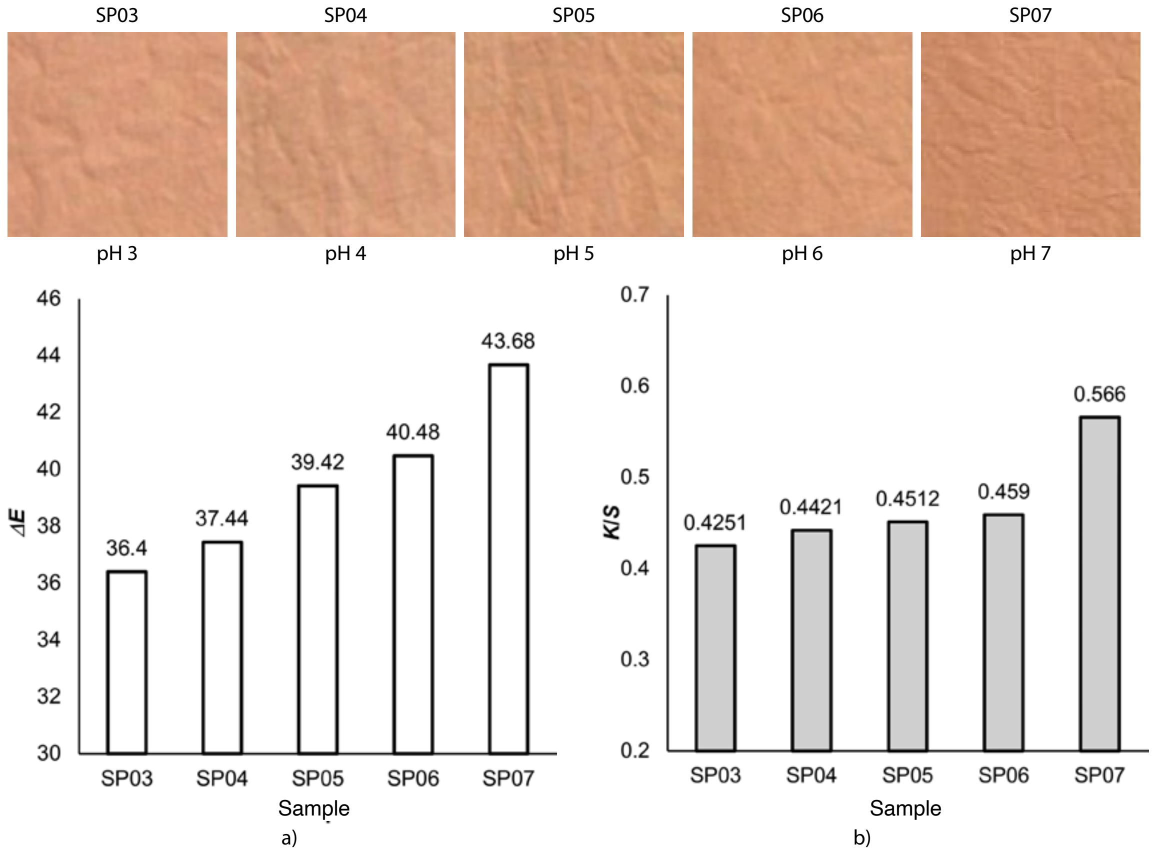
Figure 4: UV-vis spectra of MGSR extract in the absence of mordant (NNO), and in the presence of copper sulfate (NCU), potassium aluminium sulfate (NKA) and iron sulfate (NFE)

3.2 Effect of pH on dye uptake

Figure 5 illustrates the *K*/*S*, *ΔE* values and colorimetric parameters (*L**, *C**, and *h**) of cotton fabrics dyed with MGSR extract at varying pH levels from 3 to 7. The fabric images visually confirm that the colour becomes progressively darker and redder as the pH increases. The *K*/*S* values, which indicate dye uptake and colour strength, gradually rise from 0.4251 at pH 3 to 0.5660 at pH 7, showing enhanced absorption under near-neutral conditions. Similarly, the *C** values increase from 23.93 to 30.67 and the hue angle (*h**) shifts from 64.22° to 62.82°, suggesting higher colour saturation and a slightly deeper reddish tone at higher pH. The pH-sensitive behaviour of MGSR extract is likely related to the ionization and stability of phenolic or anthocyanin compounds, which are more reactive in less acidic environments. Adjusting the dye bath to near-neutral pH (6–7) can thus optimize the colour strength and stability of MGSR as a natural dye for cotton textiles.

3.3 Influence of dye concentration on colour strength and colour difference

The *K*/*S* and coloristic parameters (*L**, *C** and *h**) of cotton fabrics dyed with MGSR extract at various dilution ratios with water, ranging from 20/80 (SPC20) to 100/0 (SPC100), are presented in Table 1. The visual images and measured values show a clear trend of increasing colour depth as the concentration of MGSR extract increases. SPC20 was used as the reference sample, and all other samples were compared against it. The *K*/*S* values rise progressively from 0.3180 (SPC20) to 0.6936 (SPC100), indicating greater dye uptake and stronger coloration on the cotton fabric. This pattern is expected, as a higher MGSR/H_2O ratio provides more available dye

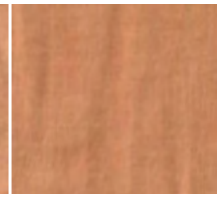


Sample	pH value	L*	C*	h*
SP03	3.0	70.16	23.93	64.22
SP04	4.0	69.69	24.90	65.67
SP05	5.0	69.44	27.49	66.44
SP06	6.0	69.23	28.79	65.76
SP07	7.0	66.59	30.67	62.82

Figure 5: a) K/S and b) ΔE values, together with a tabular representation of numerical values of coloristic parameters (L, C* and h*, are presented for cotton fabrics dyed with MGSR extract at pH 3 (SP03), 4 (SP04), 5 (SP05), 6 (SP06) and 7 (SP07)*

molecules to interact with the fibre surface. In this context, ΔE values were treated only as secondary indicators of visible colour change and were not used to interpret dye uptake, as they simply reflect the expected differences between samples with different dye concentrations. The discussion therefore focuses on the more meaningful coloristic parameters (*L**, *C** and *h**) and their trends with increasing MGSR concentration. As the MGSR concentration increased, *L** decreased from 73.51 to 63.90, indicating darker shades; *C** increased from 19.60 to 31.18, showing higher colour saturation; and *h** shifted slightly from 69.90° to 63.90°, suggesting a move toward a redder hue. These combined results clarify that the MGSR extract concentration strongly influences both the dye absorption (reflected by *K/S*) and colour appearance (*L**, *C* and h**) of the cotton fabrics.

Table 1: K/S values and colour coordinates (ΔE, L, C* and h*) of cotton fabric dyed with MGSR extract at MGSR/H_2O dilution ratios (DR) of 20/80 (SPC20), 40/60 (SPC40), 60/40 (SPC60), 80/20 (SPC80) and 100/0 (SPC100)*

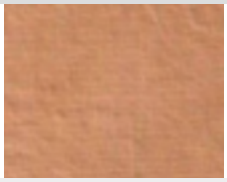
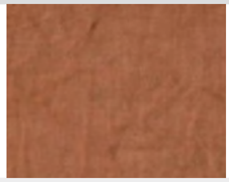
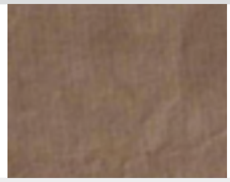
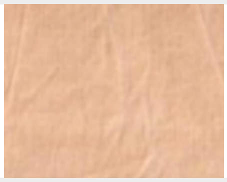
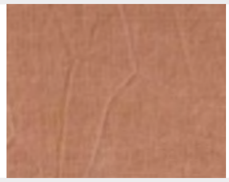
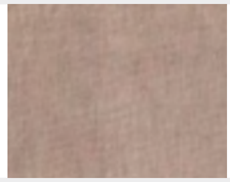
Sample	SPC20	SPC40	SPC60	SPC80	SPC100
DR	20/80	40/60	60/40	80/20	100/0
Photos					
K/S	0.3180	0.3689	0.4608	0.5542	0.6936
ΔE	-	4.32	7.87	12.38	15.36
L*	73.51	71.83	69.18	66.86	63.90
C*	19.60	23.55	26.07	29.85	31.18
h*	69.90	69.50	67.90	65.50	63.90

3.4 Role of mordants in dye fixation

The results presented in Table 2 show the *K/S* and *ΔE* values of cotton fabrics dyed with MGSR extract, with and without mordants, after multiple washing cycles. The mordants tested include potassium aluminium sulfate (SPKA), copper sulfate (SPCU) and iron sulfate (SPFE), while SPNO represents the sample without mordant. Initially, the unwashed fabrics show the highest *K/S* values, especially for SPCU (0.9488) and SPFE (1.0855), indicating enhanced colour depth due to the mordanting effect of transition metal ions. SPNO and SPKA exhibit lower *K/S* values of 0.5318 and 0.4898, respectively, suggesting that the absence or weaker complexation ability of the aluminium-based mordant results in less dye fixation. After one, two and four washing cycles, the *K/S* values decrease across all samples, indicating a gradual loss of colour due to washing. However, SPCU and SPFE retain higher *K/S* values than SPNO and SPKA, even after four cycles (0.5878 and 0.6196, respectively), demonstrating stronger dye-fibre binding and superior wash fastness. In contrast, SPKA drops to 0.2537, showing poor colour retention, likely due to the lower stability of the aluminium-dye complex.

The *ΔE* values increase with each washing cycle, reflecting noticeable colour differences. SPNO and SPKA exhibit the most significant *ΔE* values after four cycles (13.24 and 13.30), indicating substantial colour fading. On the other hand, SPCU and SPFE show lower *ΔE* values (9.50 and 8.54), confirming their better colour stability and resistance to washing. Overall, the results confirm that copper and iron sulfate mordants enhance dye uptake and the washing durability of MGSR-dyed cotton fabrics, while the aluminium-based mordant is less effective. This behaviour can be attributed to the higher coordination ability of transition metals, which form more stable complexes with phenolic components in the MGSR extract, resulting in improved colour fastness suitable for practical textile applications.

Table 2: K/S and ΔE values of cotton fabrics dyed with MGSR extract in the absence and the presence of different mordants after zero, one, two and four washing cycles

Fabric properties		**SPNO** Mordant: none pH = 5.95 ORP = 40.2	**SPKA** Mordant: $KAl(SO_4)_2 \cdot 12H_2O$ pH = 5.68 ORP = 55.5	**SPCU** Mordant: $CuSO_4 \cdot 5H_2O$ pH = 5.39 ORP = 72.7	**SPFE** Mordant: $FeSO_4 \cdot 7H_2O$ pH = 5.52 ORP = 64.7
Unwashed	a)				
	K/S	0.5318	0.4898	0.9488	1.0855
Washed (1 cycle)	a)				
	K/S	0.3935	0.3685	0.7186	0.7100
	ΔE	8.64	11.54	6.36	6.26
Washed (2 cycles)	*K/S*	0.3460	0.2584	0.6424	0.6464
	ΔE	10.64	12.64	8.48	7.56
Washed (4 cycles)	*K/S*	0.2725	0.2537	0.5878	0.6196
	ΔE	13.24	13.30	9.50	8.54

[a)] Appearance of dyed fabrics

As illustrated in Figure 6, the *K/S* and *ΔE* values of cotton fabric dyed with MGSR extract were calculated for the samples treated with varying concentrations (0.5, 1.0 and 2.0 wt%) of $CuSO_4 \cdot 5H_2O$ as a mordant. As the mordant concentration increases from 0.5 wt% (SPCU005) to 2.0 wt% (SPCU020), there is a clear increase in *K/S* values, indicating higher dye uptake and fixation on the cotton fibres. Specifically, the *K/S* value rises from 1.0501 to 1.6172, confirming that a higher mordant concentration promotes stronger dye-fibre interaction and deeper coloration.

In contrast, the *ΔE* values (10.46–16.6) represent the overall colour difference among the samples (SPCU005, SPCU010 and SPCU020) with respect to the unmordanted sample SP100 and are used here to support the visual observation of more vivid colours, rather than as a direct indicator of colour strength. It is important to emphasize that the increase in ΔE by increasing the mordant concentration only indicates that the overall colour difference become larger, but by itself it does not show how the colour is changing (i.e. whether the shade becomes darker or lighter, more or less chromatic, or shifts in hue). This improvement can be attributed to the ability of the mordant to form coordination complexes with dye molecules and the fibre, thereby enhancing dye-fibre affinity. At higher concentrations, more binding sites are likely formed, which boosts colour strength and leads to a more intense shade. The visual fabric samples also reflect this trend, showing progressively deeper brown hues with increasing $CuSO_4 \cdot 5H_2O$ levels. Overall, increasing the mordant concentration effectively intensifies the dyed colour, while *ΔE* serves only as a measure of colour difference among samples.

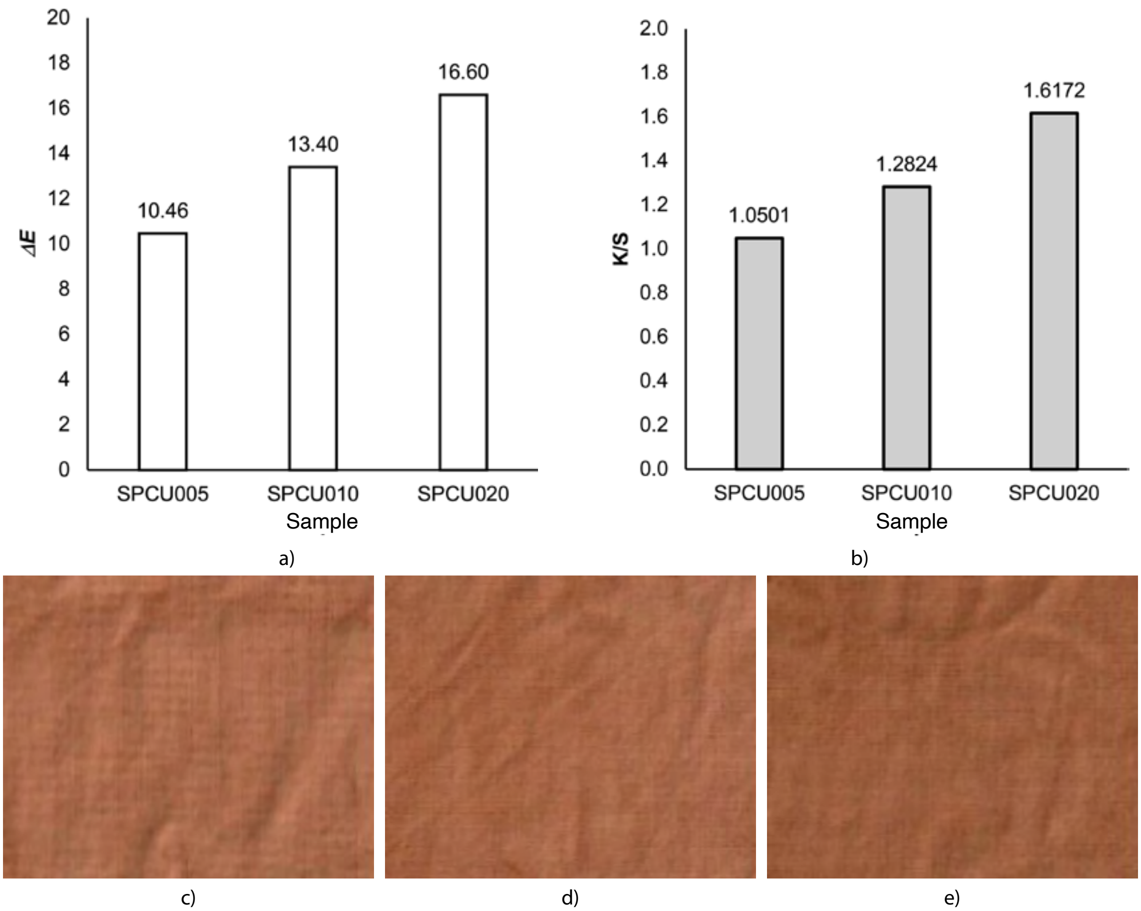


Figure 6: a) K/S and b) ΔE values of cotton fabric dyed with MGSR extract at c) 0.5, d) 1.0 and e) 2.0 wt% of $CuSO_4 \cdot 5H_2O$, denoted as SPCU005, SPCU010 and SPCU020, respectively

Figure 7 shows the *K/S* values at various dilution ratios (SP20 to SP100), both without mordant (NO) and with 1% wt of $Cu_2SO_4 \cdot 5H_2O$ as mordant (CU). As the MGSR concentration increases from SP20 to SP100, the K/S values also rise, indicating that a higher concentration of the dye extract leads to deeper coloration. Notably, SP100 (undiluted extract) achieves the highest colour strength, with a *K/S* value of 1.2504 (CU), compared to only 0.6936 (NO). This suggests that both dye concentration and mordanting play critical roles in improving colour yield. The copper mordant likely facilitates stronger coordination interactions between dye molecules and the cotton fibre, thereby improving dye uptake. Overall, the combination of high-extract concentration and Cu-mordanting provides the most optimal colour depth on cotton.

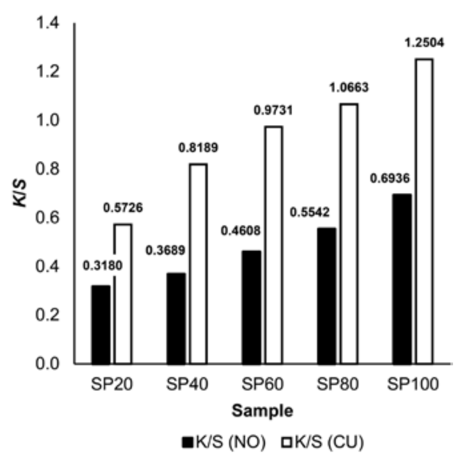


Figure 7: Change in K/S value of cotton fabric dyed with MGSR extract at various dilution ratios (SP20: 20/80, SP40: 40/60, SP60: 60/40, SP80: 80/20 and SP100: 100/0) as unmordanted (NO) and mordanted (N) with 1% wt of $Cu_2SO_4{\cdot}5H_2O$

3.5 Effect of dyeing temperature and time

Tables 3 and 4 present the dyeability of cotton fabrics dyed with MGSR extract, examining the influence of dyeing temperature and exhausting time, both in the absence (unmordanted) and presence (mordanted) of 1% $CuSO_4{\cdot}5H_2O$. As the dyeing temperature increases from 40 °C to 100 °C, the *K/S* values for both unmordanted and mordanted samples increase, indicating enhanced dye uptake at higher temperatures. For example, the *K/S* value of unmordanted fabric rises from 0.4536 at 40 °C to 0.9770 at 100 °C, while the mordanted samples show a more significant increase from 0.8255 to 2.0374. At higher dyeing temperatures, the colour of the fabric becomes visibly deeper, as reflected by the increase in *K/S* values. This trend demonstrates that higher temperatures enhance dye diffusion and fibre penetration, further supported by the improved bonding between dye molecules and cellulose fibres when a mordant is used.

Dyeing performance also improves with longer exhausting times. From 30 to 120 min, the *K/S* values increase for both treatments. For unmordanted fabrics, *K/S* improves from 0.5310 to 0.6094, while it improves from 1.2779 to 1.5830 for mordanted fabrics, thus confirming greater dye uptake. Meanwhile, unmordanted samples show higher perceptual colour variation than mordanted samples.

Table 3: Dyeability (K/S, ΔE) of cotton fabrics dyed with MGSR extract at 40 ˚C, 60 ˚C, 80 ˚C and 100 ˚C, both unmordanted and mordanted with 1% of $CuSO_4{\cdot}5H_2O$, using ST40 as the reference sample

Sample	Temp. (°C)	Unmordanted		Mordanted	
		ΔE	*K/S*	*ΔE*	*K/S*
St30 (Ref.)	40	-	0.4536	-	0.8255
St60	60	3.57	0.4889	4.12	0.9466
St80	80	6.71	0.5786	8.43	1.3386
St100	100	11.64	0.9770	14.22	2.0374

Table 4: Dyeability (K/S, ΔE) of cotton fabrics dyed with MGSR extract at 30 min, 60 min, 90 min and 120 min of exhausting time, both unmordanted and mordanted with 1% of $CuSO_4{\cdot}5H_2O$ (controlled sample is greige cotton), using St30 as the reference sample

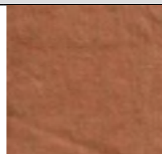
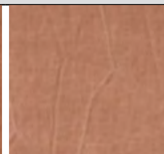
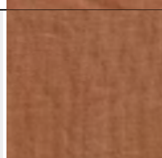
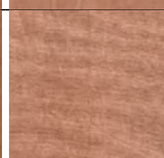
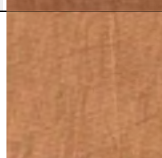
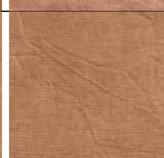
Sample	Exhausting time (min)	Unmordanted		Mordanted	
		ΔE	*K/S*	*ΔE*	*K/S*
St30 (Ref.)	30	41.60	0.5310	51.36	1.2779
St60	60	41.80	0.5313	51.50	1.2889
St80	90	42.68	0.5732	53.46	1.4347
St100	120	42.63	0.6094	54.48	1.5830

3.6 Combined effect of mordant and fixative treatment

Table 5 presents the *ΔE* values of cotton fabrics dyed with MGSR extract and mordanted with $CuSO_4{\cdot}5H_2O$, followed by treatments with or without fixative agents after zero and one washing cycle. The fixatives evaluated include sodium chloride (NaCl), potassium alum ($KAl(SO_4)_2{\cdot}12H_2O$) and acetic acid (CH_3COOH). *ΔE* represents the colour change, where a higher value indicates greater fading. For untreated fabrics (SPCUW), *ΔE* after one wash was 6.75, showing noticeable colour loss. Sodium chloride-treated samples (SPCUSC) exhibited slightly higher *ΔE* (6.39), implying limited effectiveness in wash fastness improvement. Although the *K/S* value (colour strength) of SPCUSC0 was the highest (1.15), its post-wash value decreased substantially, suggesting poor dye retention. Potassium alum (SP-

CUAW) demonstrated better performance, with a lower ΔE of 5.86, indicating improved wash fastness compared to no fixative or sodium chloride. The *K/S* values also decreased less dramatically, supporting its stabilizing effect on the dye. Surprisingly, acetic acid (SPCUAAW) resulted in the highest ΔE of 6.52, suggesting the least effective colour retention. Its low *K/S* values before and after washing further confirm weak dye fixation. Overall, potassium alum emerged as the most effective fixative among the three, providing relatively lower ΔE and better colour retention. Sodium chloride and acetic acid offered limited or no improvement over the untreated control. These results emphasize the importance of selecting appropriate fixatives to enhance the wash durability of natural dyes on cotton fabric.

Table 5: ΔE values of cotton fabric dyed with MGSR extract and mordanted with $CuSO_4 \cdot 5H_2O$, treated with or without fixative agents after zero and one washing cycle

Sample	Fixative agent	Photos of unwashed fabrics	Photos of washed fabrics one cycle	Unwashed	Washed one cycle	ΔE
				K/S		
SPCUW	None			1.08	0.73	6.75
SPCUSCW	Sodium chloride NaCl			1.15	0.78	6.39
SPCUPAW	Potassium alum $KAl(SO4)2 \cdot 12\ H_2O$			0.87	0.61	5.86
SPCUAAW	Acetic acid CH_3COOH			0.57	0.47	6.52

3.7 Physical properties of dyed cotton fabric

Table 6 exhibits the changes in physical properties of cotton fabric after dyeing with MGSR extract, compared to untreated fabric. The moisture increased by 10.58%, suggesting that MGSR-treated fabric has improved hydrophilicity. This could be due to the presence of hydrophilic functional groups in MGSR compounds, which enhance the fabric's ability to retain moisture. Air permeability slightly decreased by 3.35%, from 5.30×10^{-3} mm/s to 5.12×10^{-3} mm/s. This indicates that dyeing with MGSR extract may slightly reduce the fabric's porosity or alter the surface structure. However, the change is minimal and unlikely to significantly affect breathability. Stiffness showed a substantial increase of 99.08%, nearly doubling in value after treatment. This suggests that MGSR components may form deposits or bonds with the fibre surface, resulting in a stiffer fabric structure. While this may improve durability, it might reduce comfort and drape. Crease recovery decreased marginally from 68.05° to 67.00°, a change of just 1.54%. This implies that the dyeing process has little effect on the fabric's wrinkle resistance. Overall, MGSR dyeing alters the physical properties of dyed fabrics moderately. While the increase in moisture content and stiffness could be beneficial or detrimental depending on the application, the changes in air permeability and crease recovery are minimal, indicating that the fabric retains much of its original comfort and functionality after dyeing.

Table 6: Changes in the physical properties (moisture regain, air permeability, stiffness and crease recovery) of cotton fabric dyed with MGSR extract, compared to undyed cotton fabric

Fabric	Moisture regain (%)	Air permeability (mm/s)	Stiffness (mg.cm)	Crease recovery (°)
Untreated	5.2632	5.30×10^{-3}	344.24	68.05
Treated with MGSR extract	5.8201	5.12×10^{-3}	685.3	67
Change (%)	10.58	-3.348	99.08	-1.54

4 Conclusion

The use of MGSR extract as a natural dye for cotton fabric demonstrates promising results in terms of colour intensity, wash durability and sustainability. This study confirmed that mordanting with copper sulfate or iron sulfate enhances dye uptake and colour retention, while potassium alum provides better fastness among the tested fixatives. The optimal dyeing conditions were found at neutral pH, high temperature and extended dyeing time, all of which contributed to improved fabric coloration. Although MGSR-dyed cotton fabric showed increased stiffness, the changes in moisture regain, air permeability and crease recovery remained within acceptable limits. Overall, MGSR extract is a viable natural dye option for eco-friendly textile processing, especially when combined with appropriate mordants and fixatives to improve performance and durability.

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

Data Availability Statement: The datasets generated and analyzed during the current study, including experimental results, UV-vis spectra, and colorimetric data (L^*, a^*, b^* values) are publicly available on Zenodo at: https://doi.org/10.5281/zenodo.17873277 [29].

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Exercise Cards for Taking Active Breaks During Prolonged Sitting

Vadbene karte za izvajanje aktivnih odmorov med dolgotrajnim sedenjem

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Abstract

The consequences of prolonged sitting are faced both by employers and by employees themselves. This paper presents the findings from statistical reports and scientific studies on the negative effects of prolonged sitting on employees' health and consequently, on the importance of introducing short active breaks. A survey conducted among the employees of the Faculty of Natural Sciences and Engineering of the University of Ljubljana revealed that as many as 88.3% of respondents perform their work in a seated position for an average of 2.9 hours per day. Although more than half (55.9%) of the respondents are physically active, they still most frequently experience discomfort caused by sitting, e.g. pain in the back, neck, wrists etc. While no structured group implementation of active breaks is organised at the faculty, employees still have the option to take such breaks independently, which, according to the survey results, suits them well. The majority of respondents (76.0%) prefer performing exercises whenever they feel the need for a break. Even though half of the respondents (50%) are aware that the discomfort (pain) caused by prolonged sitting could be alleviated by taking active breaks, they rarely do so. Those who do take active breaks individually (20% every half hour, 10% every two to three hours) generally perform the exercises freely, without guidance. To ensure that employees perform appropriate exercises during active breaks – especially those that prevent the negative consequences of prolonged sitting – we developed exercise cards as part of the study. Most respondents rated the cards as visually appealing (design, colour palette, typographic choices etc.) and useful. One third of the respondents stated that they would certainly use the exercise cards to take short active breaks during extended periods of sitting at work, while slightly more than one third were undecided. The majority of the respondents (64.5%) also believe that frequent active breaks supported by the exercise cards during long periods of sitting at work would indeed contribute to increasing their physical activity. The exercise cards were distributed to employees at the beginning of the academic year, together with information on the consequences of prolonged sitting; however, this will certainly not be sufficient. To develop a culture of regular active breaks, further awareness-raising among employees will be required, with the exercise cards representing a promising starting point.

Keywords: prolonged sitting, sedentary behaviour, active breaks, exercise cards

Izvleček

S posledicami dolgotrajnega sedenja se soočajo tako delodajalci kot tudi delavci sami. V članku so podane ugotovitve iz statističnih poročil in znanstvenih raziskav o negativnih vplivih dolgotrajnega sedenja na zdravje delavcev ter posledično pomen vpeljevanja kratkih aktivnih odmorov. Iz ankete, izvedene med zaposlenimi Naravoslovnotehniške fakultete Univerze v Ljubljani, je bilo ugotovljeno, da kar 88,3 % sodelujočih svoje delo opravlja v sedečem položaju v povprečju 2,9 ure/dan. Kljub temu da je več kot polovica (55,9 %) sodelujočih telesno aktivna, pa zaradi sedenja najpogosteje občutijo bolečine v hrbtu, vratu, zapestjih itd. Skupno izvajanje aktivnih odmorov na fakulteti ni organizirano, imajo pa zaposleni možnost samostojnega izvajanja le-teh, kar jim glede na rezultate ankete tudi ustreza. Večina sodelujočih v raziskavi (76,0 %) namreč želi izvajati vaje takrat, ko potrebujejo odmor. Čeravno se polovica sodelujočih (50 %) zaveda, da bi omenjeno nelagodje (bolečine) zaradi dolgotrajnega sedenja lahko odpravili z izvajanjem aktivnih odmorov, pa to storijo le redko. Tisti, ki aktivne odmore izvajajo individualno (20 % na vsake pol ure, 10 % na vsake 2–3 ure), vaje izvajajo večinoma prosto, brez navodil. Da bi tekom aktivnih odmorov zaposleni izvajali ustrezne vaje, torej tiste, ki preprečujejo negativne posledice dolgotrajnega sedenja, smo v raziskavi razvili vadbene karte za aktivni odmor. Večina anketiranih je karte ocenila kot vizualno privlačne (izgled, barvna paleta, izbira tipografije itd.) in uporabne. Tretjina anketiranih je zatrdila, da bo vadbene karte zagotovo uporabljala za izvedbo kratkih aktivnih odmorov pri daljšem sedenju med delom, nekaj več kot tretjina pa je bila glede uporabe neopredeljena. Večina sodelujočih (64,5 %) tudi verjame, da bi pogosta izvedba aktivnih odmorov s pomočjo vadbenih kart pri daljšem sedenju med delom dejansko prispevala k povečanju njihove telesne aktivnosti. Vadbene karte so bile v začetku študijskega leta razdeljene zaposlenim skupaj z informacijo o posledicah dolgotrajnega sedenja, vendar pa to zagotovo še ne bo dovolj. Za uvedbo kulture rednih aktivnih odmorov bo potrebno nadaljnje osveščanje zaposlenih, pri čemer so vadbene karte vsekakor dober začetek.
Ključne besede: dolgotrajno sedenje, sedentarno vedenje, aktivni odmor, vadbene karte

1 Introduction

Rapid technological advancement over recent decades has reshaped not only our way of life but also the organisation of work, working hours and workplaces. The environments in which we work, spend our leisure time or commute often compel us to remain seated for long periods of time. Society is becoming increasingly sedentary, presenting new challenges at both the psychosocial level and in terms of employees' physical health. The growing seriousness of prolonged sitting as a contemporary societal issue is further reflected in the substantial increase in scientific publications on the topic, which rose by more than fifteenfold between 2010 and 2020 [1].

The European Agency for Safety and Health at Work (hereinafter EU-OSHA) [2] defines prolonged sitting (also referred to as sedentary behaviour) as behaviour lasting at least two hours and characterised by three main features: low energy expenditure, a seated posture and physical strain resulting from a limited range of movement (i.e. effort required to maintain a static position). A more precise and widely used definition, however, describes sedentary behaviour as any waking behaviour characterised by low energy expenditure (≤ 1.5 MET[1]) while in a sitting, reclining or lying posture [3].

1 MET (Metabolic Equivalent of Task) represents the amount of energy required by an individual to perform a given activity. One MET corresponds to the energy expenditure (oxygen consumption) of an average 70 kg man at rest (3.5 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$) [44].

According to statistical data [4], residents of Slovenia spend an average of 5 hours per day sitting during the working week and 4 hours per day at weekends (sedentary behaviour). Sitting time during the working week decreases with age, with individuals aged 25 to 39 spending the most time seated, averaging 6 hours per day. The analysis reveals that sitting time is most strongly influenced by the level of education, type of employment and nature of work; similar findings have been reported at the level of European Union Member States in a meta-analysis by Beller et al. [5]. As noted in the report, sitting time has increased linearly over the years covered by the research. In 2020, average sitting time on a working day was by 0.4 hours higher than in 2012, while weekend sitting time remained relatively unchanged.

It should also be noted that the COVID-19 pandemic contributed significantly to increased sitting time, as a large proportion of work was performed from home, typically in a seated position in front of computer screens. Moreover, as remote working often brings economic benefits for companies, the number of jobs performed from home within the European Union has, as expected and as confirmed by EU-OSHA research [6], nearly doubled since 2019, reaching 23% in 2024 (exceeding 40% in Finland and the Netherlands). This proportion varies across sectors, with the highest shares observed in information and communication activities (53%), followed by professional, technical and scientific activities (39%).

Prolonged sitting is most commonly encountered among office and administrative workers and employees in the transport sector; however, workers in the textile industry – garment manufacturing – are not exempt. In this sector, prolonged sitting, e.g. at sewing machines, has a substantial impact on workers' health, especially when workstations are not ergonomically designed [7–9]. A study by Šajnović et al. [10] found that Slovenian textile workers are also at increased risk of musculoskeletal disorders (e.g. pain in the back, neck and shoulders), which is reflected in higher rates of sick leave, hospitalisation and work-related disability. As suggested by the authors, these conditions could be mitigated through ergonomic workplace design and effective reorganisation of working time, including more frequent and shorter (active) breaks. The effectiveness of performing stretching exercises during working hours among textile workers is also reported in a study by Ismayenti et al. [11].

1.1 Consequences of prolonged sitting

Prolonged sitting has numerous negative consequences. In recent years, EU-OSHA has conducted research aimed at identifying workplace risk factors across various sectors [6]. Prolonged sitting (reported in 64% of analysed workplaces) and repetitive movements of the wrist/fingers or the entire arm (reported in 63% of analysed workplaces) have been identified as the most prevalent risk factors associated with musculoskeletal disorders. Daneshmandi et al. [12] report that prolonged sitting is associated with fatigue during the working day, reduced job satisfaction, hypertension and musculoskeletal disorders affecting the shoulders, lower back, thighs and knees among office workers. A study by Gao et al. [13] found that workers who predominantly sit during working hours have a 16% higher risk of all-cause mortality and a 34% higher risk of cardiovascular disease mortality compared to employees whose work is not exclusively sedentary. Furthermore, a systematic meta-analysis by Nasir et al. [14] revealed that prolonged sedentary behaviour in the workplace is associated with an increased risk (ranging from 34% to 85%) of mental health problems, including psychological distress, depression, stress, profound sadness, burnout and anxiety.

1.2 Active breaks aimed at promoting workplace health

Prolonged daily sitting must be balanced through ergonomic principles, including popular solutions such as active workstations [12], as well as regular short – primarily active – breaks, which help ensure adequate physical activity among employees.

Active breaks, often also referred to as micro-breaks, are defined by Fritz et al. [15] as planned rest periods during working hours that alleviate worker fatigue and physical discomfort. Their duration may vary from a few seconds to several minutes; however, they are all intended to support employees' well-being, job satisfaction and attitudes towards work. A study by Fischetti et al. [16] demonstrated that a 10-minute break involving outdoor physical activity or guided exercise is effective in improving selective attention and executive functions among healthcare workers. Wayne et al. [13] found that interrupting prolonged sitting every 20–30 minutes with a few minutes of light physical activity (e.g. walking or stretching) can lead to improvements in glucose levels, insulin regulation, blood pressure and other metabolic parameters over a short period of time (e.g. within a single working day). Furthermore, research by Chang et al. [17] indicates that short breaks reduce the risk of developing various health conditions (e.g. cancer, cardiovascular disease, respiratory diseases), while also emphasising the importance of individualising exercises according to workers' physical condition.

The workplace, where employees spend at least one third of their day, represents an appropriate setting for health promotion [18]. Active breaks incorporating physical activity in the workplace can be implemented in various ways, e.g. outdoor breaks, walking within the workplace, using stairs instead of lifts and performing specific stretching exercises. The latter do not require additional exercise equipment or dedicated spaces, as existing workplace elements such as chairs, tables or walls can be used to support the exercises.

Experts in the field (e.g. kinesiologists, physical education specialists, physiotherapists etc.) recommend structuring exercises for prolonged sitting into three categories, i.e. first, stretching exercises, followed by strengthening exercises and finally relaxation exercises, which involve deep breathing, calming the body and preparing to resume work [19]. Active breaks may be performed individually or in groups. In the former case in particular, it is recommended that employees perform exercises tailored to the type of work and the associated physical demands.

1.3 Exercise cards for physical activity

Cards are a combination of images, text, symbols or numbers. Unlike mobile applications, cards are simple, accessible and portable; they occupy little space, contain no distracting elements, are not dependent on an internet connection and provide clear instructions. As a medium, cards enable physical interaction, as they can be shuffled and arranged in ways that users find appropriate, engaging, and consistently varied. The information presented on the cards is concise, clearly structured and logically divided into distinct sections, which facilitates comprehension [20].

In the market analysis conducted as part of this research, we found that exercise cards in the Slovenian language are not currently available on the Slovenian market, whereas the range of exercise cards in foreign languages is considerably broader. Most available exercise card sets are of a general nature, focusing on fitness or yoga, while no card sets specifically designed for exercises during active breaks were identified. From the exercise card sets identified, five examples are presented below, all of which are intended for exercises and meditation during seated work.

The "Desk Yoga Deck" cards (Figure 1A) were first published in 2021 by Chronicle Books [21]. The overall concept was developed by two yoga enthusiasts, namely Darrin Zeer and Daisy Talleur-Zeer. The illustrations were created by the illustrator Subin Yang. One year later, the card set received a silver award at the Society of Illustrator 65 competition in the product design category. [22] The cards are organised into four categories, i.e. chair yoga, standing exercises, meditation, and Pranayama and Mudra exercises, which focus on breathing and hand movements. The exercises are suitable for office workers and are not restricted by age.

"Desk Workout Cards for Home and Office" (Figure 1B) are an exercise card brand by Zinsk, developed by a group of designers under the name Upgraded Us [23]. The company has released several sets of physical activity cards under this brand, with the set examined in this study being specifically designed for movement in the workplace. The package consists of 75 cards and the described exercises are divided into two categories, i.e. exercises performed using body weight and exercises aimed at pain relief and relaxation.

"Animal Moves Office Fitness Deck" (Figure 1C) is a set of exercise cards [24] featuring exercises inspired by animal movements, based on the book "Animal Moves Book" by Darryl Edwards [25]. The card set includes 54 cards designed to promote movement, entertainment and games. The 41 cards describe exercises performed while seated or standing at a desk, five cards present challenge-based activities and the final seven cards outline games. The exercises are suitable for both beginners and more experienced users.

"The Work Wellness Deck" (Figure 1D) is a card set developed by a business consultant and wellness mentor Landre Bickley Eliopoulos and published by Chronicle Books [26]. The set comprises 60 cards divided into three categories: Refresh, which focuses on mental health (e.g. breathing exercises); Connect, which addresses workplace relationships (e.g. practical activities for fostering positive working relationships); and Flow, which is dedicated to physical relaxation (i.e. movement and stretching exercises aimed at maintaining proper posture). The three recurring illustrations featured on the front of each category were created by the illustrator Gracie Lam [27].

The "Desk Yoga Card Deck" (Figure 1E) [28] was developed by a yoga instructor Maria Rojas [29]. The set contains 106 cards featuring exercises primarily intended for office workers who experience prolonged sitting, as well as stress and mental burnout. The cards are organised into six categories, i.e. mindful movement for relieving tension and improving posture, breathing exercises for calming the mind, meditations for refocusing, short exercises to enhance clarity and creativity, and mantras and affirmations for positive motivation. The illustrations were created by a graphic designer Irene Izquierda [30].

Figure 1: Examples of exercise card sets: "Desk Yoga Deck" (A) [21], "Desk Workout Cards for Home and Office" (B) [23], "Animal Moves Office Fitness Deck" (C) [24], "The Work Wellness Deck" (D) [26], "Desk Yoga Card Deck" (E) [28]

The aim of the present study was to analyse the current state of active breaks among employees and to develop and produce exercise cards as a means of encouraging more regular engagement in active breaks in response to prolonged sitting in the workplace.

2 Methodology

The research was conducted in three phases, each phase defining objectives that contributed to the final results.

1. The **preliminary analysis** was performed in three steps: in the first step, we administered a survey questionnaire among employees regarding their daily activity (a more detailed description is provided in section 2.1.1); in the second step, we analysed the Slovenian market for exercise cards and examined five selected sets of foreign exercise cards (a more detailed description is provided in section 2.1.2); based on the survey results and market research, we defined the **guidelines** for the design of exercise cards in the final step.
2. The process of **designing exercise cards** proceeded through several steps, which are described in detail in section 2.2.
3. The **card appearance and usability analysis** was conducted using a survey questionnaire (a more detailed description of this phase is provided in section 2.3).

2.1 Preliminary analysis

2.1.1 Survey questionnaire for assessing employees' daily activity

Software used and the foundations of the questions. The survey questionnaire for assessing employees' daily activity was developed using the Arnes 1KA application (Centre for Social Informatics, University of Ljubljana). The questions were designed based on the results of the internal employee satisfaction survey at the Faculty of Natural Sciences and Engineering, University of Ljubljana (UL NTF), which is annually conducted by the Faculty Committee for Quality and Self-Evaluation at UL NTF, and on the facts that the faculty has a reserved gym time which employees may use once per week but generally do not take advantage of, that the faculty does not offer organised exercise sessions for employees, that no active breaks are provided, and that, given the nature of their work, most employees likely perform their tasks in a prolonged sitting position, which can lead to specific physical strains. The aim of the questionnaire was therefore to determine the extent to which employees are burdened by their work in relation to its demands, how much time they spend sitting at the workplace, and whether they consequently experience pain in specific parts of the body. We were also interested in whether they engage in physical activity during working hours in the form of active breaks or outside working hours.

The questionnaire was approved by the UL NTF Research Ethics Committee at its meeting on 10 May 2025.

Survey questionnaire structure. In the first part of the questionnaire, employees used a 5-point Likert scale to assess their workload (1 – not burdensome at all, 5 – very burdensome) and the demands of their work (1 – not demanding at all, 5 – extremely demanding).

The questionnaire was then divided into items concerning work performed in a sitting or standing position. In both cases, employees reported the average number of hours per day and the types of tasks they perform while sitting or standing. For work performed in a sitting position, they also indicated any consequences they experience as a result of prolonged sitting.

The questionnaire continued with questions on the frequency and type of physical activity performed during employees' free time. For frequency, respondents chose among the following options: 1 – often, 2 – occasionally, 3 – rarely, 4 – never. If they selected options 1, 2 or 3, they were also required to indicate how many times they engage in physical activity (1 – 1–2 times per month, 2 – 1–2 times per week, 3 – 3–4 times per week or more).

This was followed by questions on active breaks. We were interested in how often they take short active breaks during working hours (1 – every half hour, 2 – every hour, 3 – every 2–3 hours, 4 – rarely, 5 – never). If employees selected options 1–4, they were asked whether they use any instructions, recommendations or similar guidance when choosing exercises for these short active breaks. If they selected option 5, they were asked to provide written explanations for why they do not take short active breaks during working hours.

Finally, employees answered a question regarding whether they would like to change their work, workplace or working environment.

Target group. The survey was active from 11 to 19 March 2025. The target group, i.e. all employees, received a link to the survey by email. A total of 59 employees voluntarily completed the survey, representing 33.5% of all employees (this is a typical response rate for employee questionnaires). Both genders were equally represented among the respondents (50.8% female and 49.2% male). 25.4% of the respondents were under 45 years of age, while the majority (74.6%) were over 45 years old.

Statistical analysis. The survey results were organised using Microsoft Excel, while some data were statistically analysed using the Chi-square test in IBM SPSS Statistics.

2.1.2 Market analysis for exercise cards for exercises during prolonged sitting

In our analysis, we first focused on the Slovenian market. We reviewed online stores offering exercise cards and found that these are primarily intended for performing yoga exercises (e.g., Libristo.si (https://www.libristo.si), Temu (https://www.temu.com), Nakitko.si (https://www.nakitko.si) etc.), and that most of them are available only in English. An exception are certain yoga exercise cards by foreign authors that have been translated into Slovenian and can be purchased in online stores, such as "Joga karte za otroke od 3 do 103 let" in the online shop Food for the mind (https://foodforthemind-si.com), "Avocado joga karte za dva in psa" in the online shop Avokado (https://www.avocado-center.si/), and "Joga za otroke – kartice gibalna abeceda" in the online shop Jogaline (https://www.jogaline.si) etc. We also identified an exception among the cards, i.e. Joga kartice Mali Ganeša (https://maliganesa.si), authored by the Slovenian creator Maja Podpečan and illustrated by Urška Kalčič.

Since we did not find any exercise cards in Slovenian designed for performing exercises after prolonged sitting, we searched for English-language examples in foreign online stores. Among the cards identified that prescribe exercises for prolonged sitting, we selected five sets for analysis, i.e. "Desk Yoga Deck", "Desk Workout Cards for Home and Office", "Animal Moves Office Fitness Deck", "The Work Wellness Deck", and "Desk Yoga Card Deck". A brief description of these sets has already been provided in section 1.3.

In the analysis of the cards, we highlighted their basic characteristics (box and card dimensions, number of cards), the elements present on the cards (images, text, symbols etc.), the illustration style, the colour palette and any additional features. The results are presented in section 3.2.

Following the survey on employees' daily activity and the analysis of the selected card sets, we formulated guidelines for the design of exercise cards, which are described in detail in section 3.2.

2.2 Design process for exercise cards

The design process for the exercise cards is presented in Table 1. As shown in the table, based on the established guidelines, we began by generating ideas for the content and visual design of the exercise cards intended for active breaks. The illustrations were created in a simplified manner, using a two-dimensional illustration style. Once the illustrations were completed, we proceeded with selecting the colour palette and typefaces. This was followed by determining the composition between the typographic and graphic elements, designing the front and back sides of the cards, and preparing the layout for print. In the final stage of the process, the design of the cardboard tuck box, created in accordance with the overall visual identity of the card set, was included as well.

Table 1: Workflow for production of cards

Phase of process	Brief description	Use of hardware/ software
Categories and exercises	Determination of the number of exercise categories, selection of exercises within each category and preparation of instructions (in collaboration with a physiotherapist).	/
Ideas	Collecting ideas for the design of the exercise cards based on the established guidelines.	/
Sketches	Based on simulated real human movements, drawing initial sketches with appropriate proportions of body structure, head shape and arm length.	Wacom tablet/Adobe Photoshop
Design of final characters and additional elements	Vectorisation of the sketches and determination of the basic appearance; design of all remaining characters.	Computer/Adobe Photoshop, Adobe Illustrator CC
Card layout and design	Determination of the basic grid for card layout; selection of typefaces and colours, and defining the composition between typographic and graphic elements.	Computer/Adobe InDesign CC
Packaging design	Adjustment of standard box grid dimensions; design of the box in accordance with the overall visual identity of the cards.	Adobe Illustrator

2.3 Survey questionnaire on appearance and usability of cards

Software used and question framework. The survey questionnaire on the appearance and usability of the exercise cards was developed using the Arnes 1KA application (Centre for Social Informatics, University of Ljubljana). The purpose of the questionnaire was to assess the appropriateness of the visual design of the exercise cards (illustrations, typology, colour palette), the comprehensibility of the exercises presented and the usability of the cards among end users. The questions were formulated on the basis of the designed prototype.

The survey questionnaire was approved by the Research Ethics Committee UL NTF at its session on 10 May 2025.

Structure of the survey questionnaire. The questionnaire was divided into six sections. In the first section, respondents evaluated the general appearance of the cards and their packaging on a 7-point Likert scale (1 – I do not like the appearance at all, 7 – I like the appearance very much). In the next section, respondents assessed the comprehensibility of the exercises across all three categories on a 5-point Likert scale (1 – strongly disagree, 5 – strongly agree). They evaluated the following statements: "The written instructions for performing the exercise are understandable.", "The instructions are too long.", "The illustrative depiction contributes to a better understanding of how to perform the exercise.", "Based on the illustrative depiction, it is possible to perform the exercise even without written instructions." and "The exercise can be performed at my workplace." Subsequently, respondents evaluated the visual appearance of the illustrations on a 7-point Likert scale (1 – The illustrations are not appealing to me, 7 – The illustrations are very appealing to me) and, in a multiple-choice question, indicated how they perceived the illustrated characters (fun, professional, realistic or simple). In the next part of the questionnaire, respondents were asked about the appropriateness of the selected colour palette. They evaluated four statements on a 5-point Likert scale (1 – strongly disagree, 5 – strongly agree): "The colour palette of the categories is sufficiently clear to distinguish between categories.", "The colour palette is visually appealing.", "The colours complement each other well." and 'The colours are playful yet calming." The following category addressed the appropriateness of the fonts. Respondents evaluated four statements on a 5-point Likert scale (1 – strongly disagree, 5 – strongly agree): "The text is sufficiently legible.", "The contrast between the text and the background is appropriate (enabling smooth reading).", "The choice of fonts aligns with the overall visual identity of the cards." and "The design hierarchy between headings and body text is clear/appropriate." The final section of the questionnaire focused on the usability of the cards. Through single-choice questions, we aimed to determine whether respondents would use the cards to carry out short active breaks during prolonged sitting at work (possible answers: yes, maybe, no), in what manner they would perform such active breaks (possible answers: as a team break or individually) and whether, in their view, frequent implementation of active breaks supported by the exercise cards during prolonged sitting would increase their level of physical activity (possible answers: yes, maybe, no).

Target group. The survey was active from 19 to 25 March 2025. It was distributed to a broader target group, i.e. employees and students of UL NTF. We opted for a larger target group for two reasons: (1) the exercise cards were originally intended for UL NTF employees; nevertheless, access will later also be provided to students whose curricula do not include physical education; and (2) to increase the number of responses, including both younger and older generations of respondents. A link to the survey was sent to the target group by email. A total of 138 respondents completed the questionnaire voluntarily. No demographic data were collected in the survey.

Statistical analysis. The survey results were processed in Microsoft Excel, while the data were analysed using IBM SPSS Statistics.

3 Results and discussion

3.1 Survey results on employees' daily activity

In the survey, we examined whether there is a relationship between job demands and employee workload (Figure 2). To test the association between the two variables, we conducted a chi-square test of independence. Based on Pearson's chi-square test (χ^2 = 34,91, $p < 0.001$), we rejected the null hypothesis that the variables are independent, as the results indicate a statistically significant association between perceived workload and perceived job demands; higher levels of job demands coincide with higher perceived workload among the respondents.

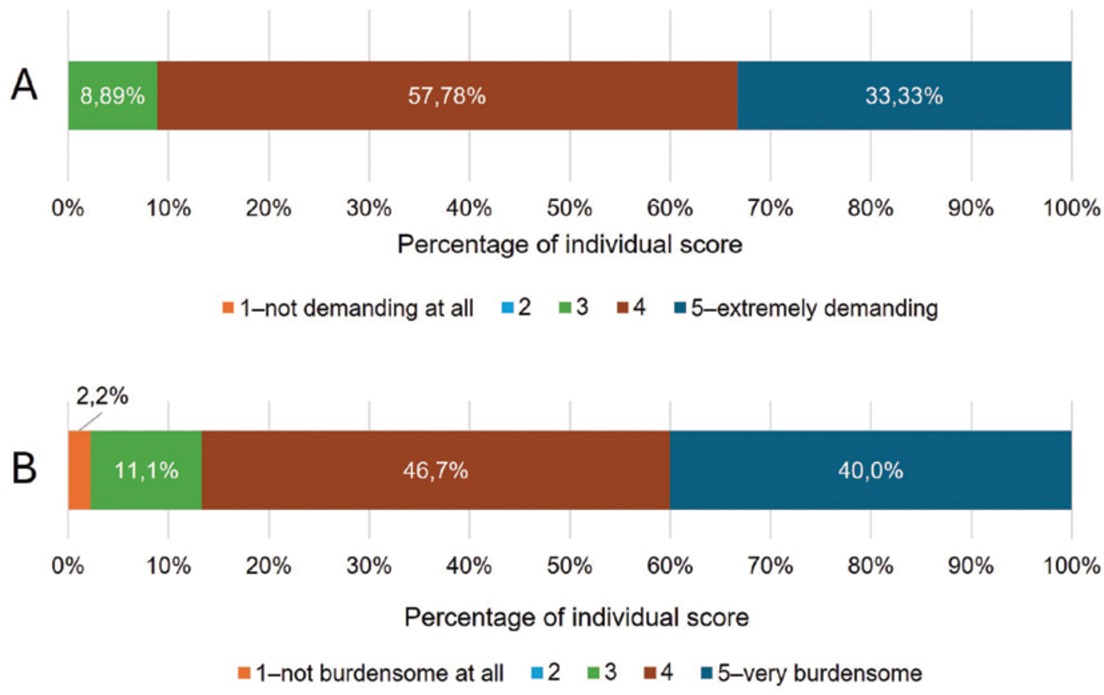

Figure 2: Job demands (A) and workload (B) of respondents

From the results, we found that 11.7% of respondents perform their work in a standing position, while the majority (88.3%) work in a seated position. Standing work is performed, e.g., in laboratories (sample preparation, practical sessions, operating equipment etc.), in other rooms where various types of practical work are conducted, during lectures, student consultations and in other forms of technical support. Seated work most commonly includes working with computers and analytical devices, as well as other desk-based tasks (reviewing seminar papers, exams, articles, proofreading etc.), attending meetings and similar activities. Respondents spend on average 2 hours per day working in a standing position ($\bar{x}$ = 2.0 h/day, SD = 0.58 h/day), while they spend on average 2.9 hours per day working in a seated position ($\bar{x}$ = 2.9 h/day, SD = 0.77 h/day).

We compared the results on time spent working in a seated position with the findings from the 2022 Eurobarometer survey [32], which showed that 19.0% of Slovenia's population spend 2 h 30 min or less seated, 43.0% spend between 2 h 31 min and 5 h 30 min, 27% between 5 h 31 min and 8 h 30 min, and the remaining 11.0% more than 8 h 30 min per day. Our results indicate that the participants in our study spend approximately the same amount of time seated as the largest share of the Slovenian population.

The survey results showed that the respondents engage in physical activity during their leisure time, with 55.9% doing so frequently, 28.8% occasionally and 15.3% rarely. We compared these findings with the Eurobarometer survey [32], which indicates that 11.0% of Slovenia's population are regularly physically active, 41.0% are almost regularly (frequently) physically active and 23.0% are rarely active, while as many as 25.0% are completely inactive. These comparisons suggest that the respondents in our survey are more physically active than the average Slovenian population. We additionally note that 10.2% of respondents engage in physical activity 1–2 times per month, 39.0% 1–2 times per week, while 50.8% engage in physical activity 3–4 times per week or more.

Despite the relatively high levels of reported physical activity outside working hours, only 7.5% of respondents do not experience any consequences of working in a seated position. As many as 30.2% of respondents report back pain, 18.1% report neck pain, 14.7% have dry and burning eyes, primarily due to computer work, 13.8% experience wrist pain, 12.1% leg pain and 11.2% of respondents suffer from headaches.

The pains reported by the respondents could be alleviated through more frequent active breaks, which, however, are rarely performed. Only 1.7% of respondents take active breaks every half hour, 20.0% every hour and 10.0% every 2–3 hours. As many as 50.0% of respondents take active breaks very rarely, while 18.3% do not take them at all. The exercises performed during active breaks are performed freely, without instructions, and only one respondent follows exercises recommended by a physiotherapist. Respondents who do not take active breaks report that they either forget about them or do not take the time due to a heavy workload, while some believe they do not need active breaks since they are sufficiently active in their free time.

A total of 48.9% of respondents do not wish to change their work, workplace or working environment, while the remaining respondents would like to better balance work and rest, spend less time at the computer and have more active breaks. Some also expressed the desire for more appropriate work equipment, particularly a height-adjustable desk and an ergonomic chair.

3.2 Analysis results of selected sets of exercise cards and establishment of guidelines for designing exercise cards for active breaks

The results of the analysis of the five selected sets of exercise cards are presented in Appendix 1. Based on these findings, we subsequently formulated guidelines for the design of exercise cards.

Designing the content and number of exercise cards:

- Selection of appropriate exercises for per-

forming active breaks during prolonged sitting, along with proposals for short exercise programmes.
- The number of exercise cards is determined based on the number of selected exercises. An additional card with short programmes and a card containing instructions for using the exercise cards will be included.
- The exercise cards will be of functional size (proposed dimensions: 70 mm × 110 mm).

General aspects of design:
- A system of categorising the cards will be used, with each category marked by its own colour scheme.
- The colour scheme of the exercise cards will be adapted to the target group (male and female users).
- For longer texts, predominantly sans-serif typefaces will be used, as they are legible, simple and convey a sense of modernity, while serif typefaces will be used for headings.
- In the design of graphic elements and their composition, consistency will be ensured (placement of graphic elements, uniform typeface selection and a consistent colour scheme).

The front side of the card will enable a quick overview of the exercise; therefore, it will include the following information: the name of the exercise, a simple and clear illustration showing how the exercise is performed, and a sequential number that will allow easy sorting of the cards as well as easier retrieval when using pre-designed exercise programmes. The entire front side will be designed with clearly indicated sections to ensure quick recognition of the content.

The reverse side of the card will include information necessary for performing the exercises. For this purpose, the following elements will be provided on the reverse side: a brief and comprehensible description of the exercise (preferably presented in numbered steps), tips on correct posture or on how to avoid common mistakes, and the recommended number of repetitions and duration of the exercise. The content on the reverse side will also be designed with clearly indicated sections, enabling quick and intuitive understanding and recognition of the information.

Packaging – the cardboard tuck box is in direct contact with the cards and protects them from abrasions and damage. It is the main marketing element and the first point of contact for new users; hence, its design must be careful and well considered. The packaging will have a simple form with a top-opening mechanism. The design of the packaging will follow the visual elements used on the cards: typography, colour palette and graphics. The packaging will display the name of the card set, an illustration of a selected exercise and office-related objects that indicate the intended use of the cards. A short description informing the user about the content/theme of the cards will also be included, e.g. "33 exercise cards for movement during work".

Based on the established guidelines, we designed the final prototype of the exercise cards.

3.3 Designing exercise card prototype

3.3.1 Selection of categories and exercises

Following the physiotherapist's recommendations, the exercises were divided into three categories, i.e. exercises for stretching and strengthening the legs; exercises for the trunk; and exercises for the upper body, i.e. the neck and arms. Each category included 11 exercises. The instructions for performing the exercises were prepared in a clear manner, using no more than four bullet points. For certain exercises, additional notes were provided to facilitate execution in cases where the original version might be too difficult for the user.

The exercise card set comprised 33 cards, to which we added two additional cards, namely one with instructions for use and one listing recommended exercise programmes.

3.3.2 Arranging elements on cards

In arranging the elements on the cards, we followed the guidelines outlined in section 3.2. All cards share the same layout style (Figure 3A), with only the colour palette varying according to the exercise category. On the front side, the exercise illustration is placed within a rounded frame; the card number is positioned in the wider upper margin and the exercise name in the wider lower margin. On the reverse side, also within a bordered frame, we included the exercise name and its description; the card number is again positioned in the wider upper margin and the number of repetitions and exercise duration in the wider lower margin. The two additional cards (Figures 3B and 3C) follow the same intended layout, except they do not include illustrations. On the first of these cards, one side contains instructions related to exercise performance, while the other side provides information about the contents of the set. The second additional card contains descriptions of the pre-prepared exercise sequences.

Figure 3: Front and reverse side of exercise cards (A), cards with instructions (B) and cards with recommended sets of exercises (C)

3.3.3 Illustrations

The illustrations (Figure 4) are created in a simple flat illustrative style, without the use of textures or shading. The application of line drawing with curved lines ensures that each depicted movement is clear, simple and easy to execute. Arrows are additionally included to facilitate the understanding of the exercise performance and to illustrate the movement pathway. Stylised figures with minimal detail enable users to focus on the execution of the exercise. The use of lighter and darker tonal values indicates which limb is positioned in the foreground and which in the background. The figures are predominantly depicted from a side view, allowing the movement sequences to be more clearly perceived.

In illustrating the figures, diversity was taken into account: female and male figures are differentiated on the basis of body size, head structure, variations in clothing, hairstyles and related features. Facial expressions are neutral and relaxed. In most cases, the figures are depicted as full-body representations, with the exception of the arm and neck categories, where the focus is placed on the upper body.

The figures are situated within a spatial context, thereby presenting users with the possibility of performing the exercises in everyday environments, e.g. office or home. For this purpose, elements including chairs, tables, a wall, a computer and plants are incorporated using a grey colour palette.

3.3.4 Colour palette

The selected colour palette consists of 19 colours, predominantly pastel tones, which are visually calming (Figure 5). Three distinct colours are used to differentiate the three exercise categories. The category of leg exercises is denoted by blue, which is associated with calmness and relaxation. The category of arm and neck exercises is indicated by green, representing health and vitality, while the category of trunk exercises is marked by pink, reflecting warmth and a soothing effect [33]. Grey is used for objects depicted in the background.

Figure 4: Diversity of figures and background elements (wall, chair)

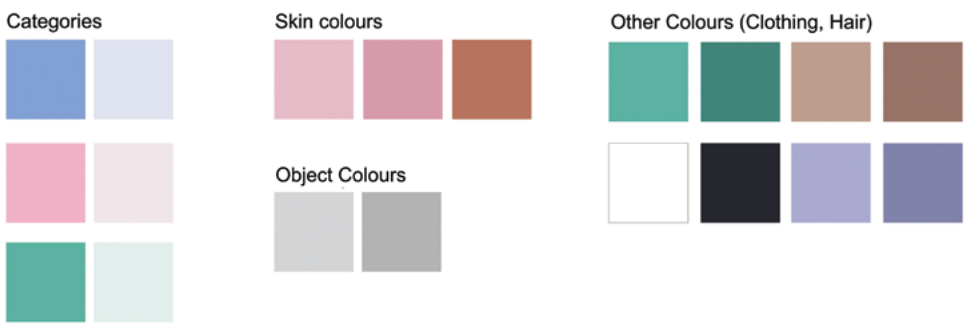

Figure 5: Selected colour palette

3.3.5 Typography

The overall visual identity of the cards is characterised by the use of two typefaces, i.e. the serif typeface Dashiell Bright for headings and the sans-serif typeface Roboto for longer bodies of text (Figure 6). Dashiell Bright is used for the exercise titles in bold uppercase letters, while Roboto, which ensures good legibility, is employed for the exercise instructions and repetitions in both light and bold weights. Both typefaces are also applied in the design of the packaging.

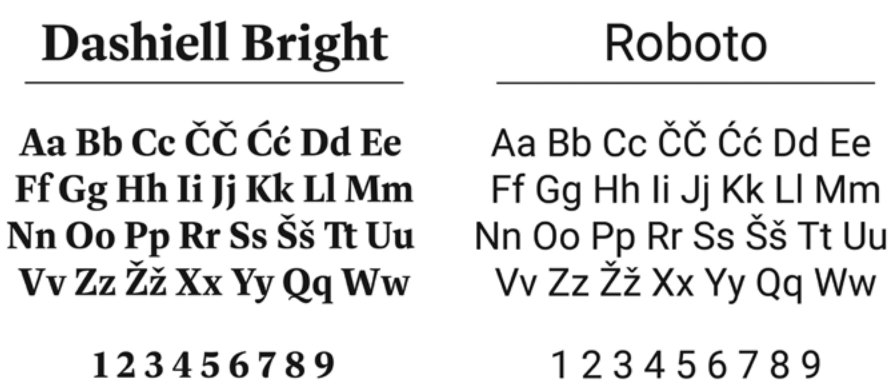

Figure 6: Selected typefaces Dashiell Bright and Roboto

3.3.6 Tuck box

For the visual design of the cardboard tuck box, the same typefaces and colour palette as those used on the cards were applied (Figure 7), with blue selected as the primary colour of the box. The front panel features the name of the exercise cards and an illustration of a person performing an exercise. The side panels include the required logos and a statement describing the project within which the cards were physically produced and used. The back panel also features an illustration of a person performing an exercise, along with information on the number of exercises included in each category. The packaging is designed in a minimalist and orderly manner. The box follows a classic tuck-end structure, with top and bottom tuck-in flaps. The dieline was exported from the Templatemaker website [34], which allows the specification of packaging dimensions and the adjustment of flap sizes. The box measures 113 mm × 72 mm × 20 mm.

Figure 7: Cardboard tuck box (packaging)

3.4 Survey results on visual design and usability of cards

The developed prototype of the card set was evaluated using a questionnaire survey. The overall appearance of the cards and packaging was rated highly by the respondents on a Likert scale, with a high mean score ($\bar{x}$ = 5.51). As shown in Figure 8, responses are concentrated at the higher end of the scale (scores 5, 6 and 7), indicating a strongly positive overall perception of the visual appearance of the card set.

The clarity and comprehensibility of the visual representation and written instructions of the exercises were evaluated using selected cards from each category (Figure 9).

As shown in Table 2, the respondents rated the clarity of the written instructions for performing the exercises in all three card examples with high mean scores ($\bar{x}$ = 4.55/4.69/4.55), indicating well-designed textual descriptions of the exercises. The contribution of the illustrative representations to improved understanding of exercise performance is confirmed by the similarly high mean scores ($\bar{x}$= 4.66/4.75/4.65), underscoring the important role of visual representations in the effective communication of instructions. Based on the low mean scores ($\bar{x}$ = 2.52/2.39/2.34), it can be concluded that the respondents generally agreed that the instructions were not overly long. However, the relatively high standard deviation values (SD = 1.52–1.63) should not be overlooked, as they indicate considerable variability in respondents' opinions and suggest that some participants may have perceived the instructions differently from the majority.

Based on the results presented in Table 2, it can be concluded that an illustrative representation without

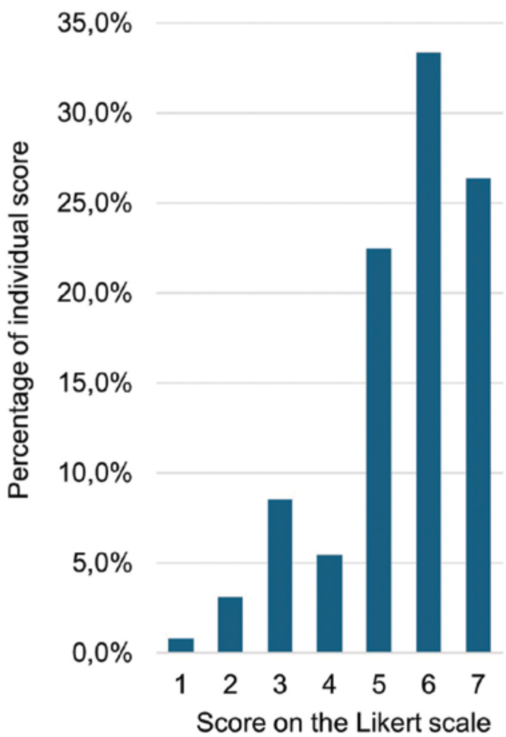

Figure 8: Distribution of ratings of overall appearance of card set on Likert scale (1 – I do not like the appearance at all, 7 – I like the appearance very much) (n = 129, Mo = 6, SD = 1.94)

written instructions is sufficient for performing the exercise. The highest level of agreement with this statement was observed for the exercise "Table push-ups" ($\bar{x}$ = 4.41, Mo = 5.0), for which the ratings were also the most consistent (SD = 0.73). High ratings indicating agreement with the statement were also reported for the exercises "Chair squat" ($\bar{x}$ = 3.79, Mo = 4.0) and "Triangle" ($\bar{x}$ = 4.10, Mo = 5.0); however, in these cases, the ratings were somewhat more dispersed (SD = 1.11), which may suggest that an illustrative representation alone is not always sufficient for understanding the exercises.

The respondents indicated that most of the presented exercises could be performed in their workplace, as reflected by the high mean feasibility rating for the exercise "Chair squat" ($\bar{x}$ = 4.31, Mo = 5.0). A similar pattern was observed for the exercise "Triangle"; however, a slightly greater variability in responses was noted (SD = 1.24), which may indicate differences in spatial or ergonomic conditions across workplaces. The lowest feasibility rating was assigned to the exercise "Table push-ups" ($\bar{x}$ = 3.94, SD = 1.31), suggesting that this exercise may be more dependent on specific spatial or technical conditions.

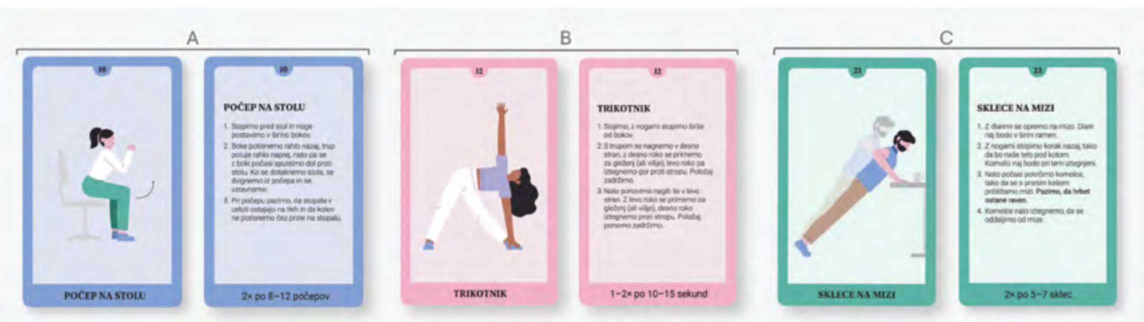

Figure 9: Selected cards from individual categories on the basis of which the clarity and comprehensibility of the exercise representations were evaluated: "Chair squat" (A; blue), "Triangle" (B; pink) and "Table push-ups" (C; green).

The respondents further evaluated the visual appearance of three illustrations on the exercise cards (Figure 10) using a 7-point Likert scale. The visual appearance of the illustrations received a high mean rating ($\bar{x}$ = 5.89, n = 116), the most frequent rating being 6 (Mo). Although the ratings were predominantly high, the relatively large standard deviation (SD = 1.53) indicates some variability in respondents' opinions, suggesting that the visual appearance of the illustrations was not perceived as equally appealing by all respondents. As shown in the diagram in Figure 10, respondents most fre-

Table 2: Ratings of clarity-related statements

Statement	Card category	n [a]	Distribution of ratings on Likert scale (1 – strongly disagree, 5 – strongly agree)					$\bar{x}$ [b]	SD [c]	M_o [d]
			1	2	3	4	5			
The written instructions for performing the exercise are clear.	Blue	130	0.00	0.77	6.15	30.77	62.31	**4.55**	0.42	5.00
	Green	124	0.00	0.00	2.42	26.61	70.97	**4.69**	0.27	5.00
	Pink	121	0.00	0.00	6.61	32.23	61.16	**4.55**	0.38	5.00
The instructions are too long.	Blue	129	27.13	24.03	24.03	19.38	5.43	**2.52**	1.52	1.00
	Green	125	31.20	28.80	15.20	19.20	5.60	**2.39**	1.60	1.00
	Pink	121	33.06	28.93	16.53	14.05	7.44	**2.34**	1.63	1.00
The illustrative representation contributes to a better understanding of how to perform the exercise.	Blue	129	1.55	0.00	6.98	13.95	77.52	**4.66**	0.55	5.00
	Green	124	0.81	0.00	4.03	13.71	81.45	**4.75**	0.37	5.00
	Pink	121	0.83	0.83	8.26	12.40	77.69	**4.65**	0.55	5.00
Based on the illustrative representation, the exercise can be performed even without written instructions.	Blue	130	1.54	12.31	21.54	34.62	30.00	**3.79**	1.11	4.00
	Green	124	0.81	2.42	12.10	24.19	60.48	**4.41**	0.73	5.00
	Pink	121	3.31	4.13	18.18	28.10	46.28	**4.10**	1.11	5.00
The exercise can be performed at my workplace.	Blue	130	1.54	5.38	12.31	22.31	58.46	**4.31**	0.97	5.00
	Green	124	4.03	6.45	25.00	20.97	43.55	**3.94**	1.31	5.00
	Pink	122	0.82	10.66	19.67	14.75	54.10	**4.11**	1.24	5.00

[a] number of respondents, [b] arithmetic mean of ratings, [c] standard deviation, [d] most frequently selected rating

quently described the illustrations as simple (42.3%) and fun (29.5%), while smaller proportions (14.1%) perceived them as realistic and professional.

The ratings of the suitability of the colour palette used for the exercise cards (Figure 11) were on average very high. The statements received mean ratings ranging from 4.31 to 4.52 on a 5-point Likert scale, the most frequent rating for all items being 5 (Mo). The participants evaluated the colour palette as sufficiently clear for distinguishing between categories, visually appealing and well balanced in terms of colour harmony. The palette was also perceived as playful and relaxing. Low to moderate standard deviation values indicate a relatively high level of consistency in the responses.

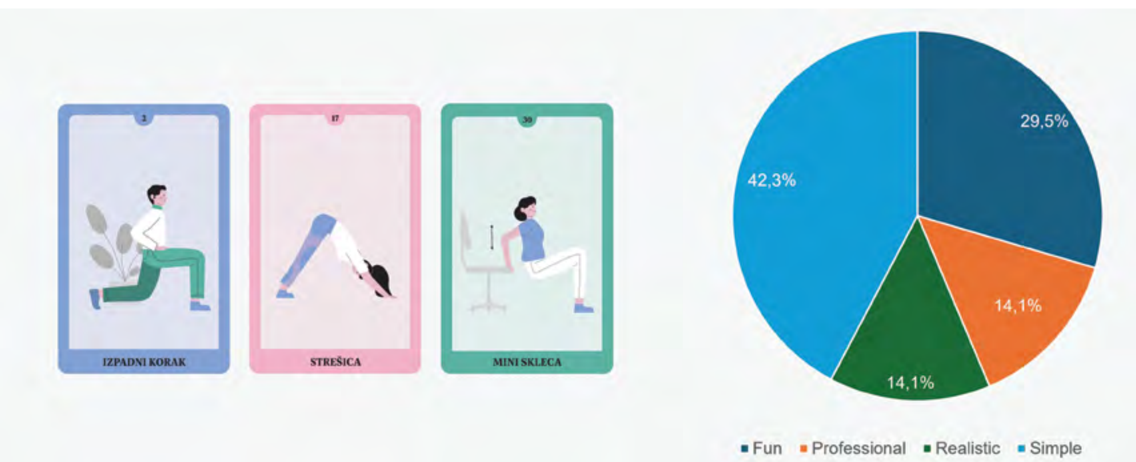

Figure 10: Illustrations of three exercise cards (left) and respondents' perceptions of illustrations (right) (n = 220)

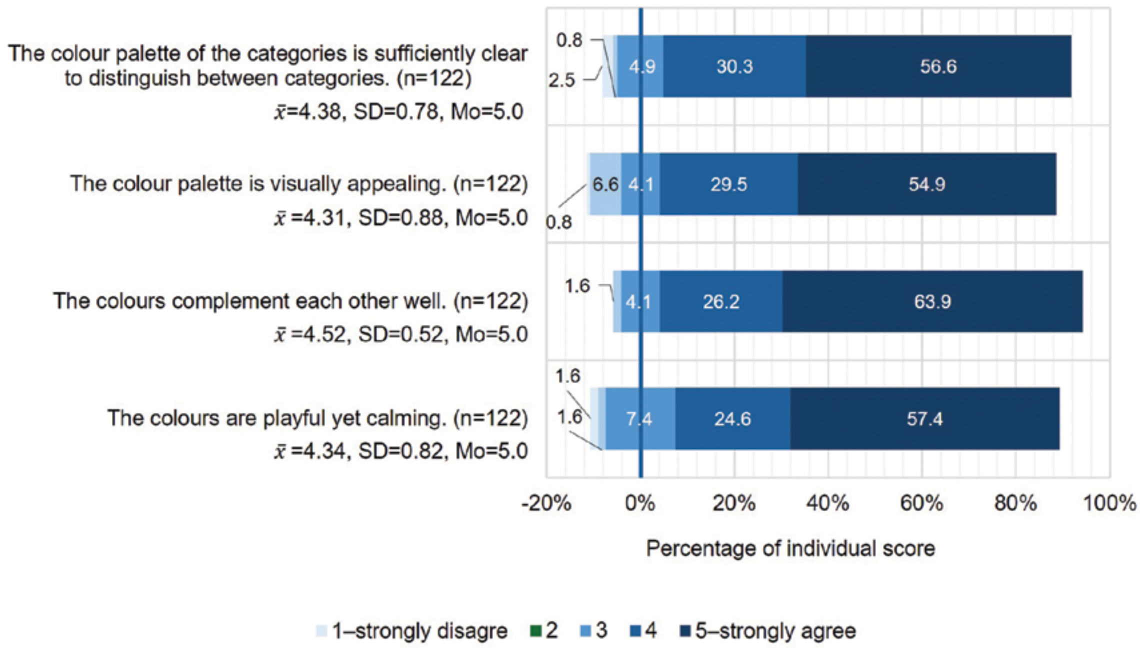

Figure 11: Colour palette suitability

The respondents rated the suitability of the selected typefaces (typography) used on the exercise cards predominantly with high mean scores (Figure 12). Text legibility received a mean rating of 4.47 (SD = 0.49), indicating clear typography with appropriate letter size and proportions. The relatively low standard deviation reflects a consistent opinion among respondents. The contrast between the text and the background received the highest mean rating (4.66, SD = 0.38), with a high level of agreement across the respondents. The alignment of the selected typefaces with the overall visual identity of the cards was rated slightly lower ($\bar{x}$ = 4.18, SD = 1.10), with greater variability in individual ratings. This outcome was expected, as this item represents a more subjective assessment related to individual aesthetic preferences and the perceived coherence of visual elements. The mean rating for the visual hierarchy between headings and body text was high ($\bar{x}$ = 4.53, SD = 0.55), indicating that the respondents were able to recognise the structure and distinguish between different textual elements, such as headings, subheadings and body text.

Approximately one third of the respondents (40.5% of n = 121) indicated that they would definitely use the exercise cards to perform short active breaks during prolonged sitting at work. The largest proportion of the respondents (43%) selected the response "maybe". This group is particularly important, as it reflects an openness towards using the exercise cards; however, additional information and motivation would be required to encourage a definitive decision regarding regular use. A total of 16.5% of respondents stated that they would not use the exercise cards. These responses may be associated with personal preferences, workplace conditions or a lack of interest in such activities.

Of those respondents who indicated that they would definitely or possibly use the cards for active breaks (n = 100), 76.0% expressed a preference for performing the breaks individually, as needed, while 21.0% would prefer to perform the exercises as part of a team break. A small proportion of the respondents (3.0%) indicated that they would perform the exercises both individually and as part of a team.

The majority of the respondents (64.5%, n = 121) believe that the frequent implementation of active breaks using the exercise cards during prolonged sit-

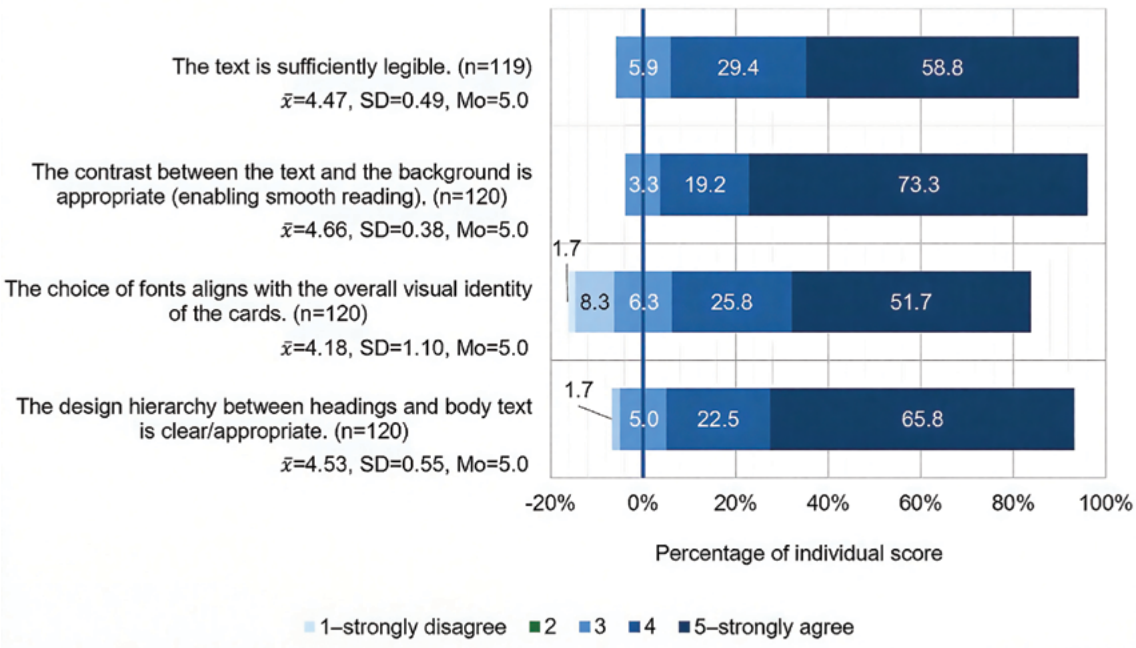

Figure 12: Suitability of selected typefaces (typography)

ting at work would indeed contribute to an increase in their physical activity. Although 28.9% of respondents were not entirely certain, they did not exclude the possibility of increased physical activity. This group represents a potential target, as appropriate presentation or positive user experience could encourage more frequent engagement in active breaks. Only a small proportion of the respondents (6.6%) felt that active breaks would not have an impact on their physical activity.

3.5 Final product

Following the analysis of the survey results on the appearance and usability of the exercise cards, the prototype was refined into its final form and prepared for printing. In selecting the materials, considerations included durability, tactile quality, visual appearance and functionality.

Card printing and finishing: 300 g/m^2 matte coated paper; double-sided digital printing; double-sided matte lamination; rounded corners.

Tuck box printing and finishing: 250 g/m^2 matte coated paper; single-sided digital printing; final die-cutting of the dieline and gluing.

The final appearance of the card set and tuck box is shown in Figure 13.

4 Conclusion

The research results confirm that prolonged sitting has a significant impact on employees' well-being and highlight the need for the introduction of short, structured active breaks. The results of the survey assessing respondents' daily activity revealed a statistically significant relationship between job demands and perceived workload, indicating that higher job demands are associated with increased levels of strain. Although the majority of respondents reported engaging in regular physical activity during their leisure time, a substantial proportion still experience discomfort in the back, neck or upper limbs during working hours.

The analysis of the current situation also showed that respondents rarely engage in active breaks. The most frequently cited reasons include a lack of time and motivation, as well as high workload, which consequently leads to prolonged sitting. For this reason, the concept of designing short, visually clear

Figure 13: Set of exercise cards for active breaks during prolonged sitting (photo: Lidija Svetek)

and quickly executable instructions in the form of exercise cards is particularly relevant, as it enables employees to incorporate movement into their working day in a quick and straightforward manner.

Based on the analysis of existing exercise card sets, guidelines were developed for the design of an original set of exercise cards for active breaks. These guidelines ensure a clearly structured, visually coherent and functional design. The exercise card set is organised into three exercise categories (legs, trunk and upper body) and includes a selection of illustrated exercises, written instructions and pre-defined programmes. Particular emphasis was placed on visual simplicity, clear and comprehensible descriptions, diversity in the illustrated figures, carefully considered colour coding of categories and typography that ensures good legibility.

The evaluation of the exercise card set prototype demonstrated a positive response from the respondents. The overall appearance of the cards was rated as very good, and high ratings were also assigned to the clarity and comprehensibility of both the instructions and the illustrations. The illustrations were perceived as simple, visually appealing and sufficiently informative for performing the exercises, while the colour palette was regarded as coherent and effective in distinguishing between categories. The majority of the respondents believed that the regular use of the cards in the form of active breaks could contribute to increased physical activity during working hours. In this context, respondents indicated a preference for performing active breaks individually, allowing them to self-regulate the timing of their breaks.

The results confirm that exercise cards have considerable potential to reduce the negative effects of prolonged sitting and to promote healthy movement habits in the workplace. The finalised exercise cards represent an effective tool that could be meaningfully integrated into broader workplace health promotion programmes. Future research would benefit from a long-term evaluation of the effects of using the exercise cards, including the frequency of exercise performance in real workplace settings and the impact of active breaks facilitated by the cards on employee productivity and satisfaction, not only at our faculty but also in a wider range of organisational contexts.

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Data availability statement
The data supporting the findings of this study are publicly available in the Repository of the University of Ljubljana (RUL) as of 9 December 2025, under the persistent identifier (PID) 20.500.12556/RUL-176689 [35].

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Appendix 1: Analysis results of five sets of exercise cards

Card set caharacteristcs	Sets of cards				
	Desk yoga deck [21]	**Desk workout cards for home and office [23]**	**Animal moves office fitness deck [24]**	**The work wellness deck [26]**	**Desk yoga card deck [28]**
Illustration style	Freehand drawing without strictly straight lines, featuring bold and colourful shapes.	Figures are digitally illustrated in vector format; shading is used in some instances; the illustration style is simple.	Clean line work with simple shading, emphasising functionality and correct exercise execution.	The illustration style conveys a sense of elegance. Illustrations are partly hand-drawn and partly digital, incorporating textures.	The illustrations are vector-based and digitally rendered in a two-dimensional flat style. The figures appear relaxed, simple and calm.
Card elements	The front side features an illustration demonstrating the exercise, supplemented with elements from the work environment (e.g. plants, lamps, desks, chairs). The top of the reverse side indicates the category name, followed by exercise instructions and a short motivational quote. The text is sometimes humorous and sometimes positively framed.	The front side displays an illustration of the exercise; more complex exercises are shown in multiple steps. Above the illustration are the exercise name, number of breaths, repetitions and duration; at the bottom, the targeted body part is indicated. The reverse side includes a smaller illustration, the exercise name, duration and a written description of the exercise sequence.	All key information is presented on the front side of the card. The upper section (a coloured rectangle) contains the exercise name and duration according to difficulty level. Below, on a white background, the exercise illustration and instructions are provided.	The front side includes an illustration and the category name, while the reverse side provides the exercise description. The environment and everyday objects are depicted using selective visual information.	In addition to an illustrated demonstration of the exercise within a white frame, the cards include the exercise name, category name, duration and a difficulty indicator in the upper right corner. Selected linear symbols (e.g. moon and sun) are also included.
Colour palette	The colour palette is highly diverse and varies by category.	The colour palette differentiates the categories: the first category is turquoise and the second orange. All elements are harmonised with the category colour.	Categories are marked with green or dark blue rectangles, while other elements and the box appear in various colours.	Dedicated illustrations for the three categories are presented on the front side, each using a distinct colour palette.	The colours of the six categories are visible in the backgrounds of the figures and vary between cool and warm tones.
Additional elements	A short guide with instructions for performing the exercises is included.	Three additional cards provide recommended stretching routines, body-part-specific routines and a suggested 5-minute workout.	Cards featuring challenges and games are included.	The content of the cards differs slightly from the others, as they include exercises focused on mental health and workplace relationships.	A small wooden card stand is included.
Card size		88 mm × 63 mm	88 mm × 63 mm	156 mm × 102 mm	80 mm × 110 mm
Number of cards	52	75	54	60	106
Box size	103 mm × 40 mm × 158 mm	95 mm × 76 mm × 36 mm	N/A	160 mm × 40 mm × 103 mm	N/A

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Into the Revolution of Industry 5.0 in Ensuring Ethical Fashion: A Review on Conceptual Framework

Industrija 5.0 - revolucija v zagotavljanju etične mode: pregled pojmovnega okvira

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Abstract

The global fashion industry faces numerous ethical concerns. The Global South, in particular, suffers from unethical practices in the fashion industry due to the complexity of the supply chain and the lack of regulations governing workers' welfare. Additionally, the rapid growth of the fashion industry has also caused a negative impact on the environment. Ethical fashion prioritizes transparency, accountability and the well-being of workers, while ensuring environmental and social sustainability. This study suggests Industry 5.0 as a suitable approach to ensure ethical fashion due to its focus on human centricity. Industry 5.0 values human well-being with a synergy of technologies such as artificial intelligence, blockchain, digital twin and energy-efficient automation. The proper implementation of Industry 5.0 in the fashion industry can promote ethical fashion practices by ensuring fair labour practices, transparency and accountability, by and minimizing environmental impacts. Through an in-depth review of literature regarding Industry 4.0, Industry 5.0 and ethical fashion, this study develops a framework for ethical fashion. A logical, human-centred framework for Industry 5.0 in the context of ethical fashion is produced by searching peer-reviewed literature for specific keywords, applying inclusion criteria and thematically analysing the content to extract significant concepts, technologies and ethical issues. This study also highlights the challenges of integrating Industry 5.0 with ethical fashion, such as building the skills of labourers, the consideration of socio-centricity and policy changes due to the emergence of Industry 5.0.
Keywords: Industry 5.0, ethical fashion, sustainable, transparency

Izvleček

Globalna modna industrija se sooča s številnimi etičnimi izzivi. Globalni jug je zaradi kompleksnosti dobavnih verig in pomanjkljivega urejanja na področju varstva delavcev še posebno izpostavljen neetičnim praksam v modni industriji. Hitra rast modne industrije ima poleg tega izrazite negativne vplive na okolje. Etična moda poudarja preglednost in odgovornost ter dobrobit delavcev ob sočasnem zagotavljanju okoljskih in družbenih vidikov trajnosti. Raziskava opredeljuje industrijo 5.0 kot primeren pristop k zagotavljanju etične mode, saj temelji na človeku usmerjenem pristopu. Industrija 5.0 poudarja blaginjo človeka v sozvočju s tehnologijami,

kot so umetna inteligenca, veriženje blokov, digitalni dvojček in energetsko učinkovita avtomatizacija. Ustrezna uvedba industrije 5.0 v modni industriji lahko prispeva k spodbujanju etičnih praks v modi, saj omogoča zagotavljanje pravičnih delovnih razmer, preglednosti in odgovornosti ter zmanjševanje okoljskih vplivov. Na podlagi poglobljenega pregleda literature o industriji 4.0, industriji 5.0 in etični modi raziskava oblikuje pojmovni okvir etične mode. Smiseln in človeku usmerjen okvir industrije 5.0 v kontekstu etične mode je razvit s sistematičnim pregledom recenzirane literature, ki vključuje iskanje po ključnih besedah, uporabo vključitvenih kriterijev ter tematsko analizo vsebin za določitev ključnih konceptov, tehnologij in etičnih vprašanj. Raziskava dodatno opozarja na izzive združevanja industrije 5.0 in etične mode, med katerimi so razvoj kompetenc delavcev, upoštevanje sociocentričnega pristopa ter potreba po spremembah načel zaradi vzpona industrije 5.0.
Ključne besede: industrija 5.0, etična moda, trajnostnost, preglednost

1 Introduction

The complexity of global fashion supply chains poses significant ethical issues, especially within the context of accountability, transparency and the multi-layered structure of networks [1]. Fashion supply chains frequently span multiple layers, incorporating several intermediaries and lower-tier manufacturers, with the majority of production taking place in the Global South, where cheap labour is easily available. These areas are usually characterised by institutional voids, such as a lack of regulatory frameworks, insufficient oversight and uneven labour standard enforcement [2]. To implement truly ethical procedures, the fashion industry must go beyond its employees and emphasize the welfare, safety and prosperity of its suppliers and workforce, the most vulnerable element in the fashion supply chain. The fashion industry is currently facing ethical challenges such as sweatshop working conditions, child labour and modern slavery, where workers face minimal safety measures, minimum wages, long working hours with unpaid overtime, exploitative contracts and a lack of workers' rights [3–6]. Despite international anti-corruption regulations, fashion supply chains remains prone to corruption and conspiracy that compromise fair practices and raise operational costs [7]. Immoral procurement practices between fashion brands and suppliers at the cost of workers' rights and safety manifest corruption. For example, suppliers may ensure transactions through unlawful payments instead of fair and transparent selection procedures [8]. In numerous scenarios, vulnerable legislative surroundings, notably in emerging finances, create possibilities for the exploitation of private authorities, bribery and unfair practices [9]. Furthermore, global textile consumption has risen to an estimated 62 million tons of clothing per year, with a projection of 102 million tons by 2030, resulting in an epidemic increase in air, water and microplastic pollution from discharge into the food chain, as well as textile waste [10–15]. The development of low-cost textile production has resulted in fast fashion, in which consumers frequently acquire trendy clothing and discard them before the product's lifecycle is complete [16, 17]. Cost, financial status, perception of oneself, risk perceptions, consumerism, beliefs/attitudes, peer groups and fashion awareness all play a role in fast fashion purchasing decisions. Fast fashion purchases are often driven by consumers' desires such as becoming trendy, gaining respect, displaying dominance, blending in with a social group and establishing a personal identity [18–20]. Fast fashion meets consumers' desires for high-end clothes at a cheaper cost, despite its detrimental socioeconomic and environmental consequences. Along with standard sustainability considerations, transformational and collaborative design approaches may enhance positive design processes [21].

This phenomenon has raised a quandary because while fast fashion helps the economy, it also leads to difficulty in the disposal of textiles, as the recycling industry must handle all of the waste generated by the textile industry [22]. In contrast to fast fashion, ethical fashion or "fashion with conscience" implies a noble strategy to attract socially concerned or young mainstream customers by manufacturing trendy garments free of unethical practices. Its primary objective is to supply stylish, contemporary apparel while ensuring equitable compensation, safe working conditions and sustainable material sourcing. Ethical fashion companies prioritise open supplier chains, cruelty-free production methods and environmentally friendly materials over wasteful waste, environmental harm and exploitative labour practices. This tactic appeals to a growing segment of the consumer base that values aesthetic appeal in addition to social and environmental impacts and demands greater accountability from companies. Ethical fashion promotes values such as sustainability, human rights and conscientious consumption through marketing, storytelling and community service. It backs global campaigns for economic equality, social justice and climate action. Ethical fashion offers trendy clothing that allows people to express their uniqueness without compromising their morals. The proposed concept is to procure garments ethically while ensuring beneficial employment guidelines and circumstances to labourers, and to offer a sustainable business model. In addition, organic substances are utilized to minimise the impact on surroundings. Ethical fashion can therefore be identified as fashionable garments that integrate fair trade standards with sweatshop-free labour situations while not affecting the environment or labourers [23, 24].

The Industrial Revolution has revolutionized workplaces to satisfy society's needs, with an increasing emphasis on implementing green practices due to environmental concerns [25, 26]. This emphasis on sustainability is a distinguishing aspect of Industry 5.0, the most recent chapter in industrial evolution. Industry 4.0, while still being implemented in some countries, lays the framework for this transformation. It highlights technical breakthroughs such as data analytics, forecasting, the Internet of Things (IOT) and blockchain to fulfil rising demand for supply flexibility and productivity [27, 28]. Industry 5.0 builds on Industry 4.0's technological base, but with a key difference: it prioritizes sustainability and human well-being over efficiency [29]. This human-centred approach recognizes existing environmental issues while stressing innovation for a more sustainable future [30]. Industry 5.0 and recycling are inextricably linked, fostering sustainability and innovation centred on human needs. This notion combines modern technology such as AI, robots, the Internet of Things (IoT) and smart sensors with human creativity and decision-making. This integration improves efficiency and precision at every stage of the recycling process, including trash sorting and material processing. The recycling of polyester, particularly recycled polyester (rPET), has gained popularity, as it involves melting existing plastic to create new polyester fibres. While consumer plastic bottles are often highlighted, rPET can also be sourced from post-industrial materials. The demand for recycled polyester continues to rise due to population growth and economic development. Polyester is widely used across various industries, benefiting from its high strength, transparency and safety properties, which are deemed to be linked to Industry 5.0, while recycling fosters sustainability [31].

The objective of this study is to address Industry 5.0 and its feasibility to ensure ethical fashion. It observes the literature gap between two topics, proposes a conceptual framework for utilizing Industry 5.0 in ethical fashion, and addresses challenges and limitations. The definitions of key terms extracted from the relevant systematic review are presented in Table 1.

Table 1: Definition of key terms used in this study

Key term	Definition
Ethical fashion	Ethical fashion is the concept of consuming clothes that are socially and environmentally conscious [32].
Industry 5.0	A collaborative industrial revolution in which humans and automation work together to increase production and efficiency, and eliminate waste with the core value of human-centricity, sustainability and resilience [33].
Circular economy	The circular economy is a closed loop manufacturing and purchasing structure that emphasizes reusing, repairing and recycling existing materials and products for as long as possible [34].

2 Literature review

2.1 Ethical fashion practice

The ethical fashion practice comprises a multidisciplinary approach. Ethical sourcing and decision-making can promote ethical practices by focusing on individual supply chain employees. The employees' perspectives on ethical sourcing and broader ethical concerns influence their moral agency to make ethical sourcing decisions [32, 35]. Ethical fashion businesses can create impactful multimedia marketing strategies on social media that align with conceptual ideals [36]. Ethical fashion practices can also be ensured by consumer awareness. Consumers are increasingly aware of ethical norms and demand collective action against immoral behaviour in society. This has led to the increased scrutiny of ethical fashion practices [37]. Upcycling, which involves transforming old clothing or waste commodities into valuable objects, is an effective strategy to promote ethical fashion. The present conceptualizations of sustainable organization are insufficient because they undermine the interpersonal perspective that sustainable organization requires. A synchronic, interpersonal approach accommodates multiple perspectives regarding ethical fashion practices [38]. Circularity in fashion consumption, as well as virtuous morality when shopping for second-hand clothing, can contribute to ethical fashion. Pleasure, shame and guilt can drive moral decision-making towards reuse and sustainability. Seduction and conversion can also support moral decision-making by overcoming aversions and desires that hinder progress in circularity and ethical fashion [39].

Industry 5.0 principles complement Industry 4.0 by promoting ethical supply chains in the fashion goods sector. While Industry 4.0 literature predominantly refers to automation, data-driven optimisation and efficiency, various studies pay insufficient attention to the ethical tensions of worker displacement, algorithmic opacity and sustainability trade-offs, highlighting the contradiction between technological advancement and social responsibility [28]. These are addressed through the integration of Industry 5.0 knowledge, focusing on human-centricity, sustainability and resilience, with a demonstration of how this developing paradigm directly fills the vacuum left by Industry 4.0 [40]. As a complement to Industry 4.0, Industry 5.0 is expected to enhance rather than replace digital capabilities with human creativity, emotional intelligence and stakeholder engagement in order to foster ethically aligned decision-making throughout sourcing, production and distribution [41]. The analytical leap is further demonstrated on the basis of a comparative synthesis; such a comparison supports our contention that Industry 5.0 offers a more balanced and ethically responsive framework than that of the techno-centred paradigm of Industry 4.0, especially in terms of labour dignity, circularity and responsible innovation [42]. Identified voids in previous literature involve the lack of adequate attention to ethical AI governance, the lack of models aimed at integrating human creativity with digital intelligence and the insufficient exploration of community-orientated supply chain resilience. With the embedding of such assessments, the revised chapter goes beyond mere summarisation in providing a coherent critique, and situates Industry 5.0 as a transformative paradigm capable of strengthening ethical fashion practices by overcoming the inherent socio-ethical limitations of Industry 4.0. Table 2 presents a comparison of Industry 4.0 and Industry 5.0 in ethical fashion supply chains.

Table 2: Comparison of Industry 4.0 and Industry 5.0 in ethical fashion supply chains

	Industry 4.0	Industry 5.0	Ethical fashion implication	References
Sustainability	Compliance-driven environmental management	Regenerative, circular and restorative sustainability models	Moves the industry from harm reduction to long-term ecological stewardship	[28, 40–42]
Transparency and traceability	Blockchain/IoT-enabled data tracking	Technology enhanced by human-centric accountability and ethical AI	Enhances trust, traceability and social justice in sourcing	
Social responsibility	Limited integration of human values	Integration of well-being, inclusion, co-creation and stakeholder values	Addresses persistent gaps in labour rights, equity and community impact	

2.2 Consumers' concerns

Ethical buyers are aware of certain difficulties and seek safeguards for production chain workers, such as safe working conditions and a minimum salary. They also minimise their influence on the environment and choose cruelty-free items. Companies that have joined the Fur Free Alliance and prohibited the use of fur in their designs include Giorgio Armani, Michael Kors and Gucci. Additionally, Chanel has recently discontinued the use of exotic leathers and furs. Companies including Gucci, Michael Kors and Giorgio Armani have joined the Fur Free Alliance, despite anti-fur campaigns in the 1980s and 1990s [43]. Although there are a growing number of ethical consumers, it is difficult to predict how this will impact consumer behaviour and if they are willing to spend more on ethical goods. Because of the inconsistent results, it is still unclear whether customers prefer socially conscious businesses or steer clear of those that are manufactured carelessly [44]. Numerous rivals in the fashion industry are dedicated to doing business ethically and have included environmental considerations in their business plans. Examples of this include companies such as Patagonia and The North Face, while others emphasise animal rights and kindness. Numerous initiatives for improved sustainability and ethical behaviour have sprung from this. However, buyers interested in ethical clothes find it challenging to make educated judgments due to the lack of transparency and the abundance of projects. Because there are so many such projects, it is difficult for customers to make wise decisions [45]. Customers are increasingly looking for labels on apparel that ensure it is made responsibly. The composition of raw materials, the place of origin, labour conditions and the environmental circumstances may all be found on these labels. An increasing number of companies are looking for certificates that say their goods are "green", "ethical" or "free of animal cruelty". While social certifications establish minimal requirements for worker rights and animal welfare, environmental certifications guarantee that dangerous chemicals are not used in manufacturing. Customers may feel more secure selecting brands that don't utilise animal products thanks to these certifications [46, 47].

2.3 Industry 5.0

Industry 5.0 refers to a collaborative industrial environment where humans and automation work together to increase production and efficiency, and eliminate waste [33]. This strategy combines the benefits of human intellect and machine capabilities, providing high precision through human control and optimal automation for efficiency [48]. It is motivated by the desire to address consumers' distinct and individualized needs by merging human ingenuity with technological capabilities. Industry 5.0 is a dynamic, resilient, and human-centric approach to industrial development in which intelligent digital ecosystems augmented by human interaction streamline operations and improve user experiences [49]. However, sustainable development is a multidisciplinary concept that integrates environmental, economic and social factors into decision-making and action. It focuses on managing societal concerns in an environmentally and economically sustainable manner while ensuring that our actions meet present needs without jeopardizing future generations' ability to meet their own [50]. Sustainable development in the Bangladeshi RMG industry should be framed around environmental responsibility, economic growth and improving garment workers' social well-being [51, 52].

The Industry 4.0 era utilized cyber-physical production systems (CPPS) to make intelligent decisions through real-time communication and cooperation among automation, thereby facilitating the flexible and efficient production of high-quality personalized inventories [53–55]. As firms embraced Industry 4.0, the Fifth Industrial Revolution (Industry 5.0) emerged. Industry 5.0 aims to achieve societal goals beyond jobs and growth by respecting the environment and prioritizing worker well-being in the production process [29, 56]. Industry 5.0 is predicated on the notion that Industry 4.0 prioritizes modernization and artificial intelligence-driven innovations over social fairness and sustainability, resulting in greater production efficiency and flexibility. Industry 5.0 emphasizes the need for research and innovation to support the industry's long-term contribution to humanity within global boundaries [52]. Before the formal implementation of Industry 5.0, there had been debates about the "Age of Augmentation", where humans and machines collaborate in synergy [57].

Industry 5.0 conjugately centres around human and environmental well-being at its core. Industry 5.0 prioritizes human demands and interests in manufacturing, transitioning from technology-driven advancement to a more societal-centric approach. Industry personnel will take on new tasks as their worth shifts from "cost" to "investment". Manufacturing technology should adapt to the requirements and diversity of workers to serve individuals and society. The goal is to establish an inclusive and secure workplace that prioritizes physical and mental welfare while also protecting workers' fundamental rights, such as autonomy, dignity and privacy. Upskilling and re-skilling are essential for industrial workers to further their careers and maintain a work-life balance [28, 29, 58]. To protect the environment, industry must be sustainable. It must create circular processes that reuse, repurpose and recycle natural resources, thereby reducing waste and environmental impacts, and eventually leading to a circular economy with greater resource productivity and efficacy [29].

Industry 5.0 focuses on integrating automation from Industry 4.0 with Sustainable Development Goals (SDGs) in a human-centred approach [59]. Due to Industry 5.0's priorities on human well-being instead of automation, there is a shift of paradigm on the concern of achieving sustainability [60]. Industry 5.0 comprises complex systems that combine sustainable technologies with social well-being, as shown in Figure 1.

Interactive human-machine technologies such as neural implants, human-centric artificial intelligence (AI), Augmented Reality (AR) and Virtual Reality (VR) can combine the efficiency of humans and machines [61–63]. Bio-inspired technologies with embedded smart materials in industries can enhance the manufacturing process while being recyclable [28, 64, 65]. Technologies such as digital twins and virtual simulation can maintain human centricity and operational safety [66]. Technologies for energy efficiency, renewables, storage and autonomy are required to

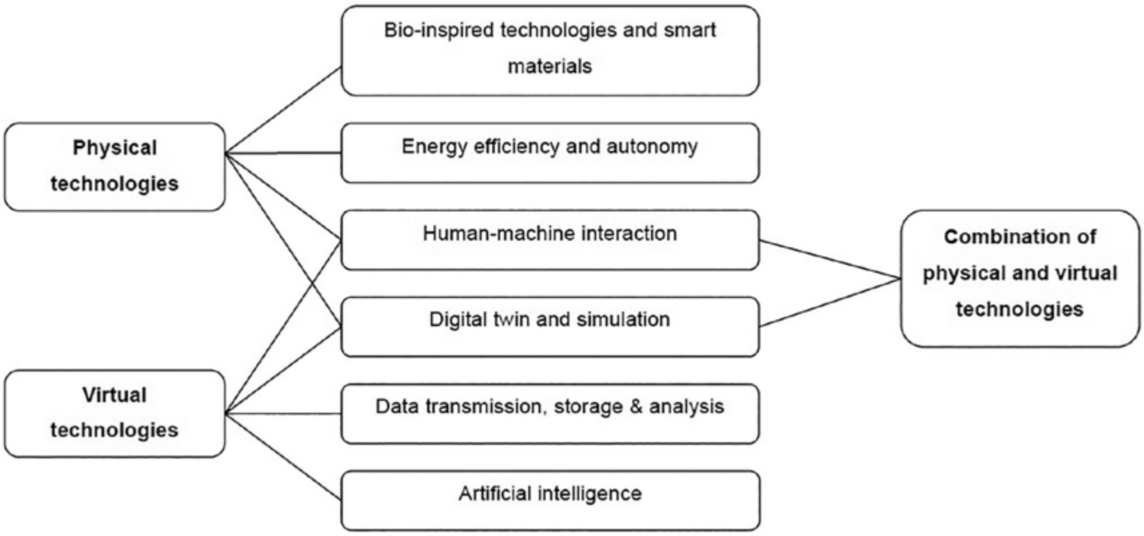

Figure 1: Technological advancements in Industry 5.0

achieve emission neutrality, including the integration of renewable energy sources and low-energy data transmission and analysis [67]. The most distinguished breakthrough in Industry 5.0 is blockchain technology, which can ensure ethical practices in industries, including the supply chain of textile industries. Transactions recorded in blockchain are transparent, traceable and cannot be falsified, thereby reducing the risk of social exploitation [68, 69]. Additionally, incorporating AI in the supply chain can reduce risk by predicting potential obstacles and taking necessary measurements through contingency plans [70].

This study observes a literature gap between ethical fashion practices and Industry 5.0. Although both topics focus on human well-being and sustainability, there is a lack of studies regarding the implementation of Industry 5.0 to ensure ethical practices in the fashion industry. This study therefore proposes a framework to fill the gap and highlights how the application of Industry 5.0 can impact ethical fashion practices.

3 Framework for implementing Industry 5.0 in ethical fashion

Industry 5.0 in ethical fashion must increase customer awareness in order to foster long-term transformation. By placing a strong focus on sustainability, ethics and transparency, this human-centred approach enables consumers to make moral purchasing decisions. Technologies that provide thorough provenance information, such as blockchain and QR code tagging, enable consumers to make informed judgments. Immersion technologies and digital twins encourage mindful consumption. Behaviour can also be influenced by social media and educational programs. As consumers become more aware of the social and environmental effects of fashion, manufacturers are being pressured to adopt more ethical methods. Raising consumer knowledge increases brand accountability and fosters a cyclical, inclusive fashion industry where ethics and innovation coexist [71].

This study proposes a conceptual framework for integrating Industry 5.0 with ethical fashion practices. The framework is structured around three mutual cores of Industry 5.0 and ethical fashion: human-centricity, sustainability, and transparency and accountability. The human-centric core of the framework emphasizes ethical labour practices, inclusive design and production, and prioritizes human well-being and ergonomics by leveraging Industry 5.0-enabled technologies, such as human-machine interaction and Artificial Intelligence. The sustainability core promotes circular economy principles by applying closed-loop systems for the reuse of materials, recycling and the use of bio-inspired technologies and smart materials enabled by Industry 5.0 [34, 72]. It also promotes the reduction of environmental impacts by using energy-efficient and autonomous technologies of Industry 5.0, and by using blockchain to promote sustainable supply chain management. Finally, the core pillar of transparency and accountability in ethical fashion can be achieved by supply chain transparency, ethical governance and consumer empowerment through Industry 5.0, as shown in Figure 2.

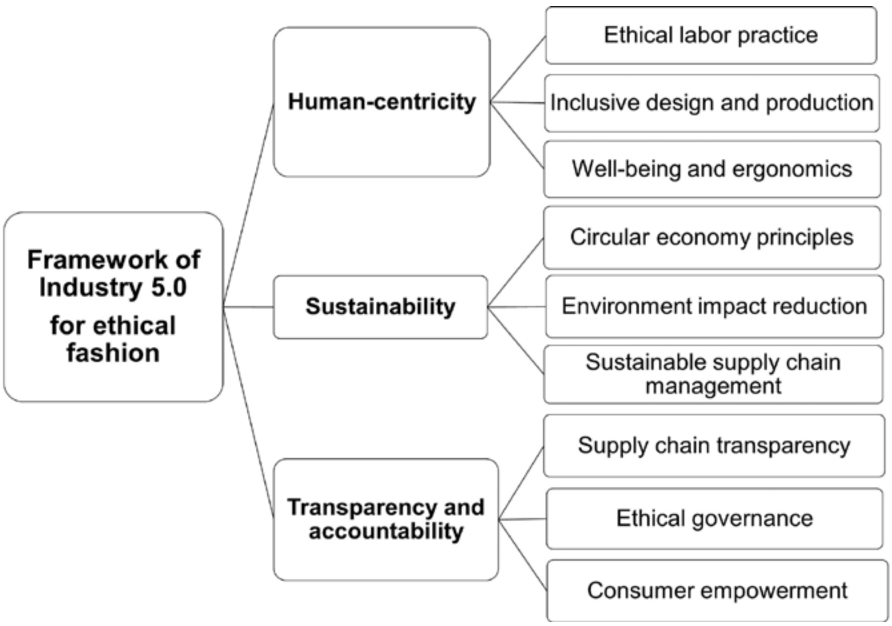

Figure 2: Conceptual framework for implementing Industry 5.0 in ethical fashion

The original theoretical basis of the conceptual framework can be found in the incorporation of stakeholder theory, the TBL framework and STS theory. The result is a more robust and unique interaction model between Industry 5.0 principles and ethical fashion practices. By combining these, however, it provided a multi-faceted basis that went beyond simply restating Industry 5.0 characteristics, such as transparency, sustainability and human-centricity; rather, it created a dynamic model to show how these ideas work in tandem to achieve ethics in fashion. Industry 5.0 conceives a humanistic vision, which resonates with the stakeholder theory that champions the inclusive creation of value among multiple actors, such as designers, workers, suppliers, consumers and policy-makers, who co-operatively interact through digital technologies and co-creation platforms, thereby ensuring transparency and ethics along the value chain [73].The TBL theory underpins the sustainability foundation of the framework, positioning Industry 5.0 technologies such as blockchain, artificial intelligence and circular manufacturing systems as facilitators of a balance between social wellbeing (people), environmental preservation (planet) and profitability (profit) [74]. STS theory extends the framework by addressing the interplay between the social and technological aspects in fashion systems, guaranteeing that automation and AI increase human creativity, empathy and moral judgment, instead of replacing them [75]. These concepts taken together demonstrate that ethical fashion in the Industry 5.0 era is a socio-ethical development where intersections between sustainability, stakeholder participation and human-machine cooperation will take place, rather than just technology advancement. A schema of such an improved conceptual framework that binds these theoretical pillars in generating the quantifiable ethical objectives of the fashion ecosystem, such as inclusion, justice, traceability and resilience, is presented in Table 3 below. Our new model thus fills the gap between theory and practice by providing a fresh interaction mechanism that interlinks technical progress with ethical imperatives. By casting out an integrated theoretical framework that may inspire empirical validation in future research, it also furthers academic discourse. The improved framework now depicts the ethical fashion ecosystem as a stakeholder-driven socio-technical system based on sustainability principles, as the ethos of Industry 5.0 lies in digital ethics and human-centric advancement [76, 77].

Table 3: Conceptual framework linking Industry 5.0 and ethical fashion

Theory	Concept	Industry 5.0	Ethical fashion's application	Outcomes	References
Stakeholder	Shared value with multiple stakeholders and engagement	Human-centric	Collaboration with designers, workers and consumers through digital tools	Transparency and inclusivity	[73]
Triple bottom line	People, planet and profit	Sustainability	Circular fashion, blockchain and co-efficient production balance	Environmental protection, social equity and profitability	[74]
Socio-technical system	Social and technical system integration	Human-machine collaboration	Balancing craftmanship with creativity	Resilience, empowerment and ethics	[75]

4 Application of Industry 5.0-enabled technologies for ethical fashion practices

The emphasis on the human-centric sustainability of Industry 5.0 facilitates the integration of ethical practices in the textile industry. The interactive human-machine synergy implemented by Industry 5.0 ensures the efficiency of human labour rather than replacing it with automation, which promotes ethical labour practices in the textile industry. Technologies for energy efficiency and renewable resources promote sustainability and ethical practices. Industry 5.0 can also integrate ethical practices in the textile industry by adopting blockchain and digital twins to promote transparency, traceability and accountability.

Unlike Industry 4.0's priority to automate, Industry 5.0's human-centric approach can lead to stronger rules and enforcement measures in the textile industry to ensure ethical fashion practices [28]. As a result, governments and authorities in many countries can make a greater impact by enacting laws to improve the transparency of social sustainability claims.

Consumers are increasingly aware of environmental and social issues, leading to a growing demand for sustainable and ethical fashion. However, many consumers lack the knowledge and tools to scrutinize sustainability claims. This makes it easier for fashion brands to deceive consumers and exploit them as an opportunity for unethical practices [78, 79]. Implementing Industry 5.0 in the textile industry can help consumers to access transparent information about products, which helps them make ethical purchase decisions and encourages the textile industry to practice ethical fashion.

The supply chain in the textile industry is often obscure, with complex routes that make it difficult to track the origin of materials and the working conditions of labourers, who suffer from low salaries, involuntary overtime, inconsistent hours and poor safety conditions [80, 81]. This obscureness allows textile industries to make misleading claims about their ethical fashion practices. Industries often use vague and misleading marketing claims to promote their products as sustainable without providing transparent proofs or certifications to support their claims of being "sustainable" or "ethical". This can be eliminated by integrating blockchain technology in the supply chain to transparently trace the sourcing of raw materials to production and overall operations, thereby ensuring social well-being and ethical fashion practices [68, 69]. AI-driven supply chains can forecast optimal inventory management to reduce waste generated in inventories through real-time data insights and the IoT (Internet of Things) [82]. AI can also optimize logistics by sourcing environment-friendly, sustainable materials and forecasting efficient routes and transportation modes [83]. Moreover, AI promotes ethical supply chain management and upholds fair labour standards with the optimization of production operations and waste reduction [84].

Some companies may focus on one aspect of sustainability, such as using recycled materials or environmental impacts while neglecting other important factors such as fair labour practices [85]. Industry 5.0 utilizes human-centric technologies for energy efficiency, renewables and autonomy, while prioritizing human well-being and maintaining higher product accessibility, an improved customer experience and sustainable talent management. This can ensure genuine sustainability efforts and ethical fashion practices [67, 86]. Moreover, Industry 5.0's circular economy principles promote recycling, reprocessing and waste minimization measures, which reduce the rebound effect [41]. Industry 5.0 incorporates data-driven decision-making, innovative design and circular strategies to help corporations reduce overconsumption, reduce post-consumer waste and manage the rebound effect, resulting in more sustainable and ethical fashion practices (Table 4) [87, 88].

Table 4: Areas to apply Industry 5.0-enabled technologies

Technologies enabled by Industry 5.0	Areas to implement	References
Human-machine collaboration	Worker well-being, ethical labour practices, improved laws and regulations	[28]
Digital twins and virtual simulation	Operation safety in manufacturing	[66]
AI and blockchain	Transparency and traceability in supply chain	[68, 69, 82–84]
Bio-inspired smart materials	Recycling materials and enhanced manufacturing	[28, 64, 65]
Energy efficient automations	Waste minimization	[67, 86]

5 Challenges and future directions

Adopting Industry 5.0 in the textile industry presents obstacles in multiple interlinked categories. The human-centric core value of technologies enabled by Industry 5.0 will not gain its full potential without the two-way interaction of humans and machines. The skills required to adapt to Industry 5.0 must be envisioned through retraining and lifelong learning concepts. Society must also integrate challenges such as youth unemployment, the ageing population and gender discrimination for the broader implementation of Industry 5.0. The heterogenic nature of society also hinders the harmonic prioritization of the values and needs of its members. While Industry 5.0 focuses its core value on individual human-centric well-being, it must integrate with the complete working environment of the textile industry, requiring a socio-centric approach. The revolution of Industry 5.0 facilitated the addressing of technological by both governments and policymakers for setting appropriate rules and regulations, which is often a lengthy process due to the slow adaptability of governments and policymakers. The textile industry has not yet fully embraced Industry 4.0. In the meantime, implementing Industry 5.0 requires an overhaul of the skills and strategies of management as a whole in the textile industry. New technologies are also required to measure the social and environmental impacts of implementing Industry 5.0 in the fashion industry [67]. A collaborative transformation that combines technological advancements with socio-human integration is about to take place in the textile industry. This change will facilitate sustainable manufacturing, individualised innovation and improved worker well-being. Deliberate upskilling and lifelong learning are crucial for reducing youth unemployment and integrating marginalised groups. Policies must support inclusion, ethical governance and technological accessibility. Industry 5.0 offers opportunities to reconsider value chains through the use of AI-human collaboration, circular economy models and real-time social impact assessment tools. Governments, educational institutions and corporate leaders will be essential in overcoming regulatory barriers.

6 Conclusion

This study concludes that Industry 5.0 has the potential to advance ethical fashion by aligning technical innovation with human-centred and ecologically sensitive ideals. It draws attention to the shared goals of Industry 5.0 and ethical fashion, which include reducing environmental harm and promoting responsibility, openness and worker welfare. By combining cutting-edge technologies with human inventiveness and moral ideals, Industry 5.0 encourages a more sustainable and socially responsible apparel business. However, this study also identifies significant limitations on the fashion industry's use of Industry 5.0. These include the industry's capacity to adapt to this new paradigm, the need for people to acquire new skills to facilitate effective human-machine collaboration and broader social implications that must be considered. Furthermore, the creation of frameworks and policies that are supportive is still necessary for the effective adoption of Industry 5.0 practices. This study lays the groundwork for future practices in the fashion industry, advocating for intersectoral collaboration, regulatory support for transparency and circularity, and pilot programs in smart-ethical manufacturing. It emphasizes the need for designers and manufacturers to adopt traceability technologies and embrace human-AI co-creation to enhance accountability. Governments are urged to foster ethical innovation through guidelines and funding, paving the way for a morally sound Industry 5.0 fashion ecology. Industry 5.0 creates new opportunities for fashion research and innovation despite these obstacles. Future research is required to examine how these technologies can be successfully scaled and integrated, as industry looks to move away from mass production and towards more individualised, moral and sustainable solutions. Ultimately, Industry 5.0 offers a route to a fashion ecosystem that is more moral, inclusive and progressive.

Data availability: The authors have cited the research data in the reference list at the end of article.

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