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Development and characterisation of conductive knitted fabrics as humidity sensors for automatic hemostasis detection

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ABSTRACT – REZUMAT

Development and characterisation of conductive knitted fabrics as humidity sensors for automatic hemostasis detection

Conductive knitted fabrics can function as humidity sensors, detecting the presence of liquids on their surface through changes in electrical resistance. This property can be leveraged for automatic hemostasis systems, where the detection of blood at a wound site triggers real-time intervention. In this study, conductive yarns including Shieldex (Statex: 60-440 Ω/m), AgSiS (Lib-40: 5 Ω/m), and stainless steel (60 Ω/m) were integrated into knitted fabrics using a Shima Seiki machine. The fabrics were characterised for mechanical strength, abrasion resistance (1,000 and 5,000 cycles), washing durability (1 and 5 cycles), and resistance to acidic and alkaline perspiration. Electrical resistance was measured under exposure to four aqueous media simulating physiological and wound conditions: deionised water (pH 6, 244 μS/cm), acidic perspiration (pH 5.5, 10.73 mS/cm), alkaline perspiration (pH 8, 11.35 mS/cm), and 20% saline solution (pH 5.0, 9.5 mS/cm). Morphological and compositional analyses were conducted using SEM, EDX, and FTIR spectroscopy. The results demonstrated that all fabrics exhibited measurable and repeatable resistance variations, with the strongest response observed for the 20% saline solution and Lib-40 conductive yarn, highlighting their potential as humidity sensors for real-time detection of bleeding events in automatic hemostasis systems.

Keywords: *conductive textiles, knitted fabrics, humidity sensor, automatic hemostasis system, electrical resistance monitoring, combat garment*

Dezvoltarea și caracterizarea structurilor textile tricotate conductive ca senzori de umiditate pentru detectarea automată a hemostazei

Structurile tricotate conductive pot funcționa ca senzori de umiditate, detectând prezența lichidelor pe suprafața lor prin modificări ale rezistenței electrice. Această proprietate poate fi utilizată în sisteme automate de hemostază, în care detectarea sângelui la nivelul unei răni declanșează o intervenție în timp real. În acest studiu, fire conductoare, inclusiv Shieldex (Statex: 60-440 Ω/m), AgSiS (Lib-40: 5 Ω/m) și oțel inoxidabil (60 Ω/m), au fost integrate în structuri tricotate utilizând o mașină Shima Seiki. Tricoturile au fost caracterizate din punct de vedere al rezistenței mecanice, rezistenței la abraziune (1.000 și 5.000 cicluri), durabilității la spălare (1 și 5 cicluri) și rezistenței la transpirație acidă și alcalină. Rezistența electrică a fost măsurată în condiții de expunere la patru medii apoase care simulează condiții fiziologice și de rană: apă deionizată (pH 6, 244 μS/cm), transpirație acidă (pH 5,5, 10,73 mS/cm), transpirație alcalină (pH 8, 11,35 mS/cm) și soluție salină 20% (pH 5,0, 9,5 mS/cm). Analizele morfologice și compoziționale au fost realizate utilizând SEM, EDX și spectroscopie FTIR. Rezultatele au demonstrat că toate tricoturile conductive au prezentat variații măsurabile și repetabile ale rezistenței electrice, cea mai puternică reacție fiind observată pentru soluția salină 20% și firul conductiv Lib-40, evidențiind potențialul acestora ca senzori de umiditate pentru detectarea în timp real a sângerărilor în sistemele automate de hemostază.

Cuvinte-cheie: *tricoturi conductive, senzor de umiditate, sistem automat de hemostază, detectarea sângerării, monitorizarea rezistenței electrice, îmbrăcăminte combatanți*

INTRODUCTION

Smart textiles are capable of converting environmental stimuli, such as temperature, light, chemical composition, humidity, or pH, into measurable physical or aesthetic responses through mechanical and electromagnetic interactions. Over the past decades, these systems have evolved from rigid electronics mounted on fabrics to fully textile-based, flexible, adaptive, and biomimetic solutions (figure 1) [1, 2].

Typically, smart textiles comprise a fabric substrate, conductive interconnectors, sensors, actuators, energy sources, and processing units, with conductivity introduced at various stages, such as during polymerisation, fibre spinning, fabric construction, or post-processing via coating or printing (figure 2).

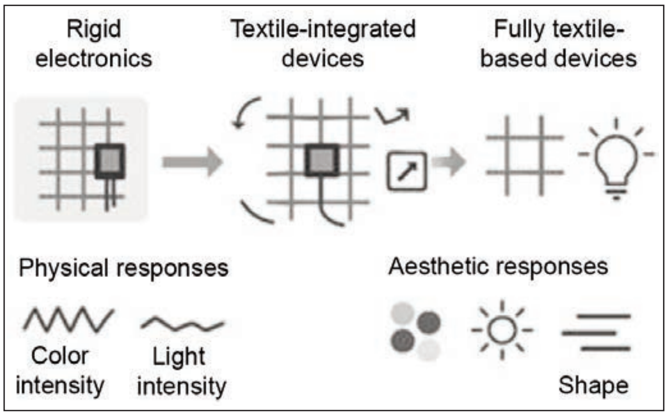


Fig. 1. Schematic illustrating the evolution of smart textiles from rigid electronics to a fully textile-based adaptive system

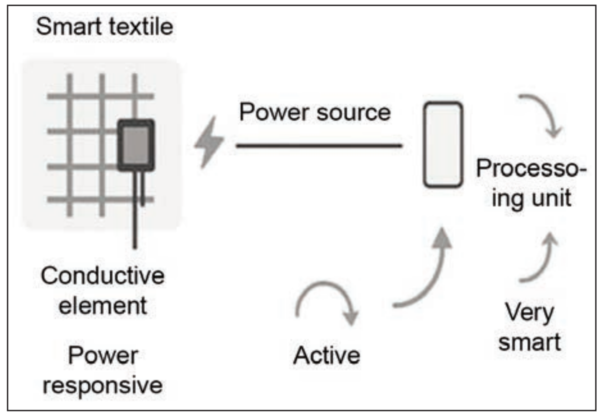


Fig. 2. Components of a smart textile system and classification according to interaction

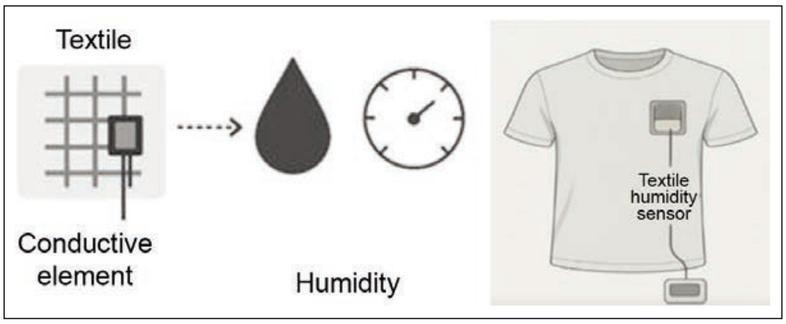


Fig. 3. Textile-based humidity sensor integrated into a wearable patch for real-time monitoring of moisture and physiological parameters [5]

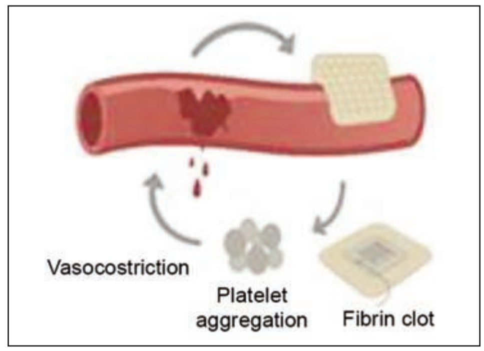


Fig. 4. Schematic representation of physiological hemostasis

Conductive additives, including metals, carbon-based fillers, graphene, nanotubes, and conductive polymers, enable electrical functionality but may influence mechanical resilience and durability. Textile-integrated sensors, fabricated at the fibre, yarn, or fabric level using knitting, weaving, embroidery, or layered structures, exploit these conductive elements to measure mechanical deformation, pressure, strain, or environmental stimuli [3, 4]. Among these applications, humidity-sensitive textiles are particularly relevant in biomedical contexts, providing critical physiological information through real-time monitoring of moisture, sweat, or wound exudates (figure 3) [5, 6].

In hemostasis, rapid detection of local moisture associated with blood or exudate can provide essential feedback on the effectiveness of dressings and interventions. Hemostasis is the physiological process that prevents and stops bleeding following vascular injury, involving vascular constriction, platelet plug formation, and coagulation to form a stabilising fibrin clot (figure 4) [7, 8].

Pathological conditions or impaired coagulation may necessitate medical intervention, highlighting the need for rapid detection systems. Conductive textiles, capable of detecting changes in electrical resistance caused by contact with blood or body fluids, can serve as sensors for automatic hemostasis systems, triggering control signals for wound management or alerting medical personnel [9, 10]. Recent work on textile-based wound dressings has demonstrated that changes in fluid presence (blood, exudate) can be detected using conductive or capacitive fabrics [11]. Similarly, textile biosensors for sweat and other body fluids have shown that smart fabrics can reliably monitor physiological moisture changes in real time [12, 13]. One recent example embedded a protein sensor into a fabric dressing for wound healing monitoring [14, 15].

In this study, we investigate the electrical and mechanical behaviour of several conductive knitted fabrics under exposure to fluids simulating blood and body perspiration, evaluating their potential as humidity sensors for real-time bleeding detection in automatic hemostasis systems (figure 5). Due to safety and regulatory constraints,

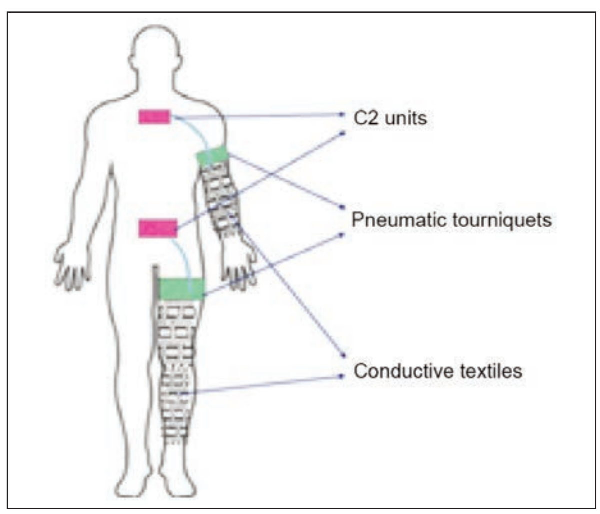


Fig. 5. Schematic representation of the automatic hemostasis system [16]

blood simulants were used; future work will include real blood testing for calibration.

GENERAL INFORMATION

Conductive yarns

The selection of conductive yarns was based on a set of electrical, mechanical, and material-related criteria. The linear resistance R_L (Ω/m) was first considered, as it represents a key electric parameter. The electric conductivity of the yarns σ [S/m] is computed based on the linear resistance R_L and the optical diameter D (equation 1) (for the length of the yarn L = 1 m):

$$\sigma = \frac{1}{R_L}\frac{L}{\frac{\pi}{4}D^2} \text{ (S/m)} \quad (1)$$

Young's modulus E was calculated by the ratio between the stress σ (N/m^2) and the strain ε (%) (2):

$$E = \frac{\sigma}{\varepsilon},\ \sigma = \frac{F}{A}.\ \varepsilon = \frac{\Delta L}{L_0} \quad (2)$$

where F is breaking force (N), A – the cross-sectional area of the wire (m^2), L_0 – initial length (m), and ΔL – elongation (m).

Knitted fabrics

Conductive fabrics were manufactured using knitting technology with conductive yarns, including Shieldex 2-Ply HC+B TPU, Shieldex Ply (STATEX), Sprinox (Ugitex), and DA 5359 (FILIX), whose physical, mechanical, and electrical properties were systematically assessed. Knitting was performed on Shima Seiki SIR 122G07 and 122G14 flat knitting machines. Figure 6 presents the technical programming drawing to create a knitting component (a sleeve) along with the main design parameters. An intarsia-type structure was produced using metallic yarn combined with Nm 50/1 cotton yarn, featuring 8-needle cotton borders. The knitted fabric measured 412 courses in length and 256 courses in width, with a stitch size of 5.3 mm (figure 6, *a*). The fabric was knitted in a sequence of 2 rows of metallic yarn alternating with 4 rows of cotton yarn (Nm 50/2), creating a conductive textile structure. Border of 6 needles using BBC-type yarn, row 122 GO7, knit length – 170 loops, maximum width – 128 loops, stitch – 10.8 mm (figure 6, *b*).

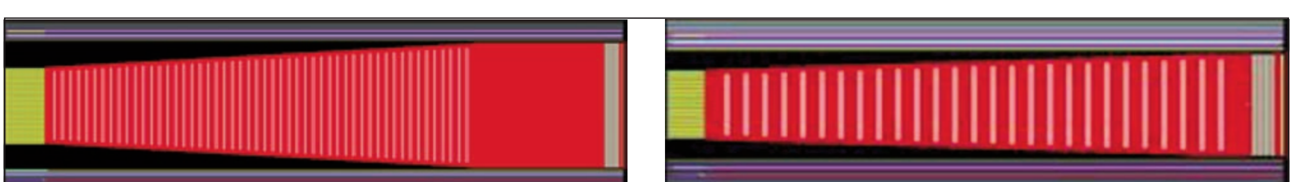
Characterisation methods of the fabrics

Given that these conductive knitted fabrics are intended for combatants, it is essential to evaluate their performance under realistic operational conditions. Abrasion tests assess mechanical durability under repeated friction and stress, ensuring the sensor maintains functionality during intense physical activity. Sweat tests, including both acidic and alkaline perspiration, simulate physiological conditions that may influence electrical response, verifying that the sensors remain accurate without false triggers. Air permeability tests ensure that the fabrics are breathable and comfortable when integrated into wearable combat gear. Finally, washing tests evaluate the durability of the textiles under repeated cleaning cycles, confirming that the electrical and mechanical properties are preserved for long-term use in the field. Together, these evaluations guarantee that the conductive fabrics can reliably function as humidity sensors for automatic hemostasis detection while withstanding the demanding conditions faced by soldiers.

Tensile strength was tested according to SR EN ISO 13935-1:2013 using a Titan Universal Strength Tester (strip method, 50 mm specimen width, 200 ± 1 mm gauge length, 20 mm/min speed). Abrasion resistance was assessed following SR EN ISO 12947-2: 2016 with a Martindale 404 tester under a load of 12 kPa and total effective mass of 795 ± 7 g, using standardised abrasive fabric and Lissajous motion. Washing durability was examined in accordance with SR EN ISO 105-C06:2010 on a GIRO HW-Jams Heal washing machine (40°C, 30 min, 4 g/l ECE detergent without optical brighteners, 150 ml washing liquid). Resistance to acidic and alkaline perspiration was determined following SR EN ISO 105-E04:2013.

SEM imaging revealed the surface morphology of the conductive textiles after durability tests, while EDX confirmed their elemental composition. FTIR analysis identified both organic and inorganic compounds present in the materials.

Four wetting media were prepared for the conductive textile structures: tap water, acidic perspiration (pH 5.5), alkaline perspiration (pH 8), and 20% saline solution. For safety and ethical reasons, blood simulants (saline and perspiration solutions) were used to reproduce the ionic and moisture characteristics of real blood. Future validation will include calibration with standardised blood simulants to confirm the detection thresholds under real biological conditions. Acidic and alkaline perspiration were prepared according to SR EN ISO 105-E04, using L-histidine hydrochloride, NaCl, and phosphate salts, with pH adjusted using 0.1 M HCl or NaOH. The saline solution was prepared at 20 g NaCl/l.



a *b*

Fig. 6. Screenshots of the structures: *a* – intarsia-type structure; *b* – conductive textile structure

Fig. 7. The measurement area

Fig. 8. Bullet imprint

Conductive textile structures were tested for performance using 10 ml of liquid, a 5s wetting time, and a 5 cm diameter test area (figure 7). Electrical resistance measurements were carried out, taking into account, as much as possible, the need to maintain the same length of the conductive yarn, despite the high elasticity of the material. Particular attention was given to the variation of the electrical resistance of each knitted structure under the four moisture conditions, as well as to the limits within which these values fall, to be correlated with the activation parameters of the primary hemostasis system control unit. The electrical resistance [Ω] was measured for the textiles in three conditions: initial, after wetting, and after wetting in a moulded "bullet imprint" (figure 8). The bullet imprint simulates localised mechanical deformation and micro-wetting caused by penetration, reflecting realistic conditions when a combatant experiences a bleeding wound. Measurements were taken using a Multimeter of type FLUKE 179, capable of measuring 0.1 Ω to ≥50 MΩ.

RESULTS AND DISCUSSION

The conducted experiments aimed to determine how conductive knitted fabrics respond electrically and mechanically to the presence of blood-simulating liquids and perspiration, to evaluate their suitability for integration into an automatic hemostasis system. Variations in electrical resistance under different wetting conditions (water, saline, acidic, and alkaline sweat) were analysed to establish the sensitivity and stability of the textile sensors in realistic physiological environments.

The following types of yarns were selected to manufacture the knitted fabrics: Shieldex 2-Ply HC+B TPU, Shieldex Ply (STATEX), Sprinox (Ugitech), and DA 5359 (FILIX). The physical-mechanical and electric properties are presented in table 1.

The diameter and cross-sectional area of the wires strongly influence mechanical behaviour, user comfort, and the feasibility of integration into textile structures. While thicker yarns provide lower resistance, they are less flexible and more difficult to conceal within fabrics, whereas thinner yarns are easier to embed but may be prone to breakage under mechanical stress. In addition, the composition and surface plating of the yarns (e.g., copper, silver-plated copper, stainless steel, or nickel–chromium alloys) were considered, as these factors not only affect conductivity and resistance to oxidation but also determine cost-efficiency and biocompatibility. Therefore, the chosen set of yarns reflects a balance between electrical performance, mechanical durability, and practical suitability for integration into conductive textiles.

The physical-mechanical properties of the manufactured knitted samples are presented in table 2.

All fabrics maintained structural integrity and electrical performance after 1,000 and 5,000 abrasion cycles, confirming suitability for combat use.

Abrasion testing ensures that blood detection remains reliable even under friction or stress. Fabrics exhibited measurable changes in resistance depending on pH, but signals remained detectable, showing reliable performance under body-fluid exposure. Knitted fabrics were sufficiently breathable, allowing moisture and air transport without compromising sensor function. Electrical and mechanical properties were largely preserved after 1 and 5 wash cycles, confirming that fabrics can withstand operational maintenance.

The following electric resistance results were collected during the wetting of the knitted fabrics with various types of droplets (table 3).

Figure 9 compares the resistance of each conductive textile structure across different conditions: initial, surface water-treated, and water-treated within the bullet imprint, simulating localised penetration.

A logarithmic y-axis was used to accommodate the wide range of values, from very low to very high (e.g., t11)

The presence of the water causes an increase in electrical resistance for all treated textile structures (t10 > 9.9%; t12: > 6.5%; t13: >16%) except t11, which remains at the same level (70.8 kΩ and 68.7 kΩ). In the case of the bullet imprint, electrical resistance decreases for all variants, with the largest reductions observed for variants t10 (< 42.0%) and t11 (< 100%); t12: < 45% except t13, which records an increase (t13 > 9.%)

The presence of acidic perspiration (conductivity: 37.2 mS/cm and pH-5.5) results in an increase in the resistance values of the treated textile structures: t10 > 2.5%; t11:7.7%; t12:14.5%; t13 > 11.4%. In variants t11 and t12, significant increases in electrical

Table 1

PHYSICAL-MECHANICAL AND ELECTRIC PROPERTIES OF CONDUCTIVE YARNS							
No.	**Properties / Yarn type**		**Unit**	**Shieldex 2-Ply HC+B TPU(Statex)**	**Shieldex Ply(Statex)**	**SprInox (Ugitech)**	**DA5393 Ecru (Filix)**
							
1	Fibrous composition		%	PA6.6/Ag-99.9%		Spun yarn	30% metal / 70% PES
2	Linear density		Tex (Nm)	15x2 (66.6/2)	14.0x2 (71.42/2)	89x2 (11.2/2)	12.67x2 (78.93/2)
			Dtex (Den)	152x2 (136.8x2)	140x2 (126x2)	890x2 (801x2)	126.7x2 (139.3x1)
	CV		%	0.38	0.83	3.63	1.89
3	Breaking strength		N	13.40	1348.30	1734.35	6.67
			Cv%	3.28	1.48	10.01	4.15
4	Breaking elongation		%	26.35	25.89	1.25	18.89
			Cv%	6.64	2.46	5.12	11.15
5	Elasticity moduls (E)		GPa	1.13	27.9	13.01	-
6	Twist fibres		T/m	643.2	620	232	28.4
			Cv%	0.49	0.68	4.90	9.85
7	Torque		-	Z	S	Z	Z
8	Twist yarn		T/m	587.2	560	138	629.6
			Cv%	2.58	0.86	2.02	6.04
9	Torque		-	S	Z	S	S
10	Linear electric resistance		Ω/m	150	440	60	940
11	Optical diameter		µm	240	248	412	160
12	Electric conductivity		S/m	146991	46930	124698	52776

Table 2

PHYSICAL-MECHANICAL PROPERTIES OF CONDUCTIVE KNITTED FABRICS								
No	**Properties**		**Unit**	**Results/variants**				**Standard**
				T10 – Shieldex PLY (Statex)	**T11 – DA 5393 (FILIX)**	**T12 – 2HC-PLY (Statex)**	**T13 – SprInox (Ugitech)**	
1	Specific mass		g/m^2	153.6	158.4	170.4	263.0	SR EN12127:2003
2	Yarns density	Warp	No yarns/ 10 cm	76	70	70	40	SR EN 1049-2:2000, Method A,B
		Weft		96	110	100	50	
3	Thickness		mm	0.92	0.8	0.95	1.20	SR EN ISO 5084:2001
4	Air permeability		l/m^2/s	3496	3258	3222	4192	SR EN ISO 9237:1999
5	Breaking force	V	N	254.22	284.22	227.54	73.2	SE EN ISO 13934-1/2013
		H		108.69	125.17	153.60	70.43	
6	Elongation at break	V	%	47.31	49.53	52.05	18,6	SE EN ISO 13934-1/2013
		H		67.91	62.67	80.86	24.15	
7	Elasticity modulus (E)	V	MPa	11.7	14,34	9.1	6.56	-
		H		3.46	5.00	4.0	4.86	
8	Abrasion resistance	1000	Cycles	No broken stitches	No broken stitches	No broken stitches	Stitches broken at 1500 cycles	SR EN ISO 12947-2/2017
		5000						

resistance are observed in the bullet imprint (t11: from 68 Ω to 169 Ω; t12 from 172.9 Ω to 600 Ω). In these cases, the bullet impact may damage or compress conductive pathways, creating microcracks. Also, acidic sweat can corrode or oxidise metallic or conductive coatings, reducing connectivity. Localised moisture can dissolve ions into insulating residues, increasing resistance. For the other textile structures,

Table 3

FABRIC USED FOR THE EXPERIMENTS							
No	**Wet environment**	**State**	**T10 – Shieldex PLY (Statex)**	**T11 – DA 5393 (FILIX)**	**T12 – 2HC-PLY (Statex)**	**T13 – SprInox (Ugitech)**	**Observation**
1	Water, pH=5.5, C=688 µS/cm, Quantyti: 5 ml	Initial	171 Ω	70.8 kΩ	214 Ω	89.9 Ω	T = 27.90°C RH = 25.0%
		Treat	188 Ω	68.7 kΩ	228 Ω	105.4 Ω	
		Bullet print	71.8 Ω	0.9 Ω	98.4 Ω	98.8 Ω	
2	Acid sweat, pH=5.5, C=37.2 mS/cm, Quantity: 5 ml	Initial	198.3 Ω	68.7 Ω	179.2 Ω	220.3 Ω	T = 31.40°C RH = 27.3%
		Treat	203.1 Ω	74 Ω	260 Ω	252.1 Ω	
		Bullet print	109 Ω	169 kΩ	600 Ω	110 Ω	
3	Alkaline sweat, pH=8.0, C=24.7 mS/cm, Quantity: 5 ml	Initial	108.5 Ω	10 Ω	86.3 Ω	147.5 Ω	T = 34.50°C RH = 28.0%
		Treat	104.6 Ω	8.52 Ω	99.8 Ω	142.8 Ω	
		Bullet print	61.5 Ω	30.7 Ω	97.6 Ω	155 Ω	
4	Saline solution, pH=5.0, C=27.4 mS/cm, Quantity: 5 ml	Initial	104.8 Ω	11.6 Ω	105.3 Ω	123.3 Ω	T = 29.10°C RH = 29.4%
		Treat	98.3 Ω	9.8 Ω	104.8 Ω	116.8 Ω	
		Bullet print	99.7 Ω	2.1 Ω	36.3 Ω	115.0 Ω	

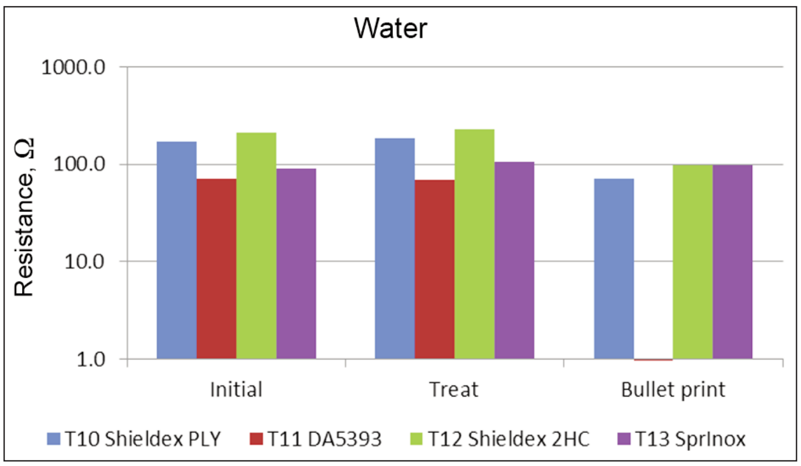


Fig. 9. Electrical resistance of conductive structures: initial, water-treated, and bullet-imprint states

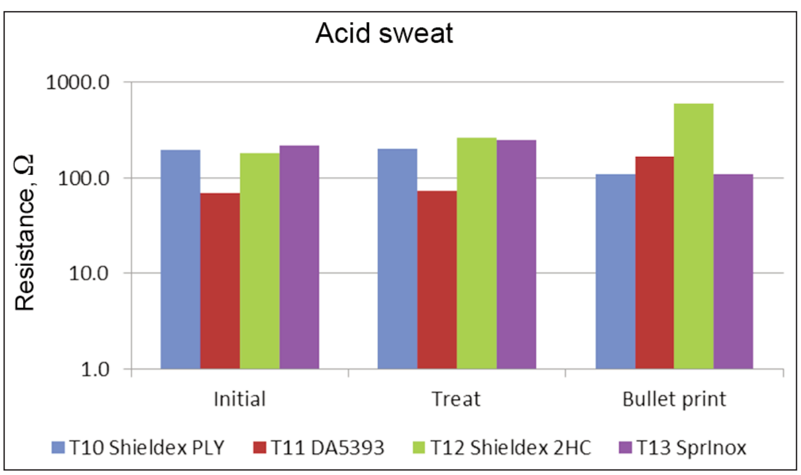


Fig. 10. Electrical resistance of conductive structures: initial, acid sweat, treated, and bullet-imprint states

electrical resistance at the bullet-imprint state, values are lower compared to the initial state: t10 109 Ω versus 198 Ω, and t13 110 Ω versus 220 Ω. In these cases, acidic sweat can act as a temporary ionic conductor, providing additional pathways for current.

The presence of alkaline perspiration (conductivity: 24.7 mS/cm, pH-8) generally reduces the electrical resistance of treated textile structures: t10 < 3.8%; t11 < 1.17%; and t13 < 0.96%. For the textile structure t12 (Shieldex 2HC), a slight, insignificant increase in resistance is observed (1.13%).

Alkaline perspiration functions as a temporary ionic conductor, leading to a decrease in electrical resistance in most cases. However, the Shieldex yarn (2HC), due to its complex structure, is more sensitive to alkaline exposure, resulting in a minor increase in resistance, likely due to possible oxidation. In the case of the bullet imprint, electrical resistance increases for most variants (t11 > 100%; t12 > 12.4%; t13 > 6%) and decreases for variant t10 (< 44%). Alkaline sweat can corrode or oxidise metallic or conductive coatings, reducing connectivity.

The presence of the saline solution (20% concentration, conductivity 27.4 mS/cm, pH 5) causes a decrease in electrical resistance for all treated textile structures (t10 < 6.8%; t11 < 16%; t12 < 1%; t13 < 6%). In the case of the bullet imprint, electrical resistance decreases for all variants, with the largest reductions observed for variants t11 (DA 5393 yarn) and t12 (Shieldex 2HC yarn) (t10 < 5%; t11 < 72%; t12 < 64%; t13 < 7%).

Saline solutions contain dissolved ions (Na^+, Cl^-). When the solution contacts the textile, these ions create additional conductive pathways along the fibres. Essentially, the textile's effective conductivity increases because the current can move through the ionic solution as well as the textile's own conductive elements. This is why electrical resistance drops across all treated textile variants.

Correlation analysis between the thread's linear electric resistance (Ω/m) and the woven fabric's total resistance (Ω) under each test condition and state was calculated. The graphical representation of the correlation between thread linear resistance and fabric sample resistance under each condition and state is presented in figure 14.

High correlations (|r| > 0.9) indicate that the linear resistance of the thread has a strong influence on the overall fabric resistance, but the direction (positive or negative) changes depending on the environment and the type of damage. Positive correlations (e.g., Water Initial, Acid Bullet): higher-resistance threads lead to higher overall fabric resistance. Negative correlations (in most other cases): suggest that lower-resistance threads yield higher fabric resistance, likely due to better conductivity pathways or interaction effects when the threads are immersed or damaged. After bullet damage, correlations often flip in sign or weaken, implying that structural damage alters the current distribution and reduces the predictable relationship between the thread's intrinsic resistance and the fabric's overall resistance.

These correlations indicate that resistance changes are detectable and predictable, providing reliable triggers for an automatic hemostasis control system.

The FTIR spectrum exhibits a characteristic band at 550 cm^{-1} corresponding to silver oxide (t10), indicating oxidation of the silver surface, likely caused by atmospheric moisture [16]. SEM analysis shows that the initial fibre samples are morphologically clean. EDS analysis reveals oxygen and carbon originating from the polymeric filament support of the silver film, with additional oxygen attributed to silver oxide. After perspiration and washing tests, a slight increase in oxygen concentration is observed, attributable to reactions between silver and oxygen.

The t11 sample, composed solely of polymeric components, displays FTIR peaks characteristic of organic functional groups [17]. SEM images show minor surface degradation after perspiration and washing, particularly following five wash cycles. EDS confirms carbon and oxygen elements typical of organic polymers.

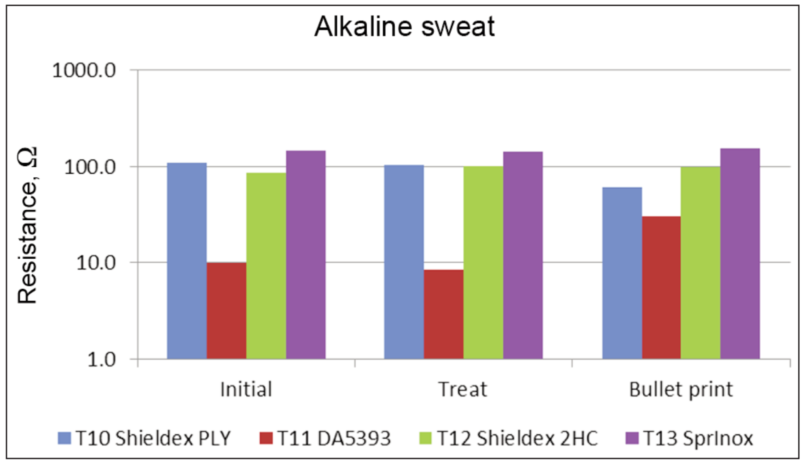


Fig. 11. Electrical resistance of conductive structures: initial, alkaline sweat-treated, and bullet-imprint states

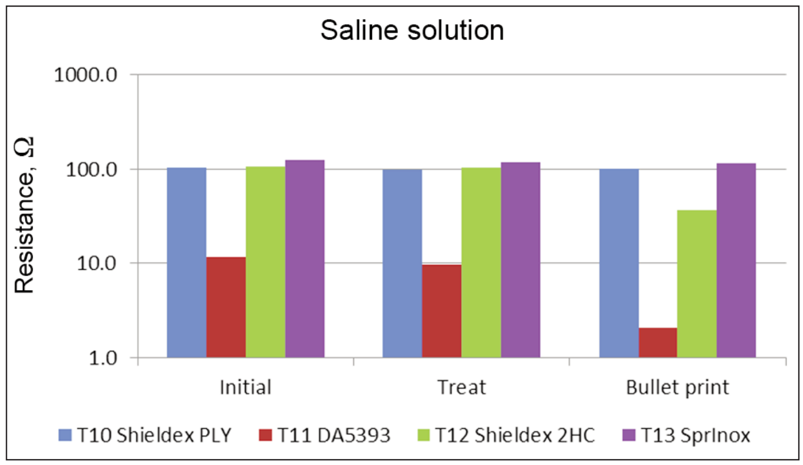


Fig. 12. Electrical resistance of conductive structures: initial, saline solution-treated, and bullet-imprint states

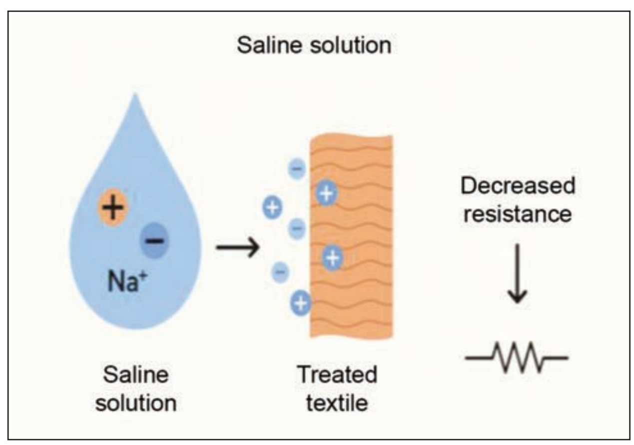


Fig. 13. Illustration of the physical principle

For sample t12, the spectral band at 550 cm^{-1}, assigned to silver oxide lattice vibrations, is evident, again indicating oxidation, possibly due to ambient humidity. SEM micrographs reveal an almost clean fibre surface, while EDS results confirm oxygen and carbon contributions from both the polymeric support and silver oxide. Samples subjected to perspiration and washing show slight oxygen increases, consistent with the high reactivity of silver toward oxidation.

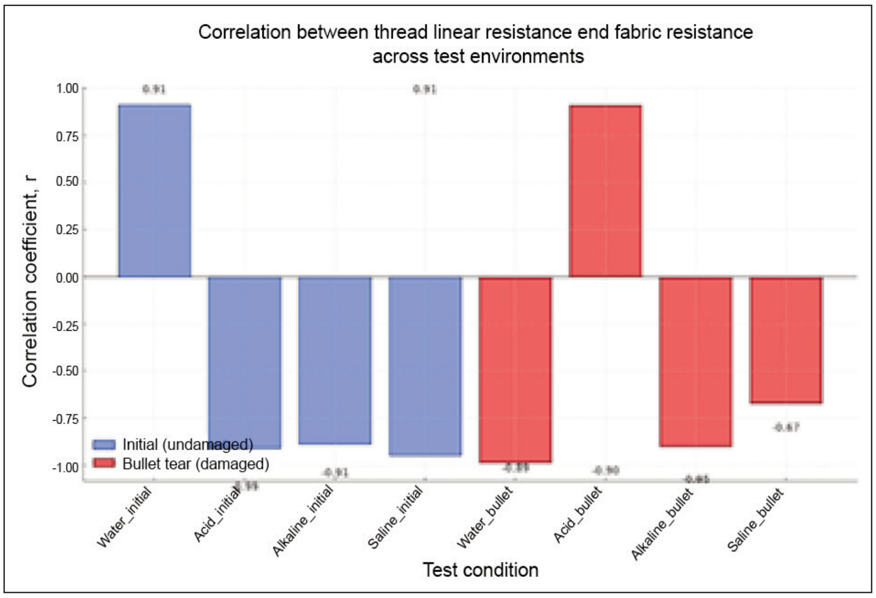
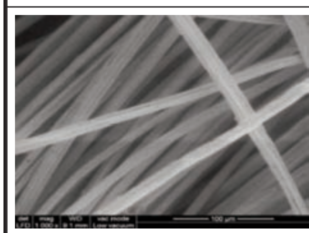
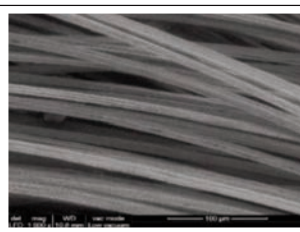
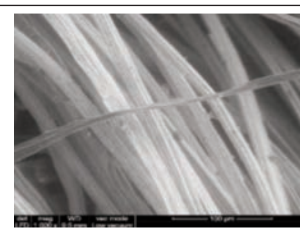


Fig. 14. Correlation between thread linear resistance and fabric sample resistance

Table 4 presents SEM micrographs and elemental data for variant t13 in the initial state and after exposure to acidic and alkaline perspiration and five washing cycles. The spectral bands at 465, 551, 1628, and 3450 cm^{-1}, characteristic of iron oxides, are absent, indicating that the iron surface remains unoxidized (figure 15). SEM images show a clean surface, and EDS detects oxygen and carbon associated with the polymeric support. Only the sample washed five times exhibits a minor oxygen increase, suggesting trace amounts of iron oxide formed through limited reaction with water.

Table 4

<table>
<tr><th colspan="4">SEM IMAGES</th></tr>
<tr><th>1000xSEM image and element concentration – Initial</th><th>1000xSEM image and element concentration – Acid perspiration</th><th>1000xSEM image and element concentration – Alkaline perspiration</th><th>1000xSEM image and element concentration – Washing (5 cycles)</th></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr>
<td><table><tr><th>Element</th><th>Weight %</th><th>Atomic %</th><th>Error %</th></tr><tr><td>C K</td><td>3.9</td><td>14.6</td><td>35.4</td></tr><tr><td>O K</td><td>3.5</td><td>9.8</td><td>20.2</td></tr><tr><td>Cr K</td><td>20.5</td><td>17.7</td><td>17.5</td></tr><tr><td>Fe K</td><td>72.1</td><td>58.0</td><td>14.5</td></tr></table></td>
<td><table><tr><th>Element</th><th>Weight %</th><th>Atomic %</th><th>Error %</th></tr><tr><td>C K</td><td>5.0</td><td>18.2</td><td>30.1</td></tr><tr><td>O K</td><td>3.5</td><td>9.6</td><td>20.4</td></tr><tr><td>Cr K</td><td>19.9</td><td>16.7</td><td>18.5</td></tr><tr><td>Fe K</td><td>71.5</td><td>55.6</td><td>13.7</td></tr></table></td>
<td><table><tr><th>Element</th><th>Weight %</th><th>Atomic %</th><th>Error %</th></tr><tr><td>C K</td><td>8.1</td><td>27.5</td><td>20.0</td></tr><tr><td>O K</td><td>2.2</td><td>5.6</td><td>30.2</td></tr><tr><td>Cr K</td><td>19.7</td><td>15.5</td><td>17.4</td></tr><tr><td>Fe K</td><td>70.1</td><td>51.4</td><td>12.8</td></tr></table></td>
<td><table><tr><th>Element</th><th>Weight %</th><th>Atomic %</th><th>Error %</th></tr><tr><td>C K</td><td>8.0</td><td>25.9</td><td>21.8</td></tr><tr><td>O K</td><td>5.3</td><td>12.9</td><td>15.0</td></tr><tr><td>Cr K</td><td>17.9</td><td>13.3</td><td>15.0</td></tr><tr><td>Fe K</td><td>68.8</td><td>47.9</td><td>12.7</td></tr></table></td>
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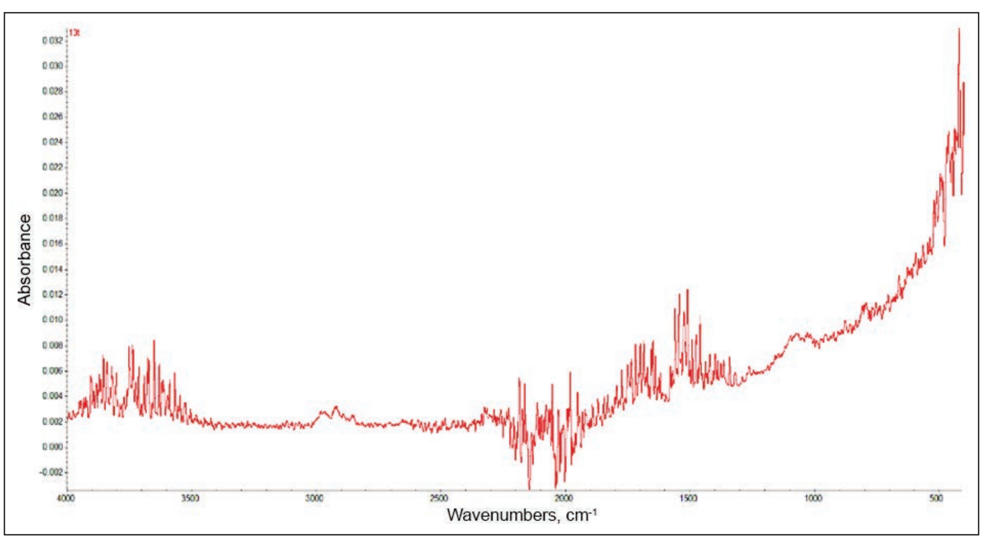

Fig. 15. FT-IR spectrum

RELEVANCE TO HEMOSTASIS DETECTION

The results demonstrate that conductive textiles can serve as functional sensors for detecting the presence of conductive fluids such as blood. During an injury, when a bullet or sharp object pierces the fabric, the contact of blood with the conductive textile alters its electrical resistance, which can be immediately detected by a control unit. This change acts as a trigger for an automatic hemostasis system, capable of initiating wound-sealing mechanisms or sending alerts to medical personnel.

The experimental findings show that:

- Electrical resistance decreases significantly upon contact with saline or blood-like fluids due to increased ionic conductivity.
- The "bullet imprint" condition simulates the localised wetting and mechanical deformation caused by penetration, confirming that the resistance change is strong enough to be used as a detection signal.
- Acidic and alkaline sweat tests demonstrate that body fluids influence sensor performance; however, the conductive pathways remain functional, confirming the textiles' potential reliability under physiological conditions.

Therefore, the conductive knitted fabrics analysed in this study can be integrated as moisture and blood-detection sensors in protective garments, providing the essential feedback component for an automatic hemostatic control system.

CONCLUSIONS

This study demonstrates the feasibility of using conductive knitted fabrics as humidity and blood sensors for integration into automatic hemostasis systems. The electrical resistance of the fabrics changes measurably upon contact with liquids, including saline and body-fluid simulants, providing a reliable detection mechanism for bleeding events.

Key findings include:

- Electrical response: All fabric variants showed significant resistance changes upon wetting, with the largest response observed for 20% saline solution, confirming sensitivity to conductive fluids similar to blood.
- Mechanical performance: Fabrics maintained integrity and consistent sensor performance after abrasion and washing cycles, demonstrating durability for wearable combat applications.
- Chemical stability: SEM, EDX, and FTIR analyses revealed minor oxidation in silver-coated yarns, while stainless steel variants remained stable, ensuring sensor reliability.
- Environmental influence: Acidic and alkaline perspiration affected resistance differently, but all fabrics maintained detectable signal changes, confirming robustness under physiological conditions.
- Application relevance: These resistance variations can serve as triggers for an automatic hemostasis control unit, enabling real-time intervention in bleeding events.

In conclusion, the conductive knitted fabrics studied here function effectively as humidity sensors capable of detecting blood or wound moisture, providing a reliable basis for automatic hemostasis systems. Changes in electrical resistance under bullet-imprint and fluid exposure provide clear signals that can trigger automatic hemostasis control units, enabling real-time intervention during bleeding events. Future work will focus on calibration with blood simulants, integration with electronic control units, and optimisation of signal thresholds for field applications.

ACKNOLEDGEMENTS

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Contemporary interpretation of the elegance of Minoan costume

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ABSTRACT – REZUMAT

Contemporary interpretation of the elegance of Minoan costume

The article addresses a highly relevant topic: the application of artificial intelligence (AI) to the design of Minoan-inspired clothing by transforming fashion illustrations into photorealistic visualisations of physical, wearable garments. Advanced AI systems have been used to develop innovative and practical fashion design solutions that capture the timeless elegance of Minoan costumes while giving them contemporary flair. The study includes an application-based analysis of five affordable AI systems that can transform fashion drawings into photorealistic images. A comparative analysis highlights the observed differences in colours and shapes between the original fashion drawings and the AI-generated models. The effectiveness of these AI systems was validated through a survey and principal component analysis. The results obtained have practical implications in areas such as fashion design, custom clothing production, sustainable fashion, marketing and the training of professionals in this field.

Keywords: *ancient Greek clothing, Minoan costume, AI tools, fashion design, principal component analysis*

Interpretarea contemporană a eleganței costumului minoic

Articolul abordează o temă de mare actualitate: aplicarea inteligenței artificiale (IA) în proiectarea vestimentației inspirate din costumul minoic, prin transformarea schițelor de design vestimentar în vizualizări fotorealiste ale unor creații vestimentare reale și purtabile. Sisteme avansate de inteligență artificială au fost utilizate pentru a dezvolta soluții inovatoare și practice de design vestimentar, care surprind eleganța atemporală a costumelor minoice, conferindu-le totodată un aspect contemporan. Lucrarea prezintă o analiză practică a cinci platforme de inteligență artificială accesibile, capabile să convertească schițele de design vestimentar în imagini fotorealiste. Analiza comparativă evidențiază diferențele de culoare și formă dintre schițele de design vestimentar originale și modelele generate cu ajutorul IA. Eficiența acestor sisteme a fost evaluată prin aplicarea unui chestionar online și prin analiza componentelor principale. Rezultatele obținute au implicații practice în domenii precum designul vestimentar, producția de îmbrăcăminte personalizată, moda sustenabilă, marketingul și formarea specialiștilor din acest domeniu.

Cuvinte-cheie: *îmbrăcăminte greacă antică, costum minoic, instrumente bazate pe inteligență artificială, design vestimentar, analiza componentelor principale*

INTRODUCTION

Historical costumes are one of the most frequently used sources of inspiration by fashion designers for the creation of new models and fashion collections [1]. Considering this, the increased interest in our cultural heritage and folk creativity is reflected in fashion design [2, 3]. Successful fashion design involves the study and analysis of the elements of traditional costumes, their symbolism, modern stylisation of ornaments, interrelationship with contemporary fashion trends, and adapting the assembly features of traditional costumes to the creation and modelling of contemporary clothing. According to Dineva [4], the subject of the study will be the elements and their modern interpretation from traditional Balkan costumes.

The Minoan costume is significantly more elaborate and modern compared to most other traditional clothing and symbolises the ancient Greek culture. As a result of extensive research on Minoan costume, it has been found that complexity, embroidery with stripes, fringes, jewels, ornaments, and colours are some of the main characteristics of this ancient civilisation, which is also confirmed by the existing murals and ceramics. Although much of the literature on Minoan costumes deals with ethnological and design considerations, a summary of these garments with ontological descriptions and numerical expressions is still necessary for these costumes to be easily accepted for modern fashion use [5].

The main materials of Minoan costumes are linen and wool. The distinctive features of the female Minoan costume are an X-shaped silhouette (hourglass);

Bell-shaped skirt made of stripes, checks, diamonds, and stripes with embroidery; fitted, hip-length or longer top, elbow-length sleeves, deep neckline revealing the breasts (it is questionable whether the Minoans always wore bare breasts or only revealed them at festivals); fastens with a belt around the waist; Short apron; Hat: high, pointed, beret, turban, triangular, with decoration: rosettes, feathers, ribbon [6].

Although the historical context of Minoan costume is extensive and this costume has enormous design potential in modern times, there is little research on consumer opinions regarding the integration of these elements into contemporary fashion. While the fashion industry continues to open up to artificial intelligence (AI) technologies, some of which are already offering notable advances in trend forecasting, inventory management, and personalised experiences, AI, particularly in modelling diffusion-based imaging systems, still has relatively unexplored potential in the field of fashion design and merchandising [7, 8].

Capable of generating highly realistic and creative fashion images, these AI systems have enormous potential to revolutionise the design process, marketing strategies and virtual customer experience.

Given the current state of scientific and technological development, the academic community and industry experts are increasingly interested in AI text-to-image generators based on machine learning and modelling techniques [9, 10]. These techniques, which translate textual descriptions of images into realistic, detailed paintings, have opened up entirely new avenues of creativity in fashion, advertising, and entertainment. Researchers' interest in using these tools to support design processes and creative workflows is growing, but most existing AI design developments remain in the digital domain, and very few of them translate designs into physical products.

Advanced AI rendering technology allows users to input initial images along with text descriptions representing fabrics and styles. This innovation leads to creativity, efficiency, and improvement in the work results of designers [11].

There is a lack of sufficient research and solid practical applications to translate AI designs into a photorealistic visualisation of a physical, wearable garment. Overcoming these gaps will help realise the full potential of AI in the fashion industry. The simulation of materials and fabrics, the integration of AI processes into manufacturing and the inclusion of real-time user feedback for customisation ensure that the methods used are not only effective but also sustainable. This study aims to contribute to the field of AI applications in fashion design by incorporating advanced systems to develop innovative and practical solutions that blend the timeless elegance of Minoan costumes with a contemporary sense of modernity.

MATERIAL AND METHODS

The integration of elements from Minoan costumes into modern clothing and textiles can be achieved in various ways, including garment and accessory manufacturing, pattern creation and design, fashion illustration, 3D modelling, and online clothing customisation simulators [7]. This approach shows how these researched costume elements and motifs can be adapted for contemporary fashion. The selected methods include fashion drawing (sketching), online clothing simulation and the use of AI.

Table 1 provides an overview of the online tools used to create photorealistic images. Additionally, a tool used for further image processing, particularly background removal, is highlighted. This step improves image comparability, as each AI generator applies its own default background, which may not match the intended presentation.

The primary colours in the clothing patterns are defined by an RGB colour model. They are then converted into Lab for the calculation data (observer 2º and illuminance D65). The colour difference (ΔE) was determined. It varies in the range of 0–100; The closer it is to 0, the more similar the colours of the compared samples are, and the closer it is to 100, the more different they are. The naked human eye distinguishes colours with $\Delta E > 20$ [12].

Table 1

ONLINE TOOLS USED IN THIS STUDY

Abbreviation	Name	Internet link	Accessed	Description
-	Remove bg	https://www.remove.bg	18.05.2024	Removes background from image
NA	NewArc ai	https://www.newarc.ai	22.06.2024	Turns any sketch into a photo using an AI tool
OA	OpenArt ai	https://openart.ai	11.07.2024	Turns any sketch into a photo using an AI tool
AR	Architect Render ai	https://app.architectrender.com	28.07.2024	Turns any sketch into a photo using an AI tool
PP	Petalica Paint	https://petalica.com	19.07.2024	Colorize sketches
RW	Runway ML	https://app.runwayml.com	29.07.2024	Turns any sketch into a photo using an AI tool

$$\Delta E = (L_c - L_a)^2 + (a_c - a_a)^2 + (b_c - b_a)^2 \quad (1)$$

where L_c, a_c, b_c are colour components of fashion drawings; L_a, a_a, b_a – colour components of AI-generated models.

Colour matching between fashion drawings and AI-generated dresses is crucial to ensure precision, accuracy, and quality of design, bringing the final products as close as possible to the original vision. AI tools offer the opportunity to refine the creative process by addressing the inconsistencies that need to be corrected.

A total of five basic formulas were used to determine silhouette shape coefficients [13]. They have the following form:

$$K_1 = \frac{A}{A_{ideal}} \quad (2)$$

$$K_2 = \frac{A}{A_{mr}} \quad (3)$$

$$K_3 = \frac{D - d}{D} \quad (4)$$

$$K_4 = \frac{d}{D} \quad (5)$$

$$V = \frac{4}{3}\pi \frac{D}{2}\left(\frac{d}{2}\right)^2 \qquad K_5 = \frac{3V}{4\pi D d^2} \quad (6)$$

where d is a minor axis of the silhouette; D – a major axis of the silhouette; P – the perimeter; A – the area; A_{ideal} – the ideal area calculated along the major and minor axes of the silhouette. A_{mr} is the area of the rectangle enclosing the silhouette. V was calculated from the major and minor axis data.

Comparing fashion drawings to AI-generated clothing shapes, shape factors K1 to K5 describe shape characteristics objectively and quantitatively. K1 and K2 determine the efficiency of the area in relation to ideal shapes and bounding rectangles and thus show consistency in design and use of space. K3 and K4 determine the degree of elongation and roundness and can help assess proportions and symmetry. K5 describes the three-dimensional occupation of space and the volumetric deviation from the ideal shape.

A Euclidean distance was calculated between the obtained shape factor values for the sketch and those from the AI-generated ones. The Euclidean distance is determined by the following formula:

$$d(k_s, k_{ai}) = \sqrt{(k_s - k_{ai})^2} \quad (7)$$

where k_s is a coefficient value of fashion drawings and k_{ai} – a coefficient value of an AI-generated model.

The survey was conducted using Google Forms (Google Inc., Googleplex, Mountain View, California, U.S.) in compliance with all the requirements of the ethical code of Trakia University, Stara Zagora, Bulgaria [14].

According to Mladenov [15], the principal component analysis (PCA), used to compare clothing samples and objects generated by AI tools, involves the creation of an orthogonal coordinate system in which the axes are ordered according to the corresponding principal component and variations of the original data. If the covariance matrix is diagonal, it means that the variables are independent. Otherwise, the data can also be displayed at its mean squared error by selecting the variable with the highest variance. The number of principal components was determined according to the criterion that it should describe more than 95% of the variance of the experimental data.

RESULTS

Photorealistic representation of fashion drawings

Six fashion drawings of Minoan-style dresses are offered. Figure 1 shows the main dress patterns based on Minoan costume.

Model M1 is a multi-layered hourglass dress with brown colours, short sleeves, and a high neckline. Model M2 represents a fitted silhouette with an accentuated waist, achieved through a colourful decorative belt. The small sleeves are attached to a bustier, while the multi-layered blue skirt extends

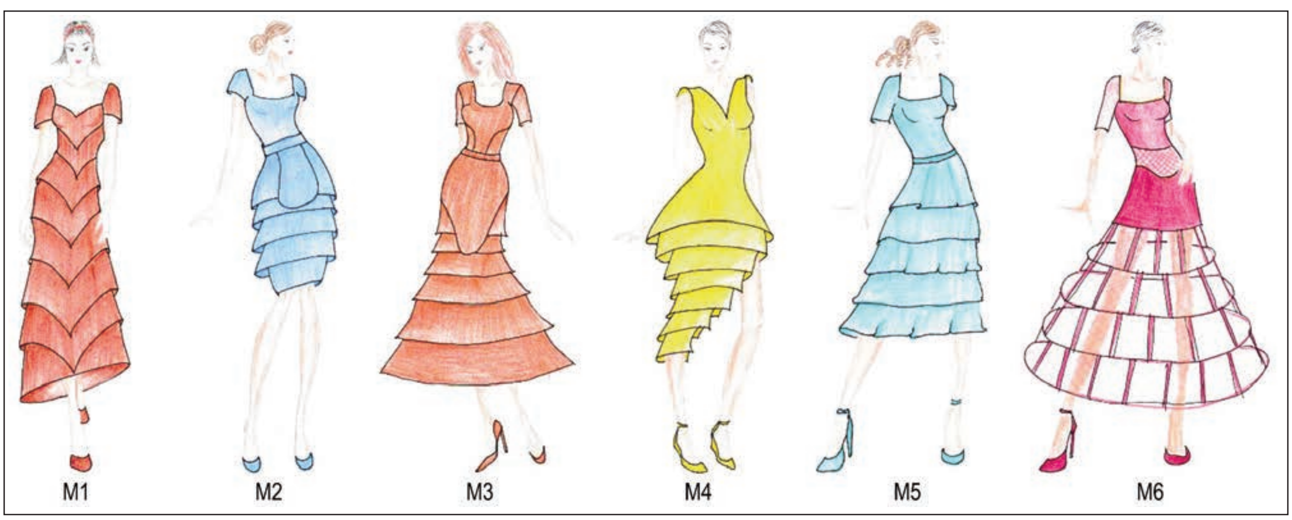

Fig. 1. Main fashion drawings

below the knee. An apron around the waist elegantly complements the ensemble. The Model M3 is very fitted; the neckline is deep and is framed by a decorative band. The hips are defined by a top skirt layer that reaches mid-thigh, highlighting the fitted waist and emphasising femininity. Below this, five additional layers progressively expand downward, creating a flowing and liberated silhouette. Model M4 is asymmetrical and multi-layered in a warm yellow colour combination with a deep plunging neckline. Model M5 has an X-shaped silhouette and combines the multicoloured skirt with the monochrome of the bustier. The deep, square neckline is adorned with Minoan motifs, while the short sleeves emphasise the neckline. The upper part of the dress is fitted, and the lower part is multi-layered, with the first layer having the possibility of being removed as a type of apron. Model M6 features a fitted silhouette at the top, with elegant mesh sleeves extending to mid-arm. The strongly cut square neckline accentuates femininity, and the waist is highlighted by a small mesh panel with a symbolic round shape. This transitions into a short skirt that follows the hips, forming the base of the richly patterned full skirt. Each successive layer expands with staggered elements, adding playfulness and elegance to the final silhouette. The dark cherry colour palette enhances the outfit's vibrancy and charm.

Table 2 presents the auxiliary descriptions (prompt) for generating photorealistic models of dresses. Model colours are also set as text descriptions. Some prompts are automatically generated by NewArc.ai, supplemented by the authors.

Figure 2 shows the models generated using NewArc.ai. The M1 model accurately represents the women's dress in an almost exact colour palette, with the correct layering of the model. An AI tool added decorations to the fabric. M2 follows the silhouette and colour, forgoing the small removable apron but adding a patch to the front of the skirt on the top layer of the dress. The model M3 respects the silhouette; the large neckline and narrow sleeves are emphasised; It is fitted around the waist. Here, the small apron is more clearly expressed. In the model M4, attention is paid to the warm yellow colour and the asymmetrical, multi-layered lower part of the dress, which is strongly fitted and has a sharp neckline, but the straps are very thin. The model M5 retains all the basic colours and shapes of the original fashion design. In the model M6, the transparency of the skirt is retained, but not completely. Floral elements that were not present in the original fashion drawing were added.

Table 2

IMAGE SUPPORTING DESCRIPTIONS (PROMPTS)

Model	Prompt
M1	Red evening gown, chevron pattern, sweetheart neckline, short sleeves, floor-length, tiered design, form-fitting silhouette
M2	Blue dress, tiered ruffled skirt, cap sleeves, fitted bodice, square neckline, high bun hairstyle
M3	Elegant coral evening gown, fitted bodice, tiered ruffled skirt, square neckline, short sleeves, cinched waist
M4	Yellow cocktail dress, v-neckline, sleeveless design, tiered ruffled skirt, fitted bodice, ankle-strap high heels
M5	Turquoise tiered dress, square neckline, short sleeves, ruffled layers, fitted bodice, matching high heels
M6	Fashion sketch, pink dress, crinoline structure, fitted bodice with straps, checkered waist detail, high heels, transparent skirt

Fig. 2. Models generated with NewArc.ai

Fig. 3. Models generated with OpenArt.ai

Figure 3 presents the models generated using OpenArt.AI, employing the same auxiliary descriptions as outlined earlier. For Model M2, additional colours were generated on the top and the first layer of the skirt. All models appear clean, without any additional accessories.

The colours of Models M5 and M6 differ slightly from their original fashion drawings. Model M1 adheres to the intended silhouette, but its colours are darker compared to the original design. Model M2 retains the silhouette, but the original colours were not preserved; white and purple were added.

Model M3 accurately maintains the original silhouette. However, the apron's belt has changed colour, making it more prominent and dynamic. Model M4 preserves the original colour palette and shape, and the sectional details are recreated with greater precision compared to outputs from other AI image generators. Model M5 replicates the silhouette, neckline shape, and narrow sleeves, but the colours are lighter and do not closely match the original design. In Model M6, the shape and silhouette align with the original, although the colours are less accurate.

Figure 4 illustrates the models generated using ArchitectRendering.ai, with the same auxiliary descriptions as previously noted. For the models M1 and M5, the AI tool introduced a pattern to the fabric. Additionally, a fashion accessory – a handbag – was added to the M5 model. The other models remain unadorned, without any additional accessories. The skirt of the M6 model is rendered as opaque.

In the model M1, the silhouette and colour are preserved, but a pattern is applied to the fabric. In the case of the model M2, the silhouette, shape, and colour are faithfully represented; however, the apron lacks a belt, which may affect its mobility. The models M3 and M4 retain all elements of the original fashion design. For the model M5, the AI generated larger drapes than those in the original image, and the sleeves appear wider than in the initial fashion drawing. Lastly, in the model M6, the transparency characteristic of the original design is successfully maintained.

Fig. 4. Models generated with ArchitectRendering.ai

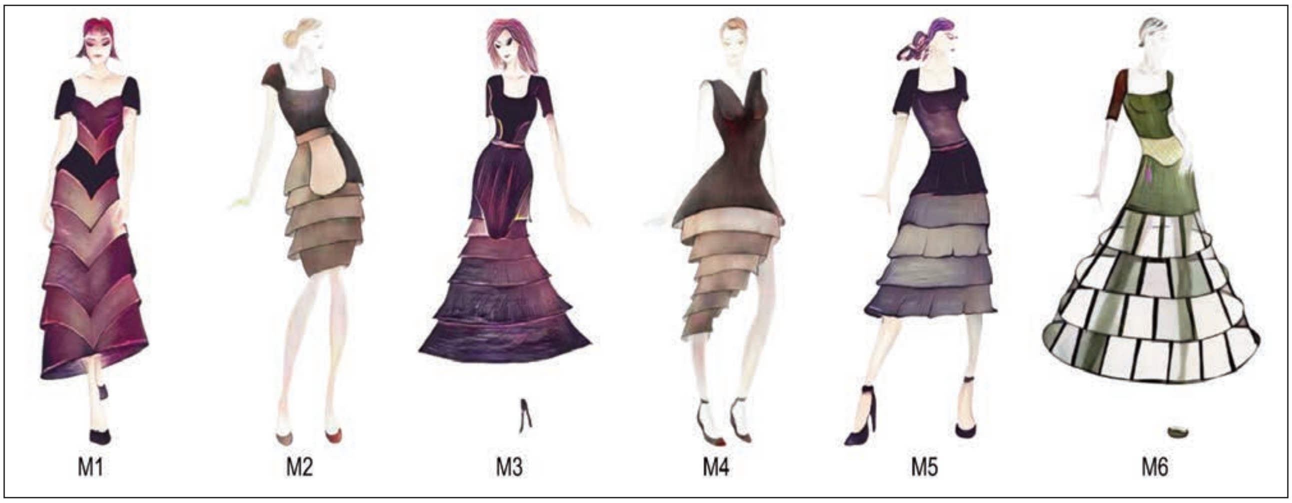

Fig. 5. Models generated with Petalica Paint

Figure 5 shows the models created with Petalica Paint. The same auxiliary descriptions as above are used. All models hold the silhouettes and original models, but the colour combinations do not match.

Figure 6 shows the models generated with RunWayML. The same auxiliary descriptions as above are used. The fabrics generated are clean, without patterns. In models M1 and M4, the elements specific to the Minoan costume are highlighted. In model M2, white and golden skirt colours have been added. Also, as in the original fashion design, model M6 features a see-through skirt. The models are clean, without added accessories. Model M1 has outlines in the layers of the dress, which may not be well received by some users. In model M2, the silhouette, main colour, and mobility of the apron are preserved, but the last three layers of the multi-layered dress do not match the original. In model M3, there is a complete match with the original in silhouette, belt, and mobility of the apron, but it does not correspond in colour. Model M4 has added contours at the ends of the asymmetric dress, which may not be well received by some users. Model M5 differs only in colour from the original fashion drawing. Model M6 retains the transparency of the skirt and sleeves, but the model is too stylised.

Figure 7 shows the primary colours used in fashion drawings and AI-generated images. Visual colour analysis shows that these AI-generated images match the underlying fashion drawings. There is no match at all with Petalica Paint. Additionally, the model M6 generated with RunWayML shows a significant difference in the base colour generated. To illustrate these colour differences in more detail, numerical analysis is required.

Table 3 shows values from the lab colour model for the primary colours presented. Colour component values from the Lab model show that the NewArc.ai-generated objects predictably have the closest match to the source fashion drawings, performing strongly for M3 and M4. OpenArt.ai shows sufficient accuracy, but with deviations for M2, M3, and M6.

ArchitectRendering.ai only performs well on M4, deviating from many other models. Significant inconsistencies are observed in the models generated with Petalica Paint and RunWayML, more evident in the

Fig. 6. Models generated with RunWayML

models M2, M3, and M6. In all AI instruments, significant deviations in the lab values of the colour components are observed for the M6 model.

Table 4 shows the colour difference between the fashion drawings and the AI-generated dress models. The colour difference analysis shows that NewArc.ai

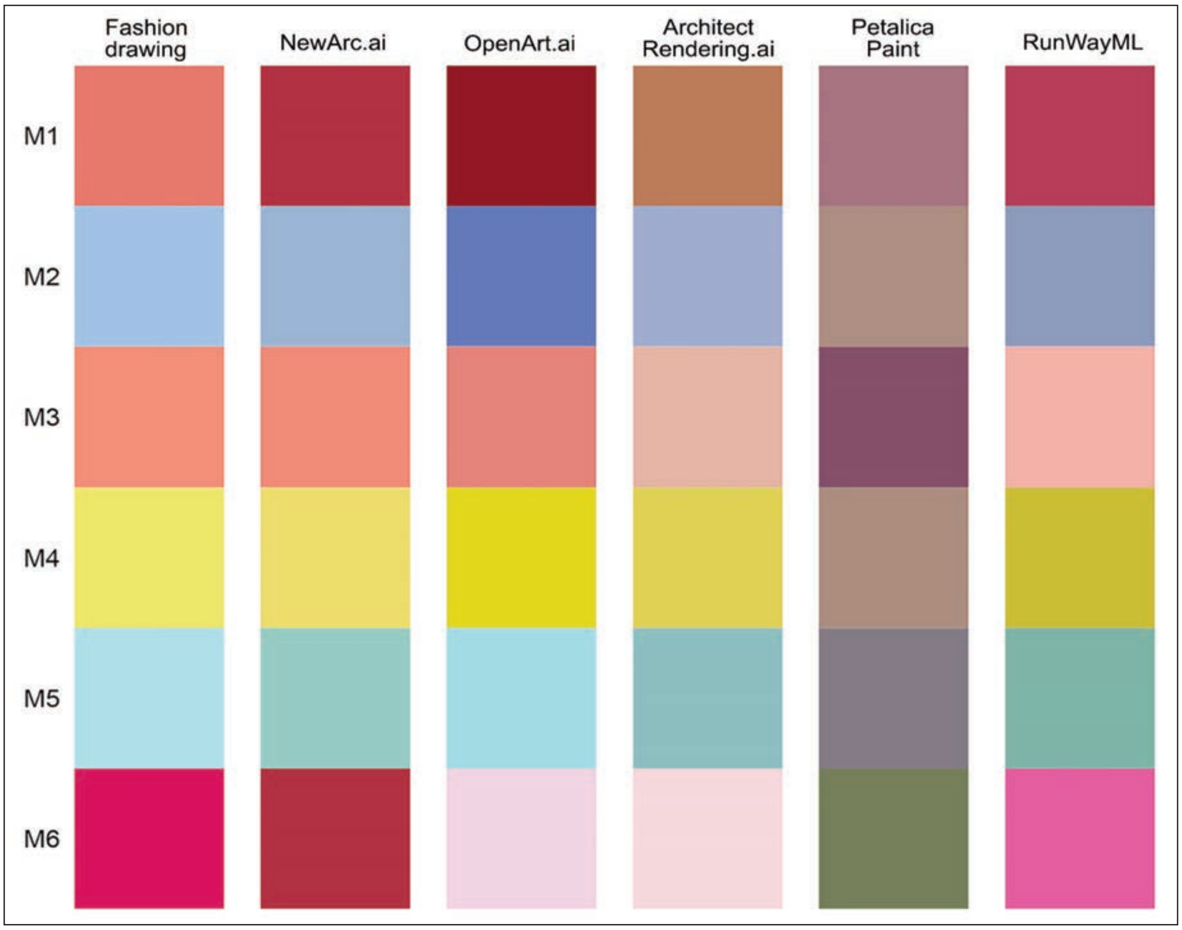

Fig. 7. Main colours from fashion drawings and AI-generated images

Table 3

LAB VALUES OF MAIN COLOURS

Source	Model / Colour	M1	M2	M3	M4	M5	M6
Fashion drawing	L	57.81	70.55	62.92	86.66	79.67	47.99
	a	53.52	–10.65	49.83	–0.63	–27.61	73.03
	b	34.41	–41.82	37.76	64.93	–14.81	24.66
NewArc.ai	L	41.05	60.66	61.94	82.06	67.63	63.25
	a	54.56	–7.24	50.23	3.26	–23.71	36.47
	b	28.21	–23.36	35.9	60.17	–3.36	7.11
OpenArt.ai	L	28.34	40.79	58.39	77.34	76.49	81.53
	a	50.1	5	46.57	–2.32	–27.38	20.42
	b	32.22	–46.11	27.49	78.25	–15.33	–8.51
Architect Rendering.ai	L	50.74	58.66	68.49	75.94	62.2	82.66
	a	29.79	–1.74	22.78	1.99	–19.94	18.07
	b	31.79	–24.72	18.41	62.01	–8.68	0.73
Petalica Paint	L	44.68	50.95	31.89	50.66	42.13	41.57
	a	24.42	14.38	25.44	13.14	3.3	–7.84
	b	2.12	11.76	–3.38	13.08	–5.22	17.52
RunWayML	L	41.35	51.59	70.33	67.1	57.65	53.25
	a	52.21	–2.54	32.87	0.88	–23.8	63.23
	b	17.94	–21.89	19.12	62.22	0.43	–5.07

Table 4

COLOUR DIFFERENCE ΔE BETWEEN FASHION DRAWINGS AND AI-GENERATED MODELS						
Model \ Source	**Sketch**	**NewArc.ai**	**OpenArt.ai**	**Architect Rendering.ai**	**Petalica Paint**	**RunWayML**
M1	0	17.88	**31.66**	**24.12**	**33.39**	17.82
M2	0	19.58	**30.77**	**22.61**	**65.89**	**21.68**
M3	0	2.22	12.48	**31.85**	**56.29**	**27.82**
M4	0	6.51	15.89	11.11	**65.28**	20
M5	0	14.06	3.2	**21.97**	**45.75**	**24.68**
M6	0	**40.31**	**72.69**	**73.3**	**81.93**	**32.39**

has a closer colour match to the original fashion drawings than the other AI tools, especially for the M3 and M5 models. OpenArt.ai performs well on the model M5, although there are significant deviations for the M6 model. ArchitectRendering.ai has moderate colour accuracy, but there is a slight colour difference for the M4 model. A significant colour difference is observed in all models generated with Petalica Paint, which is greatest in models M2, M4, and M6. RunWayML shows average results. For M1 and M5, the results are more accurate, but for M3 and M6, there are serious deviations. As for the colour reproduction for the model M6, all the AI tools do not show a sufficiently accurate result.

Table 5 shows the results of determining the shape coefficients. Comparing the coefficient values, it becomes obvious that most AI tools do reproduce the shapes of models M1 to M5, and their coefficients are very close to those in the original fashion drawings. However, all instruments lack sufficient accuracy in the model M6, showing significant biases, especially for the K1 and K2 coefficients. In most models, OpenArt.ai and ArchitectRendering.ai show the greatest accuracy, while Petalica Paint and RunWayML show some differences, although overall,

Table 5

COEFFICIENTS OF FORM										
Source	**Fashion drawing**					**NewArc.ai**				
Model \ Coefficient	K1	K2	K3	K4	K5	K1	K2	K3	K4	K5
M1	0.83	0.65	0.71	0.29	0.13	0.93	0.73	0.76	0.24	0.13
M2	0.59	0.47	0.70	0.30	0.13	0.66	0.52	0.76	0.24	0.13
M3	0.69	0.54	0.63	0.37	0.13	0.70	0.55	0.68	0.32	0.13
M4	0,76	0,59	0,68	0,32	0.13	0.82	0.64	0.72	0.28	0.13
M5	0.59	0.47	0.62	0.38	0.13	0.62	0.49	0.65	0.35	0.13
M6	0.77	0.60	0.37	0.63	0.13	0.52	0.41	0.63	0.37	0.13
Source	OpenArt.ai					ArchitectRendering.ai				
Model \ Coefficient	K1	K2	K3	K4	K5	K1	K2	K3	K4	K5
M1	0.92	0.73	0.76	0.24	0.13	0.89	0.70	0.73	0.27	0.13
M2	0.60	0.47	0.74	0.26	0.13	0.67	0.52	0.71	0.29	0.13
M3	0.71	0.56	0.68	0.32	0.13	0.70	0.55	0.69	0.31	0.13
M4	0.80	0.63	0.71	0.29	0.13	0.77	0.60	0.72	0.28	0.13
M5	0.66	0.52	0.66	0.34	0.13	0.62	0.49	0.64	0.36	0.13
M6	0.15	0.12	0.62	0.38	0.13	0.37	0.29	0.69	0.31	0.13
Source	Petalica Paint					RunWayML				
Model \ Coefficient	K1	K2	K3	K4	K5	K1	K2	K3	K4	K5
M1	0.82	0.64	0.58	0.42	0.13	0.93	0.73	0.76	0.24	0.13
M2	0.52	0.41	0.64	0.36	0.13	0.54	0.42	0.75	0.25	0.13
M3	0.68	0.53	0.65	0.35	0.13	0.70	0.55	0.62	0.38	0.13
M4	0.73	0.57	0.69	0.31	0.13	0.81	0.64	0.70	0.30	0.13
M5	0.54	0.43	0.65	0.35	0.13	0.64	0.50	0.67	0.33	0.13
M6	0.31	0.24	0.56	0.44	0.13	0.51	0.40	0.56	0,.44	0.13

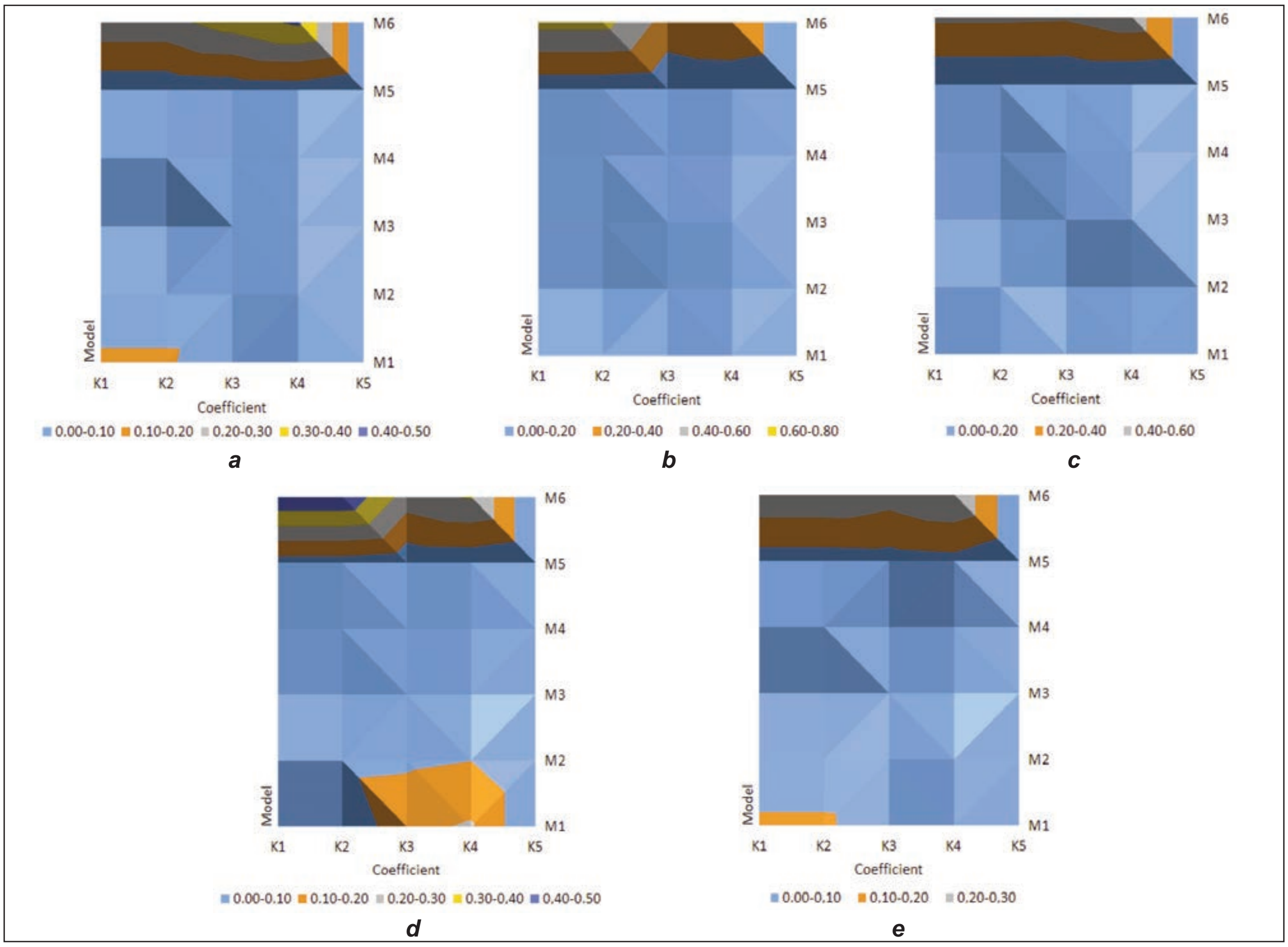

Fig. 8. Euclidean distances between fashion drawings and AI-generated models: *a* – NewArc.ai; *b* – OpenArt.ai; *c* – ArchitectRendering.ai; *d* – Petalica Paint; *e* – RunWayML

relatively close replications are obtained for most models.

Figure 8 plots the Euclidean distances between the shape factors of the fashion drawings and those of the AI-generated models. The Euclidean distances for the AI-generated dress patterns with respect to the original ones show that in most cases, the AI tools can reproduce the shapes of the M1 to M5 patterns with fairly low distances and therefore a significant match. In parallel, all instruments have significant difficulties with M6, showing larger distances and therefore larger differences with the original. In most of the models, OpenArt.ai and ArchitectRendering.ai perform well enough, except when working with M6. This means that while these current AI tools are able to reproduce simple or more common forms of fashion drawings, they struggle with more complex or unique designs like the M6.

Survey results

A survey was conducted on users' opinions about the created photorealistic dress models. Figure 9 shows an overview of the survey form used. The survey involved 73 respondents who selected the clothing models a total of 393 times (with the possibility of selecting more than one model).

Table 6 shows the results of the survey. The number of selected models is indicated. Dress models show that they are selected differently depending on which AI tool they were generated with. In this case, it is noticeable that M1 is most often selected by NA (31 times) and by RW (17 times), thus showing a preference for models generated with these two tools. Again, although M2 generated with NA is also more frequently selected (30 times), it does not share the same position among all other instruments. While the average choice in most instruments is M3, M4, and M5, the top choice is NA, a testament to the dominant role it plays. M6 is less popular overall but has a notable PP selection (14 times), indicating a specific colour or shape preference unique to PP.

Figure 10 shows the results of a principal component analysis. The two principal components describe

Table 6

SURVEY RESULTS – NUMBER OF RESPONSES

Model / AI tool	M1	M2	M3	M4	M5	M6
NA	31	30	18	27	27	25
OA	9	12	12	16	13	11
AR	6	8	13	9	15	12
PP	4	5	6	5	6	14
RW	17	7	9	6	12	8

Note: NA – NewArc.ai; OA– OpenArt.ai; AR – Architect Render.ai; PP – Petalica Paint; RW-Runway ML.

Fig. 9. Survey form – general view

96.09% of the variance in the analysed data. Dress patterns M1 to M6 are more or less related to the two main components. M1 and M5 fit the main trends in the data due to their positive relationship with PC1 and therefore reproduce common characteristics or styles. In contrast, M6 exhibits a negative relationship with PC1 and PC2, indicating unique or distinct characteristics that none of the other models have. M3 and M5 have high positive principal component values at PC2. Therefore, they bring up different points of variability associated with quite different design elements. The AI tools also show a non-uniform scatter in the principal components plot. NA is strongly positively correlated with PC1, which has a dominant trend or influence in the data set as a result of its capabilities and wider selection by users. However, PP is strongly negatively correlated with PC1, which means that it represents the opposite trend. On the other hand, RW and AR, respectively positively and negatively correlated with PC2, are related to very different aspects of variation and thus can be used for some specific tasks or functions.

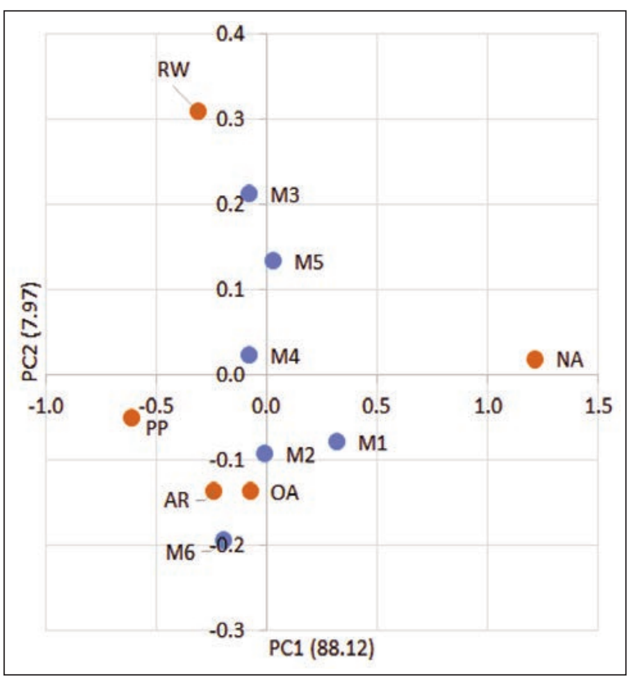

Fig. 10. PCA of survey results: NA – NewArc.ai; OA – OpenArt.ai; AR – ArchitectRender.ai; PP – PetalicaPaint; RW – Runway.ML

A comparative analysis of AI tools

Table 7 below compares the AI tools used on key performance indicators for generating photorealistic images. NewArc.ai matches the closest colour equivalent to the original designs for M3 and M5, with high shape accuracy and low Euclidean distances, making it the most preferred tool, especially for M1 and M2. OpenArt.ai, while reasonably accurate to colours with minor deviations, especially in M2, M3, and M6, describes shape well at small distances; however, it is generally averaged over user choice, correlating positively with both PC1 and PC2.

ArchitectRendering.ai has average colour accuracy and is best with M4. It maintains high shape accuracy, low Euclidean distances, and average user choice, with a positive correlation with PC2, indicating that it is a suitable tool in certain design variations. On the other hand, PP produces highly divergent colours, primarily in the M2, M4, and M6 models, while the differences according to the shape factors are larger and the Euclidean distances are larger too, and it is the least selected tool overall. It is also strongly negatively correlated with PC1; therefore, very often it shows the opposite trend compared to NA.

Table 8 presents a summary of how successful the corresponding AI tool was in realising photorealistic models for fashion drawings M1 to M6. NewArc.ai performs well on models M1 to M5, but quite poorly on M6. OpenArt.ai performs well on models M1, M3, M4, and M5, but encounters problems with M2 and M6. ArchitectRendering.ai does well with models M1 through M5, as is the case with other tools; however, every tool fails when it comes to the M6 model. For PP, poor performance is seen in all models, hence large deviations in accuracy. RW does well with the

Table 7

BENCHMARKING THE RESULTS SHOWN BY AI TOOLS					
AI Tool	**Colour difference**	**Shape coefficients**	**Euclidean distances**	**Survey results**	**Principal component analysis**
NewArc.ai (NA)	The closest match for M3 and M5	High accuracy, minor deviations in M6	Low distances for M1-M5, high for M6	Most selected, especially for M1 and M2	Strongly positively correlated with PC1, indicating a strong influence
OpenArt.ai (OA)	Sufficient accuracy, deviations in M2, M3 and M6	High accuracy but minor deviations in M6	Low distances for M1-M5, high for M6	Average selection, performs well for the M5	Positive correlation with PC1 and PC2 indicates variability
Architect Rendering.ai (AR)	Moderate colour accuracy, best for M4	High accuracy, minor deviations in M6	Low distances for M1-M5, high for M6	Average selection, good for M4	Positive correlation with PC2 is associated with specific design variations.
Petalica Paint (PP)	Significant colour differences in M2, M4 and M6	Variations were observed in M6	Larger distances indicate more deviations from the original	Least selected overall, but noticeable for the M6	Strong negative correlation with PC1, indicating the opposite trend of NA

Table 8

COMPARATIVE ANALYSIS OF THE EFFECTIVENESS OF PHOTOREALISTIC REPRODUCTION OF FASHION DRAWINGS						
AI Tool	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**
NewArc.ai (NA)	Y	Y	Y	Y	Y	N
OpenArt.ai (OA)	Y	N	Y	Y	Y	N
ArchitectRendering.ai (AR)	Y	Y	Y	Y	Y	N
Petalica Paint (PP)	N	N	N	N	N	N
RunWayML (RW)	Y	N	N	Y	Y	N

Note: Y – yes; N – No.

M1, M4, and M5 models but poorly with the M2, M3, and M6. This means that most of the tools do reasonably well with the uncomplicated designs of M1 through M5, but fail miserably with the more complex designs of M6.

DISCUSSION

Historical costumes have always served as a source of inspiration for fashion designers. According to Pendergast et al. [1], reinterpreting historical elements offers an opportunity for innovation while preserving the memory of the original. According to Kazlacheva et al. [3], the cultural heritage has recently been given a second life. Therefore, interest in the manifestation of folk creativity remains relevant for solving modern design tasks. Dineva [4] examines historical Balkan clothing, and she argues that traditional clothing can offer a range of design elements that are quite applicable in contemporary fashion. A very good example is that of the Minoan costume described by Papadopoulou et al. [5]. For example, the intricate details of Minoan tapestries, including the layering of skirts, embroidery, and colour combinations, are the inspiration for modern clothing. This falls in line with the general trend of incorporating as many elements of historical costumes as possible to create something original and modern.

In adapting historical prototypes to modern costumes, aesthetic requirements are not enough; there is also a mission requirement seeking an understanding of their symbolic meanings. This would therefore include an hourglass silhouette, a bell-shaped skirt in Minoan costume, and an exaggerated headdress that takes on a variety of complex shapes, ending in a plume of feathers or a horn-like projection on the back [6]. Such stylisations can be introduced into contemporary dress collections as a way of continuing the past and expressing a sense of historical continuity and cultural depth. In modernising stylisation, the preservation of historical authenticity is balanced with the introduction of contemporary relevance.

Artificial intelligence (AI) integrated into fashion design brings some significant steps forward in the industry. If we take a closer look at Sun [7] and Zhang et al. [8], regarding AI technologies related to trend forecasting, inventory management, and personalisation, it can be seen that they have truly revolutionised the design and merchandising processes. This was echoed by Liu et al. [9] and Shaheen et al. [10], who say that AI-generated imagery can enhance designer creativity and efficiency with newer ways to experiment with historical elements and therefore lead to innovations in collection building. These guidelines are supplemented and refined in the current development through a benchmarking of AI tools and a survey.

Regarding the different AI tools available, each has its own levels of performance in fashion design. As the results obtained in this article show, NewArc.ai is the clear leader in user preference and quite strong in the M1 and M2 models. This could indicate that this model borrows heavily from designs that would be considered modern. The high positive correlation with PC1 further indicates the dominant influence on fashion trends. The Runway ML tool is mainly preferred for the M1 model. Its correlation with PC2 means that it focuses on different elements of design variation than NewArc.ai. Users prefer the M6 model generated with PetalicaPaint. This means that this AI tool is suitable for certain tastes or other unique design elements that other tools have not been able to capture. OpenArt.ai and ArchitectRender.ai generate a more balanced selection between models, with no one dominating. This is because their correlations with the principal components are different and therefore, they lead to different design results.

CONCLUSION

The present study, therefore, highlights the potential that AI holds in fashion design and how its applications could revolutionise the industry's approach to creativity and, ultimately, responsiveness to consumer preferences. This comparative study aims to explore how blending historical and contemporary patterns with modern technologies could play a crucial role in fashion design. For example, historical costumes, such as those of the Minoan civilisation, can be adapted to contemporary fashion, providing both depth and continuity. Now that all of these concepts are integrated into the process through AI technologies, designers can work more freely and iteratively improve their results. The skills gap across these different AI tools further underscores the need to combine historical inspiration with renewed innovation.

It has been noticed that the preference for AI-generated dress models depends on the specific tool that generated them, where tools like NewArc.ai take a leading role by fitting into the modern design trend. Quantitative analysis shows that models like M1 and M5 include highly preferred design elements, while other models, such as M6, provide preferences for niches with specialised tools such as Petalica Paint.

The principal component analysis has shown that 96.09% of the total variance is covered by the first two components, underlining clear trends and distinctions in the variability of the designs. While some AI tools were aligned positively with dominant or unique aspects in design trends, other strongly relates negatively to the contemporary style in the output and accentuate its unique role.

These findings add to some of the empirical evidence that may contribute to the diverse literature on the diversity of AI-generated designs and how those are received by users. The present study has established the strong influence of AI tools in setting dominant design trends while proving the unique contribution made by niche tools toward diverse creative output.

The results of the present study may be applied to practice in at least the following directions: fashion design, clothes customisation, sustainable fashion, marketing, and professional training. However, significant challenges also remain, with a special emphasis on technological implementation: fabric simulation, integration into production methods, the process of customisation, and ethical treatment of users.

Overcoming these challenges requires further research. Development should be done in enhancing the AI algorithms, prototyping, and testing, integrating AI experts with the fashion industry. Besides, there should be sustainable development and the development of platforms that can facilitate feedback from consumers. Addressing these areas ensures that AI can achieve its fullest potential, bringing innovation, efficiency, and sustainability to the fashion industry.

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Quantification and evaluation of chemical footprint with four methods: A case of the dyeing and printing process of a polyester dress

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ABSTRACT – REZUMAT

Quantification and evaluation of chemical footprint with four methods: A case of the dyeing and printing process of a polyester dress

The textile printing and dyeing industry, with huge chemical demand, has a negative impact on the ecosystem. Chemical footprint quantifies the toxic impacts of chemical pollutants by assessing their behaviour in the environment. In this paper, four methods were used to calculate and evaluate the chemical footprint of a polyester dress printing and dyeing process. The chemical footprint of the printing and dyeing process of a polyester dress, calculated with USEtox, Assessment of Mean Impact, Score System, and Strategy Tool, was 1585.51 PAF×m^3×day, 14089.04 l, 331, and 75, respectively. Scouring, colouring, pretreatment, and printing were identified as the major procedures contributing, with the antifoaming agents and the chelating disperse agents as the major auxiliaries contributing. The results of the Strategy Tool are limited in their representativeness of environmental load. Compared to other methods, AMI ensures that the evaluation results are scientific while maintaining user-friendliness.

Keywords: *chemical footprint, polyester, printing and dyeing, toxic effects, environmental impact*

Cuantificarea și evaluarea amprentei chimice cu patru metode: un studiu de caz privind procesul de vopsire și imprimare a unei rochii din poliester

Industria de imprimare și vopsire a materialelor textilelor, cu o cerere enormă de produse chimice, are un impact negativ asupra ecosistemului, amprenta chimică cuantificând impactul toxic al poluanților chimici prin evaluarea comportamentului acestora în mediu. În acest articol, au fost utilizate patru metode pentru a calcula și evalua amprenta chimică a unui proces de imprimare și vopsire a unei rochii din poliester. Amprenta chimică a procesului de imprimare și vopsire a unei rochii din poliester, calculată cu USEtox, Assessment of Mean Impact, Score System și Strategy Tool, a fost de 1585,51 PAF×m^3×zi, 14089,04 l, 331 și, respectiv, 75. Spălarea, colorarea, pretratarea și imprimarea au fost identificate ca fiind principalele procese care contribuie la acest impact, iar agenții antispumanți și agenții dispersanți chelatori au fost identificați ca fiind principalii adjuvanți care contribuie la acest impact. Rezultatele Strategy Tool sunt limitate în ceea ce privește reprezentativitatea lor pentru impactul asupra mediului. În comparație cu alte metode, AMI asigură faptul că rezultatele evaluării sunt științifice, menținând în același timp ușurința în utilizare.

Cuvinte-cheie*: amprenta chimică, poliester, imprimare și vopsire, efecte toxice, impact asupra mediului*

INTRODUCTION

The practice of dyeing is among humanity's most ancient crafts and represents an essential component of the modern textile industry [1]. It serves to enhance the value of products, provides employment, and improves the well-being of people. Concurrently, the textile printing and dyeing industry is a chemical-intensive industry in which chemicals play a pivotal role. It employs over 8,000 chemicals and produces over 700,000 tons of synthetic dyestuffs globally yearly [2, 3]. Some of the textile auxiliaries used in the manufacturing process are released into the environment in the form of wastewater and waste gases, which have the potential to negatively impact the natural environment and ecosystems [4].

Increasing environmental issues and consumer awareness of sustainable products are forcing governments to implement control policies and compelling manufacturers to re-examine all aspects of dyeing processes in search of environmentally friendly technologies to reduce the negative environmental impact of production [5]. While current guidance on chemical risk assessment in production systems is aimed at facilitating the implementation of management activities, chemical footprint (ChF) is based on a life cycle assessment and presents a new solution for chemical risk assessment in the textile field from the perspective of quantifying toxic impacts [6, 7]. Tian et al. analysed the toxic impacts of chemicals emitted during the production of one kilometre of fabric using the Institute of Public and Environmental Affairs database, and the results revealed that mass and toxicity analyses differ in their ranking of the toxic impacts [8]. Qian et al. performed a ChF assessment on 1 kg of cotton woven fabric from yarn to finished fabric, and they identified the production processes and the pollutant sources that contribute most to the ChF [9]. Qian et al. evaluated the ChF of VOCs in the production of polyester fabrics, identified the pollutants with the most significant contribution to ChF at each process stage, and pointed out the direction of improvement in the dyeing and finishing process to reduce the toxic impact of VOCs [10].

The use of some chemicals has been neglected in some ChF studies due to issues such as the confidentiality of textile auxiliaries by their manufacturers and the lack of data on textile chemical use and characterisation factors, so researchers in the field have gradually introduced methods to improve the feasibility of ChF studies [11]. In this paper, we used four methods to quantify ChF in the printing and dyeing process of a polyester dress. We compared these four methods in terms of feasibility and evaluation results. This study not only provides a reference for polyester textile manufacturers to identify priority pollutants and reduce the toxic impact of chemicals, but also guides the selection and optimisation of methods for subsequent ChF studies.

METHODS AND DATA

System boundary and data

ChF accounting begins with the definition of the functional unit. The functional unit selected for this study is a 100% polyester dress, and the basic information about this dress is presented in table 1. The system boundary of this case is then determined based on the functional unit; this entails defining the starting and ending points of the evaluation range within the production process. Figure 1 depicts the system boundary of the polyester dress. In this study, the dyeing process encompasses scouring, alkali weight reduction, colouring, reduction clearing, and finishing, while pretreatment, printing, reduction clearing, and finishing are included in the printing process. The chemicals within the system boundary are limited to those dyes and auxiliaries that are used directly, with the chemicals used indirectly to produce the dyes and auxiliaries excluded from the system boundary. The input and output data for textile chemicals within the system boundary are collected from the Mistra Future Fashion Consortium (http://mistrafuturefashion.com/).

Table 1

BASIC INFORMATION ABOUT THE EVALUATED POLYESTER DRESS

Property	Part	
	Cover part	Under part
Mass (g)	241	231
Textile material	100% polyester	100% polyester
Dtex (g/10000 m)	119/114 (warp/weft)	114

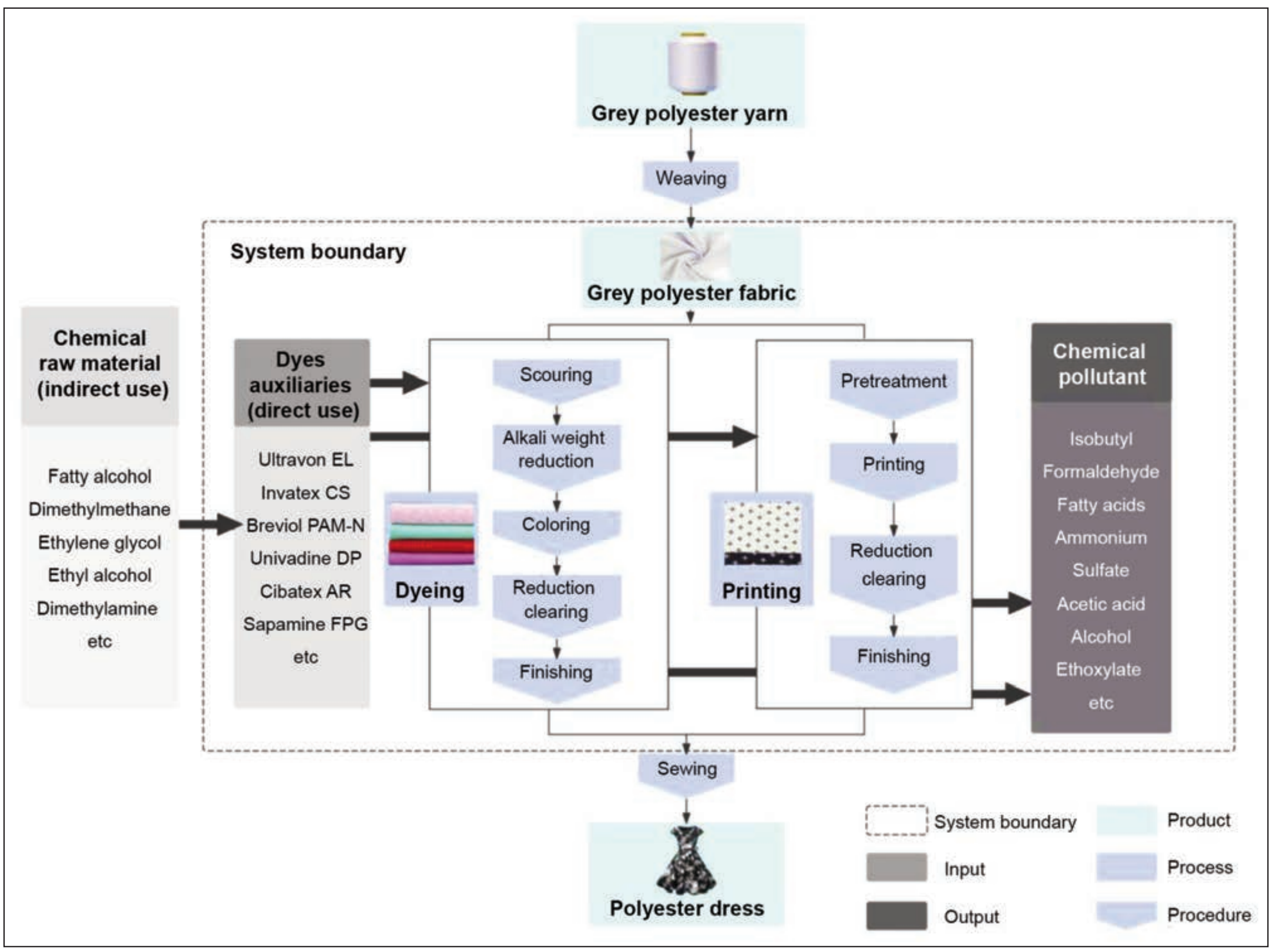

Fig. 1. System boundary of the evaluated polyester dress

Methods

The toxic impacts of chemicals input and output in the wet treatment of the polyester dress were evaluated by four methods: USEtox, the Assessment of Mean Impact (AMI), the Score System, and the Strategy Tool.

USEtox is an environmental model developed jointly by the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC), which assesses the toxic impacts of chemical pollutants emitted into the environment by quantifying three steps: environmental fate, exposure and effects [12]. Each chemical is assigned two highly integrated characterisation factors (CF), representing the hazards to humans and ecosystems, respectively. The ChF can be calculated using USEtox as shown in equation 1.

$$ChF_j = 290 \times \Sigma_{i=1}^{n} Q_{ij} \times FF_i \times XF_i \times EF_i = 290 \times \Sigma_{i=1}^{n} Q_{ij} \times CF_i \qquad (1)$$

where ChF_j is the total ChF of procedure j (cases for human toxicity or PAF×m^3×day for ecotoxicity), Q_{ij} – the emission of substance i in procedure j, FF_i – related to the residence time of substance i in the corresponding environment (day), XF_i is represented by the fraction of substance i transferred to the receptor population in a specific time period (day^{-1} for human or dimensionless for ecotoxicity), the human toxicity. EF_i reflects changes in the probability of disease due to changes in the intake of substance i (cases/kg) and the ecotoxicity. EF_i reflects changes in the potential effect fractions of species in response to changes in concentration (PAF×m^3/kg), CF_i denotes the characterization factor that integrates the quantitative results of the three components of fate, exposure and effect of substance i in the environment (PAF×m^3×day).

AMI method characterises the average toxic impacts by considering the toxic effects of different classes of organisms as an alternative to species sensitivity distribution (SSD) curves for calculating ecological thresholds [13]. In this method, toxicity data from a minimum of three organism classes (vertebrates, invertebrates, plants) are required to represent each of the three base trophic levels in the food chain relationships. The ChF, based on this approach, represent the volume of water required to dilute the contaminant to a safe concentration. The ChF based on the AMI method can be expressed as equation 2.

$$ChF_j = \Sigma_{i=1}^{n} \frac{C_{i,j}}{HC_5(NOEC)_i} \cdot V \qquad (2)$$

where C_{ij} is the exposure concentration in the aqueous phase of substance i in procedure j (g/L), V – the volume of the water environment (L), $HC_5(NOEC)_i$ – the safe threshold for the aquatic ecosystem of substance i (mg/L), indicating that the vast majority of species in aquatic ecosystems are unaffected.

The concentration of the contaminant in the water environment is primarily determined by the fate process, so it can be expressed as equation 3.

$$C_i = \frac{Q_i \cdot F_i}{V} \qquad (3)$$

where Q_i is the mass of substance i emitted (g), F_i – the proportion of substance i that fate into the water environment, so equation 2 can be transformed into equation 4.

$$ChF_j = \Sigma_{i=1}^{n} \frac{Q_{i,j}}{HC_5(NOEC)_i} \cdot F_i \qquad (4)$$

The Score System is a semi-quantitative method by scores several major factors [14]. The following four criteria of the toxic impact are scored: A-amount of substance, B-biodegradability, C-bioconcentration factor and D-toxicity. Each criterion will be scored between 1 and 4. According to the Score System, the four scores are multiplied to obtain a toxic impact value for each substance. The value of 4 should be given to a criterion in the case of data missing for the criteria [15]. The scoring guidelines for the four criteria are presented in table 2.

The above three methods account for emitted substances; the data used for the calculation of the USEtox method, AMI method and Score System is found in table 2.

Table 2

THE SCORING CRITERIA OF THE SCORE SYSTEM

Criteria			Score 1	Score 2	Score 3	Score 4
Amount of substance (kg/week)			<1	1–10	10–100	>100
Biodegradability	Surface water (%)		>60	10–60	<10	
	BOD/COD			>0.5		≤0.5
Bioconcentration	Bioconcentration factor (L/kg)		<100			≥100
	MW:500–1000 g/mol	Oil-water partition coefficient (P_{ow})	1000	≥1000		
		Water solubility (g/L)	>10	2–10	<2	
	MW<500 g/mol	P_{ow}	<1000	≥1000		
		Water solubility (g/L)	>100	2–100	0.02–2	<0.02
Toxicity	EC_{50} (mg/L)		>1000	101–1000	10–100	<10

Table 3

THE HAZARD LEVEL OF THE STRATEGY TOOL	
Hazard level	**Risk phrase**
Score 1	R20 R20/21 R20/21/22 R20/22 R21 R21/22 R22 R36 R36/38 R38 R50 R53
Score 3	R23 R23/24 R23/24/25 R23/25 R24 R24/25 R25 R34 R35 R36/37 R36/37/38 R37 R37/38 R41 R43 R48/20 R48/21 R48/22 R51/53 R52/53
Score 10	R26 R27 R28 R40 R42 R42/43 R45 R46 R48/23 R48/24 R48/25 R49 R60 R61 R62 R63 R64 R68 R50/53 R53

The Strategy Tool is a semi-quantitative method based on the available information in the Safety Data Sheets (SDS). According to the chemical risk phrases of the health and environmental hazards in the SDS, this method evaluates only the chemicals that are inputs to the production process. All relevant risk phrases were grouped into three levels. Substances with the highest level of risk phrase are scored 10, followed by 3 and 1, as shown in table 3. The number of exposure scenarios is also considered in the Strategy Tool, being set to the number of classified substances [16].

RESULTS AND DISCUSSION

USEtox results

Figure 2 presents the ChF results of a polyester dress with USEtox in the dyeing and printing process; the total ChF with USEtox was 1585.51 PAF×m^3×day, of which 459.73 PAF×m^3×day and 1125.88 PAF×m^3×day were for the dyeing process and printing process, respectively. The ChF values vary widely between procedures; the printing procedures contribute the most to ecotoxicity with a result of 1058.6 PAF×m^3×day, followed by colouring at 301.94 PAF×m^3×day, with both accounting for nearly 70% of the total. The smallest contributor to ChF is the reduction clearing procedure in the dyeing process, which is below 10 PAF×m^3×day. The ChF of the remaining procedures are within the same order of magnitude.

Compared to natural fibres, rayon, and nylon, polyester has no functional groups to give affinity for usual dyestuffs [17]. In the printing procedure, the dyestuff is mechanically fixed to the fibre surface by the paste. Due to the presence of a certain amount of surfactant in the paste, the surface tension between the gas and the liquid is relatively low, which makes the paste prone to bubbles when subjected to mechanical vibration and roller extrusion. A large quantity of antifoaming agents is used in the printing

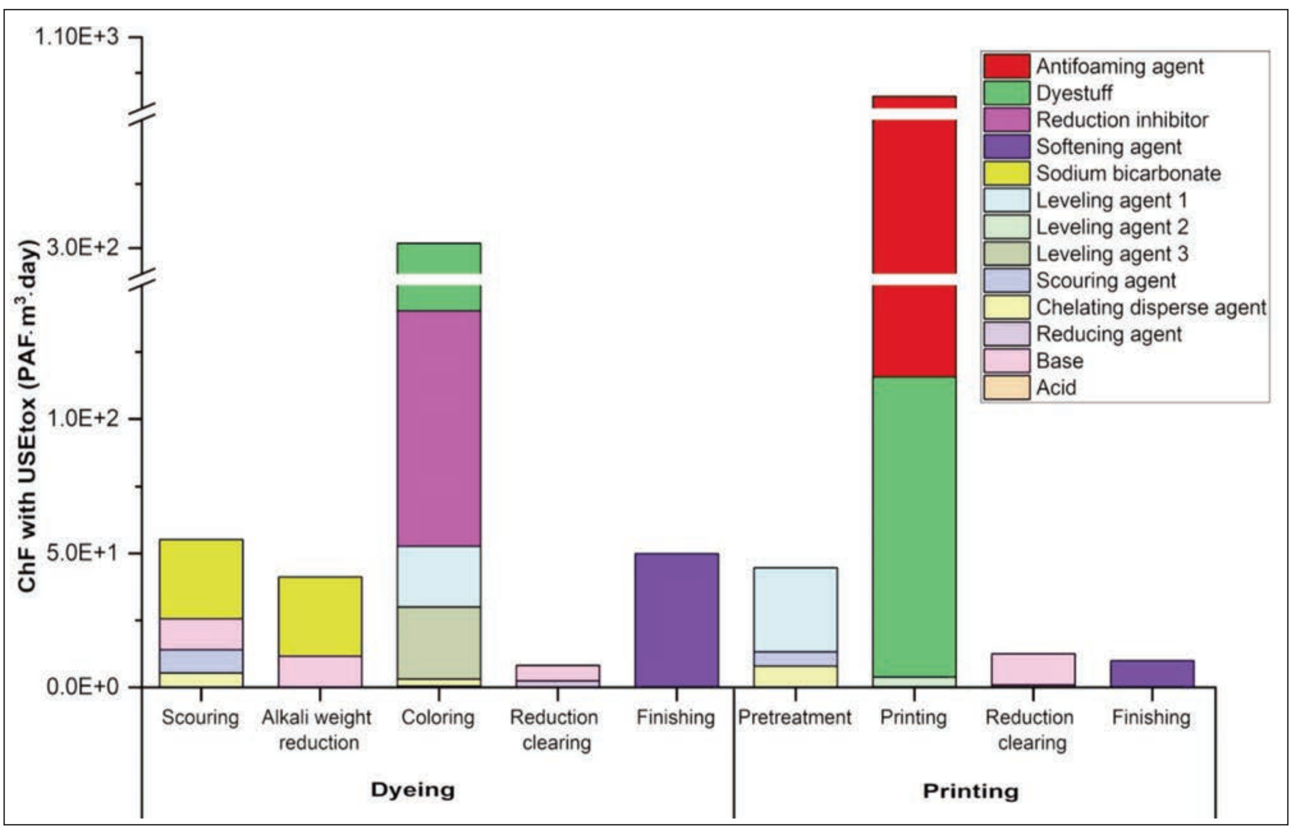

Fig. 2. Printing and dyeing process ChF of polyester dress obtained with USEtox

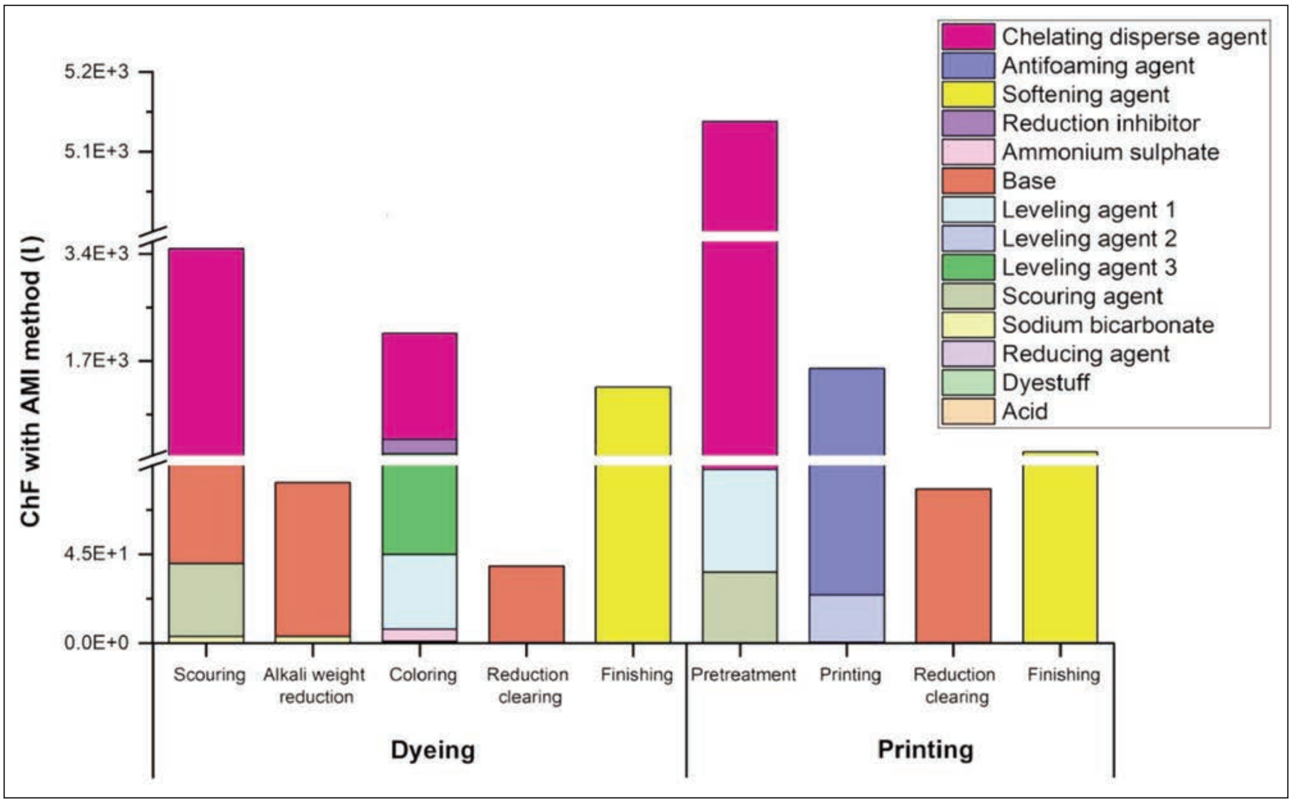

Fig. 3. Printing and dyeing process ChF of polyester dress obtained with USEtox

procedure to avoid problems such as blurred colours and uneven patterns by promoting liquid film drainage and destroying the film's elasticity, causing the bubble to burst [18]. In the dyeing procedure, as disperse dyestuffs are insoluble in water, it is necessary to use a large amount of levelling agent to make the dyestuffs and polyester come into contact quickly to improve the dyeing efficiency [19]. Reduction inhibitors help minimise reductive dye decomposition occurring during dyeing.

In the USEtox method, isobutyl acrylate had the most ecotoxicity impact on the environment among all the discharged chemical pollutants, accounting for 63.61% of the total ChF, followed by dyestuff, with a value of 273.52 PAF×m^3×day. Acetic acid and diethylene glycol monomethyl ether were the two substances that caused the least environmental load in this method, both less than 1 PAF×m^3×day. The isobutyl acrylate emissions from scouring agent, levelling agent 1 and antifoaming agent, 90.31% of which comes from the antifoaming agent in the printing procedure, which has the largest CF of any pollutant in this case. Although the CF of dyestuff is an order of magnitude smaller than the former, dyestuff is the main chemical for colouring and printing, and due to its minimal solubility in water, a large amount is needed to ensure the effect of the dyeing and printing process. A certain amount of acetic acid was used in the colouring and printing procedures; it mainly played a role in maintaining pH stability during the production process, and most of the acetic acid was neutralised in the reduction cleaning procedure [20]. Diethylene glycol monomethyl ether emission from levelling agent 2.

AMI results

The ChF results of the polyester dress with the AMI method in the dyeing and printing process are illustrated in figure 3. It can be seen from figure 3 that the total ChF with the AMI method is 14089.04 L, ecotoxic impact mainly occurs in pretreatment (36.48%), scouring (24.74%), colouring (15.19%), printing (11.22%) and finishing (9.12%) in the dyeing process. The toxic impact of alkali weight reduction and reduction clearing is much smaller than that of other procedures, both below 100 L.

The impacts of pretreatment, scouring, and colouring mainly come from the chelating dispersant agent. Chelating dispersing agents can combine with metal ions (Ca^{2+}, Mg^{2+}, Fe^{3+}) in water to form complexes that prevent metal salts from affecting the dyeing process, thus achieving the objective of improving the brightness and colour fastness of dyeing [21, 22]. In the AMI method, the largest contributor to ChF of all chemical pollutants is alcohols, C12-14, ethoxylated, accounting for 71.69% of the total ChF, followed by isobutyl acrylate, with 11.78%. The toxic impacts of Sodium sulfite (0.12 L), formaldehyde (0.14 L), diethylene glycol monomethyl ether (0.27 L), acetic acid (0.59 L), and dyestuff (0.64 L) are much less than other pollutants.

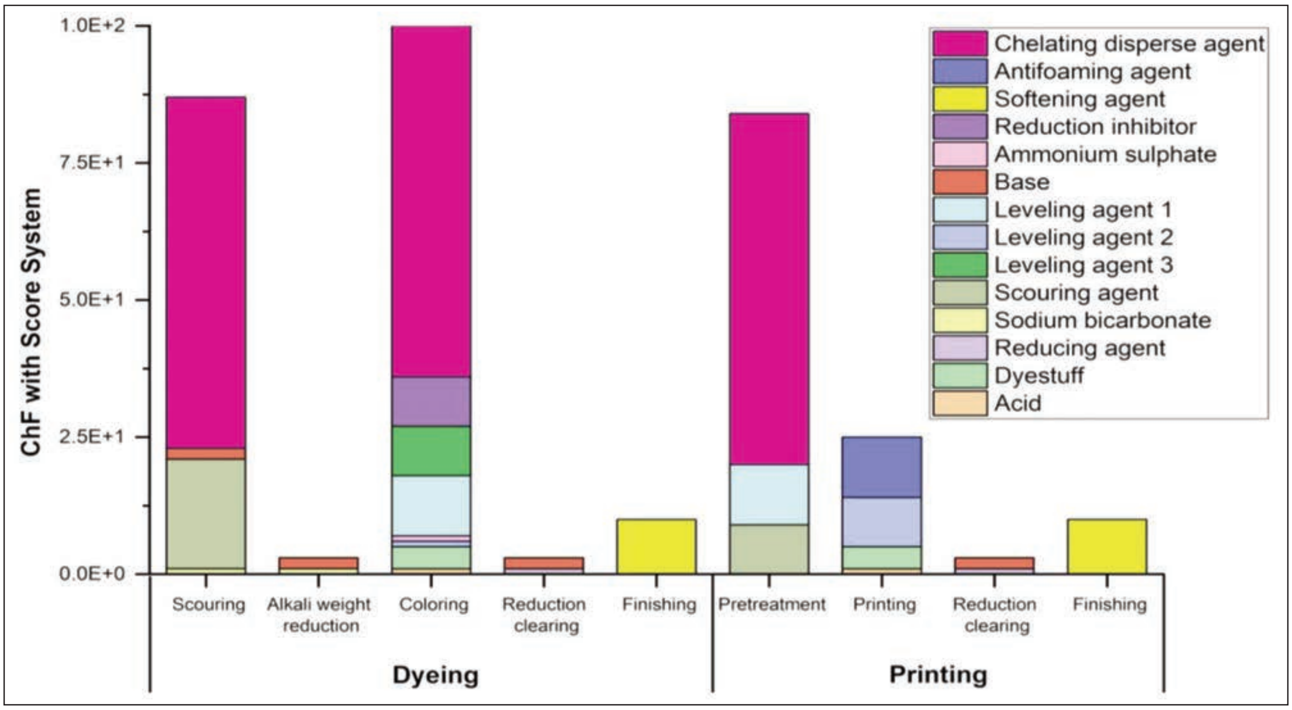

Fig. 4. Printing and dyeing process ChF of the polyester dress obtained with the Score System

Score system results

Figure 4 displays the toxic impact of the polyester dress in the dyeing and printing process (331). The Score System points out colouring (100), scouring (87), and pretreatment (84) as the three most significant procedures for environmental impacts, mainly because they all use chelating disperse agent in their production. The poor performance of the chelating disperse agent is due to the worst possible scores for bioaccumulation, biodegradability, and toxicity.

Strategy tool results

The ChF results with the Strategy Tool are illustrated in figure 5. Compared with the results of the previous

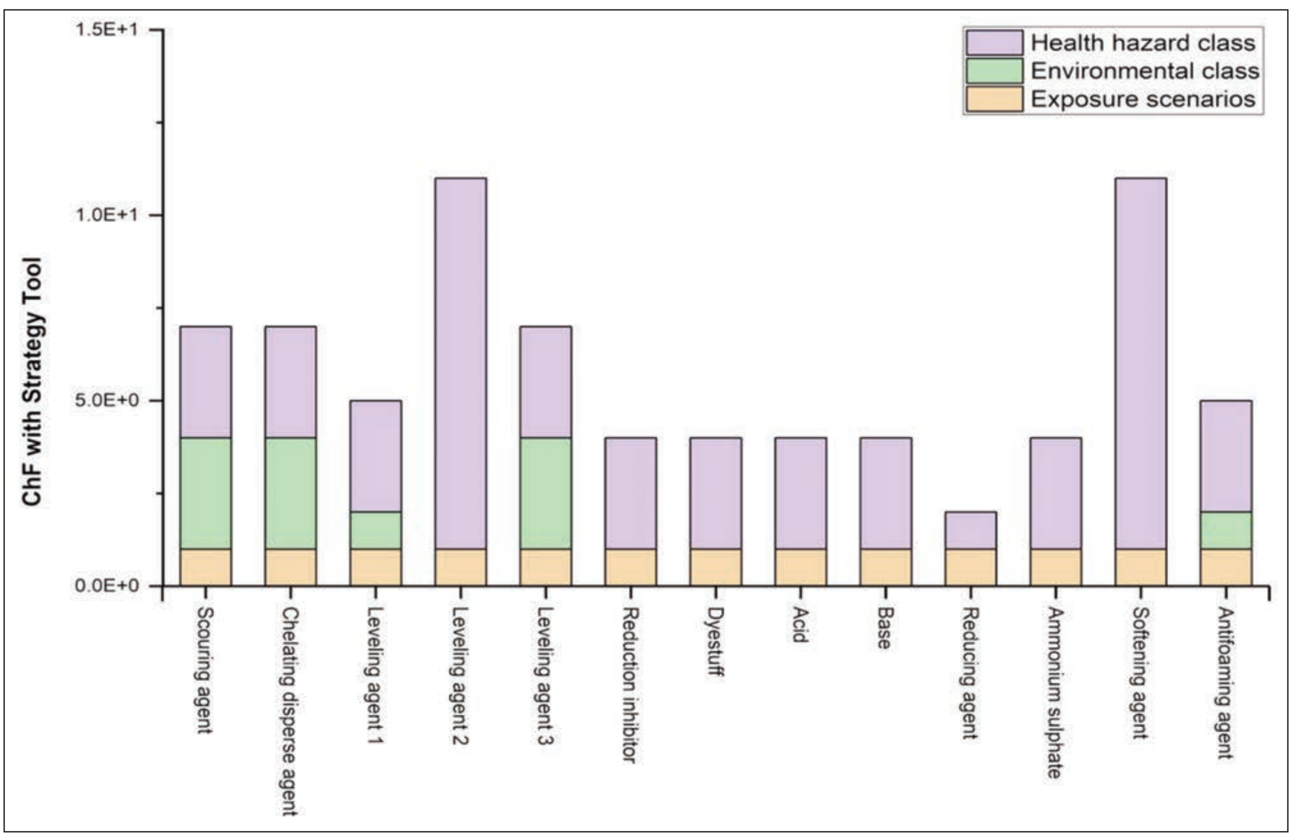

Fig. 5. Printing and dyeing process ChF of polyester dress obtained with the Strategy Tool

methods, the differences between the auxiliaries in this result are relatively minor. The Strategy Tool indicates that the levelling agent 2 and softening agent are the most significant textile auxiliaries based on health impact. If only environmental impact is considered, scouring agent, chelating disperse agent, and levelling agent 3 are the most important auxiliaries to be concerned about.

Comparison of the use and results from the methods

The four methods do not give a consistent assessment of chemicals in the dyeing and printing process. The difference in results can be explained by the difference in emphasis angle and embodiment scale of each method.

In the results with the Strategy Tool, the small difference in each of the auxiliaries is because this method mainly evaluates from the perspective of the type and number of auxiliaries used, and ignores the specific quality of chemicals used, which may lead to misguided assumptions that the choice of auxiliaries for each process is not important. The results of AMI and Score System are very similar in the order of the various processes, with the top three contributing procedures being scouring, colouring, and pretreatment, and the three least contributing procedures being alkali weight reduction and reduction clearing in dyeing and printing. The chelating disperse agent is the most influential auxiliary for both methods. These similarities show the commonality of the two methods in the assessment thread to a certain extent. However, the score of the chelating disperse agent in the result with USEtox is low, probably due to the uncertainty in the CF, which reflects the problem of excessive reliance on CF.

In terms of the assessment thread, both USEtox and AMI incorporate the persistence of chemical pollutants indirectly into the potential to cause harm, rather than treating persistence as a separate criterion like the Score System. The assessment thinking of the Strategy Tool is mainly classifying the risk of auxiliaries according to the risk labelling in the SDS, which focuses more on the protection of the people involved in the production and pays less attention to the environmental impacts caused by the chemical pollutants after production.

Regarding practical usability, the strategy tool is undoubtedly the most convenient method, especially for the auxiliary manager of the production side, but the cost is that the results are limited in science. Although the Score System is simple to use, its results do not accurately reflect the load in a specific area when compared to USEtox and AMI. USEtox is efficient enough for skilled ChF practitioners, and its main advantage is that it combines the fate results at different intervals with the ecotoxicity impacts, but the high integration of USEtox can inconvenience the ChF accounting process in the absence of CF. AMI is easier to use than USEtox in the quantification and evaluation of ChF, and it retains the science and efficiency of the fate results for chemical pollutants, but also gives the practitioner freedom in the core toxic effects.

CONCLUSIONS

The chemical pollutants emitted during the printing and dyeing process of the polyester dress have a serious impact on the environment. ChF accounting and evaluation can quantify the ecotoxicity impacts of chemical pollutants and identify the most important affecting procedures and auxiliaries. In this paper, four methods were used to calculate and evaluate the ChF of the polyester dress printing and dyeing process, and the practical usability and results of the four methods were compared. The ChF of the printing and dyeing process of a polyester dress calculated with USEtox, AMI, Score System, and Strategy Tool is 1585.51 PAF×m^3×day, 14089.04 L, 331, and 75, respectively. Scouring, colouring, pretreatment, and printing were identified as the major procedures contributing to ChF, with antifoaming agent and chelating disperse agent as the major auxiliaries contributing to ChF.

The two semi-quantitative methods, the score system and the strategy tool, are relatively easy to use, although the Strategy Tool is assessed on a more user-protective basis, so the results of the Strategy Tool are limited in their representativeness of environmental load. Compared to other methods, AMI ensures that the evaluation results are scientific while maintaining user-friendliness. Further investigation is desired on how the various approaches work together, and the combined results of various methods can be considered. It is important to explore the combination of user-friendliness and representativeness for the accounting and evaluation of ChF to guide the textile industry towards more green chemical management.

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A dynamic capability perspective on the influencing factors of supply chain resilience in Chinese small and medium-sized green textile enterprises

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ABSTRACT – REZUMAT

A dynamic capability perspective on the influencing factors of supply chain resilience in Chinese small and medium-sized green textile enterprises

With the increasingly intensified market competition, Chinese small and medium-sized green textile enterprises (SMGTEs) are now facing more supply chain challenges, such as sharp demand fluctuations, rising costs and even supply chain disruptions. As one of the most important abilities to deal with uncertainty and risk, supply chain resilience is of great significance for the survival and development of Chinese SMGTEs. Therefore, this study first constructed a theoretical framework of the influencing factors of supply chain resilience from a dynamic capability perspective for Chinese SMGTEs based on in-depth interviews. The measurement model was then designed, followed by a questionnaire survey and factor analysis. This study also used statistical models to empirically verify the effect of dynamic capability factors on supply chain resilience for Chinese SMGTEs. The research results will provide practical guidance for Chinese SMGTEs to sustainably improve their supply chain resilience and market competitiveness.

Keywords: *dynamic capability, supply chain resilience, Chinese enterprises, small and medium-sized enterprises, green textile industry*

O perspectivă dinamică asupra factorilor care influențează reziliența lanțului de aprovizionare în întreprinderile textile ecologice mici și mijlocii din China

Odată cu intensificarea concurenței pe piață, întreprinderile textile ecologice mici și mijlocii (SMGTE) din China se confruntă în prezent cu mai multe provocări legate de lanțul de aprovizionare, cum ar fi fluctuațiile puternice ale cererii, creșterea costurilor și chiar întreruperi ale lanțului de aprovizionare. Fiind una dintre cele mai importante abilități de a face față incertitudinii și riscului, reziliența lanțului de aprovizionare are o mare importanță pentru supraviețuirea și dezvoltarea SMGTE-urilor din China. Prin urmare, acest studiu a construit mai întâi un cadru teoretic al factorilor care influențează reziliența lanțului de aprovizionare din perspectiva capacității dinamice pentru SMGTE-urile din China, pe baza unor interviuri aprofundate. Apoi a fost proiectat un model de măsurare, urmat de un chestionar și o analiză factorială. Acest studiu a utilizat, de asemenea, modele statistice pentru a verifica empiric efectul factorilor de capacitate dinamică asupra rezilienței lanțului de aprovizionare pentru SMGTE-urile din China. Rezultatele cercetării vor oferi îndrumări practice pentru SMGTE-urile din China în vederea îmbunătățirii durabile a rezilienței lanțului de aprovizionare și a competitivității pe piață.

Cuvinte cheie: *capacitate dinamică, reziliența lanțului de aprovizionare, întreprinderi chineze, întreprinderi mici și mijlocii, industria textilă ecologică*

INTRODUCTION

The slowdown of economic growth has continued to be a cause for concern about the supply chain resilience of the green textile industry. The domestic trend of consumption downgrade in textile products is obvious. The shrinking demand of traditional Western markets, as well as frequent international trade frictions, has further aggravated the supply chain risk of the green textile industry. Besides, the highly homogeneous products have triggered fierce price competition, leading to reduced profit margins and innovation activities in the supply chain of the green textile industry. The inflated prices of raw materials have also threatened the survival of green textile enterprises, and a large bankruptcy boom has appeared recently. These shocks all negatively affect the stability and response speed of the supply chain in the green textile industry.

Supply chain resilience is directly related to the survival and development of green textile enterprises, especially of small and medium-sized green textile enterprises (SMGTEs). For example, HY Textile Company was a typical Chinese SMGTE with a poor supply chain resilience that produced women's clothing and maintained high standards of materials. Due to strict requirements for materials, the suppliers of HY Textile had strong bargaining power on purchasing prices. At the end of 2024, HY Textile received several large orders from its regular clients in Europe. Soon afterwards, the suppliers of HY Textile suddenly raised prices to take advantage of an unexpected increase in market demand. In order to avoid losing clients and paying a penalty, HY Textile continued to execute these orders and changed suppliers urgently. Soon afterwards, the entire production process was interrupted due to poor-quality materials, and the company went bankrupt. Unlike HY Textile, DK Textile Company stabilised its material prices by signing long-term contracts with four key suppliers in advance one year ago. Additionally, DK Textile shared its production schedules with its suppliers, allowing suppliers to understand its production progress in real time and to deliver materials on time. Moreover, DK Textile achieved profit sharing with its key suppliers by returning a fixed portion of the cost savings from material purchases to its suppliers. As a far-sighted SMGTE, DK Textile successfully survived in recent bankruptcy wave with a resilient supply chain.

In the Chinese green textile industry, SMGTEs account for a large proportion of the market and often suffer more severe competition and survival pressure. Compared with large green textile enterprises, supply chain disruptions, delivery delays, and rising costs are more common in SMGTEs [1]. Besides, the highly diversified product mix and rapid technological progress make the supply chain of SMGTEs more dynamic and complex. Due to limited access to resources, SMGTEs are more vulnerable when dealing with supply chain fluctuations. Therefore, it is meaningful to explore the ways to improve the supply chain resilience of Chinese SMGTEs. Investigating the influencing factors of supply chain resilience will benefit the risk identification of the supply chain for Chinese SMGTEs as well as the formulation of smart strategies for high-quality supply chain management.

LITERATURE REVIEW

Supply chain resilience

Supply chain resilience is widely recognised as an ability of an enterprise, and the main disputes about the concept of supply chain resilience occur due to the different emphases on the attributes of resilience. Christopher and Peck [2] emphasised the recovery attribute of supply chain resilience and defined supply chain resilience as the ability to restore to its original condition or to a more ideal condition after being disrupted. This concept was then modified, and supply chain resilience was claimed to be the ability to execute an action plan and achieve expected performance [3]. Different from the first viewpoint, Klibi and Martel [4] focused more on the avoidance attribute of supply chain resilience and defined supply chain resilience as the ability to avoid disruptions and to quickly recover from unfavourable events. Fiksel [5] emphasised the resistance attribute when conceptualising supply chain resilience and proposed that supply chain resilience is the ability to maintain the structure and function of the supply chain when there is an outside interference. Rice and Sheffi [6] soon put forward a similar definition that supply chain resilience is the ability to absorb disruption risk and positively affect supply chain performance. The rest scholars pointed out that the cost of recovery should be considered in the concept, and therefore supply chain resilience can be defined as the ability to reduce loss and to recover with acceptable cost after unfavourable supply chain events [7]. Referring to previous literature, this paper defines supply chain resilience as the ability to effectively withstand disruptions and to recover rapidly after disruptions at a relatively low cost.

The influencing factors of supply chain resilience

Most of the existing literatures determine the influencing factors of supply chain resilience from a qualitative point of view, and only focuses on a few influencing factors of supply chain resilience and the ordering of these factors. The specific research conclusions are shown in table 1. Current research results have a lot of overlapping elements, and research conclusions are scattered. The specific effects of the influencing factors of supply chain resilience are not quantified in most articles. Besides, most of the studies are for listed companies, and there is a lack of studies about the influencing factors of supply chain resilience for small and medium-sized enterprises or for the green textile industry.

As for the dimensions of the influencing factors of supply chain resilience, scholars have different research results. Hohenstein et al. [14] classified the influencing factors of supply chain resilience into active and passive groups. Chowdhury and Quaddus [20] claimed that the influencing factors of supply chain resilience have three dimensions: proactive capability, reactive capability and the quality of supply chain design, and constructed a framework of the influencing factors of supply chain resilience accordingly. Lu et al. [21] used CiteSpace to visualise the core research issue of supply chain resilience and proposed that the influencing factors of supply chain resilience should be categorised into three dimensions: enterprise factors, supply chain network factors and macro environment factors. However, there is a lack of relevant research towards small and medium-sized enterprises or the green textile industry.

Comments

The existing research on the influencing factors of supply chain resilience is limited to the analysis of a single or a few factors and therefore lacks a systematic framework. As a result, it is hard to comprehensively understand the influencing factors of supply chain resilience. Besides, there is a lack of sufficient empirical research evidence, especially research samples of small and medium-sized enterprises and green textile enterprises, leaving the reliability of existing research conclusions questioned.

In addition, current studies focus more on static influencing factors, such as macro environment, market demand and raw material supply, instead of dynamic capability to deal with supply chain disruption risk. Dynamic capability refers to the potential of an enterprise to quickly make adjustments to resource

Table 1

THE INFLUENCING FACTORS OF SUPPLY CHAIN RESILIENCE	
Main viewpoints	**Scholars**
Risk management culture, supply chain collaboration, agility, and supply chain design affect supply chain resilience.	Christopher and Peck [2]
The consistency and integration of logistics can improve supply chain resilience.	Ponomarov and Holcomb [8]
The flexibility of procurement and order fulfilment, manufacturing capacity, efficiency, visibility, adaptability, anticipation, recovery, decentralisation, collaboration, organisation structure, market position, safety, and financial strength can affect supply chain resilience.	Pettit et al. [9]
Supply chain collaboration, supply chain design, and supply chain agility have an important impact on supply chain resilience.	Peck et al. [10]
Risk management and knowledge management can improve the flexibility, response time, transparency and collaboration of the supply chain, which has a positive effect on supply chain resilience.	Juttner and Maklan [11]
Integration capability, close communication and cooperation have positive effects on supply chain resilience.	Wieland and Wallenburg [12]
Flexibility, visibility and information sharing can affect eight supply chain resilience elements.	Pereira et al. [13]
Collaboration, inventory management, pre-defined decision plan, redundancy, visibility, agility and flexibility are proposed to be the influencing factors of supply chain resilience.	Hohenstein et al. [14]
Supply chain re-engineering, emergency strategy, redundancy, efficiency, collaboration, information sharing, agility, visibility, reaction speed, risk management culture, leadership and risk management team are proposed to affect supply chain resilience.	Kamalahmadi and Parast [15]
Supply chain visibility, reserve capacity, supplier dispersion, cooperation, adaptability, flexibility and the level of fluctuation are identified as the influencing factors of supply chain resilience.	Osaro et al. [16]
The application of big data analysis tools in the planning, coordination, and control stages of supply chain management plays a key role in improving supply chain resilience.	Mandal [17]
Risk management culture, coordination, risk and benefit sharing, financial strength, robustness, collaboration, agility, supply chain design, spare inventory, supplier concentration, adaptability, trust, information sharing, information integration, information preparation, information recovery, and information response are important influencing factors of supply chain resilience.	Naimi et al. [18]
The cognitive gap and social gap between retailers and suppliers affect supply chain resilience.	Li [19]

allocation and strategic planning in order to adapt to a changing environment. In fact, dynamic capability is essential to improve supply chain resilience. For example, when the supply chain is at risk of disruption, enterprises need to quickly adjust procurement strategies, manufacturing plans and logistics arrangements to ensure continuous operation. In order to complete these adjustments, enterprises should have strong information collection and processing capability, decision-making capability and execution capability, which all fall into the category of dynamic capability.

Therefore, this paper will investigate the influencing factors of supply chain resilience of Chinese SMGTEs from a dynamic capability perspective and will provide more specific theoretical guidance and practical suggestions for Chinese SMGTEs to improve supply chain resilience. Through strengthening dynamic capability factors, Chinese SMGTEs can better understand the coping strategy and recovery mechanism when facing supply chain disruption, so as to help Chinese SMGTEs deal with supply chain resilience concerns better in the future.

RESEARCH METHODS

This paper will follow a normative scale development process to explore the dynamic capacity factors affecting the supply chain resilience of Chinese SMGTEs and then adopt regression models to examine the relationship between these dynamic capacity factors and supply chain resilience. The research process is composed of four steps, which are illustrated in table 2.

The first step is to use an in-depth interview and coding process to investigate the dynamic capacity factors affecting the supply chain resilience of Chinese SMGTEs, as well as the measurement model of these dynamic capacity factors. Existing literature and interview materials complement each other, ensuring the adequacy of the measurement model of dynamic capacity factors. The participants of the in-depth interview are supply chain managers of SMGTEs, related government officials and industry experts selected from Guangdong, Henan, Sichuan and Liaoning of China, which are representative provinces from the Eastern region, Central region, Western region and Northeastern region of China, respectively.

The second step is to conduct a questionnaire survey and perform exploratory factor analysis to modify the measurement items of the dynamic capacity factors affecting the supply chain resilience of Chinese SMGTEs. The structure of the measurement model, as well as specific measurement items developed by

Table 2

RESEARCH PROCESS AND METHODS				
Steps	**Research purposes**	**Research methods**	**Participants/ Respondents**	**Number of participants/ respondents**
Step 1	Identify dynamic capacity factors, and develop an initial measurement model and questionnaire	Literature review; In-depth interview	The supply chain managers of SMGTEs, related government officials and industry experts from four representative provinces of China	26 interviewees
Step 2	Complete exploratory factor analysis	Questionnaire survey	The supply chain managers of SMGTEs from four representative provinces of China	250 questionnaires were distributed, and 226 valid questionnaires were collected.
Step 3	Complete confirmatory factor analysis	Questionnaire survey	The supply chain managers of SMGTEs from four representative provinces of China	250 questionnaires were distributed, and 211 valid questionnaires were collected.
Step 4	Empirically test the effect of dynamic capability factors on supply chain resilience	Questionnaire survey; Regression model	The supply chain managers of SMGTEs from all over China	300 questionnaires were distributed, and 279 valid questionnaires were collected.

qualitative research methods (i.e., in-depth interview and coding process) in the first step, still needs to be checked statistically. The factors with eigenvalues greater than 1.0 will be extracted to see if the structure is consistent with the one developed in the first step. The measurement items with factor loadings lower than 0.5 will be deleted to ensure the measurement items are statistically reasonable. The respondents of the questionnaire survey are supply chain managers of SMGTEs from four representative provinces of China.

The third step is to conduct a questionnaire survey again and perform confirmatory factor analysis to further verify the measurement items from the second step. The respondents are still the supply chain managers of SMGTEs from four representative provinces of China.

The last step is to construct a conceptual framework illustrating the expected relationships between dynamic capacity factors and the supply chain resilience of Chinese SMGTEs and conduct a further questionnaire survey with the respondents from all over China. The data collected from this survey is then used to empirically test research hypotheses.

THE MEASUREMENT MODEL OF DYNAMIC CAPACITY FACTORS

Data Collection

Referring to the research of Chen et al. [22], this study adopted semi-structured in-depth interviews to collect data from the supply chain managers of SMGTEs, related government officials and industry experts from four representative provinces of China. An interview outline containing 13 questions was drafted based on existing literature before the interview. The draft was then submitted to industry experts and supply chain managers of Chinese SMGTEs for review and was modified according to the feedback. The final version of the interview outline contains 10 questions and is shown in table 3. Government officials and industry experts were invited to avoid cognitive limitations of supply chain managers, allowing researchers to explore dynamic capability factors from different perspectives. In order to ensure the quality of interview materials, the 26 participants of this study have at least 5 years of relevant work experience in Chinese SMGTEs and are between 36 to 57 years old. Each interview lasted about 30 minutes.

Coding process

This paper identified dynamic capability factors affecting the supply chain resilience of Chinese SMGTEs by following a normative coding process in grounded theory. This paper dug deeply into text data through three steps: open coding, axial coding and selective coding. In order to ensure the scientificity and rationality of the coding results, two researchers performed the coding process at the same time. When there was any inconsistency in terms of coding results, a third researcher joined the discussion and made the final decision.

Open Coding

Word-by-word analysis method was adopted to extract key phrases from the original text materials. These key phrases were then integrated into 107 initial concepts according to the similarity of meaning. The initial concepts are then divided into 16 initial categories by following the logical consistency principle. For example, “it’s hard to borrow money from banks in a bad economic environment” is conceptualised as a “financing channel”, which is then categorised into “financial capability”. The examples of open coding results are shown in table 4.

Axial coding

Based on the results of open coding, the potential logical relationships among 16 initial categories were

Table 3

INTERVIEW OUTLINE	
Number	**Questions**
1	What problems do you think exist in terms of the supply chain resilience of Chinese SMGTEs?
2	What features should the supply chain with ideal resilience have in Chinese SMGTEs?
3	What dynamic capability factors do you think can affect the supply chain resilience of Chinese SMGTEs?
4	What are the differences between large green textile enterprises and SMGTEs in terms of the dynamic capability factors affecting supply chain resilience?
5	What are the differences between green textile enterprises and the enterprises from other industries in terms of the dynamic capability factors affecting supply chain resilience?
6	What are the differences among different types of SMGTEs in terms of their contribution to supply chain resilience?
7	Please describe the actions you are taking to improve the supply chain resilience of SMGTEs.
8	What would you do if the supply chain were suddenly disrupted?
9	What dynamic capability factors do you think SMGTEs should invest in more to improve their supply chain resilience?
10	If you have the opportunity to receive guidance on supply chain resilience management, what would you most like to receive guidance on?

Table 4

THE EXAMPLES OF OPEN CODING RESULTS		
Key original phrases	**Concepts**	**Initial categories**
“The more suppliers to choose from, the lower the possibility of supply chain disruption”	The number of suppliers	Supplier management capability
“Some suppliers are dishonest and sometimes can’t deliver goods on time”	The reputation of the supplier	
“It would be better if the channels of raw material could be more dispersed”	Supplier concentration	
…	…	
“It’s hard to borrow money from banks in a bad economic environment”	Financing channel	Financial capability
“Although the goods are shipped, the money is slow to come back”	The collection of accounts receivable	
…	…	
“If the manufacturing process can be automated, the cost will be lower in the long run”	Manufacturing automation	Informatization capability
“The combination of digital technology and management reduces the waste of resources”	The digitisation of the operation	
…	…	
“More types of products, more orders”	Product variety	Structural capability
“Outdated equipment restricts productivity, and we can’t take more orders”	Manufacturing process	
“Suppliers are far away, and raw materials are always slow to arrive at our company”	Space layout	
…	…	
“Sometimes partners don’t share information with us”	The breadth of information shared	Information sharing capability
“The raw materials were out of stock in the supply chain at the beginning of this month, and we knew this until the middle of this month”	Timely information sharing	
“Everyone was nervous with negative news and started to buy raw materials in advance, and then it was proved to be false news”	The accuracy of the information shared	
…	…	
“The supplier said he would deliver products on time, but I couldn’t trust him”	The level of trust	Trust capability
“Suppliers don’t share similar business values with us, and they are unreliable”	Business cultural integration	
…	…	

Table 4 (continuation)

"It would be better if upstream and downstream companies make plans together"	Joint planning	Coordination capability
"If partners can work with us to solve problems, things will be easier"	Joint problem-solving	
"He was not the person who could make decisions after spending a lot of time with him"	Effective communication	
"We need a win-win cooperation and take risks together"	Risk sharing	
"Not acceptable if all the benefits go to partners"	Benefits distribution	
…	…	
"We have learned all of these from zero"	Knowledge acquisition	Learning capability
"Be good at summarising lessons and don't always fall in the same place"	Knowledge internalization	
…	…	
"Top management is old and conservative, and never accepts cooperation with competitors"	Component innovation	Innovation capability
"They were so busy with new business, and optimisation plans were rejected"	Activity optimization	
…	…	
"Poor judgment of customer needs, often overstocking"	Demand forecasting	Forecasting capability
"Technology upgrades too fast, and old products find it hard to survive"	The prediction of the development direction	
"We never expect raw materials to be out of stock so quickly"	Raw material forecasting	
…	…	
"Political atmosphere is so strong that decisions are slow"	The speed of decision-making	Agility
"It's too late to react"	Flexibility	
…	…	
"You need to have a keen sense of risk"	Risk identification	Risk awareness
"Employees have no idea about risk management"	Risk management culture	
…	…	
"When something goes wrong, team members come from many departments"	Risk management team	Risk management capability
"No one is good at emergency management. Who can make the plan?"	The development of an emergency plan	
"A plan that works today can't be executed tomorrow"	The execution of the emergency plan	
…	…	
"It's important to have an overall strategy, or every department will do its own thing"	Systematic planning	Strategic planning capability
"The plan was done at the beginning of the year, and there has been no adjustment till now"	Plan adjustment	
…	…	
"The transportation staff are not professional enough, and the percentage of damage is not acceptable.	Product transportation	Logistics management capability
"Now we have real-time positioning and can see where the cars are, and we can solve problems quickly"	The modernisation of logistics facilities	
…	…	
"The ordered chips have been sold to a competitor"	The control of key raw materials	Inventory management capability
"We don't have much inventory, so we can't take an emergency order"	Finished goods management	
…	…	

further investigated, and the initial categories were then summarised and classified into 5 main categories. For example, supplier management capability, financial capability, informatisation capability and structural capability are categorised into the main category of supply chain resource management capability. The axial coding results are illustrated in table 5.

Selective coding

Selective coding refers to the process of systematically linking other categories around the core category and verifying the relationship among them. The

Table 5

AXIAL CODING RESULTS		
Main categories	**Initial categories**	**Connotation**
Supply chain resource management capability	Supplier management capability	Supplier management capability refers to the control over the number of suppliers, supplier reputation, and supplier concentration in the supply chain.
	Financial capability	Financial capability is the capability to ensure the stability of cash flow through financing activities and the timely collection of accounts receivable, as well as the capability to maintain acceptable financial indicators.
	Informatization capability	Informatisation capability refers to the capability to achieve the automation of the manufacturing process and the digitalisation of the operation process.
	Structural capability	Structural capability is the capability to construct a complex supply chain structure by improving product variety, upgrading the manufacturing process, and rationalising spatial layout.
Supply chain collaboration capability	Information sharing capability	Information sharing capability refers to the capability to share accurate information widely and timely manner among supply chain members.
	Trust capability	Trust capability refers to the capability to establish mutual trust relationships and achieve cultural integration with supply chain members.
	Coordination capability	Collaboration capability refers to the capability to jointly plan and coordinate with other supply chain members, communicate effectively, share risks and reasonably distribute benefits.
Supply chain growth capability	Learning capability	Learning capability refers to the capability to continuously acquire and internalise new knowledge.
	Innovation capability	Innovation capability refers to the capability to innovatively modify chain components and optimise chain activities.
	Forecasting capability	Forecasting capability refers to the capability to analyse and predict client needs, future development directions and raw material supply.
Supply chain risk control capability	Agility	Agility refers to the capability to make rapid and efficient adjustments according to external changes.
	Risk awareness	Risk awareness refers to the capability to identify risk and maintain an excellent risk management culture.
	Risk management capability	Risk management capability refers to the capability to build a risk management team, formulate and implement emergency plans.
Supply chain operation capability	Strategic planning capability	Strategic planning capability refers to the capability to formulate overall strategic plans and problem-solving methods to achieve goals.
	Logistics management capability	Logistics management capability refers to the capability to improve product transportation and the modernisation level of logistics facilities.
	Inventory management capability	Inventory management capability refers to the capability to obtain manufacturing resources and reasonably control inventory levels.

core category of this study is dynamic capability factors affecting the supply chain resilience of Chinese SMGTEs. Based on the core category and dynamic capability theory, the dynamic capability model of Chinese SMGTEs can be developed and is illustrated in figure 1.

The dynamic capability of Chinese SMGTEs is composed of five factors: supply chain resource management capability, supply chain collaboration capability, supply chain growth capability, supply chain risk control capability and supply chain operation capability. The detailed explanation of each factor is illustrated in table 6.

The elements of each dynamic capability are associated with each other and work together to construct a specific dynamic capability. These five dynamic capability factors combine to influence the supply chain resilience of Chinese SMGTEs, and there is an inherent hierarchical structure between these five dynamic capability factors and supply chain resilience. Based on coding results and dynamic capability theory, these five dynamic capability factors are at the capability layer, and supply chain resilience is at the goal layer. The capability layer effectively supports the resilience function of the supply chain in Chinese SMGTEs.

THE SCALE DEVELOPMENT FOR DYNAMIC CAPACITY

Questionnaire design

Based on coding results, an initial scale including 28 measurement items was developed. In order to ensure that the measurement items are consistent with research concepts, content validity was tested

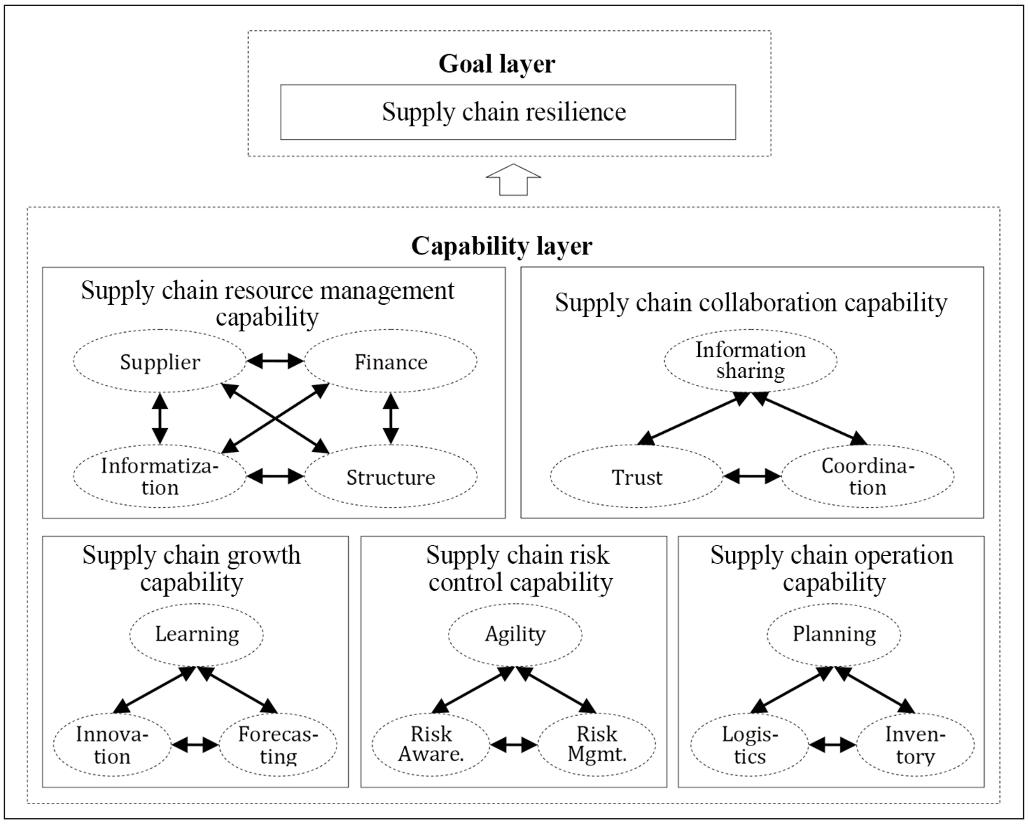

Fig. 1. The dynamic capability model of Chinese SMGTEs

Table 6

EXPLANATION OF DYNAMIC CAPABILITY FACTORS	
Dynamic capability factors	**Explanation**
Supply chain resource management capability	The capability of an SMGTE to reasonably integrate its supply chain resources to obtain sustainable competitiveness
Supply chain collaboration capability	The capability of an SMGTE to jointly plan and execute supply chain plans with the enterprises at other chain nodes to share resources and benefits, to maximise the efficiency of the supply chain
Supply chain growth capability	The capability of an SMGTE to constantly grow by expanding the supply chain
Supply chain risk control capability	The capability of an SMGTE to identify, evaluate, monitor and control supply chain risk that may have a negative impact on business operations, and to ensure the stability, security and sustainability of the manufacturing process by formulating corresponding response strategies and taking measures
Supply chain operation capability	The capability to manage goods and service flows among suppliers, manufacturers, distributors and customers to meet customer needs and optimise operational efficiency.

through expert judgment. Five experts were first invited to evaluate whether measurement items matched the dynamic capability factors affecting supply chain resilience, and 21 measurement items were retained after revision. Subsequently, 10 supply chain managers of Chinese SMGTEs were invited to provide feedback on the readability of the questionnaire, and 19 measurement items were finally determined.

The questionnaire has two sections. The first section is a survey about the basic information of Chinese SMGTEs, including questions such as age, business size and the location of the enterprises. The second section is a survey of the dynamic capacity factors that affect supply chain resilience, including 19 measurement items, and the 7-point Likert scale was adopted to measure each item. The scale consists of below points: 1-strongly disagree; 2-disagree; 3-slightly disagree; 4-neutral; 5 slightly agree; 6-agree; 7-strongly agree.

Survey respondents

The respondents of this survey are 500 supply chain managers of SMGTEs from four representative provinces of China. The questionnaires were distributed twice, and 250 questionnaires were distributed each time. In the first stage, 226 valid questionnaires were collected for exploratory factor analysis. In the second stage, 211 valid questionnaires were collected for confirmatory factor analysis. The basic characteristics of SMGTEs are shown in table 7.

Table 7

THE BASIC CHARACTERISTICS OF SMGTES FOR FACTOR ANALYSIS			
Items	**Options**	**Frequency**	**Percentage (%)**
Age	0–3 years	122	27.92
	3–10 years	266	60.87
	More than 10 years	49	11.21
Business Size	0–50 people	156	35.70
	51–150 people	202	46.22
	151–300 people	47	10.76
	301–500 people	26	5.95
	More than 500 people	6	1.37
Location	Eastern region	134	30.66
	Central region	117	26.77
	Western region	97	22.20
	Northeastern region	89	20.37

Exploratory factor analysis

This paper used SPSS 26.0 to conduct exploratory factor analysis for 19 measurement items, and the type of rotation was orthogonal rotation. In the first round of exploratory factor analysis, 5 factors with eigenvalues greater than 1.0 were extracted. Two items with factor loadings lower than 0.5 (i.e., "our enterprise makes full use of digital technology to support operational processes" and "our enterprise timely adjusts strategic plan according to external changes") were deleted. In the second round, 5 factors with eigenvalues greater than 1.0 were extracted, and the item "our enterprise is good at obtaining key raw materials" with a factor loading lower than 0.5 was deleted.

In the third round, the KMO value is 0.741, and Bartlett's test of sphericity is significant, indicating that the dataset is suitable for exploratory factor analysis. Five factors with eigenvalues greater than 1.0 were extracted, and the cumulative variance explained was 71.156%. The factor loadings of each item ranged from 0.788 to 0.855, indicating that the factor structure was ideal. Cronbach's Alpha values of each factor ranged from 0.727 to 0.852, all of which are greater than 0.7, indicating high reliability of the measurement model and good stability of the scale. According to coding results, these 5 factors are named as supply chain resource management

Table 8

EXPLORATORY FACTOR ANALYSIS RESULTS					
Factor	**Component**				
	F1	**F2**	**F3**	**F4**	**F5**
A1 Our enterprise has many high-quality suppliers.	0.788				
A2 Our enterprise has good cash flow.	0.820				
A3 Our enterprise has a fully automated manufacturing process.	0.841				
A4 The structure of our supply chain is complex.	0.855				
B1 Our enterprise has a good level of information sharing.		0.833			
B2 Our enterprise fully trusts our supply chain partners.		0.845			
B3 Our enterprise can cooperate well with other enterprises in the supply chain.		0.846			
C1 Our enterprise is good at learning new knowledge of the supply chain.			0.820		
C2 Our enterprise is good at innovating supply chain activities.			0.841		
C3 Our enterprise can predict future supply and demand well.			0.832		
D1 Our enterprise can quickly adjust supply chain activities according to external changes.				0.817	
D2 Our enterprise has a good awareness of supply chain risk.				0.836	
D3 Our enterprise is able to manage supply chain risk well.				0.842	
E1 Our enterprise is good at making a strategic plan for the supply chain.					0.797
E2 Our enterprise is good at transportation logistics management.					0.802
E3 Our enterprise has good control of the level of finished products.					0.789
Cronbach's Alpha	0.852	0.808	0.813	0.804	0.727
Eigenvalue (Non-rotated)	3.197	2.756	2.435	1.827	1.170
Variance Explained (%)	17.565	13.893	13.780	13.470	12.448
Cumulative Variance Explained (%)	17.565	31.458	45.239	58.709	71.156

Table 9

CONFIRMATORY FACTOR ANALYSIS RESULTS				
Latent variables	**Items**	**Standardised factor loading**	**AVE**	**CR**
Supply chain resource management capability	A1	0.784	0.530	0.818
	A2	0.734		
	A3	0.672		
	A4	0.719		
Supply chain collaboration capability	B1	0.782	0.634	0.838
	B2	0.731		
	B3	0.869		
Supply chain growth capability	C1	0.832	0.727	0.888
	C2	0.898		
	C3	0.825		
Supply chain risk control capability	D1	0.678	0.561	0.792
	D2	0.712		
	D3	0.847		
Supply chain operation capability	E1	0.722	0.579	0.804
	E2	0.821		
	E3	0.735		

Table 10

DISCRIMINANT VALIDITY RESULTS					
Dimension	**1**	**2**	**3**	**4**	**5**
1 Supply chain resource management capability	0.728				
2 Supply chain collaboration capability	0.721	0.796			
3 Supply chain growth capability	0.645	0.611	0.852		
4 Supply chain risk control capability	0.669	0.614	0.574	0.749	
5 Supply chain operation capability	0.671	0.624	0.598	0.694	0.761

Note: The diagonal values are the square root of AVE values.

capability, supply chain collaboration capability, supply chain growth capability, supply chain risk control capability and supply chain operation capability, which are measured by 16 items. The details of exploratory factor analysis results are illustrated in table 8.

Confirmatory factor analysis

AMOS 24.0 was used for subsequent confirmatory factor analysis. According to the results, $\chi/2df = 1.265$, $TLI = 0.981$, $CFI = 0.985$, and $RMSEA = 0.036$, representing a good fit of the measurement model. The results of confirmatory factor analysis are shown in table 9. Except for 2 items, the standardised factor loadings are all higher than 0.7. The standardised factor loadings of the rest 2 items are still higher than 0.6, and all items are significant at 1% level. The composite reliability (CR) values of all five dimensions are greater than 0.7, and all average variance extracted (AVE) values are greater than 0.5.

Discriminant validity is tested by comparing the square root of AVE values with the correlation coefficients among variables. As shown in table 10, the square root of AVE values for each dimension is higher than the correlation coefficients, indicating that all dimensions have ideal discriminant validity.

EMPIRICAL ANALYSIS

Research Hypotheses

Strong supply chain resource management capability means enterprises can establish long-term relationships with qualified suppliers to guarantee the uninterrupted supply of raw materials when market fluctuations or emergency events occur [23], reducing supply chain disruption risk and improving supply chain resilience. Besides, good supply chain resource management capability generates sufficient financial reserves to deal with market and technological changes [24] and therefore enhances supply chain resilience in the face of uncertainty. In addition, well-developed expertise in supply chain resource management allows SMGTEs to optimise the usefulness of data resources and supply chain efficiency, leading to timely detection and solutions to supply chain risk and therefore increasing supply chain resilience [25]. Reasonable supply chain resource management capability also benefits the continuity and stability of the supply chain when there are demand changes or supply chain disruptions by allowing enterprises to take advantage of the network layout and make necessary adjustments fast [26]. Based on the above analysis, the following research hypothesis can be developed.

Hypothesis 1: Supply chain resource management capability has a positive effect on supply chain resilience in Chinese SMGTEs.

The enterprises with good supply chain collaboration capability are able to track key information such as market trends and customer preferences closely by actively sharing information with other members in the supply chain, reducing the level of information asymmetry and allowing enterprises to adjust strategies quickly [27]. This helps enterprises to avoid potential disruption risk in the supply chain and therefore improve supply chain resilience. Strong supply chain collaboration capability also contributes to creating an atmosphere of trust, which increases the willingness of supply chain members to share resources and to jointly deal with supply risk [28]. A good atmosphere of trust reduces the possibility of the occurrence of opportunistic behaviours, thereby improving risk resistance and supply chain resilience. The positive effect of supply chain collaboration capability on supply chain resilience can also be explained by process integration between enterprises and their supply chain partners. The process integration reduces resource waste and optimises resource allocation among supply chain members [29], and therefore improves supply chain resilience. Based on these analyses, the following hypothesis can be developed.

Hypothesis 2: Supply chain collaboration capability has a positive effect on supply chain resilience in Chinese SMGTEs.

Reasonable supply chain growth capability means enterprises can continuously acquire and absorb new knowledge to innovate manufacturing technologies and operation methods with the purpose of adapting to market changes and consumer preferences [30]. Through learning, enterprises can adjust supply chain strategies promptly and enhance the flexibility of the supply chain, and therefore improve supply chain resilience. Strong supply chain growth capability also helps enterprises understand market dynamics and grasp future industry trends [31], allowing enterprises to make more accurate manufacturing plans and inventory decisions, thereby enhancing supply chain resilience. Based on these analyses, the hypothesis is developed accordingly.

Hypothesis 3: Supply chain growth capability has a positive effect on supply chain resilience in Chinese SMGTEs.

Well-developed supply chain risk control capability allows enterprises to adapt to market changes and emergency events by making necessary adjustments to manufacturing and logistics plans quickly [32], contributing to the stability of the supply chain. The enterprises with better supply chain risk control capability are also able to identify risk earlier so that corresponding measures can be taken to prevent adverse events. They are also more willing to invest in building a complex risk management system, which further reduces reaction time and the cost of recovery and therefore improves supply chain resilience [33]. Besides, strong supply chain risk control capability makes it possible for the enterprises to seize new opportunities because it helps enterprises save time and energy, so that enterprises have extra resources to expand their supply chains [34]. Therefore, the following hypothesis can be developed.

Hypothesis 4: Supply chain risk control capability has a positive effect on supply chain resilience in Chinese SMGTEs.

By developing supply chain operation capability, enterprises are able to identify key profit drivers and optimise resource allocation [35], increasing the possibility of the supply chain to maintain normal work in a complex environment. It also allows the enterprises to prepare and make adjustments in advance towards expected market changes according to the strategic plan [36], thereby reducing the negative effect brought by adverse events in the supply chain. Strong supply chain operation capability also guarantees the timely delivery of products and flexible coordination in transportation networks when supply chain disruptions occur, thereby improving supply chain resilience [37]. The enterprises with good supply chain operation capability can achieve better control over inventory when market conditions change [38]. Maintaining inventory cost at a low level in a depressed market and achieving a rapid supply restoration to seize new opportunities are both important to reduce loss and to keep supply chain resilience at a reasonable level. Based on these analyses, a hypothesis is listed as follows.

Hypothesis 5: Supply chain operation capability has a positive effect on supply chain resilience in Chinese SMGTEs.

Variables

The dependent variable of this paper is the supply chain resilience of Chinese SMGTEs. Referring to the measurement method of Pettit et al. [9], supply chain resilience is measured by supply chain disruption frequency, recovery time and recovery cost. All items are measured using a 7-point Likert scale, with 1 to 7 indicating strongly disagree, disagree, slightly disagree, neutral, slightly agree, agree and strongly agree, respectively.

The independent variables of this paper are supply chain resource management capability, supply chain collaboration capability, supply chain growth capability, supply chain risk control capability and supply chain operation capability. The measurement method of these 5 independent variables depends on the scale developed earlier in this paper. In addition, the age, the business size and the region of the enterprises are selected as control variables [39].

Survey respondents

This empirical analysis surveyed 300 supply chain managers of Chinese SMGTEs all over China. Most

Table 11

THE BASIC CHARACTERISTICS OF SMGTES FOR EMPIRICAL ANALYSIS			
Items	**Options**	**Frequency**	**Percentage (%)**
Age	0–3 years	71	25.45
	3–10 years	184	65.95
	More than 10 years	24	8.60
Business Size	0–50 people	85	30.47
	51–150 people	141	50.54
	151–300 people	43	15.41
	301–500 people	7	2.51
	More than 500 people	3	1.08
Location	Eastern region	125	44.80
	Non-eastern regions	154	55.20

of these supply chain managers work in the SMGTEs with clear supply chain networks and which are the cores of networks. After deleting invalid questionnaires, there are 279 questionnaires left. The basic characteristics of the enterprises are shown in table 11.

Empirical results

Reliability and validity test

According to reliability test results, Cronbach's Alpha values of supply chain resource management capability, supply chain collaboration capability, supply chain growth capability, supply chain risk control capability, supply chain operation capability and supply chain resilience are 0.815, 0.823, 0.853, 0.772, 0.789 and 0.775, respectively, which are all greater than 0.7.

The results of confirmatory factor analysis show that the standardised factor loadings of each item range from 0.656 to 0.894. The CR values of supply chain resource management capability, supply chain collaboration capability, supply chain growth capability, supply chain risk control capability, supply chain operation capability and supply chain resilience are 0.816, 0.830, 0.855, 0.783, 0.790 and 0.778, respectively, which are all greater than 0.7. AVE values of each factor are 0.527, 0.621, 0.663, 0.548, 0.557 and 0.539, respectively, all of which are greater than 0.5. The square root of the AVE values of each factor is greater than the correlation coefficients, indicating that the scale has excellent discriminant validity.

In addition, common method bias may occur due to the fact that the independent variables and the dependent variable are measured in the same survey. In order to test the severity of common method bias, the principal component analysis method was adopted. It is found that the first common factor explains 14.012% of total variance, which is less than 40%. Therefore, the degree of common method bias in this paper can be considered as not significant.

Descriptive statistics

This paper uses Stata 15.0 to conduct descriptive analysis and correlation analysis, as well as follow regression analysis, and the results are shown in table 12. It can be seen that the correlation coefficients among variables are all less than 0.7. Besides, the variance inflation factors (VIF) of all regression models are less than 5, which are reported in table 13.

Therefore, there is no multicollinearity problem in this study. According to correlation analysis results, supply chain resource management capability, supply chain collaboration capability, supply chain growth capability, supply chain risk control capability and supply chain operation capability are significantly positively associated with supply chain resilience, and subsequent regression analysis can be conducted.

Regression results

The regression analysis results are shown in table 13. Columns 1 to 5 illustrate the regression results of the effects of each dynamic capability factor on the supply chain resilience of Chinese SMGTEs, and

Table 12

DESCRIPTIVE STATISTICS AND CORRELATION ANALYSIS									
Variable	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1. Resilience	1								
2. Resource	0.555***	1							
3. Cooperation	0.582***	0.512***	1						
4. Growth	0.534***	0.503***	0.460***	1					
5. Control	0.586***	0.469***	0.416***	0.454***	1				
6. Operation	0.541***	0.416***	0.419***	0.414***	0.462***	1			
7. Age	0.572***	0.455***	0.508***	0.436***	0.568***	0.494***	1		
8. Scale	0.624***	0.515***	0.609***	0.547***	0.562***	0.460***	0.611***	1	
8. Region	0.434***	0.266***	0.430***	0.284***	0.449***	0.322***	0.438***	0.460***	1
mean	4.363	4.066	4.205	4.393	4.778	4.835	1.832	1.932	0.552
sd	0.672	0.993	1.003	0.842	0.919	1.078	0.560	0.808	0.498

Note: ***, **, and * indicate significance levels of 1%, 5%, and 10%, respectively.

Table 13

REGRESSION RESULTS						
Factor	**(1)**		**(2)**		**(3)**	
	Resilience	**VIF**	**Resilience**	**VIF**	**Resilience**	**VIF**
_cons	2.583***		2.627***		2.460***	
	(14.74)		(14.98)		(11.13)	
Age	0.251***	1.75	0.271***	1.73	0.279***	1.72
	(2.94)		(3.08)		(3.29)	
Scale	0.245***	1.93	0.242***	2.04	0.244***	2.01
	(4.97)		(5.11)		(4.92)	
Region	0.182***	1.33	0.127**	1.38	0.176***	1.33
	(3.11)		(2.06)		(2.88)	
Resource	0.184***	1.42				
	(4.48)					
Cooperation			0.167***	1.72		
			(3.97)			
Growth					0.187***	1.46
					(3.87)	
N	279		279		279	
R^2	0.513		0.497		0.498	
Adj. R^2	0.506		0.490		0.491	
Factor	**(4)**		**(5)**		**(6)**	
	Resilience	**VIF**	**Resilience**	**VIF**	**Resilience**	**VIF**
_cons	2.463***		2.551***		1.579***	
	(10.97)		(13.98)		(5.50)	
Age	0.228***	1.85	0.226**	1.82	0.103	1.99
	(2.64)		(2.53)		(1.28)	
Scale	0.269***	1.86	0.282***	1.79	0.115**	2.36
	(5.73)		(6.30)		(2.15)	
Region	0.117*	1.39	0.153**	1.34	0.087	1.45
	(1.84)		(2.55)		(1.60)	
Resource					0.094***	1.70
					(2.84)	
Cooperation					0.110***	1.89
					(2.99)	
Growth					0.090***	1.65
					(2.70)	
Control	0.188***	1.73			0.126***	1.87
	(3.75)				(2.63)	
Operation			0.159***	1.41	0.101***	1.52
			(4.56)		(2.90)	
N	279		279		279	
R^2	0.499		0.507		0.584	
Adj. R^2	0.492		0.500		0.572	

Note: ***, **, and * indicate significance levels of 1%, 5%, and 10%, respectively. The values in parentheses are t-values.

Column 6 illustrates the regression result of the effect of all dynamic capability factors on the supply chain resilience of Chinese SMGTEs. According to the results, supply chain resource management capability, supply chain collaboration capability, supply chain growth capability, supply chain risk control capability and supply chain operation capability have significant positive effects on supply chain resilience, and these effects are still significant in Column 6. Therefore, these five dimensions of dynamic capability can all improve supply chain resilience in Chinese SMGTEs, and all hypotheses are supported.

Robustness test

This paper adopted two methods for robustness checks. Firstly, the Bootstrap method was used to test the robustness of previous research conclusions. The number of Bootstrap times is set to be 1,000,

Table 14

BOOTSTRAP RESULTS							
Type of regression	**Explanatory variables**	**Observed coef.**	**BootSE**	**Bootstrapping**			
				95% CI (BC)		**95% CI (P)**	
				Upper	**Lower**	**Upper**	**Lower**
Single factor	Resource	0.184	0.043	0.109	0.281	0.107	0.279
	Cooperation	0.167	0.042	0.093	0.257	0.089	0.255
	Growth	0.187	0.049	0.094	0.283	0.101	0.290
	Control	0.188	0.052	0.089	0.288	0.091	0.289
	Operation	0.159	0.035	0.091	0.228	0.090	0.228
Multi-factor	Resource	0.094	0.034	0.031	0.168	0.029	0.165
	Cooperation	0.110	0.039	0.039	0.190	0.039	0.190
	Growth	0.090	0.035	0.029	0.160	0.026	0.159
	Control	0.126	0.048	0.030	0.218	0.036	0.226
	Operation	0.101	0.035	0.034	0.172	0.031	0.169

Note: BC indicates bias-corrected confidence interval and P indicates percentile confidence interval.

and the confidence interval is 95%. The test results are shown in table 14. The bias-corrected confidence intervals of all variables do not contain 0, indicating that the research conclusions are still valid.

In addition, 90% of the samples were randomly selected for regression analysis in order to further check robustness, and the research results are consistent with previous ones. The detailed results are shown in table 15. The robustness test results indicate that the positive effects of supply chain resource management capability, supply chain collaboration capability, supply chain growth capability, supply chain risk control capability and supply chain operation capability on supply chain resilience in Chinese SMGTEs are robust.

Table 15

REGRESSION RESULTS FOR 90% OF RANDOM SAMPLES						
Factor	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	Resilience	**Resilience**	**Resilience**	**Resilience**	**Resilience**	**Resilience**
_cons	2.532***	2.588***	2.434***	2.389***	2.515***	1.387***
	(14.16)	(14.58)	(10.63)	(9.88)	(13.69)	(5.60)
Age	0.252***	0.285***	0.293***	0.229**	0.230**	0.090
	(2.73)	(2.99)	(3.19)	(2.44)	(2.35)	(1.02)
Scale	0.221***	0.219***	0.223***	0.242***	0.263***	0.081
	(4.31)	(4.45)	(4.31)	(4.96)	(5.62)	(1.55)
Region	0.208***	0.132*	0.193***	0.128*	0.156**	0.095
	(3.33)	(1.96)	(2.94)	(1.89)	(2.38)	(1.63)
Resource	0.202***					0.101***
	(4.71)					(2.91)
Cooperation		0.179***				0.127***
		(4.26)				(3.55)
Growth			0.193***			0.091***
			(3.90)			(2.74)
Control				0.210***		0.147***
				(3.78)		(2.81)
Operation					0.171***	0.114***
					(4.85)	(3.19)
N	251	251	251	251	251	251
R^2	0.511	0.491	0.491	0.494	0.504	0.597
Adj. R^2	0.503	0.483	0.482	0.486	0.496	0.584

Note: ***, **, and * indicate significance levels of 1%, 5%, and 10%, respectively. The values in parentheses are t-values.

CONCLUSIONS AND SUGGESTIONS

Conclusions

This paper investigates the influencing factors of supply chain resilience in Chinese SMGTEs from a dynamic capability perspective. Through in-depth interviews and factor analysis, five key dynamic capability factors were determined to be able to affect supply chain resilience in Chinese SMGTEs, including supply chain resource management capability, supply chain collaboration capability, supply chain growth capability, supply chain risk control capability and supply chain operation capability. The measurement model constituted by 16 measurement items (i.e., supplier management capability, financial capability, informatization capability, structural capability, information sharing capability, trust capability, coordination capability, learning capability, innovation capability, forecasting capability, agility, risk awareness, risk management capability, strategic planning capability, logistics management capability and inventory management capability) was also developed based on coding results. It is a complex process to improve supply chain resilience in Chinese SMGTEs, and five dynamic capability factors can combine to achieve this goal. Besides, the effects of these five dynamic capability factors on supply chain resilience in Chinese SMGTEs were empirically examined, and regression results indicate the significant positive effect of all five dynamic capability factors on supply chain resilience in Chinese SMGTEs.

Managerial implications

This paper explores the ways for Chinese SMGTEs to enhance supply chain resilience in a highly volatile and competitive market with data support from interviews, questionnaire survey and empirical examination. The research results of this paper can be used by Chinese SMGTEs in three ways.

Firstly, this paper provides guidance on the ways to enhance supply chain resilience through dynamic capability for business managers in Chinese SMGTEs. Due to the increasing complexity of the green textile industry, the disruption risk of the supply chain faced by Chinese SMGTEs has risen rapidly, and supply chain resilience has become an effective weapon for Chinese SMGTEs to gain competitive advantages. Chinese SMGTEs can follow the dynamic capability framework developed in this paper to gain sustainable resilience of the supply chain.

The specific actions that can be taken are listed as follows:

- Chinese SMGTEs can improve supply chain resource management capability by optimising supplier management, strengthening liquidity management, accelerating information construction and upgrading supply chain layout.
- Chinese SMGTEs should focus on facilitating information sharing, process connection and technology integration to ensure close cooperation among supply chain members and to amplify synergistic effect in supply chain resilience.
- Chinese SMGTEs should pay attention to the growth capacity of the supply chain. Active exploration of new technologies stimulates innovation and makes continuous supply chain upgrades possible.
- Chinese SMGTEs can consider establishing a risk control system for the supply chain to identify supply chain risk and take action quickly.
- Chinese SMGTEs can improve supply operation capability by improving strategic planning skills. It is also necessary for Chinese SMGTEs to modify scheduling systems to reduce logistics costs and improve efficiency, and to consider optimising warehouse layout to improve inventory turnover.

Secondly, the research results of this paper provide insights into optimal resource allocation for Chinese SMGTEs. Research results show that there are five different dynamic capability factors that can improve the supply chain resilience of Chinese SMGTEs. According to regression results, the effect of supply chain risk control capability is greater than other factors, followed by supply chain collaboration capability, supply chain operation capability, supply chain resource management capability and supply chain growth capability. In case of limited resources, Chinese SMGTEs can reasonably allocate resources to maximise the effect of the dynamic capability combo on supply chain resilience.

Thirdly, the research results of this paper encourage Chinese SMGTEs to pay more attention to the relationship among supply chain members. In past practice, Chinese SMGTEs often did not realise the importance of relationship management. However, supply chain resilience is usually restricted by the features of the relationship. Therefore, Chinese SMGTEs must choose supply chain partners with similar cultural backgrounds and values. Meanwhile, the ability of Chinese SMGTEs to absorb knowledge is particularly important in the process of cooperation.

Limitations and further research

This paper combines qualitative and quantitative research methods to explore the structure of dynamic capability and its effect on the supply chain resilience of Chinese SMGTEs. Although some meaningful results have been generated, there are still some limitations that deserve further investigation in the future.

Firstly, there is a limitation in the research object. Due to the scarcity of industry-oriented research on the supply chain resilience of small and medium-sized enterprises, this paper takes SMGTEs in China as the research object. Therefore, research results and managerial implications are both relevant to Chinese SMGTEs. It is necessary to conduct further exploration to verify if the research results of this paper can be applied to large green textile enterprises or to traditional textile enterprises. Besides, Chinese SMGTEs are typical labour-intensive enterprises with certain capital and technological features. It is possible to apply current research results to an enterprise in the industry with similar features, such as furniture, toy and food processing industries. The next step is to explore the shaping of supply chain resilience through dynamic capabilities in these industries.

Secondly, the research sample deserves further exploration. At the qualitative research stage, this paper selects only 26 supply chain managers of SMGTEs, related government officials and industry experts from four representative provinces of China as interviewees. Although these interviewees have excellent knowledge about the supply chain of Chinese SMGTEs, the information obtained is still limited. It is expected to invite more participants to join the interview in future research. At the quantitative research stage, most respondents of the questionnaire survey come from economically developed cities, leading to the fact that the data collected will inevitably have certain regional features and may limit further application of research results. This problem may be solved by expanding respondents to more regions and increasing the sample size in future research.

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Weaving techniques and pathology of the historical textiles at the Moghadam Museum from Iran

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ABSTRACT – REZUMAT

Weaving techniques and pathology of the historical textiles at the Moghadam Museum from Iran

Textiles at the Moghadam Museum (Tehran, Iran) are considered a valuable heritage collection that has a historical legacy of more than 2,200 years. They comprise a variety of weaving and stitching techniques, textures, materials, patterns and designs, and they are from a wide range of national and ethnic people who lived in the Persian plateau during the above-mentioned two millennia. The valuable collection was gathered by its founders, Dr. Mohsen Moghadam and his wife, Mrs. Selma Kiyoomjian. They utilised different sustainable preservation techniques and restoration methods, based on the historical value, size, and material of the textiles. After their demise, facilities limitations and poor maintenance gave way to the occurrence of irreparable damage to the collection. High fluctuations of the environmental conditions, in humidity and temperature, accompanied by low ventilation, resulted in the growth of fungi and the attack of insects on some of the textiles. Exposure to light also paled the colours in some of the textiles. In terms of weaving technique, three textile types are discussed in the present research study, including mixed-weaving technique (the Parthian Empire, 247 BC till 224 AD), Ghalamkaar textiles and textiles with metal-threads (both during the Safavid dynasty, 1501 AD till 1722 AD).

Keywords: *cultural heritage, historical textiles, environmental conditions, insects, Moghadam Museum*

Tehnici de țesere și patologia textilelor istorice din Muzeul Moghadam din Iran

Textilele din Muzeul Moghadam (Teheran, Iran) sunt considerate o colecție de patrimoniu de mare valoare, având o moștenire istorică de peste 2.200 de ani. Acestea includ o varietate de tehnici de țesere și cusături, diferite texturi, materiale și modele, provenind dintr-o mare diversitate de comunități și culturi care au locuit pe platoul Persan de-a lungul ultimelor două milenii. Valoroasa colecție a fost adunată de fondatorii muzeului, dr. Mohsen Moghadam și soția sa, doamna Selma Kiyoomjian. Aceștia au aplicat diverse metode de conservare și restaurare sustenabilă, alese în funcție de valoarea istorică, dimensiunea și materialul fiecărui obiect textil. După dispariția lor, limitările infrastructurale și întreținerea deficitară au dus la apariția unor deteriorări ireparabile ale colecției. Fluctuațiile mari ale condițiilor de mediu interne: umiditate, temperatură, ventilație insuficientă etc. au favorizat dezvoltarea fungilor și deteriorarea unor materiale ca urmare a prezenței insectelor. Expunerea la lumină a determinat, de asemenea, decolorarea unor țesături. În ceea ce privește tehnicile de țesere, prezenta lucrare analizează trei tipuri de textile: țesături realizate prin tehnica mixtă de țesere (datând din perioada Imperiului Part, 247 î.Hr. – 224 d.Hr.), textile Ghalamkaar și țesături cu fire metalice (ambele aparținând perioadei dinastiei Safavide, 1501–1722 d.Hr.).

Cuvinte-cheie: *patrimoniu cultural, textile istorice, condiții de mediu interne, insecte, Muzeul Moghadam*

INTRODUCTION

Textiles and fabrics are considered a valuable and reliable source of information about the past communities, on their activities that were common among them, the materials they used, their cultural and religious beliefs, and even the superstitions that the people permanently or temporarily believed [1]. Moreover, the gradual development of different weaving and stitching techniques over the history of civilisation is considered a good example of human learning capabilities and their innovative approaches. The emergence of some weaving techniques and patterns is even rooted in cultural, social, and religious aspects. Some weaving techniques and patterns are indicative of how cultures were mixed so that eventually a new pattern has emerged. For instance, a case study on a peasant's traditional garment (about two thousand years old) indicated how Trajan's Column in Rome (113 AD) influenced certain elements in Romanian garments [2, 3]. Careful elaboration on the emergence and process of production for different textiles and fabrics in the past can reveal many other hidden aspects of the society in which they were produced and mixed. In this connection, it is believed that principles of weaving techniques originated in an ancient civilisation located in Western Asia, which over time were passed on to other cultures and nations [4, 5].

Iran is located in a strategic geopolitical region that has received a variety of different techniques, arts, and skills in textiles and fabrics. Iranian artists and craftsmen mixed domestic techniques and innovative skills with those introduced from other nations to eventually develop outstanding patterns of high quality, lasting for generations. Over the first four millennia of the textile industry, there were only two main weaving techniques known in the Persian plateau, namely the plain weaving technique (occurring in the fourth and fifth millennium) and the tablet weaving technique on terra-cotta (occurring in the late third or early second millennium BC). Both these techniques were found in the Susa region. After these two main techniques, the tapestry weaving style was introduced in the Western regions of Iran, followed by shuttle weaving techniques first in the Eastern and then in the Western regions of Iran, which enabled the making of different patterns. Tapestry was first initiated in Egypt about 1500 BC. It was considered the basis of weaving technique in the East until as late as the 14th Century AD [4]. The real history of the textile industry in Iran actually started when all the above-mentioned had already been introduced in the Plateau. The Golden Age of textile art in the Persian plateau happened during the sixteenth and seventeenth centuries (AD) [6]. A combination of different factors resulted in the blooming of the textile industry in this era, including the utilisation of complex and mixed stitching techniques, the usage of different long-lasting and newly developed colours and designs, and the use of metal threads (mostly silver and gold threads) in textiles [6, 7].

The textile collection at the Moghadam Museum includes artistic heritage that provides historical information on a period of more than two millennia. All the items were gathered by the founders of the Museum, Dr Mohsen Moghadam (Persian: محسن مقدم) and her wife, Mrs Selma Kiyoomjian (Persian: سلما کیومجیان). Many nations and ethnic groups lived at one time or another in the Persian plateau. The Different preservation techniques and restoration methods were used by the founders, according to each textile specimen, age, type of material, size, colour, etc. After their demise, irreparable damage was suffered by the textiles collection because of facility limitations and poor maintenance. The internal microclimate conditions (temperature and humidity), low ventilation, and other possible factors contributed over time to the development of microorganisms and insect attacks, as also reported in previous studies [8–11]. Because historical places and objects are of great value from social, cultural, ethnic, religious, and even touristic purposes, and they are considered a historical identity of the people living there [12, 13], the present paper intends to categorise some of the most important textiles based on their weaving techniques, and to estimate which dynasty they belong to. Moreover, fungal damages to the textiles were observed to determine the main fungal species that attacked and deteriorated these historical textiles.

GENERAL INFORMATION

Description of the textile collection and apparatuses

Textiles and fabrics at the Moghadam Museum in Tehran (Iran) cover a wide time span of more than 2,200 years, contemporary to many dynasties that ruled in Iran. The Empires and dynasties from which the weaving techniques and textiles were gathered by the founders of the Moghadam Museum are as follows:

- Parthian Empire (247 BC – 224 AD)
- Sassanid Empire (224 AD – 651 AD)
- Safavid dynasty (1501 AD – 1722 AD)
- Afsharid dynasty (1736 AD – 1751 AD)
- Zand dynasty (1751 AD – 1794 AD)
- Qajar dynasty (1789 AD – 1925 AD).

In the present study, two weaving techniques belonging to the Parthian Empire and the Safavid dynasty are evaluated. The founders collected the specimens from different cities and regions of Iran, and probably from other neighbouring countries that previously belonged to the Persian plateau. They used different preservation techniques and restoration methods, based on the historical value, size, and material of the textiles. Their reports indicate that no damage was done to the collection during their living periods. However, after their demise and because of the 1979 Iranian Revolution, poor maintenance caused irreparable damage to some of the unique textile specimens in the collection.

In the present research study, SEM image and elemental analysis were done by SEM-EDX electronic microscope: VEGA/TESCAN-XMU, VEGA/TESCAN-LMU apparatus. The light microscopy images with magnification were carried out by an Olympus light microscope DSX1000.

Categorisation of the textiles

There are many types of textiles and fabrics at the Moghadam Museum based on the microscopic observation, weaving techniques, patterns, and fibres of the textiles, relating to different historical dynasties and ethnic groups who lived in the Persian plateau in Iran over the last two millennia. In the present research study, three of the textile types and specimens are discussed based on their weaving techniques.

Mixed-weaving textiles

The specimen under the mixed-weaving technique (complex stitching technique) is the inventory code No. 2333, as one of the oldest specimens at the Moghadam Museum (figure 1). The founders of the Moghadam Museum categorised this specimen under the Sassanid Empire (the 3rd to 7th centuries AD). However, a recent study has categorised it under the Parthian Empire (the 3rd century BC till the early 3rd century AD) [14]. Therefore, in the present study, the term "Parthian-Sassanid Empires" is used for this specimen.

The Parthian-Sassanid specimen is comprised of three parts, sewn together (figure 1, bottom). The two

Fig. 1. Front (top, left) and back (top, right) sides of the textile under the inventory code No. 2333, belonging to the Parthian-Sassanid Empires (more than 2,000 years old); delicate embroidery showing the outline of a woman (bottom, right), using the slit-tapestry weaving technique (bottom, right, magnification ×40)

main parts have a slit-tapestry weaving technique (figure 1, bottom, right), having a small part on the left with a simple taffeta weaving technique. On the textile, the outline of two people is decorated using embroidery (figure 1, top left). Visual observation and microscopic images revealed that the brown fibres in this historical textile specimen were wool, and the light colour fibres were made of linen, which confirms a previous study on this specimen [14].

Ghalamkaar textiles. The term Ghalamkaar or Ghalamkar was derived from the way this type of textile is produced (figure 2). Ghalamkaar or Kalamkaari (Persian: قلمکار) is a type of textile (usually cotton textile) on which block-printing is delicately done. The origin of this type of textile printing is Isfahan (located in the central parts of Iran). Over centuries, this artistic textile painting was also introduced to the Indian state of Andhra Pradesh. Traditionally, only natural dyes are used in Ghalamkaari. The dying process usually involves twenty-three steps.

Originally, patterns and designs were painted with delicate brushes on cotton and silk fabrics. However, this process was really time-consuming. Moreover, the patterns were not identical. Therefore, artists produced wooden stamps to replace brushes. As the production process was simplified and this type of textile became more popular, different types of textile materials were also used, like cotton, linen, calico, and duck [15]. Researchers estimate that it goes back to the 10th and 11th centuries AD, as three stone stamps were found in Nishapur (Persian: نیشابور) historical excavation. In the Safavid dynasty (the 16th century till early 18th century) and during King Abbas realm, people showed a special eagerness for this type of textile, giving way to the

Fig. 2. Ghalamkaar textile specimen on taffeta cotton fabrics using gold-Ghalamkaar technique or gold-printing Ghalamkaar (top) (inventory code numbers 4448-72); close-up images (magnification ×40)

initiation of different ways and methods to produce Ghalamkaar textiles.

Ghalamkaar textile collection at the Moghadam Museum includes Iranian and Indian Ghalamkaar specimens. Different printing techniques were used on the Ghalamkaar textiles, including brush printing, different wooden or metal stamps, and gold printing. Elemental analysis of the gold-printing Ghalamkaar (inventory code numbers 4448-72, figure 2) revealed that more than 88% of the printing was comprised of gold (figure 3). SEM images of the fabric beneath the gold-printing in the specimen 4448-72 Ghalamkaar fabric are shown in figure 4. Elemental analysis of the fabric revealed it is comprised of 46% carbon and 52% oxygen.

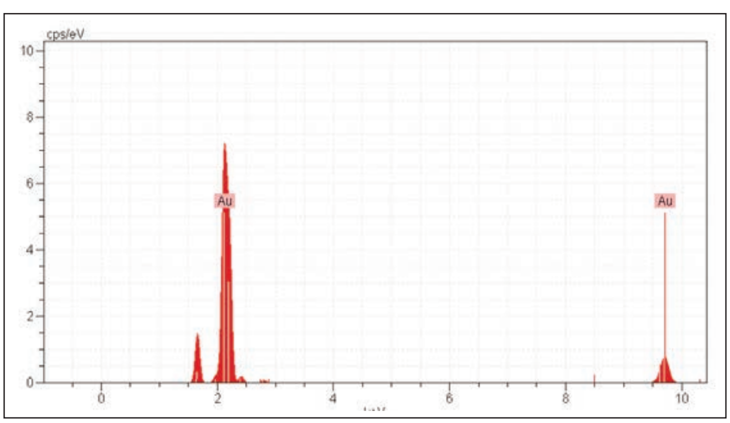

Fig. 3. Elemental analysis of the gold-printing on the Ghalamkaar textile specimen on taffeta cotton fabrics using the gold-Ghalamkaar technique or gold-printing Ghalamkaar (inventory code numbers 4448-72)

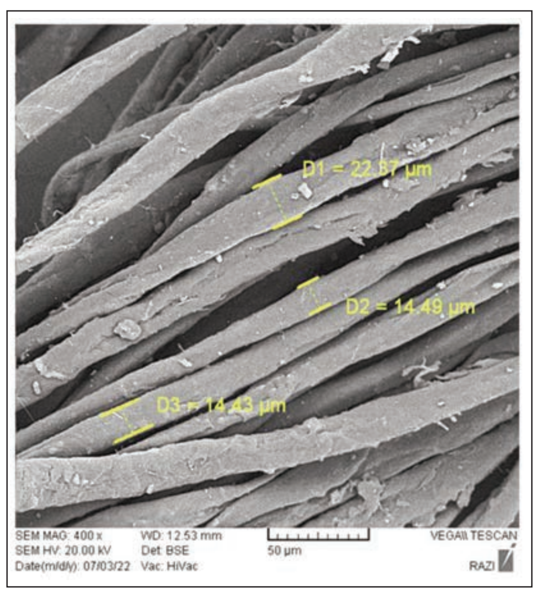

Fig. 4. SEM images of the cotton threads (taffeta cotton fabric beneath the gold-printing) in the gold-printing Ghalamkaar (inventory code numbers 4448-72)

Textiles with metal-threads

The textiles with metal threads at the Moghadam Museum are mostly made with gold and silver threads [16]. Gold and silver threads are produced with a core thread made in silk, with two delicate threads in gold or silver winded and drawn around the core thread. In order to produce the metal threads, metals (either gold or silver) are first melted to be passed through a number of small holes in sequence, the diameter of which becomes smaller gradually. Eventually, delicate metal threads are formed that are as this as hair. These round threads are then delicately hammered and flattened so that they can be more easily wound around the silk core thread. The thickness of the metal threads significantly influences the softness or coarseness of the produced metal-thread textile. There are several different metal-thread textiles and fabrics, depending on the extent of metal threads that are used in the whole textile structure [17, 18].

The Safavid textile specimen with inventory code No. 3674 is a specimen with metal threads, related to the Safavid dynasty (the 16th century till the early 18th century). This specimen has two decorative sides, with two series of warps (figure 5). The warps are in navy blue and orange colours that make up the background colour of the textile on each side. Wefts are in different colours, including yellow, green, cream, orange, white, and light blue (figure 6).

Fig. 5. Safavid textile with metal thread (inventory code No. 3674, the 16th century till early 18th century) with two decorative sides in different background colours of navy blue (right) and orange (left)

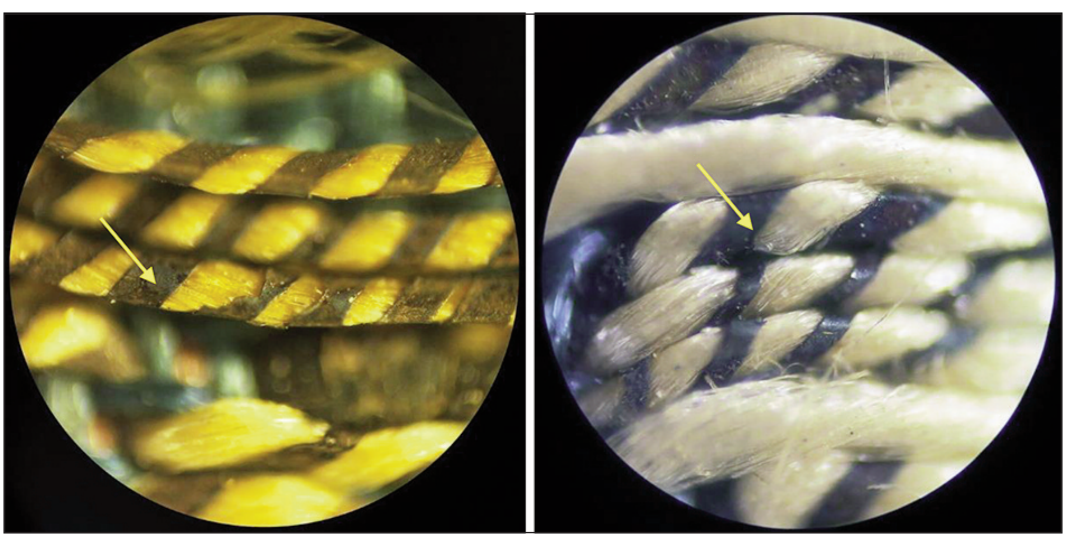

Fig. 6. Microscopic images of the metal threads (↑) wound round silk cores in different colours in the Safavid textile with metal thread (inventory code No. 3674, the 16th century till early 18th century) (magnification ×100)

Microscopic analysis revealed that all threads used in this textile are of silk. The weaving technique in this specimen is Z-type for the warps and wefts. The diameter of the warps is bigger than that of the wefts. Density is about 36–37 warps and 46–47 wefts in each centimetre. The background weaving technique is taffeta [19].

CONCLUSIONS

Upon personal endeavour and private expense account, the founders of the Moghadam Museum (Dr. Mohsen Moghadam and her wife, Mrs. Selma Kiyoomjian) got together a priceless collection of different textiles and fabrics woven by artists from the Persian plateau, and from European artists as well. The collection covers a long history, as old as 2,200 years, and over different Empires and dynasties that ruled in the above-mentioned vast region. The present study categorised three textile specimens in this collection, based on their weaving techniques. The strategic location of the Persian plateau made it a crossroad of different civilisations, where remarkable works by outstanding artists were mixed to form new patterns and weaving techniques. The Persian artists kept this legacy that went back many years in time and conserved the history of many nations and civilisations, from the Nile in Egypt to China and Japan, and from the European countries to South East Asia. Though many scattered studies have been carried out on several specimens in this valuable collection of textiles and fabrics at the Moghadam Museum, there is still a great need to do research from different aspects, like the development procedure of weaving techniques over the history of the Persian plateau for about 2,500 years. A joint scientific and historical cooperation between Iran and different European and Asian countries, with a focus on this collection, can reveal many facts about the history of weaving techniques, patterns in textiles and fabrics, and indoor air quality, which have an impact on the artefacts.

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Comparative research about the moisture management and thermal properties of some knitted fabrics produced from different blended yarns spun on ring, mechanical compact and Siro spinning

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ABSTRACT – REZUMAT

Comparative research about the moisture management and thermal properties of some knitted fabrics produced from different blended yarns spun on ring, mechanical compact and Siro spinning

The yarn spinning method and the utilised raw material play a significant role in determining the comfort properties of fabrics. Spinning methods, such as conventional ring, mechanical compact, and Siro spinning, influence the yarn's structure, uniformity, and surface characteristics, which in turn affect fabric properties like moisture management and thermal comfort. This study explores the moisture management and thermal comfort properties of knitted fabrics produced from different blended yarns spun on three distinct spinning techniques: Conventional ring, mechanical compact, and Siro spinning. For analysing how different spinning methods and yarn types influence some comfort properties, Moisture Management Test (MMT), Alambeta Tests and air permeability tests were performed in the context of this research. For the statistical analyses, a Two-way ANOVA test was performed in order to investigate the effect of yarn spinning method and yarn type on moisture management, thermal comfort and air permeability properties of knitted samples. The findings revealed that spinning methods and fibre blends significantly impact the properties of the fabric. The research aims to provide insights into the relationship between yarn structure and fabric behaviour, offering valuable guidance for textile development and innovation.

Keywords: *yarn spinning, mechanical compact spinning, Siro spinning, moisture management, thermal properties, air permeability*

Cercetări comparative despre managementul umidității și proprietățile termice ale unor tricoturi produse din diferite fire în amestec pe mașini de filat cu inele, mașini de filat compacte mecanice și mașini de filat fire Siro

Metoda de filare a firelor și materia primă utilizată joacă un rol semnificativ în determinarea proprietăților de confort ale materialelor textile. Metodele de filare, precum filarea convențională cu inele, filarea mecanică compactă și filarea firelor Siro, influențează structura, uniformitatea și caracteristicile suprafeței firelor, care, la rândul lor afectează proprietățile materialelor textile, precum gestionarea umidității și confortul termic. Acest studiu explorează proprietățile de gestionare a umidității și confortul termic ale tricoturilor produse din diferite fire în amestec filate folosind trei tehnici distincte de filare: filarea convențională cu inele, filarea mecanică compactă și filarea firelor Siro. Pentru a analiza modul în care diferitele metode de filare și tipul de fire influențează unele proprietăți de confort, în cadrul acestei cercetări au fost efectuate teste de gestionare a umidității (MMT), teste Alambeta și teste de permeabilitate la aer. Pentru analizele statistice, s-a efectuat testul ANOVA bidirecțional pentru a investiga efectul metodei de filare a firelor și al tipului de fire asupra proprietăților de gestionare a umidității, confortului termic și permeabilității la aer ale eșantioanelor tricotate. Rezultatele au arătat că metodele de filare și amestecurile de fibre au un impact semnificativ asupra proprietăților tricotului. Cercetarea își propune să ofere informații despre relația dintre structura firelor și comportamentul materialului textil, oferind îndrumări valoroase pentru dezvoltarea și inovarea în domeniul textil.

Cuvinte-cheie*: filarea firelor, filarea mecanică compactă, filarea firelor Siro, gestionarea umidității, proprietăți termice, permeabilitate la aer*

INTRODUCTION

With the growing global awareness of textile garments, comfort satisfaction, and mechanical fabric properties have become increasingly important. Mechanical properties like abrasion resistance, pilling, and bursting strength are essential for evaluating fabric durability. At the same time, comfort properties are closely associated with the wearer's sensory and non-sensory experience, influenced by various physical and psychological factors. Different fibres and fibre blends may be utilised for varying spinning systems. Although the conventional ring spinning system is the most popular among others, some other varying systems may also benefit from such as compact spinning, air jet spinning, and Siro spinning. Etc. The developments in spinning systems have reached their highest level for reducing hairiness. It is known that although short fibres are sometimes desired due to their giving soft touch to the fabric, the yarn will reveal appearance deformities when there is a high number of longer hairs. This will also reflect on the physical fabric properties, certainly. The main trend for reducing hairiness has focused on two methods where the number of fibres in 1 cm or the total length of hairs in 1 m was aimed to be decreased [1]. Kaynak and Çelik also supported that yarns produced using different spinning technologies vary not only in their structure but also in their bulk, mechanical, and surface characteristics. These variations in yarn properties significantly influence the properties of the fabrics made from them. Each spinning technology has its unique advantages and limitations, which are inherent to the specific system [2].

The well-known compact system is mostly preferred in yarn spinning mills owing to its elimination of the spinning triangle with the fibre condensation. This condensation process may be pneumatically or mechanically. In the pneumatic systems, condensation occurs after the drafting procedure before the yarn formation. The fibre flow reaching the spinning triangle is so narrow. All fibres are caught by the spinning triangle. In the process, all the fibres from the remaining spinning triangle are collected and fully integrated into the yarn. Rieter® K-44, Suessen® Elite, Zinser, and Toyota® RX-240 are well-known pneumatic compact spinning systems. The second method for fibre condensation is mechanical condensation. This process can be enhanced by using a mechanically funnel-shaped condenser placed between the aprons and the delivery rollers. The use of condensers offers a highly effective way to achieve fibre condensation. Rocos, the rotorcraft compact spinning system, operates based on the principle of mechanical condensation. According to a previous study, mechanical compact spinning significantly improves yarn imperfections and reduces hairiness. Other studies have also evaluated the properties of core-spun yarns produced using various spinning methods, including mechanical condensation. The COMPACTeasy device is another mechanical compacting system that achieves true compacting without additional energy consumption, thanks to its y-channel compactor. The Swinsol® mechanical compact apparatus is one of the latest systems used in spinning mills, producing yarns with reduced hairiness, optimal strength, and elongation properties, even with less twist [3–5]. Siro spinning is another innovative yarn spinning method which combines the principles of ring spinning and rotor spinning. In the Siro spinning machine, two drafted strands are twisted together in a manner like ring spinning. However, unlike traditional methods, Siro spinning allows for the simultaneous twisting of two strands, resulting in a more compact and stronger yarn [6, 7].

There are some early studies related to the investigation of the effect of spinning method, yarn material type on some fabric properties. For example, Elrys et al. performed a study about the mechanical and comfort properties of knitted fabrics produced from dual-core and tri-core spun yarns, where tri-core yarn provided better modulus and elastic recovery in blended cotton/Tencel [8]. Another experimental study was conducted by Gedilu et al., where rotor-spun yarn knitted fabrics demonstrated higher thermal insulation behaviour and air permeability compared to ring-spun yarn knitted fabric [9]. Core yarn type, sheath sliver type, and yarn linear density significantly influence the comfort properties of core-spun vortex knitted fabrics, including moisture management, water vapour permeability, and air permeability in Günaydın and Çeven's study [10]. Yarn properties, such as yarn count, twist, and combing process, significantly affect the thermal comfort of 1*1 rib knitted fabrics, with increased water vapour permeability reducing thermal resistance in Özdil's study [11]. Compact spun yarn knitted fabrics showed higher thermal insulation behaviour and low stress mechanical characteristics compared to ring spun yarn knitted fabrics in Manonmani et al.'s study [12]. Kayabaşı and Yılmaz investigated the properties of fabrics made from vortex, OE-rotor, and ring-spun yarns. The yarns were produced using cotton and viscose fibres in three different yarn counts: Ne 12/1, Ne 16/1, and Ne 28/1. Their findings revealed that fabrics made from OE-rotor and vortex yarns exhibited superior water transfer rates compared to those made from ring-spun yarns [13].

As it is understood in the early literature mentioned above, the number of examples regarding to effect of some yarn properties on fabric features may be increased. However, it is thought that there is a gap in the literature related to the investigation of moisture management and thermal comfort properties of fabrics produced from conventional ring, mechanical compact and Siro yarns of different fibre blends.

Our experimental study mostly focuses on producing knitted sports socks using various fibre types, including natural fibres (cotton, bamboo) and synthetic-natural blends (polyester-cotton, micromodal-cotton). The selection and combination of fibres significantly influence the thermal and comfort properties of socks, which are essential for consumer satisfaction, particularly in active or prolonged use such as sports or daily wear. Cotton is a widely used natural fibre known for its breathability, softness, and moisture absorption capabilities. It provides a comfortable feel against the skin, making it ideal for daily use. However, cotton tends to retain moisture, which may lead to discomfort during high-sweat activities unless blended with moisture-wicking fibres. Utilising cotton, whether in carded yarn or combed yarn, will directly influence the yarn properties such as yarn hairiness, hence the comfort and thermal properties of fabrics produced from those yarns. Bamboo fibre is also natural but offers additional thermal regulation and antimicrobial properties. It is softer than cotton, often compared to silk in texture, and is excellent for temperature control and odour management. Bamboo enhances skin friendliness, making socks more comfortable for sensitive users. Blending synthetic fibres like polyester with cotton improves the mechanical strength, durability, and moisture management of socks. Polyester is hydrophobic, helping to wick moisture away from the foot, while cotton provides softness and breathability. This combination aims to optimise comfort for athletic or long-duration use. Micromodal is a type of regenerated cellulose fibre known for its luxuriously soft touch, high moisture absorption, and smoothness. When blended with cotton, the result is a sock that is lightweight, breathable, and exceptionally comfortable, especially for casual or indoor wear. Micromodal also maintains shape retention and colourfastness, contributing to long-term comfort.

This study has been performed to make a comparative analysis of moisture management and thermal comfort properties of knitted fabrics made of ring, mechanical compact, Siro spun yarns of different fibre blends. Conventional ring, mechanical compact and Siro yarns produced from five different raw materials (100% Bamboo, 50%-50% combed cotton-micromodal, 100% carded cotton, 100% combed cotton, 50%-50% carded cotton-polyester) were separately utilised as the yarn material for the knitted fabrics.

MATERIAL AND METHOD

Yarn production

Siro, conventional ring and mechanical compact spun yarns of Ne 12/1 from 5 different slivers (100% Bamboo, 50%-50% combed cotton-micromodal, 100% carded cotton, 100% combed cotton, 50%-50% carded cotton-polyester) were produced by using a carded and combed production line. Fibre blends were firstly opened and cleaned in a blowroom. After the blowroom, a carding machine was used to produce card slivers, which were then subjected to 1st drawing machine, 2nd drawing machine, then to a roving machine and finally to mechanical compact, conventional ring or Siro spinning systems. An additional combing process was included in the stages to produce combed yarns. An additional Swinsol® compacting apparatus was utilised for the mechanical compact system (figure 1).

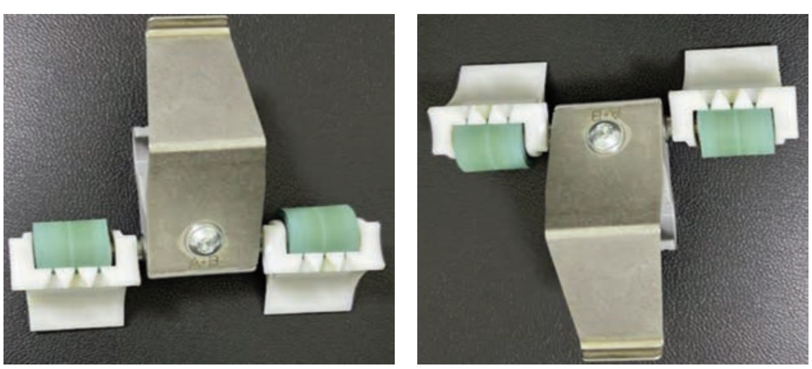
Produced rovings of Ne 1.04 were spun into yarn numbers of Ne 12/1 on the Siro, mechanical compact (The Swinsol® mechanical compact apparatus) and on the conventional ring system. All yarn samples of the same yarn count were produced with the same spinning parameters, namely the same twist multiplier, draft, and spindle speed on above mentioned spinning systems. To minimise any possible variation, 5 cops from each spinning machine for each yarn count were available to determine their properties. The yarn tests were carried out on Uster Tester 5, Uster Tensorapid 4 by feeding cops of each system in the same order to the testers. The tests were carried out under standard atmospheric conditions, and the samples were conditioned for a minimum of 24 hours before the tests. The measured yarn parameters, including evenness, hairiness, and tensile properties, are displayed in tables 1 and 2, respectively. Additionally, Zweigle test results were also obtained as an additional measurement for yarn hairiness (table 2). The Zweigle G565 Hairiness tester was used for measuring yarn hairiness. The hairs up to 25 mm in length (the projected length on an axis perpendicular to the yarn axis) emerging from a yarn are counted by means of a series of photocells. The yarn and projecting fibres interrupt a light beam, hence affecting a fluctuation in the measurable luminance of the light beam [14].

Fabric production

Fifteen different supreme fabrics were separately produced from combed, carded cotton, polyester cotton, bamboo, micromodal-cotton blended yarns spun on conventional ring, mechanical compact and Siro spinning systems, respectively, by using Faycon CKM 01-S model knitting machine (gauge 18 and diameter 3 $^{1/2}$). After the knitting process, fabrics were exposed to soft washing at 30°, then conditioned for 24 hours in standard atmospheric conditions before the conducted tests [15]. The structural properties of the supreme knitted fabric samples are indicated in table 3.

Moisture management test

Moisture Management Tester (MMT, SDL Atlas) was used to measure moisture management properties of fabrics based on the AATCC 195-2009 standard [16]. The device evaluates the moisture management in many aspects, considering the fabric's top and bottom sides [17]. The results were expressed in terms of the wetting time (sec), absorption rate (% /sec), spreading speed (mm/sec) and maximum wetted radius for top and bottom surfaces (mm), accumulative one-way transport index (AOTI), and overall moisture management capability (OMMC). The terms along with their definitions are given below. Additionally, table 4 reveals the grading of moisture management terms indices, where the indices are graded and converted from value to grades of five levels: 1 – Poor, 2 – Fair, 3 – Good, 4 – Very good, and 5 – Excellent.



a *b*

Fig. 1. Swinsol® apparatus: *a* – front side; *b* – back side

Table 1

YARN EVENNESS AND TENSILE PROPERTIES						
Spinning method	**Yarn material**	**CV**	**IPI**	**H**	**Rkm (kgf/Nm)**	**Elongation (%)**
Conventional ring	Combed cotton	9.50	11.5	7.32	16.81	6.26
	Carded cotton	13.67	148.5	9.63	13.99	5.8
	Polyester-carded cotton	11.50	102	7.27	20.05	9.77
	Bamboo	8.67	8.5	6.87	19.65	16.73
	Micromodal-combed cotton	9.72	191.9	6.97	15.03	8.12
Mechanical compact	Combed	9.70	13.5	5.82	17.91	6.87
	Carded	13.83	209.5	6.83	14.84	5.74
	Polyester-carded cotton	11.62	114	6.06	20.5	9.74
	Bamboo	8.58	2.5	5.62	20.15	16.77
	Micromodal-combed cotton	9.54	11	7.17	15.7	8.16
Siro spinning	Combed	9.47	6	7.18	16.78	6.67
	Carded	12.93	119.5	8.54	14.8	6.56
	Polyester-carded cotton	11.86	96	7.54	19.74	10.56
	Bamboo	8.31	5.5	6.49	19.25	17.68
	Micromodal-combed cotton	9.54	11	7.17	15.7	8.16

Table 2

ZWEIGLE HAIRINESS RESULTS (S1, S2, S3; NUMBER OF HAIRS LONGER THAN 1,2,3 MM RESPECTIVELY)				
Spinning Method	**Yarn type**	**S1**	**S2**	**S3**
Conventional ring spinning	Combed cotton	9.50	11.5	7.32
	Carded cotton	13.67	148.5	9.63
	Polyester-carded cotton	11.50	102	7.27
	Bamboo	8.67	8.5	6.87
	Micromodal-combed cotton	9.72	191.9	6.97
Mechanical compact spinning	Combed cotton	9.70	13.5	5.82
	Carded cotton	13.83	209.5	6.83
	Polyester-carded cotton	11.62	114	6.06
	Bamboo	8.58	2.5	5.62
	Micromodal-combed cotton	9.54	11	7.17
Siro spinning	Combed cotton	9.47	6	7.18
	Carded cotton	12.93	119.5	8.54
	Polyester- carded cotton	11.86	96	7.54
	Bamboo	8.31	5.5	6.49
	Micromodal-combed cotton	9.54	11	7.17

Wetting Time (sec) defines the wetting time of the test fabric for both top and bottom sides in seconds after the test is started. Absorption rate (%/sec) defines the average speed of liquid moisture absorption for both top and bottom sides of the specimen during the liquid dropping interval. Maximum wetted radius (MWR_{top}, MWR_{bottom}) defines the maximum wetted ring radius for both top and bottom sides, respectively, where the slopes of water content become greater than Tan 15. Spreading Speed defines the cumulative wetting spreading speed (mm/sec) between the centre of the specimen where the liquid is dropped and the maximum wetted radius. The cumulative one-way transport index (AOTI) defines the division of the area difference between the maximum wet radius in the top and the maximum wet radius in the bottom by the test time. Overall moisture management capacity (OMMC) is an index revealing the fabric's ability to transport liquid moisture. This index consists of three aspects of performance: moisture absorption rate of the bottom side (BAR), one-way liquid transport capacity (OWTC), and spreading/ drying rate of the bottom side (SS_b), which is the maximum spreading speed. The larger the OMMC is, the higher the overall moisture management ability of the fabric. The overall moisture management capacity (OMMC) is defined as:

$$OMMC = 0.25\,BAR + 0.5\,OWTC + 0.25\,SS_b \quad (1)$$

Table 3

EXPERIMENTAL DESIGN					
Fabric Code	**Spinning method**	**Yarn structure**	**Linear yarn density**	**Twist value (turns per meter)**	**Fabric thickness (mm)**
Combed	Conventional ring	Combed cotton	Ne 12/1	540	1.49
	Mechanical compact				0.96
	Siro				0.86
Carded	Conventional ring	Carded cotton			0.9
	Mechanical compact				0.85
	Siro				0.90
Polyester-cotton	Conventional ring	Polyester carded cotton yarn (50%-50%)			0.96
	Mechanical compact				1.32
	Siro				0.93
Bamboo	Conventional ring	Bamboo yarn			0.90
	Mechanical compact				0.90
	Siro				0.99
Micromodal-cotton	Conventional ring	Micromodal-combed cotton yarn (50%-50%)			0.91
	Mechanical compact				0.87
	Siro				0.95

Table 4

MOISTURE MANAGEMENT GRADE						
Grade		**1**	**2**	**3**	**4**	**5**
Wetting time	Top	≥120	20–119	5–19	3–5	<3
		No wetting	Slow	Medium	Fast	Very fast
	Bottom	≥120	20–119	5–19	3–5	<3
		No wetting	Slow	Medium	Fast	Very fast
Absorption rate	Top	0–10	10–30	30–50	50–100	>100
		Very slow	Slow	Medium	Fast	Very fast
	Bottom	0–10	10–30	30–50	50–100	>100
		Very slow	Slow	Medium	Fast	Very fast
Max. wetted radius	Top	0–7	7–12	12–17	17–22	>22
		No wetting	Small	Medium	Large	Very large
	Bottom	0–7	7–12	12–17	17–22	>22
		No wetting	Small	Medium	Large	Very large
Spreading speed	Top	0–1	1–2	2–3	3–4	>4
		Very slow	Slow	Medium	Fast	Very fast
	Bottom	0–1	1–2	2–3	3–4	>4
		Very slow	Slow	Medium	Fast	Very fast
AOTI	Top	<–50	–50 to 100	100–200	200–400	>400
		Poor	Fair	Good	Very good	Excellent
OMMC	Bottom	0.0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	>0.8
		Poor	Fair	Good	Very good	Excellent

Thermal comfort properties

The definition of thermal properties mentioned in this part, such as thermal conductivity, thermal resistance, thermal absorptivity, fabric thickness, and thermal diffusivity, is briefly summarised below.

Thermal conductivity (λ) is an intensive property of a material that indicates its ability to conduct heat. The measurement result of thermal conductivity is based on equation 2:

$$\lambda = \frac{q}{A \cdot \frac{\Delta t}{h}},\ \mathrm{Wm^{-1}K^{-1}} \qquad (2)$$

where q is amount of conducted heat; A – area through which the heat is conducted; ΔT – drop of temperature and h – fabric thickness (mm).

Thermal diffusivity, a, characterises the velocity of propagation of thermal impulse through the material, and can be expressed as follows:

$$a = \frac{\lambda}{\rho c} \quad (m^2/s) \qquad (3)$$

here ρ means density (kg m^{-3}) and c is the specific heat of fabric (J/kgK).

Thermal absorptivity, b, is the objective measurement of the warm-cool feeling of fabrics. This parameter allows assessment of the fabric's character in the aspect of its "cool warm" feeling [18]. As already mentioned, in the last decades, most of the studies dealing with thermal comfort properties of textiles were devoted to the measurement of steady-state thermal properties such as thermal conductivity and thermal resistance, but later, Kawabata & Yoneda emphasised the importance of a new transient property, so-called 'warm-cool feeling' also. This property tells us whether a user feels 'warm' or 'cool' at the first short contact of the fabric with human skin. In 1987, Hes introduced the term 'thermal absorptivity' as a measure of the 'warm-cool feeling' of textiles. The equation 4 displays the calculation of thermal absorptivity.

$$b = \sqrt{\lambda \cdot \rho \cdot c}, \quad Wm^{-2}s^{1/2}K^{-1} \qquad (4)$$

Thermal resistance, r, is a measure of the body's ability to prevent heat from flowing through it. Under a certain condition of climate, if the thermal resistance of clothing is small, the heat energy will gradually reduce with a sense of coolness. Thermal resistance is connected with fabric thickness by the relationship 5 [18–20]:

$$r = \frac{h}{\lambda}, \quad m^2KW^{-1} \qquad (5)$$

where r is the thermal resistance; h – fabric thickness and λ – thermal conductivity coefficient.

Air permeability

Air permeability of knitted fabrics may be influenced by fabric structure, fabric weight, as well as chemical treatments during finishing. Air permeability of fabrics was measured based on EN ISO 9237 standard by means of SDL Atlas Digital Air Permeability Tester Model M 021 A [21]. Measurements were performed by application under 100 Pa air pressure per 20 cm^2 fabric surface. Averages of measurements from 10 different areas of fabrics were calculated [21]. In the early literature, it was mentioned that the air permeability of woven fabric is mainly dependent on the fabric structural property that is related to fibre density, linear density of warp and weft yarns, yarn type, weave construction, warp and weft density, etc. Certain characteristics of textile fibres, yarns and fabrics may be associated with air permeability properties [22–25].

Statistical analyse

In order to analyse the spinning method and yarn type on fabric moisture management, thermal comfort and air permeability properties, a randomised two-factor analysis of variance (two-way ANOVA) was used for the determination of the statistical significance of these two main parameters. The means were compared by means of SNK tests. The value of the significance level (α) selected for all statistical tests in the study was 0.05. The treatment levels were marked in accordance with the mean values, and levels marked by a different letter (a, b, c) indicate that they were significantly different. In order to obtain a correlation coefficient between fabric properties (fabric thickness-thermal resistivity), Pearson correlation analyses were also performed within the study. The statistical evaluations were done by using SPSS 23 Statistical software package.

RESULTS AND DISCUSSION

Moisture management properties

The moisture management performances of fabrics were evaluated in terms of wetting time (sec), absorption rates (%/sec), maximum wetted radius (mm), spreading speed (mm/sec) for top and bottom surfaces, accumulative one-way transport index (AOTI) and overall moisture management capacity (OMMC). Detailed test results for each test term of Moisture management properties were given in bar graphs, and SNK tests were performed respectively in order to evaluate the significant influence of yarn type and spinning method on fabrics' moisture management properties and compare the means of those properties. Discussion of ANOVA and SNK results for each term will be mentioned within each related section (table 5, table 6).

Wetting time

The wetting time of knitted fabrics after the liquid has been applied is indicated in figure 2. It is anticipated

Table 5

ANOVA RESULTS FOR MOISTURE MANAGEMENT PROPERTIES								
Main effect	**Top wetting time (sec)**	**Bottom wetting time (sec)**	**Top absorption rate (%/sec)**	**Bottom absorption rate (%/sec)**	**Top spreading speed (mm/sec)**	**Bottom spreading speed (mm/sec)**	**AOTI**	**OMMC**
Spinning method (S)	0.22	0.97	0.50	0.73	0.68	0.58	0.85	0.59
Yarn type (Y)	0.33	0.05	0.08	0.52	0.95	0.19	0.00*	0.46
interaction of spinning method and yarn type (S*Y)	0.02*	0.00*	0.00*	0.54	0.28	0.17	0.00*	0.57

Note: *Statistically significant (5% significance level).

Table 6

SNK RESULTS FOR MOISTURE MANAGEMENT PROPERTIES						
Parameter		**Top wetting time (sec)**	**Bottom wetting time (sec)**	**Top absorption rate (%/sec)**	**Bottom absorption rate (%/sec)**
Yarn type	Combed	8.41 a	46.30 ab	26.04 a	21.93 a
	Carded	10.04 a	74.01 b	25.23 a	4.16 a
	Polyester-cotton	8.34 a	46.79 ab	32.47 a	25.43 a
	Bamboo	30.88 a	20.68 a	7.42 a	19.95 a
	Micromodal-combed	16.33 a	45.43 ab	8.19 a	22.87 a
Spinning Method	Conventional ring	11.62 a	45.54a	15.08a	15.23a
	Mechanical compact	14.33 a	46.20a	19.70a	18.10a
	Siro	18.45 a	48.19a	24.83a	23.27a
Parameter		**Top spreading speed (mm/sec)**	**Bottom spreading speed (mm/sec)**	**AOTI**	**OMMC**
Yarn type	Combed	1.44 a	1.03 a	795.02 a	0.49 a
	Carded	1.44 a	0.59 a	1343.32 cd	0.51 a
	Polyester-cotton	1.22 a	1.16 a	1029.43 ab	0.49 a
	Bamboo	1.20 a	1.43 a	1476.12 d	0:58 a
	Micromodal-combed	1.40 a	1.62 a	1138.04 bc	0.61 a
Spinning Method	Conventional ring	1.20 a	1.04 a	1139.71 a	0.50 a
	Mechanical compact	1.32 a	1.09 a	1143.48 a	0.54 a
	Siro	1.49 a	1.37 a	1185.97 a	0.57 a

Note: The different letters (a,b,c) next to the counts indicate that they are significantly different from each other at a significance level of 5%.

from figure 2 that knitted fabrics generally revealed higher bottom wetting time compared to top wetting time. There is no prominent trend for wetting time of samples compared to the spinning method or yarn type. According to figure 2, the maximum top wetting time was found among the samples produced from bamboo mechanical compact yarn, while the minimum value was found among the samples produced from combed cotton mechanical compact yarn. When it comes to bottom wetting time; Maximum bottom wetting time was observed among samples produced from combed cotton ring yarn, while the minimum value was observed among the samples produced from combed cotton yarns spun on the mechanical

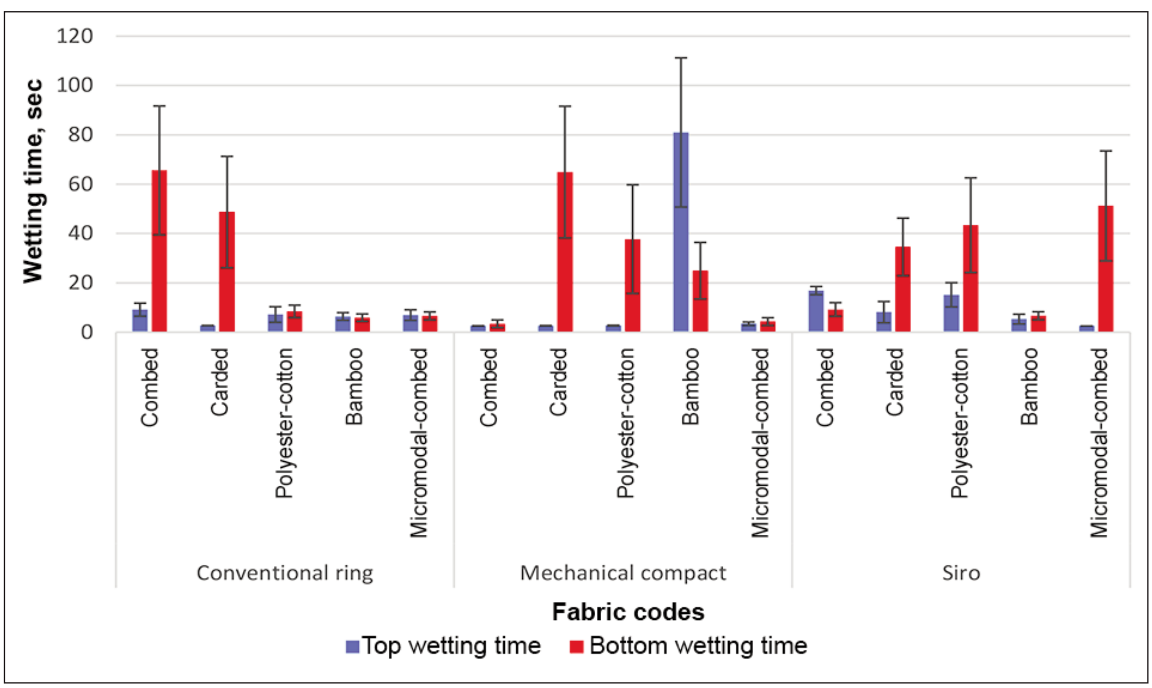


Fig. 2. Wetting time of knitted samples

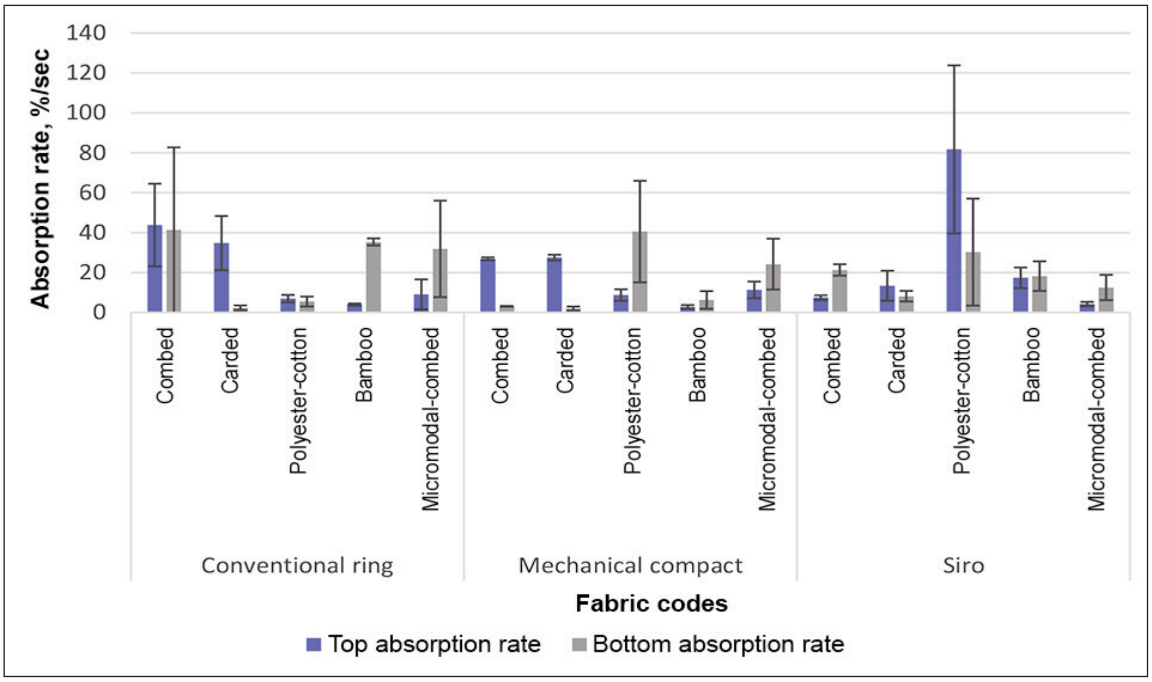


Fig. 3. Absorption rate (% /sec)

compact system. Additionally, two-way ANOVA was performed to analyse the effect of spinning method and yarn type on top and bottom wetting time (table 5). According to table 5, both factors were non-significant on the top and bottom wetting time results at a significance level of 0.05. However, the interaction of these two factors was significant on the top and bottom wetting time results at a significance level of 0.05.

Absorption rate

The top absorption rate (%) of fabric samples produced from polyester-cotton Siro yarn revealed the highest value among all samples, whereas samples from bamboo yarn produced on a mechanical compact system indicated the minimum top absorption rate (figure 3). When it comes to the bottom absorption rate (%) of fabric samples, samples produced from combed conventional ring yarn displayed the highest bottom absorption rate (%), whereas samples produced from carded cotton yarn spun with the mechanical compact system revealed the minimum absorption rate among all samples. It is also observed that samples of Bamboo and micromodal-combed yarns spun on conventional ring system, polyester-cotton yarn, bamboo, micromodal-combed cotton yarn spun on mechanical compact systems as well as samples of combed cotton, bamboo,micromodal-combed cotton spun on Siro systems displayed higher bottom absorption rate (%) compared to top absorption rate (%) which reveals that the fabric may transfer the sweat from the fabric surface contacting the human skin to the other surface. This would promote liquid transfer to the bottom face by a capillary wicking mechanism and provide a dry feeling to the consumer (figure 3). Additionally, a two-way ANOVA test was performed in order to analyse the significant effect of spinning method and yarn type on top and bottom absorption rate results. Top and bottom absorption rate values were neither significantly influenced by spinning method nor by yarn type at a significance level of 0.05 according to ANOVA results. The interaction of spinning method and yarn type factors was also non-significant on the top and bottom absorption results (table 5).

Spreading speed

According to figure 4, samples made of micromodal-combed cotton yarn spun on a mechanical compact system indicated the maximum spreading speed (mm/sec), while samples made of carded cotton yarn spun on a mechanical compact system indicated the minimum spreading speed (mm/sec) for bottom surfaces among all samples. Regarding to top spreading speed, samples from bamboo Siro yarn indicated the maximum top spreading speed, while samples from bamboo yarn produced on a mechanical compact system revealed the minimum top spreading speed. Figure 4 also reveals that fabric samples made of micromodal-combed cotton yarn produced on a conventional ring and produced on a mechanical compact system provided higher bottom spreading speed compared to top spreading speed, which may indicate satisfactory moisture management in the fabric. The higher the bottom spreading speed of the fabric, the greater the evaporation from the bottom layer and the less time the fabric takes to dry. In other words, the inner side of the knitted fabrics made of micromodal-combed cotton yarns produced on conventional ring and mechanical compact transfers water to the outer side by capillary forces and the water transferred is absorbed by the outer side. An ANOVA test was also conducted to investigate the effect of spinning method and yarn type on top and bottom

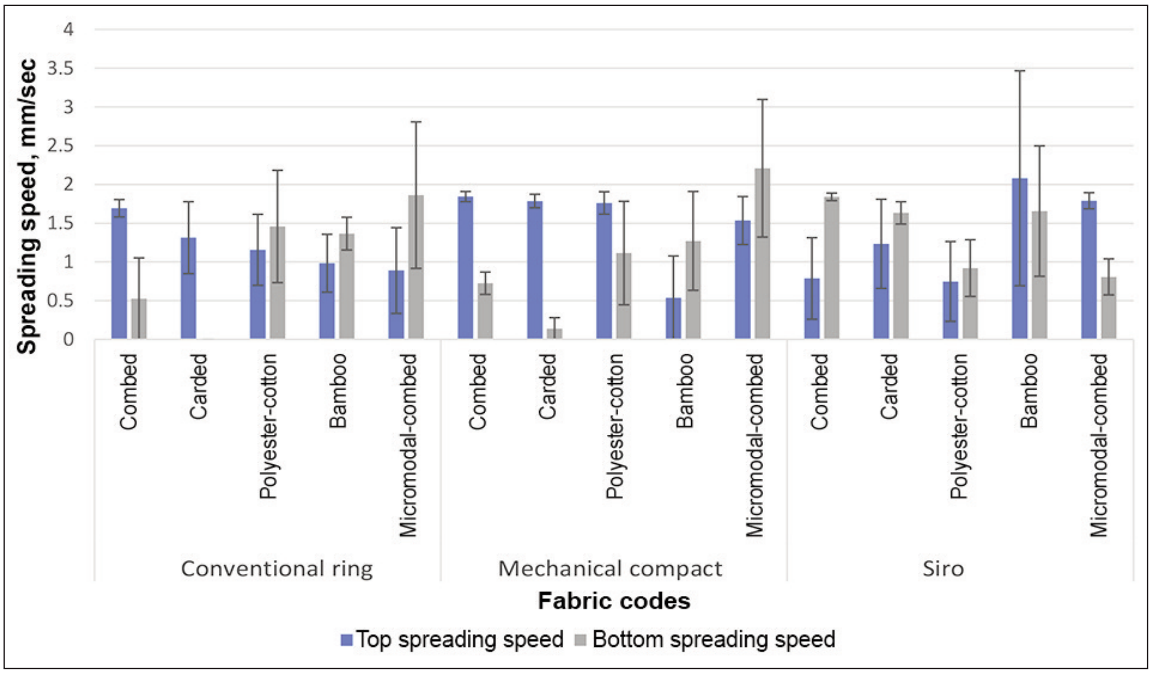


Fig. 4. Spreading speed (mm/sec)

spreading speed values of the samples at a significance level of 0.05. According to the ANOVA test, spinning method and yarn type factors, as well as their interaction, were both non-influential factors on top spreading speed and bottom spreading speed values at a significance level of 0.05.

Accumulative one-way transport index

Figure 5 indicates the cumulative one-way transport index of knitted fabrics provided from different yarns. The maximum accumulative one-way transport index was obtained from samples of polyester-cotton yarns produced with a conventional ring spinning system, whereas the minimum value was found among the conventional ring cotton yarns. The result may be due to the implementation of capillary action of polyester fibre, which helps the sweat to transport from the inner side (human skin) to the outer layer. As the spreading speed results are associated with the cumulative one-way transport index (figure 4), it is anticipated that samples made of polyester-cotton yarns have generally higher bottom spreading speed compared to top spreading speed, which reveals the ability of liquid transfer from top to bottom layer (figure 4).

ANOVA test indicated that yarn type had a significant effect, while spinning method did not have any significant effect on AOTI results of samples at a significance level of 0.05. The interaction of spinning method and yarn type was also significant on the

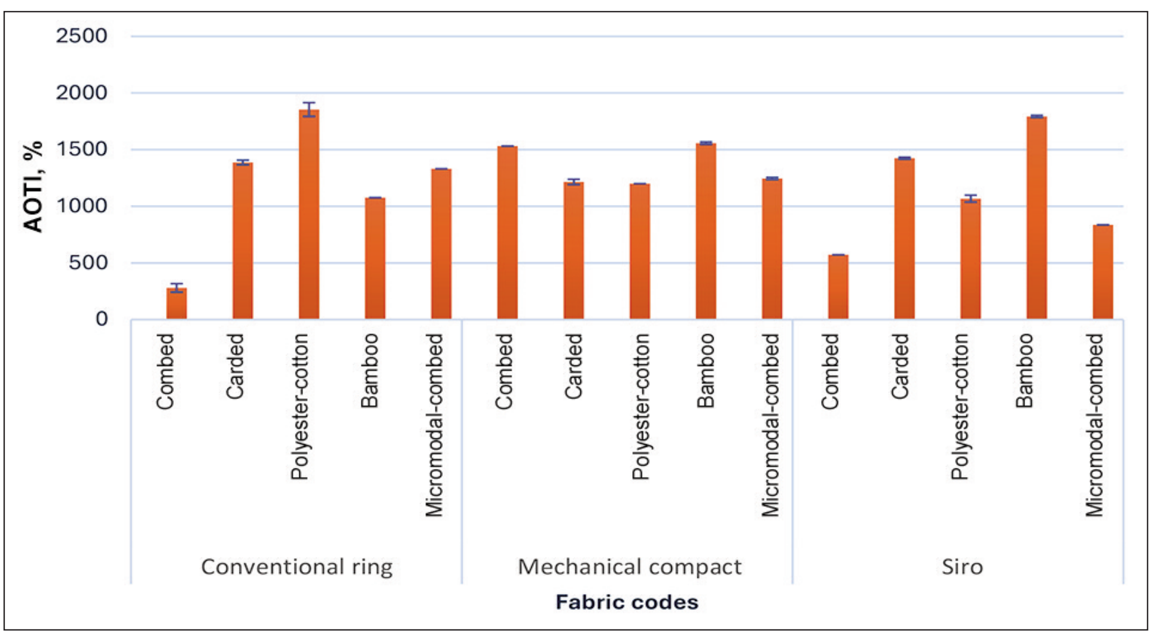


Fig. 5. Accumulative one-way transport index

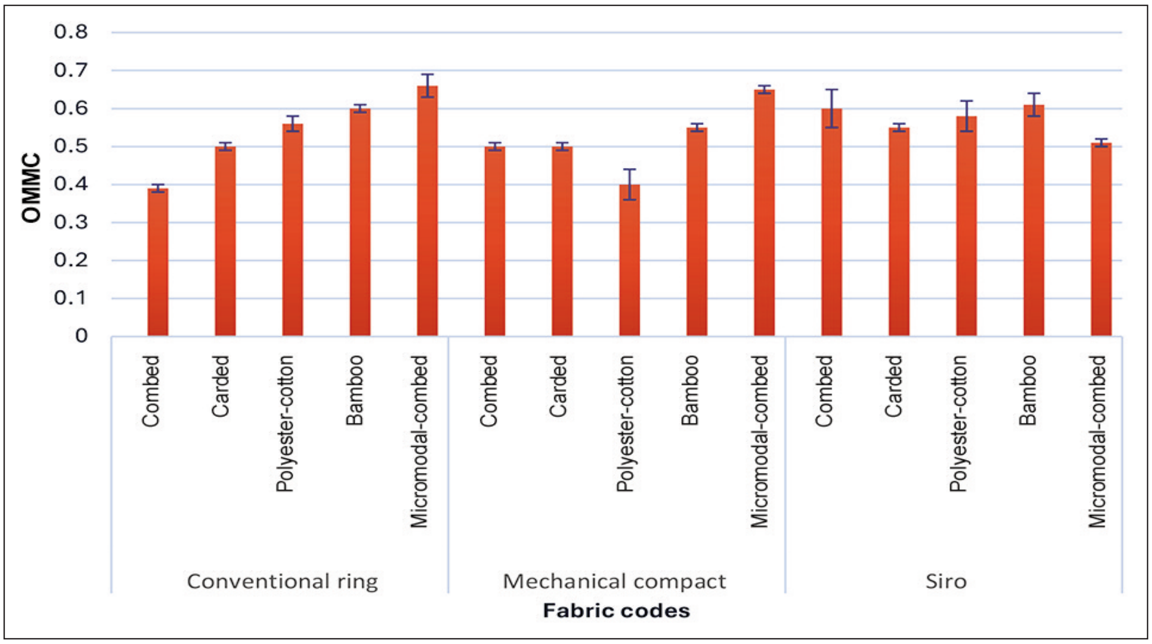


Fig. 6. Overall moisture management capacity (OMMC)

AOTI results at a significance level of 0.05. SNK results also showed that fabric samples produced from different yarn types revealed statistically different AOTI results. Considering AOTI results, the minimum value was obtained from samples made of combed yarns, while the maximum value was found among samples made of bamboo yarns, about yarn type. As a general evaluation, the AOTI results of samples generally revealed the ranges between 500 and 1200, which means they show an excellent grade over 400 (table 4). It is known for the fabric that has a value higher than 400; one-way transport is defined as excellent (table 4).

Overall moisture management capacity

OMMC is an index that reflects the overall ability of a fabric to manage the transport of liquid moisture. A higher OMMC value indicates a greater overall moisture management capability. This capacity demonstrates the fabric's effectiveness in quickly and efficiently transferring liquid sweat from the skin's surface to the outer layer, helping to keep the skin dry. As it is revealed in figure 6, OMMC results of samples are in the range between 0.33 and 0.66, which shows that they are all in good grade according to the grading of MMT indices in table 4. As a general evaluation, fabric samples from bamboo and micromodal-cotton blended yarns spun on conventional ring and mechanical compact systems revealed better MMT results compared to their counterparts made of cotton and polyester-cotton yarns. The highest moisture management capacity value was obtained among the samples from micromodal-cotton blended conventional ring yarns, while the minimum value was obtained from samples produced from conventional ring cotton yarns. Additionally, an ANOVA test was performed in order to analyse the effect of spinning type and raw material type on OMMC results of samples at a significant level of 0.05. According to the ANOVA test, spinning method, yarn type, and their interaction were non-significant factors on overall moisture management capacity at a significant level of 0.05.

Thermal properties of knitted fabrics

Thermal properties of knitted fabrics, such as thermal resistance, thermal conductivity, and thermal absorptivity, may be influenced by the constituent yarn properties, considering their spinning type and raw material of the blend. Thermal properties of blended samples were evaluated in terms of thermal conductivity, thermal absorptivity, thermal resistance, and fabric thickness. For evaluating the influence of spinning method and yarn type on fabrics' thermal properties, a completely randomised two-factor analysis of variance (ANOVA) was performed. ANOVA results for thermal properties of fabrics were displayed in table 7. The effect of the above-mentioned factors on thermal property results at a significance level of 0.05 was discussed within each related part with ANOVA and SNK table evaluation.

Thermal conductivity

Figure 7 reveals the thermal conductivity of blended knitted fabrics. According to figure 7, the Maximum thermal conductivity value was obtained from samples produced from combed cotton yarns spun with a mechanical compact system, while the minimum value was found among polyester-cotton blended samples with the yarns spun on a mechanical compact system. As it is observed, there is no prominent trend for thermal conductivity results of samples regarding to fibre blend type or yarn spinning method. Additionally, two-factor analysis of variance (ANOVA) was conducted in order to investigate the effect of yarn type and spinning method on thermal

Table 7

ANOVA RESULTS FOR THERMAL PROPERTIES				
Main effect	**Thermal conductivity (λ)**	**Thermal absorptivity (b)**	**Thermal resistance (r)**	**Fabric thickness (h)**
Spinning method (S)	0.37	0.35	0.52	0.43
Yarn type (Y)	0.00*	0.00*	0.00*	0.17
Interaction of spinning method and yarn type (S*Y)	0.0**	0.00*	0.00*	0.00*

Note: *Statistically significant (5% significance level).

Table 8

SNK RESULTS FOR THERMAL PROPERTIES					
Parameter		**Thermal conductivity (λ)**	**Thermal absorptivity (b)**	**Thermal resistance (r)**	**Fabric thickness (h)**
Yarn type	Combed	65.41 c	180.94 a	14.02a	1.10 a
	Carded	64.43 c	179.06 a	15.18 c	0.97 a
	Polyester-cotton	56.58 a	163.20 a	15.26 c	1.03 a
	Bamboo	61.58 b	212.06 b	14.64 b	0.90 a
	Micromodal-combed	64.40 c	199.40 b	14.00 a	0.90 a
Spinning method	Conventional ring	62.34 a	184.96 a	14.55 a	1.01 a
	Mechanical compact	62.01 a	183.69 a	14.60 a	1.00 a
	Siro	63.08 a	192.16 a	14.70 a	0.92 a

Note: The different letters (a,b,c) next to the counts indicate that they are significantly different from each other at a significance level of 5%.

conductivity. According to the ANOVA table (table 7), yarn type and the interaction of yarn type and spinning method were significantly influential factors, while spinning method was a non-significant factor on thermal conductivity at a significance level of 0.05. SNK tests were also performed to make a comparable analysis between the knitted samples produced from different yarn types, as well as between the knitted samples from yarns spun on different methods (table 8). Table 8 also reveals that knitted samples produced from different yarn types possessed different thermal conductivity, while thermal conductivity results of fabric samples produced from yarns of different spinning methods did not possess different values at a significance level of 0.05. Considering the SNK results for yarn type, the Minimum thermal conductivity was found among samples with polyester-cotton blended yarns, while the maximum value was obtained from samples with combed cotton and carded cotton yarns, which were observed under the same subset at a significance level of 0.05 (table 8).

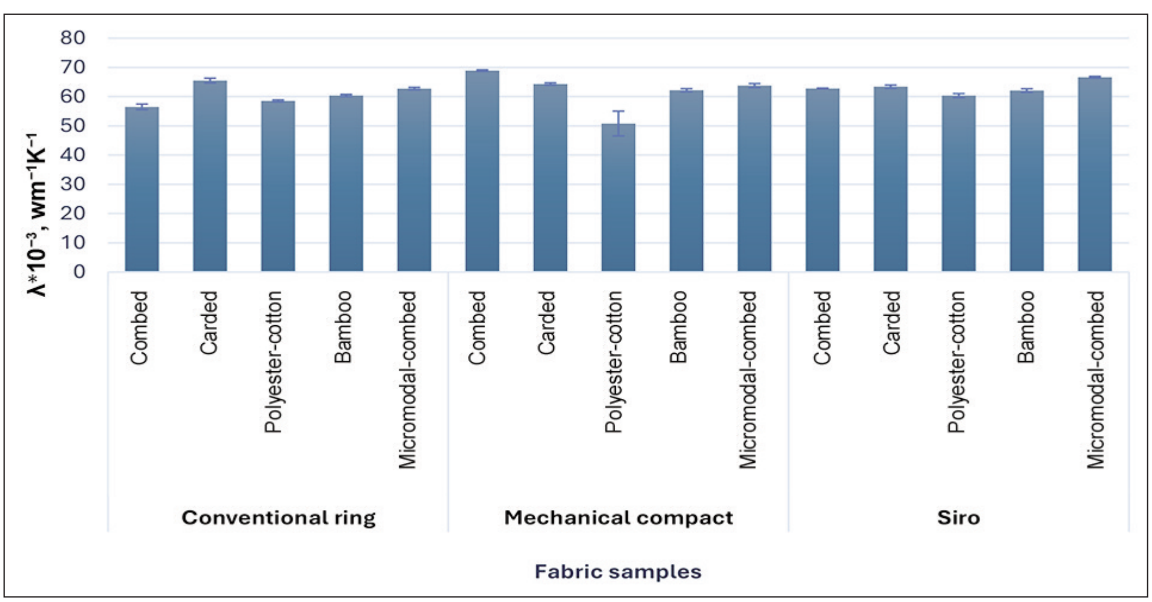


Fig. 7. Thermal conductivity

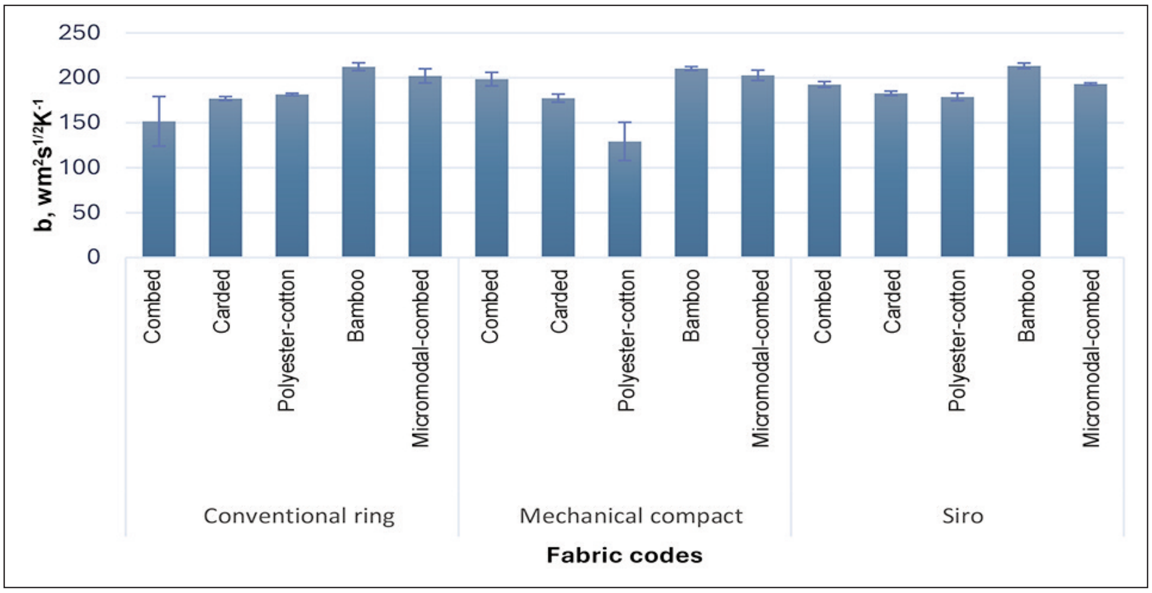


Fig. 8. Thermal absorptivity results

Thermal absorptivity

Figure 8 indicates the thermal absorptivity results of samples produced from different yarn types spun on different spinning methods. According to figure 8, the maximum thermal absorptivity value was obtained from samples with bamboo Siro yarn, while the minimum value was found among samples from polyester-cotton yarns spun with a mechanical compact system. As a general evaluation, the bamboo fabrics produced indicated slightly higher thermal absorptivity values compared to their counterparts with other yarn types within each group spun with the same spinning method. This may be anticipated as garments made of bamboo fabrics feel much cooler and are appropriate to be utilized for summer clothes. ANOVA results also revealed that yarn type was a significant factor, while spinning method was a non-significant factor at a significance level of 0.05. Additionally significant influence for the interaction of spinning method and yarn type was observed on thermal absorptivity results of samples (table 7). SNK results also revealed that knitted samples produced from different yarn types possessed different thermal absorptivity *b* ($W \cdot m^{-2} \cdot s^{1/2} \cdot K^{-1}$) at a significance level of 0.05. On the other hand, samples of yarns spun with different spinning methods were observed under the same subset at a significance level of 0.05 (table 8).

Fabric thickness

Figure 9 indicates that maximum fabric thickness is observed among samples made of combed cotton

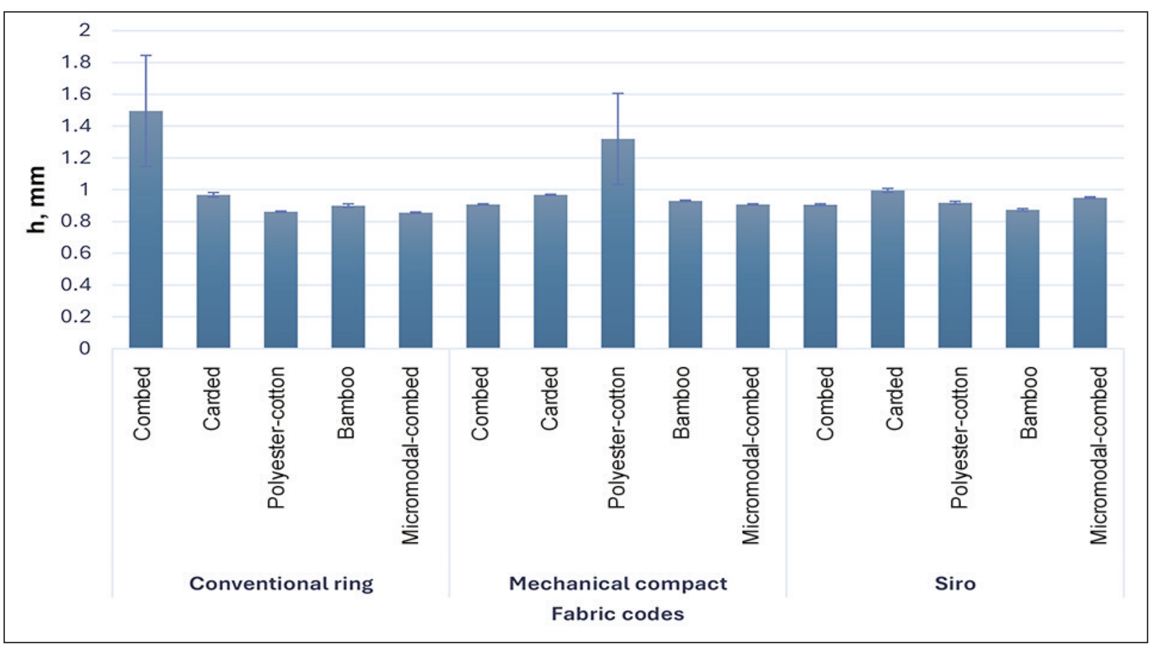


Fig. 9. Fabric thickness of fabrics

yarn produced with a conventional ring system, while minimum fabric thickness was found among samples produced from polyester-cotton yarn spun on a conventional ring system. ANOVA results (table 7) indicated that yarn type and spinning method were non-significant factors on fabric thickness; however, the interaction of yarn type and spinning method was an influential factor at a significance level of 0.05.

Thermal resistance

Thermal resistance is another considerable parameter from the point of view of thermal insulation and is directly related to fabric structure. Figure 10 indicates the thermal resistance of fabrics. It is generally known that the fabric thickness parameter is directly related to the thermal resistance results. As fabric thickness and thermal resistance results are observed in figure 9 and 10, respectively, it is understood that both results are compatible with each other. According to figure 10, there is no clear trend for thermal resistance results regarding to fabrics' constituting yarn type. However, fabric samples from combed cotton yarns indicated slightly lower thermal resistance value compared to samples of other yarn types among the fabric groups with mechanical compact spun and Siro spun yarn. ANOVA results also indicated that yarn type and the interaction of spinning method and yarn type factors were influential factors on thermal resistance property at a significance level of 0.05 (table 7). The spinning method factor was again non-significant on thermal resistance values. SNK results also revealed that samples of different yarns indicated different thermal resistance values at a significance level of 0.05, where micromodal-combed cotton samples indicated the lowest value, while polyester-cotton knitted samples revealed the highest thermal resistance at a significance level of 0.05. Additionally thermal resistance value of carded samples and of polyester-cotton samples were observed under the same subset at a significance level of 0.05 (table 8).

Additionally, in order to reveal the correlation between fabric thickness and fabric thermal resistivity, a correlation analysis was conducted between these two parameters (table 9). Fabric thickness is directly linked to thermal resistance. It is commonly understood that thicker fabrics tend to exhibit higher thermal resistance. Some studies have also highlighted a direct proportional relationship between fabric hairiness and thermal resistance [11]. In our study, correlation analysis showed a positive relationship between fabric thickness, as measured by the Alambeta instrument, and thermal resistance, with a correlation coefficient of 0.73.

Table 9

CORRELATION BETWEEN FABRIC THICKNESS AND THERMAL RESISTIVITY

Parameter	Correlation coefficient
Fabric thickness and thermal resistivity	0.73*

Note: *Correlation is significant at the 0.01 level.

Air permeability

Figure 11 reveals the air permeability results of knitted samples. Maximum air permeability was obtained from samples produced from bamboo Siro yarns, while the minimum value was found among the samples produced from carded yarns. The result is attributed to the more hairy yarn structure of carded cotton yarns. As a general evaluation, samples from bamboo yarn are more satisfying when compared to those made of other yarn types among each spinning method, whereas samples from carded yarns reveal low air permeability values. Additionally, the ANOVA table (table 7) indicates that yarn type and interaction of spinning method and yarn type factors were significant factors, whereas spinning method alone was a non-significant factor on the air permeability values of samples at a significant level of 0.05. SNK results

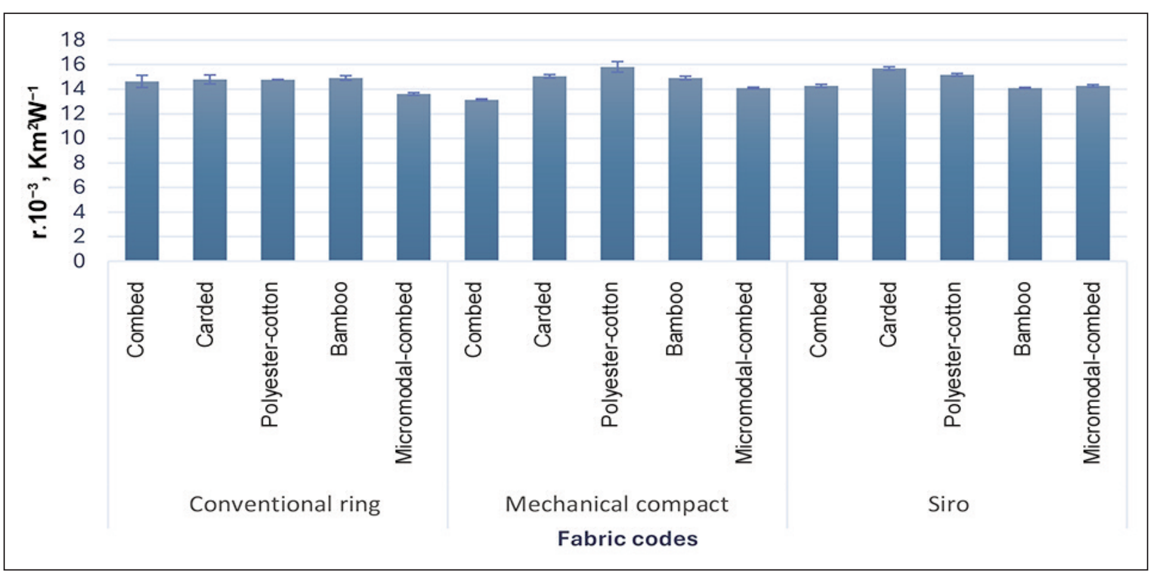


Fig. 10. Thermal resistance of fabrics

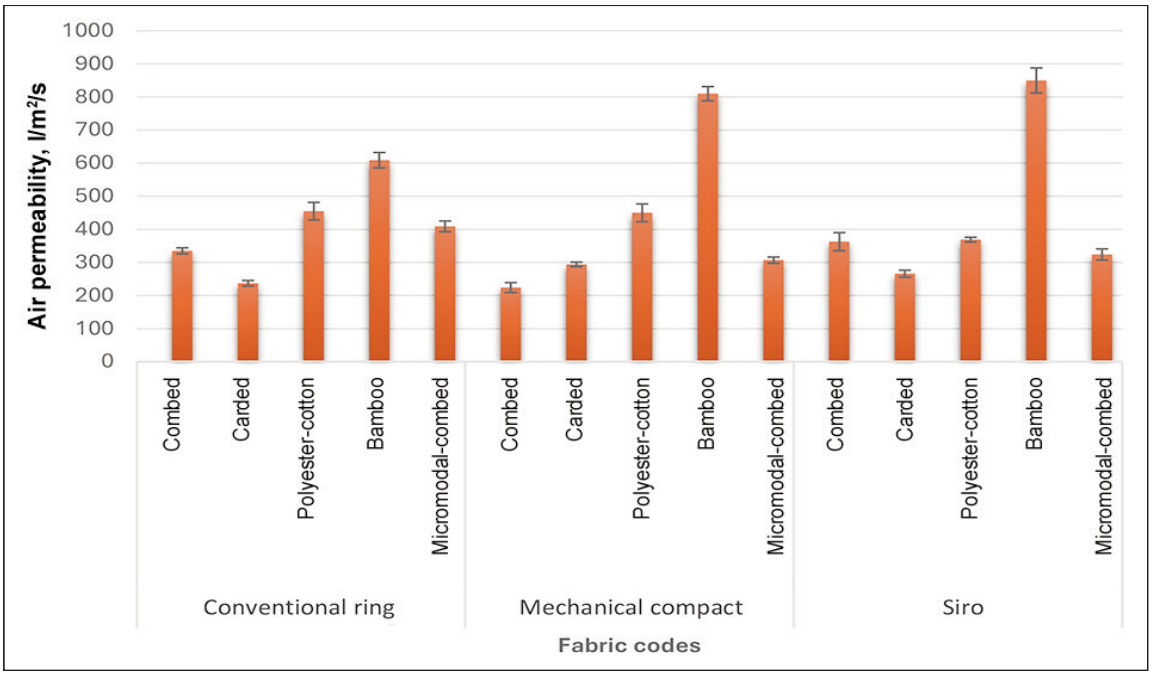


Fig. 11. Air permeability

also indicated that fabric samples produced from different yarn types possessed different air permeability values, where minimum air permeability was obtained from samples produced from carded yarns, and maximum air permeability was found among samples from bamboo yarns. The results are compatible with the Zweigle hairiness results, where bamboo yarns revealed lower s1, s2, and s3 values (table 2).

Table 10

ANOVA RESULTS FOR AIR PERMEABILITY (l/m^2/s)	
Main effect	**Air permeability (sec)**
Spinning method (S)	0.13
Yarn type (Y)	0.00*
Interaction of spinning method and yarn type (S*Y)	0.00*

Note: *Statistically significant (5% significance level).

Table 11

SNK RESULTS FOR AIR PERMEABILITY PROPERTIES		
Parameter		**Air permeability (l/m^2/s)**
Yarn type	Combed	316.33 b
	Carded	268.86 a
	Polyester-cotton	425.6 d
	Bamboo	743 e
	Micromodal-combed	357 c
Spinning Method	Conventional ring	407.92 a
	Mechanical compact	426.04 a
	Siro	432.52 a

CONCLUSION

The manuscript investigates the moisture management and thermal comfort properties of knitted fabrics made from yarns produced using three different spinning techniques: conventional ring, mechanical compact, and Siro spinning. Various fibre blends, including bamboo, combed cotton, carded cotton, polyester-cotton, and micromodal-combed cotton, were used to produce yarns that were then knitted into fabrics. The study applied moisture management tests, thermal comfort analyses, and air permeability evaluations to assess the influence of spinning methods and fibre blends on fabric performance.

The findings revealed that spinning methods and fibre blends significantly impact the properties of the fabrics. Fabrics from Siro spun and mechanical compact yarns demonstrated enhanced moisture management and air permeability compared to conventional ring-spun fabrics. Statistical analyses highlighted significant interactions between spinning methods and yarn types, particularly in determining moisture transfer and thermal resistance properties.

In particular, the effects of the fibre types used in this study on moisture and thermal comfort properties can be summarised as follows: **Bamboo-based fabrics** exhibited the highest air permeability and thermal absorptivity values, supporting their suitability for breathable, cool-feel applications. This makes them suitable for summer wear. Combed cotton provided better yarn evenness and lower hairiness, resulting in more uniform fabrics with higher air permeability. Carded cotton, being more hairy, exhibited greater thermal resistance but lower air permeability, due to its dense and less uniform surface. **Polyester-Cotton Blend** showed the highest accumulative one-way transport index (AOTI), thanks to polyester's hydrophobic nature and cotton's absorbency. The result was efficient moisture wicking but relatively lower thermal absorptivity. **Micromodal-combed cotton** fibre blend demonstrated balanced performance, offering high OMMC values and strong moisture transport capability, combined with moderate thermal absorptivity. These characteristics indicate suitability for comfort-focused applications.

This study provides valuable insights into the interplay between spinning methods, yarn structure, and fibre blends in determining the comfort and performance of knitted fabrics. Siro spinning and mechanical compact spinning showed advantages in improving moisture management and air permeability, while bamboo and micromodal-cotton yarns contributed to superior thermal comfort properties. These findings emphasise the importance of selecting appropriate spinning techniques and fibre combinations to meet specific end-use requirements in textile applications.

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Relationship between green human resource management practices & environmental sustainability by green innovation

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ABSTRACT – REZUMAT

Relationship between green human resource management practices & environmental sustainability by green innovation

Protecting natural resources for future generations has become an important concern in the debates among policymakers and institutions. Sindh is the third largest province by geography and the second most urbanised province, located in the southeast of Pakistan. This study aims to empirically analyse the role of green human resource management practices on environmental sustainability in higher educational institutions in Sindh, Pakistan, particularly those offering degrees and responsible for research in textile engineering and fashion design. Further, we explore whether green innovation as a potential mediator stimulates the relationship between green human resource management and environmental sustainability. We employed a quantitative research technique and retrieved data from 376 respondents who are employees of higher education institutions. This study for analysis used SPSS 26 and partial least squares based on structural equation modelling (SEM). Our outcomes suggested that green human resource management promotes environmental sustainability. Notably, green recruitment and selection (0.384) exerts the strongest influence on environmental sustainability, followed by green training and development (0.341), green compensation and reward (0.232) lastly green performance management (0.184) also contribute positively to environmental sustainability. All relationships observed in the study were statistically significant ($p<0.05$). The current study finds that green innovation partially mediates the relationships between all constructs and plays a crucial role in enhancing environmental sustainability. This study provides insightful recommendations for educational institutions currently operating in Pakistan and other emerging economies to achieve sustainability objectives. It also promotes eco-friendly practices and raises awareness among stakeholders, contributing to the achievement of environmental sustainability.

Keywords: *environmental sustainability, green HRM, green innovation, textile and fashion design, higher educational institutions, Pakistan*

Relația dintre practicile ecologice de gestionare a resurselor umane și sustenabilitatea mediului prin inovare ecologică

Protejarea resurselor naturale pentru generațiile viitoare a devenit o preocupare importantă în dezbaterile dintre factorii de decizie și instituții. Sindh este a treia provincie ca mărime din punct de vedere geografic și a doua provincie ca grad de urbanizare, situată în sud-estul Pakistanului. Acest studiu își propune să analizeze empiric rolul practicilor de gestionare ecologică a resurselor umane asupra durabilității mediului în instituțiile de învățământ superior din Sindh, Pakistan, în special cele care oferă diplome și sunt responsabile de cercetarea în domeniul ingineriei textile și al designului de modă. În plus, explorăm dacă inovarea ecologică, ca potențial mediator, stimulează relația dintre managementul ecologic al resurselor umane și sustenabilitatea mediului. Am utilizat o tehnică de cercetare cantitativă și am colectat date de la 376 de respondenți, care sunt angajați ai instituțiilor de învățământ superior. Acest studiu a utilizat pentru analiză SPSS 26 și metode parțiale ale celor mai mici pătrate bazate pe modelarea ecuațiilor structurale (SEM). Rezultatele noastre sugerează că managementul ecologic al resurselor umane promovează sustenabilitatea mediului. În mod deosebit, recrutarea și selecția ecologică (0,384) exercită cea mai puternică influență asupra sustenabilității mediului, urmată de formarea și dezvoltarea ecologică (0,341), compensarea și recompensarea ecologică (0,232) și, în cele din urmă, managementul performanței ecologice (0,184), care contribuie, de asemenea, în mod pozitiv la sustenabilitatea mediului. Toate relațiile observate în studiu au fost semnificative din punct de vedere statistic ($p<0,05$). Studiul actual constată că inovarea ecologică mediază parțial relațiile dintre toate constructele și joacă un rol crucial în îmbunătățirea durabilității mediului. Acest studiu oferă recomandări pertinente pentru instituțiile de învățământ care funcționează în prezent în Pakistan și în alte economii emergente, în ceea ce privește obiectivele de sustenabilitate. De asemenea, promovează practici ecologice și crește gradul de conștientizare în rândul părților interesate, contribuind la sustenabilitatea mediului.

Cuvinte-cheie: *sustenabilitate ecologică, gestionarea ecologică a resurselor umane, inovare ecologică, design textil și de modă, instituții de învățământ superior, Pakistan*

INTRODUCTION

Since industrialisation has significantly advanced societal development, it has also been associated with serious challenges, such as environmental degradation. Consequently, these issues necessitate the adoption of sustainable practices. Moreover, modernisation has also increased environmental awareness, and active campaigns regarding sustainability driven by civil societies have further compelled organisations to embrace eco-friendly initiatives [1]. However, a concrete effort is required from civil society stakeholders to achieve environmental sustainability. Higher educational institutions are one of the main actors in the services industry, having a critical role in shaping the future. Their primary responsibility is to provide knowledge-based services and innovations to society. Moreover, these are also the main source of skilled human resources for organisations. Besides this, higher education institutions are equally responsible for sustaining the environment.

Therefore, as their third mission, HEIs are also responsible for upgrading society to support the ecology. Beyond their traditional functions, it is essential for HEIs to integrate initiatives and policies into their operations and practices that promote sustainability [2]. The concept of Green Human Resource Management (GHRM) has emerged as one of the transformative practices for embedding environmental. It incorporates strategies within traditional work processes to address environmental challenges, and its significant environmental benefits have drawn increasing attention today.

Therefore, advanced governance models are implementing these practices. At the same time, organisations are also considering adopting GHRM as a possible change agent [3, 4]. Various GHRM practices have significant potential to enhance organisational commitment to environmental wellbeing. Therefore, researchers are interested in a more keen understanding of the relationship between environmental sustainability and GHRM practices by highlighting the need for this tool to be utilised in organisations [5, 6]. Green innovation (GI) refers to adopting eco-friendly products and processes to reduce environmental harm. This emerging concept is particularly relevant in all sectors, including the services sector, such as higher education, where integrating green practices can significantly lower the environmental footprints. Pakistan, being the fifth most populous country globally, has a rich history of textile production, with evidence of cotton cultivation and fabric manufacturing dating back to ancient times. This heritage is evolving into a diverse textile industry and impacting worldwide through its traditional craftsmanship. Currently, the country operates various operational textile units, whereas Sindh is particularly the home of the textile industry because of its several industrial zones. There are 09 working locations for Cotton processing, 04 leather industries, 04 wool processing industries, 05 manufacturing silk and rayon, and 04 for jute production, as well as many small and medium enterprises (SMEs) related to fashion design are empowering themselves in this region. These industries gain a direct supply of human resources from regional higher education institutions offering related degrees (HEIs) [7]. These institutions in Sindh are established to produce skilled human resources related to textile and fashion design education to meet local and global economic demands. Despite their significant economic and cultural contributions, HEIs in Sindh province are facing urgent challenges, particularly related to environmental degradation.

Furthermore, there is a limited understanding of how GHRM and GI influence sustainability within HEIs in Sindh. It highlights a critical gap, as environmental challenges threaten the long-term sustainability of different sectors in Pakistan. Previously, much of the literature emphasised the influence of GHRM and GI on environmental sustainability, but their application in HEIs, especially within developing countries like Pakistan, has remained underexplored. Given this background, the current study seeks to bridge this identified gap by investigating the relationship between GHRM practices and environmental sustainability in Sindh province HEIs. Secondly, this study intended to contribute to the literature by extending the role of GI as a mediating factor. Drawing on the Resource-Based Theory (RBT), which emphasises the strategic value of internal organisational resources. This research examines how HEIs can leverage GHRM to achieve their sustainability goals. Furthermore, this integration of GHRM practices and GI is expected to offer actionable insights into how HEIs can address environmental issues and strengthen their practices according to the global sustainability standards. This research is novel and contextually relevant by offering theoretical contributions to the literature. Furthermore, it provides practical recommendations to institutional leaders to align their operations with sustainability trends. By focusing on the intersection of GHRM, GI, and environmental sustainability, this study underscores the importance of embedding GHRM practices within the operational frameworks of HEIs. Insights of this study will benefit HEIs in Sindh province and serve as a reference for the institutions of other regions of Pakistan, neighbouring countries, and other nations that are grappling with environmental challenges.

The study is divided into five main sections. The first section introduces the overall study. The second section presents a review of relevant literature, the development of hypotheses and the research framework. The third section details the research methodology and data collection process. The fourth section analyses the findings based on empirical data. Finally, the fifth section concludes the study, discusses implications for future research, provides recommendations, and the last chapter is followed by a reference.

REVIEW OF LITERATURE AND HYPOTHESIS DEVELOPMENT

Green human resources and environmental sustainability

Nowadays, traditional Human Resource Management (HRM) practices are shifting to modern approaches [8]. This change has initiated the development of strategies that incorporate environmental objectives to achieve dual goals such as organisational competitiveness and sustainability. The concept of Green Human Resource Management (GHRM) has previously been examined from various perspectives. For example, Renwick et al. characterised GHRM as a subset of HRM that focuses on environmental impact [9]. At the same time, Opatha and Arulrajah see it as a mechanism to cultivate environmentally conscious employees who can contribute to environmental objectives [10]. Similarly, Masri and Jaaron highlighted the GHRM role in encouraging eco-friendly behaviours among employees [11]. These practices also support organisational efforts to achieve the environmental goals [12]. Previously, researchers have underscored enough evidence through different studies that GHRM practices are essential for sustaining the organisational environment [13]. However, it was observed that developing countries are less studied in terms of practising these practices, and the authors emphasised exploring these areas further to enhance environmental sustainability [6]. Previously, we have seen much empirical evidence that suggests a significant relationship between GHRM and environmental sustainability. For instance, in the context of the Malaysian manufacturing sector, Hossain documented the positive connection between GHRM and Environmental Performance (EP) [14]. By exploring another setting of the hospitality industry, it was argued that GHRM practices significantly mediate the relationship between proactive pro-environmental behaviour (PEB) and green inclusive leadership (GIL), which improves sustainability [15, 16]. Prior studies have acknowledged that GHRM practices are essential for Environmental Sustainability (ES). However, the literature has insufficient evidence to confirm the relationship between GHRM and ES and green Innovation (GI) in the context of higher education institutions, mainly located in an underdeveloped region. This relationship has been unexplored empirically until now. Therefore, based on the recommendation of Pham et al. [6], this study intended to empirically fill this gap. The current study will examine the 04 dimensions to explore the impact of GHRM on ES.

Green compensations and rewards

Institutions attract employees through compensation to sustain eco-friendly practices. These incentives range from monetary or verbal appreciation to additional skill enhancement training. These strategies can be a win-win for both employers and employees. These compensations help in improving work-life balance, promoting eco-friendly behaviours, and also instil a sense of future confidence in the participants. This can reshape the approach toward sustainability [16, 17]. Previously, empirical evidence acknowledged that green compensation improves sustainability. For instance, a study conducted by Das in the context of ISO 14004 manufacturing organisations, the author articulated that green compensations are essential for environmentally aware organisations to fulfil their sustainability goals. The study also highlighted the long-term benefits of green compensation to improve sustainability [18]. In another study, the author suggested that compensation can significantly influence Organisational Citizenship Behaviour for the Environment (OCBE). It was also noted that employees with less than five years of service are more attracted to these compensations, which encourage them to engage in pro-environmental behaviours. This study further emphasised the need to explore GHRM practices with other variables to achieve environmental sustainability [19]. Similarly, a study of the healthcare sector posits that organisations can boost their sustainability efforts by providing green compensation by inspiring employees to be more aware of and engage with environmental challenges. This approach plays a key role in conserving natural resources and safeguarding ecosystems, which leads to long-term environmental sustainability [20]. In another study, Amjad surveyed the textile sector of Pakistan and affirms that green compensation is significantly associated with employee performance and organisational sustainability [21]. Based on these findings, we propose the hypothesis (H1): Green compensation and reward positively impact environmental sustainability.

Green performance assessment and appraisal

Performance assessment is a process that regularly evaluates an employee's performance to sustain organisational objectives. In contrast, assessing employee environmental activities within an organisation's environmental management is called Green Performance Management. It is very crucial to integrate environmental objectives into organisational frameworks. Performance assessment strategies ensure the enhancement of environmental outcomes in the organisation by fostering employees toward green practices. Scholars believe that assessing employees' contributions towards environmental goals can drive pro-environmental attitudes.

Furthermore, it aligns individual actions with organisational sustainability objectives to lead to environmental sustainability [6, 22, 23]. Many researchers, such as Arulrajah and Kuo, have acknowledged the importance of green performance appraisals. Furthermore, the authors articulated that managers are responsible for supervising employees and assessing their contributions toward eco-friendly practices to promote continuous environmental improvements in the organisation [10, 24].

Nowadays, organisations can evaluate employee performance more easily by incorporating technology that streamlines the process, facilitates assessment and enhances the environmental outcomes [25].

However, improper policy implementation, limited resources, or lack of awareness can impact the effectiveness of these systems. Organisations should establish common standards for implementing green performance assessments to address these challenges and clearly define their indicators. This includes incorporating new criteria into performance evaluations to assess workers' technical and behavioural competencies, such as environmental stewardship, innovation, diversity, and collaboration. These competencies strengthen the organisational core principles and align employee efforts with sustainability goals [26]. The literature suggests that effectively implemented green performance assessments significantly contribute to achieving environmental sustainability. Thus, we hypothesise that (H2): green performance assessment positively impacts environmental sustainability.

Green recruitment and selection

Green recruitment integrates environmental sustainability standards into the hiring processes by focusing on recruiting pro-environmental candidates. It also involves designing job descriptions that emphasise environmental responsibilities [27]. This approach ensures its genuine importance at the entry point of the HRM system and underscores the organisation's enthusiasm for environmental sustainability by recruiting environmentally conscious employees. It helps to reduce resources during the hiring process and ensures that employees are effectively aligned with the organisation's pro-environment attitude. This will lead to a long-term impact on environmental sustainability [28]. According to past research, green recruitment has a long-term impact on organisational sustainability. Pham and Khattak highlighted in this context that organisations implementing green hiring strategies are more likely to attract environmentally aware candidates and build a workforce that is actively involved in sustainability efforts [5, 29]. Latha indicated that by utilising digital platforms such as digital applications and interviews, organisations can reduce the environmental footprint of recruitment processes [30]. Another study was conducted during the post-pandemic period, and the data were collected from Pakistan's telecom industry. The author documented the positive impact of GRS on the decrease of the environmental footprint during the pandemic [31]. Kuo et al. articulated that green recruitment enhances the organisation's overall environmental performance by creating a workforce attuned to ecological preservation [24]. Lastly, wang found that organisations experience practical benefits by adopting GRS. The author recognised green recruitment and selection (GRS) as an important practice that directly helps organisations to obtain green human capital. In addition, this study also emphasised that through GRS, organisations can recognise the positive attributes of employees, which contribute in the form of environmental sustainability [32]. Based on the above-mentioned literature support. We have supported this hypothesis: H3 Green recruitment and selection positively impact environmental sustainability.

Green training and development

Training is a critical tool to elevate the employees' competencies and enables them to be more committed to organisational tasks [33]. As a driving force for environmental sustainability, GHRM integrates green training into the HRM process to equip employees with in-depth knowledge and expertise to make decisions that contribute to saving the environment [9]. These trainings are considered the central aspect of green human resource management. Because it is involved in the development of educational programs and raising awareness among employees to incorporate the environmental sustainability goals in the organisational objectives [34]. These trainings foster energy conservation, resource efficiency, and employee productivity. It not only encourages organisations to pursue environmental preservation but also inspires their stakeholders to adopt sustainable green practices [35]. Previously, these trainings have been explored in various dimensions. Literature suggests that organisations can gain multiple edges, such as environmental, social, and economic performance, by implementing serious and well-designed training. Bukhari, in this regard, documented that green training supports the organisation's long-term success by enhancing employee workplace safety and is responsible for reducing production expenses, leading to better environmental outcomes [36]. Similarly, studies reported the impact of green training on workers' organisational citizenship behaviour toward the environment (OCBE). The results consistently indicate that green training is responsible for fostering pro-environmental behaviour among the employees, which significantly improves the organisation's environmental performance. Furthermore, green training provides meaningful awareness regarding environmental concerns and rectifies employees' behaviour toward an eco-friendly attitude that leads to a sustainable environment [37]. In the past, several studies have been associated with the examination of green training in different contexts, i.e., hospitality, information technology and pharmaceutical industries. And demonstrated a significant relationship with Environmental sustainability [38, 39]. However, higher educational institutions are the critical pillars for achieving sustainability. This sector is still unexplored as yet. Therefore, extending the previous literature, the current study expects a direct link between green training and environmental sustainability in the context of higher educational institutions. Hence, we have proposed this hypothesis: H4: Green Training significantly affects environmental sustainability.

Mediating role of green innovation

Innovation is a novel idea that is practically applicable, and incorporating the term 'green' ties it to environmental benefits. Literature has viewed green innovation as one of the most promising approaches to addressing environmental challenges [40].

The Organisation for Economic Co-operation and Development (OECD) defined Green Innovations (GI) as "the creation of goods and services, procedures, marketing strategies, organisational structures, and new or enhanced institutional arrangements that, whether on purpose or not, lessen their environmental effect when compared to alternative approaches". Literature divides green innovation into two components: green product and green process innovation. GI has the potential to enhance environmental sustainability by incorporating value addition in systems or processes [41]. Various organisations and countries have already incorporated GI into their processes to compete with their competitors and to address the challenges of environmental degradation [42]. Previously, numerous studies have explored the GI, for instance. The study conducted by Singh focused on the manufacturing firms to evaluate green performance (GP), found that GI builds a connection between GP and Green Transformational Leadership [43]. Correia further conducted a study in the health sector of Pakistan and concluded that green innovation (GI) strengthens the link between green human resource management (GHRM) and sustainable performance. This study further highlighted that organisations that adopt green innovation practices can ensure the protection of the environment in the long run [44].

In parallel with other variables, Green Innovation (GI) has also been identified as a potential mediator between Green Human Resource Management (GHRM) and Environmental Performance (EP). In this regard, Kuo and Fang have seen the positive mediation role of GI between GHRM practices and environmental performance. Authors also articulated that organisations with strong GHRM initiatives can encourage employees to innovate in sustainable practices, a continuous process to enhance environmental sustainability [24, 41–45]. Moreover, another study documented that GI has a significant mediating potential to establish a link between GHRM and EP [46]. Thus, GI has been previously proven as a potential mediator between different scenarios and contexts. However, the interaction of GI and GHRM practices based on RBV theory remains untested in the context of higher educational institutions. Therefore, we have proposed the following hypothesis: Green Innovation mediates the relationship between GHRM practices and Environmental Sustainability.

RESEARCH METHODOLOGY

The current study was conducted at 13 higher education institutions in Sindh Province, which play an important role in providing human resources, education, and research for the Textile and Fashion Design sector in Sindh Province of Pakistan. We targeted 08 institutions of textile education, offering many programs such as Textile, Dyeing and Printing, Textile Marketing, Fashion Design Management, Appearance Merchandising, and Ceramic Design. Additionally, 05 public sector engineering universities were selected that offer a graduate degree in textile engineering. Geographically, these institutions were distributed as follows: 08 institutions were located in District Karachi, 03 in Jamshoro, 01 in Nawabshah, and 01 in Rohri city. Before the data collection, we obtained approval from the ethical committee, and to maximise the response rate, weekly email reminders were sent to non-respondents for four weeks. We also contacted institutional managers to reinforce these reminders internally to ensure an adequate sample size. We targeted the employees of selected institutions related to the textile sector, with a total population size of 6,568. We explored official websites and institutions' annual reports to identify the population size. Lastly, we approached university resource persons to gather the number of employees. After collecting the population size, we categorised the employees into 05 categories: Upper Management, Middle Management, Lower Management, Academic and Administrative Staff. Then, we employed a Stratified Simple Random

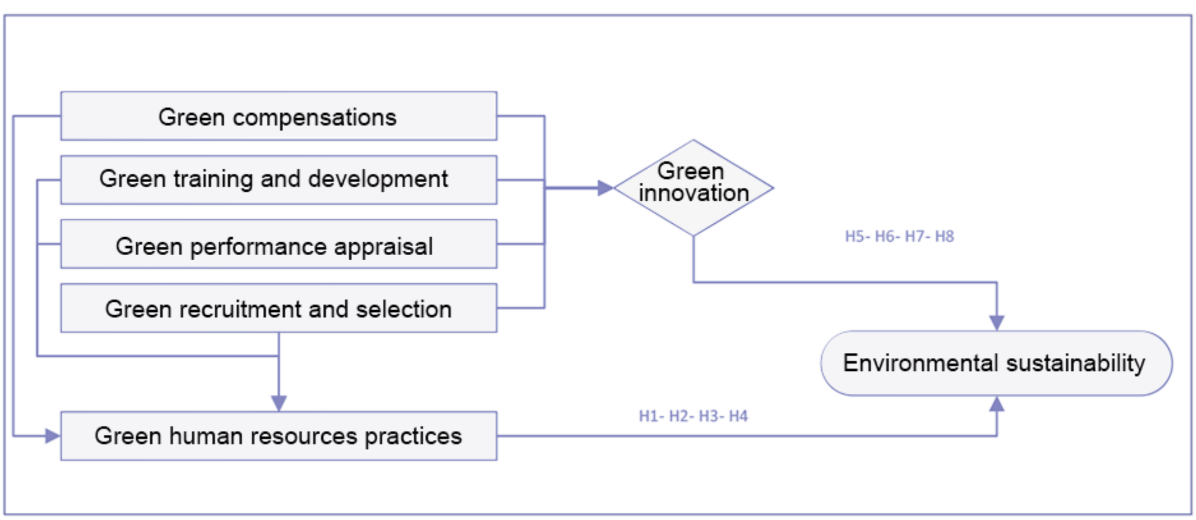

Fig. 1. Conceptual model

Sampling technique to ensure an adequately representative sample. The data collection relied on a structured questionnaire. We initially distributed the questionnaires through Google Forms and emails. The survey instrument included details about the study's purpose, data confidentiality, respondent anonymity, and informed consent; we also sent an encouragement letter to participants to respond truthfully. In the second phase, the physical copies were distributed to respondents in institutions located in Jamshoro District; our research team personally handed out the physical questionnaires at each institution, and to ensure consistency, a standardised procedure was followed: each questionnaire included a cover letter explaining the study's purpose, assurances of confidentiality and instructions for returning the completed form. Initially, we drafted the instrument in English. However, since most people primarily speak Urdu (native language), it was translated into Urdu by a bilingual academic expert, then retranslated back into English by another translator to ensure accuracy and to improve the questionnaire's validity and reliability. After this translation, certain items were refined based on insights gained from the Urdu version of the survey. After refinement, we conducted the pilot survey, and the questionnaire was sent to 24 respondents within the Jamshoro Education city in 02 higher educational institutions to evaluate the effectiveness and clarity of the questionnaire; upon feedback from the respondents, some rectifications were incorporated into the questionnaire, and the primary survey was conducted. A total of 460 questionnaires were distributed among the respondents, and 388 were returned, yielding a response rate of 84.35%. Incomplete responses with missing data were excluded from the analysis to ensure data integrity and consistency; later on, 376 were utilised in hypothesis testing [47]. The data was collected between August 2024 and October 2024. We included five key constructs in the study, which were adopted from previously tested frameworks. Four items of Green Training and Development (GTD) and five indicators of Green Compensation and Reward (GCR) were derived from Daily et al. and Jabbour [3, 48, 49]. Green Performance Assessment (GPA) had 05 items evaluated based on the framework suggested by Masri and Jaaron [11]. Five questions regarding Green Recruitment and Selection (GRS) were examined using criteria from Pham et al. [5]. Lastly, we adopted 03 items from the study of Chen et al. [50] to evaluate the mediating influence of Green Innovation (GI). All current study constructs were measured using a 5-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree) to ensure consistency and comparability across variables. SPSS version 26 was utilised to analyse respondents' demographic information, then the measurement and structural model analysis utilising the Partial Least Squares (PLS) Structural Equation Model with Smart PLS-4. Additionally, the internal consistency of the scales was assessed using Cronbach's Alpha and Composite Reliability (CR) scores. Model fit was evaluated using R^2 and Q^2 values, which provided insights into the model's explanatory power and predictive relevance.

RESULTS

Demographic distribution

Table 1 illustrates the demographics of the respondents and offers a comprehensive overview of the study's participants. 376 employees have participated

Table 1

PARTICIPANT SPECIFICATIONS (n = 376)

Demographics	Description	Respondents (n)	Percentage (%)
Biological Sex	Male	249	66.4
	Female	127	33.6
	Total	376	100.0
Marital Status	Married	313	83.5
	Not married	63	16.5
	Total	376	100.00
Occupational position	Lower management	75	19.948
	Middle Management	57	15.152
	Upper Management	59	15.705
	Academia	91	24.211
	Supporting Staff	95	25.266
	Total	376	100
Level of education	Bachelor (16 years)	215	57.2
	Master (18 years)	111	29.5
	Ph.D.	43	11.4
	Post Doc	07	1.9
	Total	376	100

Table 1 (continuation)

Demographics	Description	Respondents (n)	Percentage (%)
Experience	Less than 5 years	75	19.95
	6 to 10 years	113	30.05
	11 to 15 years	95	25.27
	16 to 20 years	58	15.43
	More than 20 years	35	9.30
Total		376	100

Source: Author's self-conducted survey, August 2024 – October 2024.

in the research and represent a diverse background. Regarding gender distribution, 66.4% (n=249) of the respondents were male, whereas 33.6% (n=127) were female. In terms of the marital status of respondents, 83.24% (n=313) reported being married; this indicates a significant proportion of the respondents with familial responsibilities. On the other hand, 16.76% (n=63) were unmarried. Furthermore, the designation distribution allowed us to know that 19.95% (n=75) of respondents were from lower management, such as office superintendents and assistants, 15.15% (n=57) from middle management, such as Assistant managers, 15.71% (n=59) from the upper management, Registrar, Controller of Examinations, Planning Officer and Managers of Quality Enhancement Cell. The academic staff represented 24.21% (n=91) of the total respondents in various positions such as lecturers, assistant professors, associate professors, and professors. These individuals were engaged in teaching and research within the institutions, and their diverse expertise and professional backgrounds provided valuable insights into the academic landscape of textile and fashion design education in the region. While the supporting staff comprised 25.27% (n=95) of participants, these included office assistants, laboratory attendants, and clerks. With respect to educational qualifications, 57.2% (n=215) of respondents held a bachelor's degree (16 years of education) and primarily worked in the supporting staff or lower management, 29.52% (n=111) had a master's degree (18 years of schooling), 11.44% (n=43) were Ph.D. holders and mostly was from the academia, and 03 was from the middle management. 1.86% (n=7) had a postdoctoral degree and worked in academia. Finally, the respondents' work experience spanned various ranges as follows: 19.95% (n=75) had less than five years of experience, 30.05% (n=113) had six to ten years of experience, 25.27% (n=95) had eleven to fifteen years of experience, 15.43% (n=58) had sixteen to twenty years of experience, and 9.30% (n=35) had more than twenty years of experience. These demographic insights demonstrate the respondents' diversity and ensure a well-represented sample for hypothesis testing and to achieve the study's objectives.

Justification of using the Measurement Model: this model allowed us to study and quantify these constructs through observable indicators and thoroughly analyse their relationships.

Measurement model

The internal consistency of the constructs, described in table 2, was evaluated using Cronbach's alpha, which exceeded the recommended threshold of 0.70, as outlined by Hair Jr. et al. [51]. Additionally, the composite reliability values surpassed the threshold of 0.7, ranging from 0.79 to 0.920, as Hair Jr. et al. indicated. According to Zain [52], the rule of thumb for

Table 2

VALIDITY AND RELIABILITY OF THE CONSTRUCT

Construct	Item	Outer loading	α (≥0.70)	CR (≥0.70)	AVE (≥0.50)	ViF
Environmental sustainability	ES1	0.793	0.92	0.91	0.64	2.422
	ES2	0.820				2.657
	ES3	0.850				2.721
	ES4	0.787				2.285
	ES5	0.790				2.202
	ES6	0.792				2.726
	ES7	0.775				2.555
Green compensation and reward	GCR1	0.797	0.87	0.87	0.63	2.458
	GCR2	0.799				2.285
	GCR3	0.806				2.202
	GCR4	0.780				2.726
	GCR5	0.801				2.555

Table 2 (continuation)

Construct	Item	Outer loading	α (≥0.70)	CR (≥0.70)	AVE (≥0.50)	ViF
Green innovation	GI1	0.791	0.79	0.78	0.71	1.392
	GI2	0.867				2.124
	GI3	0.855				1.984
Green performance assessment	GPA1	0.867	0.91	0.90	0.76	3.027
	GPA2	0.894				2.124
	GPA3	0.839				1.984
	GPA4	0.898				3.362
	GPA5	0.855				2.604
Green recruitment and selection	GRS1	0.841	0.91	0.91	0.73	2.652
	GRS2	0.856				2.705
	GRS3	0.894				3.541
	GRS4	0.817				2.528
	GRS5	0.849				2.713
Green training and development	GTD1	0.868	0.90	0.79	0.78	2.561
	GTD2	0.885				2.667
	GTD3	0.890				2.844
	GTD4	0.858				2.134

Note: α: Cronbach's alpha; CR: Composite Reliability; AVE: Average Variance Extracted; ViF: Variance Inflation Factor.

Average Variance Extracted (AVE) suggests that values should not be below 0.5. Similarly, table 2 also illustrates that all AVE values for the constructs of the study were more significant than 0.5, indicating the statistical accuracy of the study. The assessment of measurements supported the conclusions drawn by Ying et al. and Korankye et al. [53, 54].

Discriminant validity

Tables 3 and 4 illustrate the variables' discriminant validity to evaluate the distinct measures from the other factors. We followed Henseler et al. [55] and adopted the Fornell and Larcker (1981) criteria. According to Fornell and Larcker (1981), diagonal values should exceed their corresponding correlation coefficient, represented as the square root of the Average Variance Extracted (AVE) values in the diagonal, while Henseler et al. argue that the HTMT ratio of correlations is more reliable than the Fornell-Larcker Criterion we assessed our variables with both HTMT and Fornell-Larcker's measures the discriminant validity of the constructs in the study was satisfactory HTMT values was below the threshold of 0.90, while Based on the Fornell-Larcker criterion in our study all variables shows the satisfactory discriminant validity except one pair of GCR and GPA with high correlation 0.841 then AVE 0.794 and the HTMT threshold was with value of 0.940 exceeded the threshold.

Structural model assessment

The proposed structural model will highlight the interdependence of relationships between green human resource practices and environmental sustainability. Meanwhile, this study will allow us to examine the mediation level of green innovation similarly; the Partial Least Squares (PLS) structural model finally analyses the relationship between regression coefficients and t-values in hypothesis testing.

Table 3

DISCRIMINANT VALIDITY (HETEROTRAIT-MONOTRAIT RATIO)

Variable	ES	GCR	GI	GPA	GRS	GTD
ES						
GCR	0.759					
GI	0.829	0.776				
GPA	0.714	0.940	0.768			
GRS	0.786	0.836	0.865	0.782		
GTD	0.722	0.889	0.809	0.839	0.878	

Table 4

DISCRIMINANT VALIDITY (FORNELL-LARCKER'S CRITERION)

Variable	ES	GCR	GI	GPA	GRS	GTD
ES	**0.801**					
GCR	0.668	**0.794**				
GI	0.789	0.641	**0.841**			
GPA	0.611	0.847	0.647	**0.869**		
GRS	0.734	0.729	0.739	0.714	**0.849**	
GTD	0.665	0.787	0.691	0.764	0.793	**0.874**

Note: ES: Environmental sustainability; GCR: Green Recruitment and Selection; GI: Green Innovation; GPA: Green performance assessment; GRS: Green Recruitment and Selection; GTD: Green Training and Development.

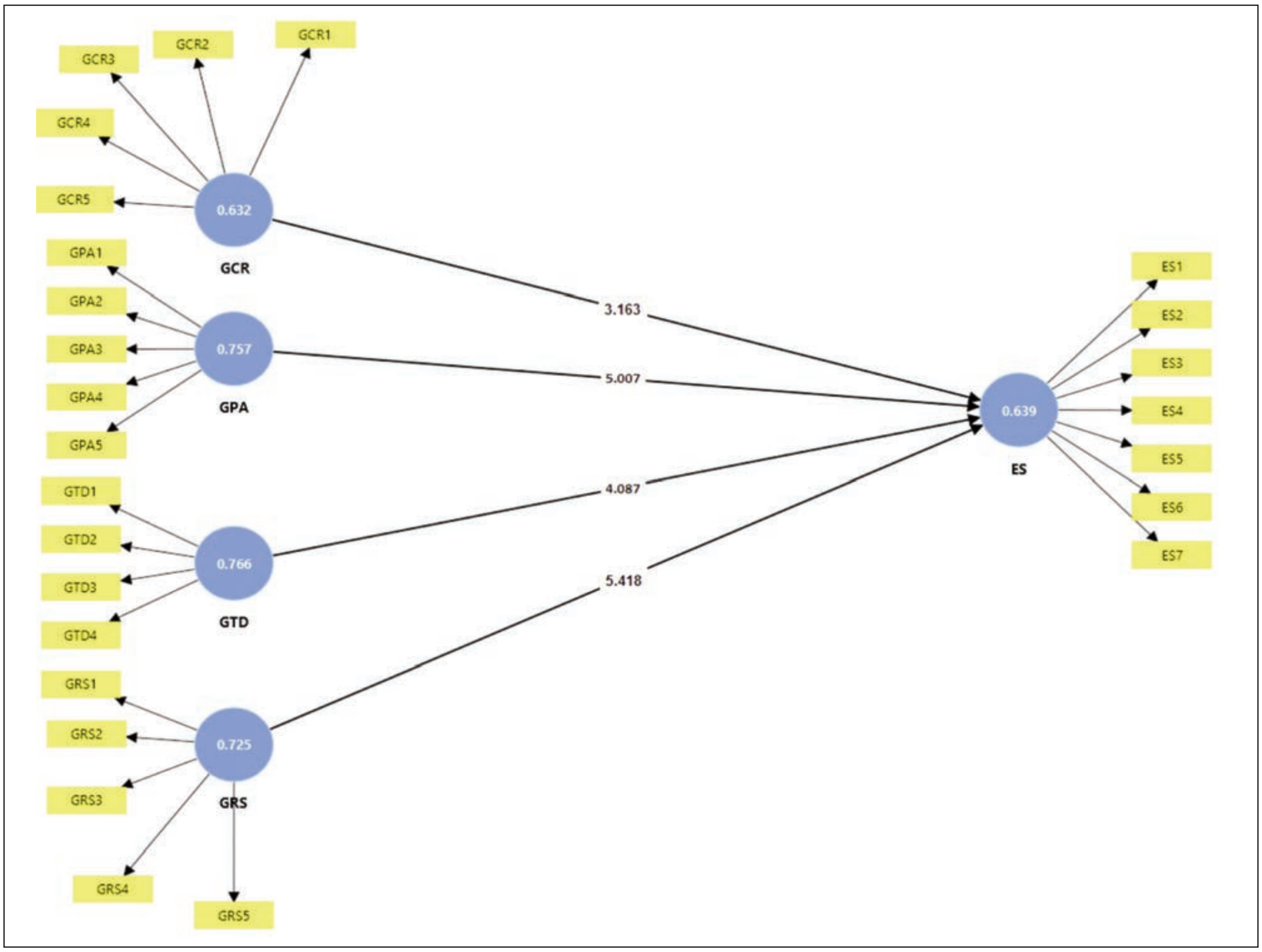

Fig. 2. The structural model for direct relationships (extracted from SmartPLS 4.0)

Standardised beta values indicate an indirect effect in regression analysis; t-values and beta values assess significance. Henseler et al. T-values above 1.64 are statistically significant and guide hypothesis decisions.

Hypothesis testing

Direct Relationships between the variables are shown in table 5. The structural model suggested that the strongest relationship was H3 between GRS and ES, the coefficient of this relationship was 0.385, while the mean of this relationship was 0.387, STDEV was 0.050. Lastly, the T-statistic and p-value were 4.186 and 0.028, respectively; this indicates a strongly positive and statistically significant and strong relationship. In contrast, the model suggests the weakest relationship was between hypothesis 02 between GPA & ES, which has a path coefficient of 0.184, a mean of 0.189, a standard deviation of 0.047, a T-statistic of 5.007, and a p-value of 0.003. Despite the high T-statistic indicating statistical significance, the lower path coefficient shows a moderate positive effect of GPA on ES and the hypothesis was also supported. Further, on behalf of the examination. All 04 hypotheses of this study were supported, and the relationships were statistically significant and contributed positively to Environmental sustainability, but GRS was more substantial than the other variables.

Table 5

HYPOTHESIS TESTING (DIRECT RELATIONSHIPS)

Relationship	Path	Mean	STDEV	T-stat	p-values	Result
H1: GCR → ES	0.231	0.239	0.071	3.163	0.002	Supported
H2: GPA → ES	0.184	0.188	0.047	5.007	0.055	Supported
H3: GRS → ES	0.385	0.387	0.050	4.186	0.028	Supported
H4: GTD → ES	0.341	0.345	0.066	5.418	0.001	Supported

Note: ES: Environmental sustainability; GCR: Green Recruitment and Selection; GI: Green Innovation; GPA: Green Performance Assessment; GRS: Green Recruitment and Selection; GTD: Green Training and Development.

Table 6

MEDIATION RELATIONSHIP (HYPOTHESIS TESTING)							
Relationship	**Path**	**Mean**	**STDEV**	**T-stat**	**p-values**	**Decision**	**Mediation Type**
H5: GPA → GI → ES	0.450	0.454	0.080	4.867	0.002	Support	Partial mediation
H6: GRS → GI → ES	0.367	0.368	0.062	5.906	0.000	Support	Partial mediation
H7: GTD → GI → ES	0.322	0.324	0.066	3.857	0.001	Support	Partial mediation
H8: GCR → GI → ES	0.319	0.324	0.066	4.288	0.003	Support	Partial mediation

Note: ES: Environmental sustainability; GCR: Green Recruitment and Selection; GI: Green Innovation; GPA: Green Performance Assessment; GRS: Green Recruitment and Selection; GTD: Green Training and Development.

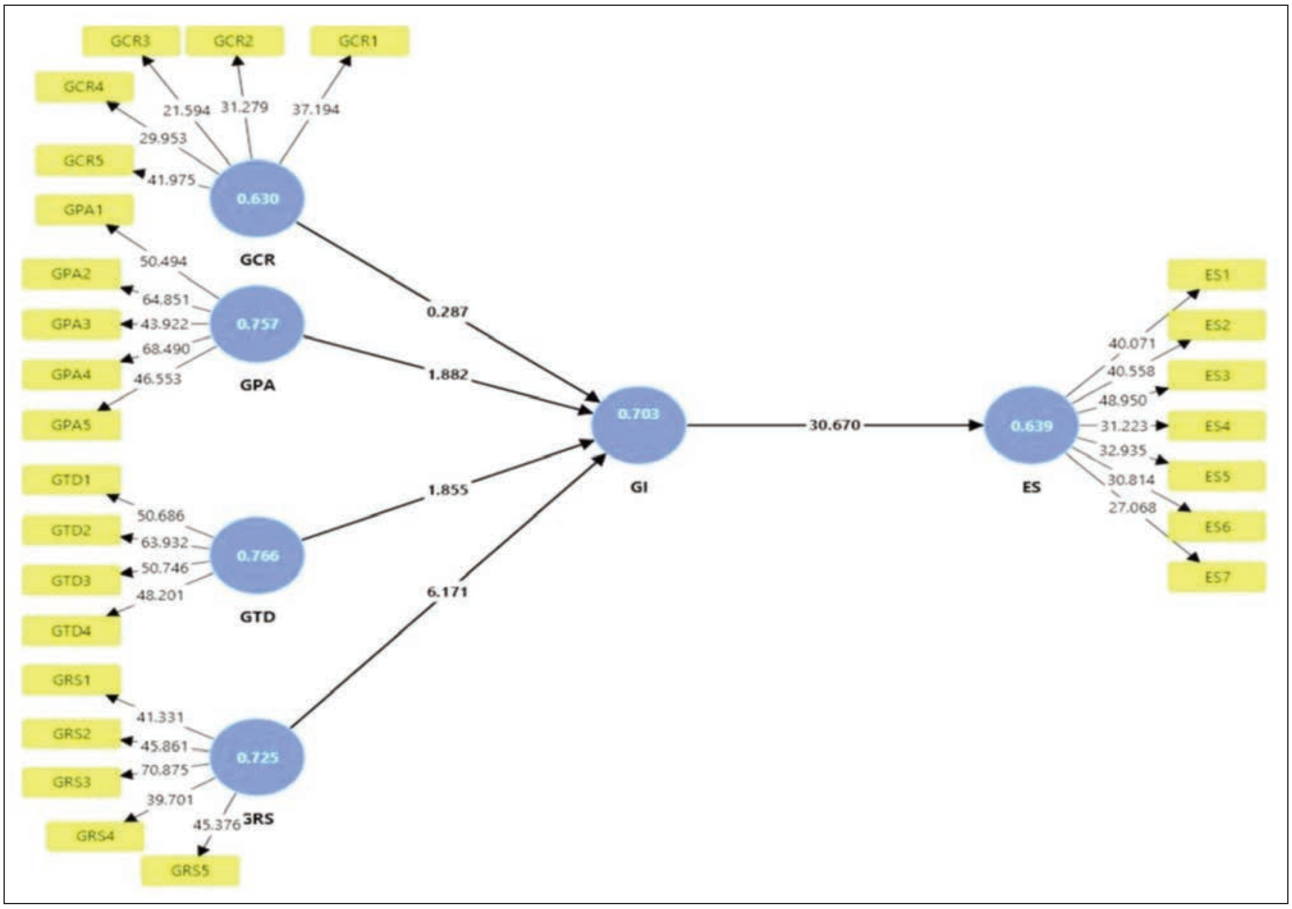

Fig. 3. The structural model for indirect relationships (extracted from SmartPLS 4.0)

About mediating effects, the analysis confirmed a mediating impact of GI in shaping the connection between GHRM Practices and ES. Table 6 demonstrates the correlation between GPA and ES (β=0.450, t-statistics=4.867, p<0.002).

The relationship between GRS and ES (β=0.367, t-statistics=5.906, p<0.000), GTD and ES (β=0.322, t-statistics=3.857, p<0.001) were positively and significantly mediated by GI. Additionally, GI positively and significantly mediated the relationships between GCR and ES (β=0.319, t-statistics=4.288, p<0.003). As a result, all hypotheses H5, H6, H7, and H8 are supported.

R2 values range from zero to one, as suggested by Chin [56], with 0.13 considered poor, 0.33 moderate, and 0.67 strong. The coefficient of determination for endogenous constructs is demonstrated in table 5, while figure 2 illustrates the PLS bootstrapping process.

Table 7

ASSESSMENT OF R^2 AND Q^2			
Variable	**R^2**	**R^2 Adjusted**	**Q^2**
GI	0.629	0.621	0.413
ES	0.588	0.583	0.355

Note: ES: Environmental Sustainability; GI: Green Innovation.

DISCUSSION AND CONCLUSION

This study aimed to address two key research questions: Do GHRM practices promote environmental sustainability in the context of HEIs? Second, does green innovation mediate the relationship between GHRM practices and environmental sustainability?

The data was collected from the textile and fashion design higher educational institutions (HEIs) in Pakistan's southeastern and second-largest province. The study confirms that GHRM practices are important in enhancing environmental sustainability. Moreover, findings reveal that all GHRM practices explored in this study were positively correlated with ES. All hypotheses of the study were significantly accepted. Among our hypotheses, Green Recruitment and Selection (GRS) had the most decisive impact on Environmental Sustainability (ES) (path coefficient = 0.385). It is suggested that institutions prioritising sustainability in their hiring processes are more likely to achieve better environmental outcomes; these results are linked with previous research of Jabbour [3] and Pham [5], who emphasised the strategic role of recruitment in embedding environmental values within an organisation. Moreover, the hypothesis regarding Green Compensations (GCR) and Green Training exhibited significant correlation with ES and supported the idea that incentivising and equipping employees with sustainable practices can improve environmental change. These results were consistent with the Daily et al. [48] study. The hypothesis of Green Performance Appraisal (GPA) showed a weaker correlation with ES (path coefficient = 0.184) and suggested that performance appraisals alone may not be as effective as more proactive measures like recruitment and training; these findings also align with Jabbour's [3] and Pham et al. [5] who assert that performance evaluations need to be complemented by broader organisational initiatives to be truly impactful in advancing sustainability. As the study's second objective, we studied the mediating relationship of Green Innovation between the GHRM and ES. It was observed that GI partially mediates the relationship, indicating the potential of GHRM and these practices not only directly influence sustainability but also create the environment for GI, which will contribute to long-term environmental sustainability. Our results were consistent with the findings of Awais-E-Yazdan and Aftab [41, 42], who also studied the GI and demonstrated that GI is a critical mediator in the relationship between GHRM practices and environmental sustainability. Furthermore, Hussain [46] showed that organisations with strong GHRM initiatives are more likely to foster green innovation, which leads to overall improved sustainability outcomes. Our study emphasises the importance of GHRM practices and incorporating GI in higher educational institutions to achieve environmental sustainability. It is suggested that HEIs must focus on the GHRM practices to create a virtuous cycle of engagement, innovation, and environmental stewardship. Furthermore, they can create an example within the educational sector, the industries they serve, and society. Although this study focused on higher educational institutions of one province, the findings may have broader applicability due to the common characteristics of academic institutions nationwide. We believe a similar relationship can be observed in other provinces, such as Punjab, Khyber Pakhtunkhwa, or Balochistan. Additionally, the generalizability of these results could extend to neighbouring countries due to the same culture. However, Future research could explore these practices in different geographical or cultural settings to confirm the applicability of the results.

Managerial implications

The findings of this study provide several important insights for managers. First, this study has demonstrated how underdeveloped countries, such as Pakistan, achieve environmental sustainability by implementing Green Human Resource Management (GHRM) practices. Secondly, higher education institutions (HEIs) have a significant role in mitigating environmental degradation along with their routine operations. It suggested that by integrating GHRM practices, HEIs can reduce their environmental footprint and serve as role models for other sectors to adopt sustainable practices. Therefore, administrators of HEIs must prioritise green recruitment, training, compensation, and performance appraisals within institutional processes. These practices will motivate employees and other stakeholders to embrace sustainability initiatives. That leads to long-term environmental sustainability. Secondly, we have found the critical role of green innovation in driving environmental sustainability. Our study demonstrated that green innovation significantly mediates the relationship between GHRM and environmental sustainability. Therefore, it is recommended that administrators and managers integrate green innovation into institutional operations, invest in sustainable technologies, and foster an innovation-driven culture that aligns with long-term sustainability goals.

LIMITATIONS

Despite the strengths of this study, certain restrictions must be acknowledged, creating avenues for future research. First, the study focuses exclusively on higher education institutions (HEIs) in Sindh, Pakistan. This narrow geographical scope may limit the generalizability of the findings to other regions or industries. Future studies should extend their scope to other key sectors or geographic areas, including cross-country comparisons, to enhance the applicability of results. Additionally, comparative studies between developed and developing regions could provide deeper insights into contextual influences on the effectiveness of Green HRM (GHRM) practices. Second, this study considers only Green Innovation as a mediating variable. Future research should explore additional mediators, such as Green Passion, Green Servant Leadership, Green Work-Life Balance, and STARA capabilities, to provide a more comprehensive understanding of the relationship between GHRM and environmental sustainability. Furthermore, due to time and resource constraints, this study does not examine the moderating effects of key constructs. Future researchers should investigate the role of potential moderators to derive more nuanced and impactful conclusions. Third, using a cross-sectional research design limits the ability to establish causality. Longitudinal studies are needed to examine the long-term impact of GHRM on environmental sustainability and to establish more explicit cause-and-effect relationships. Finally, this study relies on survey data, employing a five-point Likert scale. While efficient, this method may not fully capture the nuanced perspectives of participants and introduces the possibility of response bias.

Future research should consider a mixed-method approach, incorporating qualitative techniques such as interviews and case studies. Additionally, gathering data from multiple stakeholders could provide a more holistic perspective and mitigate potential biases.

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On-demand fashion: wardrobe management and trading community

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ABSTRACT – REZUMAT

On-demand fashion: wardrobe management and trading community

The concept of on-demand fashion has been around for some time. Still, its implementation remains challenging due to fast-paced consumer habits that prioritise quick acquisition over thoughtful decision-making. Intelligent wardrobe management and second-hand fashion exchange have emerged to maximise the use of existing clothing and promote more conscious and sustainable consumption behaviours. This study first provides an in-depth analysis of relevant research and the current state of the industry, summarising the technological pain points in existing wardrobe management systems and second-hand trading platforms, as well as the negative user experiences that impact user engagement. It then addresses typical issues faced by consumers in managing their wardrobes and collects 512 valid feedback responses. Finally, based on consumer feedback and a review of the current situation, this study proposes the construction of an on-demand fashion community that integrates both wardrobe management and second-hand trading. The platform consists of four main modules: My Wardrobe, Outfit, Community, and Profile, with a particular focus on the interactive scenarios of the innovative Outfit and Community modules. The platform proposed in this study is expected to promote more sustainable and conscious fashion consumption.

Keywords: *fashion on demand, fashion community, smart wardrobe, second-hand, sustainability*

Moda la cerere: gestionarea garderobei și comunitatea de tranzacționare

Conceptul de modă la cerere există de ceva timp, dar punerea sa în practică rămâne o provocare din cauza obiceiurilor de consum rapide ale consumatorilor, care prioritizează achizițiile rapide în detrimentul luării unor decizii bine gândite. Gestionarea inteligentă a garderobei și schimbul de articole de modă second-hand au apărut pentru a maximiza utilizarea articolelor de îmbrăcăminte existente și pentru a promova comportamente de consum mai conștiente și mai durabile. Acest studiu oferă mai întâi o analiză aprofundată a cercetărilor relevante și a stării actuale a industriei, rezumând punctele slabe tehnologice ale sistemelor existente de gestionare a garderobei și ale platformelor de tranzacționare second-hand, precum și experiențele negative ale utilizatorilor care afectează implicarea acestora. Apoi, abordează problemele tipice cu care se confruntă consumatorii în gestionarea garderobei acestora și colectează 512 răspunsuri valide. În cele din urmă, pe baza feedback-ului consumatorilor și a unei analize a situației actuale, acest studiu propune construirea unei comunități de modă la cerere, care integrează atât gestionarea garderobei, cât și comerțul cu articole second-hand. Platforma este alcătuită din patru module principale: My Wardrobe, Outfit, Community și Profile, cu un accent special pe scenariile interactive ale modulelor inovatoare Outfit și Community. Se preconizează că platforma propusă în acest studiu va promova un consum de modă mai durabil și mai conștient.

Cuvinte-cheie*: modă la cerere, comunitate de modă, garderobă inteligentă, second-hand, sustenabilitate*

INTRODUCTION

Sustainable fashion seeks to reduce environmental impacts in design, production, and consumption by using eco-friendly materials, lowering resource use, preventing pollution, and enhancing product durability [1]. However, rapid consumption and overproduction are significant factors hindering its sustainable development. Thus, promoting sustainable consumption practices and product management is key, and it is the core objective of our proposed approach.

For more sustainable consumption, the on-demand fashion isn't new, but its implementation is challenging. Fast-paced lifestyles favour quick acquisitions over the thoughtful decision-making that on-demand fashion requires. However, growing environmental concerns are shifting consumer priorities – nearly 60% of global consumers value sustainability when purchasing apparel [2]. Almost three-fifths of consumers worldwide said that sustainability was at least slightly important to them when purchasing apparel. This forces industry leaders to rethink their business models. While digital fashion is gaining traction as a way to break old consumption habits, it may merely add to overall consumption without reducing physical clothing purchases and their environmental impact.

In this context, maximising the utilisation of consumers' existing clothing is a solution that addresses the root cause of overconsumption and meets the practical needs of ordinary users [3, 4], which is mostly related to the research topic of capsule wardrobe creation [5–7]. By making full use of existing wardrobe items, consumers can not only better understand and utilize their current clothing (Survey shows that consumers experience on average 36 times "wardrobe panic" annually, when they struggle to pair items together from their wardrobes to compose a nice outfit.), but also optimize their styling choices and effectively reduce the demand for new clothing, providing a practical solution for sustainable fashion. Through intelligent wardrobe management systems, users can easily find the right combinations for themselves in their busy lives, achieving the perfect integration of fashion and sustainability.

And for more sustainable product management, the next question we need to consider is: even after maximising the use of existing clothing, what should be done with items that consumers no longer wish to use? According to statistics, the main disposal methods for clothing include reuse, recycling, incineration, and landfilling [8]. Among these, reuse and recycling are particularly emphasised for their significant advantages in extending garment lifespan, reducing waste, and conserving resources. Indeed, the global secondhand clothing market is showing tremendous growth potential. By 2025, its revenue is projected to reach 77 billion U.S. dollars, almost triple the 27 billion recorded in 2020 [9]. This trend toward circular models is expected to remain robust, with the secondhand market anticipated to expand by an additional 185% by 2029 [10], thus positioning itself as a key driver for sustainable fashion. As a result, researchers boldly assert that the future of fashion is secondhand. The demand for resale is huge, but why are online secondhand clothing platforms struggling? A report from *Marketplace* points out that, for buyers, concerns about product quality and cleanliness are the primary reasons for their reluctance to embrace secondhand clothing [11]. However, this can be alleviated through high-quality images and detailed descriptions of the products. For sellers, the greatest barrier is the time and effort involved (sorting through unwanted clothes, preparing photos, and writing descriptions). The next major challenges are pricing and handling special situations (such as returns and exchanges) [12].

Given these circumstances, we propose an innovative solution that integrates on-demand fashion principles. Our approach targets sustainable consumer behaviour and product management by utilising intelligent management and trading platforms to optimise clothing usage and extend garment lifecycles. The smart wardrobe provides personalised recommendations based on user needs, reducing unnecessary purchases and resource waste. Meanwhile, the trading community offers a channel for secondhand clothing transactions, promoting garment reuse and lowering the demand for new production. In other words, we must consciously model clothing combinations and streamline the steps involved in secondhand fashion transactions.

RELATED WORK

Capsule wardrobe

Research on smart fashion recommendations has increased the sales of fashion products, particularly in the fast fashion sector. Compatibility-based fashion recommendations can help consumers make more conscious purchasing decisions, thus reducing the harmful environmental impact of the fashion industry. A promising topic to explore is the fashionable and sustainable capsule wardrobe building. A capsule wardrobe is a concept of a limited sample of convertible clothing pieces that complement each other. The conception of a capsule wardrobe is not new, but has been very popular recently and discussed on social media [4]. To maximise the utilisation of existing clothing combinations, researchers need to address two main challenges. First, an accurate model of visual compatibility is required. This involves capturing how multiple visual items interact, often based on subtle visual properties. Second, there is the complex problem of combination. Haiso and Grauman [5] proposed an unsupervised generative visual topic model, generalised from Correlated Topic Models, to model the compatibility between fashion items. They developed an EM-like iterative method to solve the combination problem. Dong et al. [13] treated each outfit as a sequence of items, with each item being regarded as a time step input for a bidirectional LSTM to model compatibility. They also proposed a combination optimisation method to adaptively adjust the number of items in an outfit. Furthermore, Chen et al. [7] proposed TensorNet (which consists of two core modules: a Cross-Attention Message Passing module and a Wide&Deep Tensor Interaction module) to simultaneously model the local and global visual compatibility of a set of outfits. Since their research assumes that a capsule wardrobe has already been established, they did not discuss the combination problem. A more comprehensive work is by Patil, Banerjee and Sural [6]. As mentioned in their paper, their work does not focus on the prediction of compatibility between items, but assumes there is a set having all possible compatible outfits. Their research focuses on solving an inherently NP-hard complex combinatorial problem that simultaneously considers compatibility, versatility of individual items, and the overall shopping budget of the outfits. Recently, Tanaka and Ozaki [14] have also explored a more comprehensive investigation of the combination problem.

Considering the practical establishment of an automatic capsule wardrobe based on the user's existing clothing, the literature review has summarised several points worthy of our consideration and learning: First, in terms of visual compatibility, it is necessary to simultaneously consider both global and local aspects. Second, regarding the combination problem, it is worth contemplating how to address the impact on outfit ensembles of individual items that may be added or removed at any time. Finally, in terms of data, it is crucial to model using the user's existing clothing (the original wardrobe).

Smart wardrobe management

Smart wardrobe management is a product of contemporary times and evolving user needs. With the aid of continuously updated technologies, the functionalities of wardrobe management systems have been extended in many aspects. Currently, academic research and application design primarily focus on real-time management [15], such as *Closet+* [16], *Stylebook* [17], automatic outfit recommendation [18], like *Cladwell* [19] and *Smart closet* [20]; user preference learning [18, 21], exemplified by *Stylebook*, and lifecycle management [22], such as *Save your wardrobe* [23].

Real-time management primarily enables dynamic updates of clothing statuses to enhance management efficiency and is a fundamental feature of current smart wardrobe systems on the market. The differences among these systems mainly involve factors such as the number of clothing images that can be uploaded at once, the total wardrobe capacity, and data synchronisation capabilities. This study focuses on the function of automatic outfit recommendation. Currently, most smart wardrobe applications only allow users to manually create outfits. While this offers flexibility, it falls short in helping users efficiently utilise their existing clothing. In contrast, automatic outfit recommendation aims to generate diverse styling options based on the contents of the user's wardrobe. Users simply select suitable outfits from the recommendations, find the corresponding items, and can head out immediately. Although manually creating outfits can spark inspiration, over time, it is not significantly different from the traditional dressing process and may struggle to continuously engage users. User preference learning has great potential for exploration to better serve intelligent outfit matching. Moreover, lifecycle management aligns seamlessly with this research's concept of integrating wardrobe management and trading. By focusing on the usage frequency or lifecycle of clothing to encourage the rational use of resources – such as selling, donating, or recycling – it represents an important step toward sustainable fashion.

Based on the statistical results of global downloads over the past three years for smart wardrobe management applications from the App Intelligence module in *Sensor Tower* [24], this paper summarises and analyses the top 9 applications in table 1. It can be seen that current smart wardrobe management

Table 1

SUMMARY OF SMART WARDROBE MANAGEMENT APPLICATIONS

Application name	Main functions	Highlights	Limitations
Cladwell [19]	Real-time management; Automated outfit recommendation	• Ask Cladwell (powered with ChatGPT, get personalised style advice anytime).	• Template-based attribute generation; • Generate outfits based on attribute values.
Stylebook [17]	Real-time management; User preference learning; Automated outfit recommendation	• Outfit shuffle (generate outfits like shuffling cards).	• Manual attribute editing; • Generate outfits based on attribute values.
Smart closet [20]	Real-time management; Automated outfit recommendation	• Shop all your favourite brands and keep track of your wishlist in one place.	• Manual attribute editing; • Generate outfits based on attribute values.
Pureple [26]	Real-time management; Automated outfit recommendation	• Fashion community (discover new styling ideas).	• Manual attribute editing; • Generate outfits based on attribute values.
Acloset [25]	Real-time management; Automated outfit recommendation; Lifecycle management	• Automatic attribute recognition; • Preloved (sell clothes forgotten in your closet).	• Generate outfits based on attribute values.
Indyx [27]	Real-time management	• Personal styling services.	• Manual attribute editing.
MyWardrob [28]	Real-time management	• Fashion community (discover new styling ideas).	• Manual attribute editing.
Whering [24]	Real-time management; Automated outfit recommendation	• Outfit shuffle (generate outfits like shuffling cards).	• Template-Based attribute generation; • Generate outfits based on attribute values.
Save your Wardrobe [23]	Real-time management; Lifecycle management	• Provide a range of on-demand local aftercare services.	• Manual attribute editing.

systems have basically not implemented automatic recognition of individual item attributes or the generation of outfits based on fashion compatibility. The Preloved module in *Acloset* [25] is similar to the concept of this plan; the difference is that users need to sort out clothing they no longer use, photograph it, and upload it to the Preloved community for sale.

Second-hand fashion market and community transactions

As indicated by the data in the introduction, the second-hand clothing market is gradually becoming a significant branch of the fashion industry, with its sales far surpassing those of other categories of second-hand products. Not only does second-hand fashion hold substantial economic and ecological importance, but it also prompts changes in consumer behaviour patterns. Brands such as *Nike, H&M,* and *Lululemon*, along with online platforms like *The RealReal* [29], *Sellpy* [30], are actively developing second-hand trading platforms. By providing services for buying and selling second-hand clothing, these platforms help consumers extend the lifecycle of their garments. Another notable feature of the second-hand fashion market is the rise of community trading models, where consumers engage in direct exchange and purchase of items through online community platforms. This model not only increases user engagement but also strengthens interaction and trust among consumers. Platforms like *Depop* [31] and *Poshmark* [32] combine second-hand trading with social media elements, forming a social fashion community that enhances user participation and transaction frequency through interactions such as likes and comments. The promotion of second-hand fashion directly responds to consumers' demand for sustainable and green fashion. Consumer motivations in the second-hand fashion market differ from those in the traditional fashion market; primary motivations often include concern for sustainable development, affordable prices, and a preference for uniqueness and vintage styles. Research indicates that these consumer psychologies and preferences are enabling the second-hand market to gradually shed labels like "cheap" or "substandard products," leading to its widespread acceptance and integration into mainstream fashion [33].

However, the sustainable fashion industry, particularly second-hand clothing, is still in its infancy, especially in the emerging economies. The primary reason is that consumers lack awareness of the environmental advantages and economic value of second-hand clothing, followed by the complexity of product uploading and management [34] . For example, some studies have pointed out that users face cumbersome steps when uploading second-hand items – such as organising items, taking photographs, adding detailed descriptions, and setting prices – which leads to significant time and energy consumption. This becomes a barrier to participation in the second-hand market [35]. These obstacles make users feel that the entire process is lengthy and not worth the effort, resulting in resistance toward the

Table 2

SUMMARY OF MAINSTREAM SECONDHAND FASHION TRADING PLATFORMS			
Platform name	**Main functions**	**Highlights**	**Ease of getting started**
The RealReal [29]	• Professional authentication; • Luxury focus.	Specialises in luxury items with authentication services.	★ ★ More complex start-up requires professional review and item submission, but the platform assists with uploads and pricing.
Poshmark [32]	• One community, thousands of brands, and a whole lot of second-hand style.	Strong social integration resembles social media.	★ ★ ★ Relatively easy, user-friendly process for uploading items, but requires manual descriptions and pricing.
Thredup [37]	• Full-service consignment; • Automated pricing.	Full-service model, minimal user effort.	★ ★ ★ ★ Simple start-up, users only need to send items, and the platform handles the rest.
Depop [31]	• One community, thousands of brands, and a whole lot of second-hand style.	Social media-like interface, user-run shops.	★ Requires users to manually take photos, add descriptions, and set prices, a more involved process.
Vinted [38]	• One community, thousands of brands, and a whole lot of second-hand style.	No seller fees, promotes a community atmosphere.	★ Requires users to manually take photos, add descriptions, and set prices, a more involved process.
ReGAIN [39]	• Shopping, sharing, second-hand trading, and social interaction are integrated into one.	Send unwanted items and get access to discount coupons.	★ ★ ★ ★ Simple start-up, users only need to send items, and the platform handles the rest.

Notes: The ratings range from 1 to 5 stars, with 5 stars indicating the easiest platform to start using, based on the overall user experience and simplicity of listing items.

platform. Further research indicates that the lack of automation and intelligent technologies – such as technical tools to simplify the product upload process – makes platform usage seem burdensome and difficult to maintain attractiveness [36]. Therefore, how to simplify these steps through technological means (e.g., automatic image analysis and recommended descriptions) is a challenge and a potential improvement direction faced by many second-hand platforms. This work summarises the current mainstream second-hand trading platforms, particularly focusing on ease of use (table 2).

METHODOLOGY

User survey

This study previously conducted an online questionnaire survey with 512 valid responses on the current status of consumers' wardrobes. Firstly, figure 1, *a* presents the distribution of participants' gender, age, and occupation.

Secondly, regarding the current state of wardrobes, we set up two questions to collect feedback, and the results are shown in figure 1, *b*. It is evident that this data reveals the common phenomenon of most people

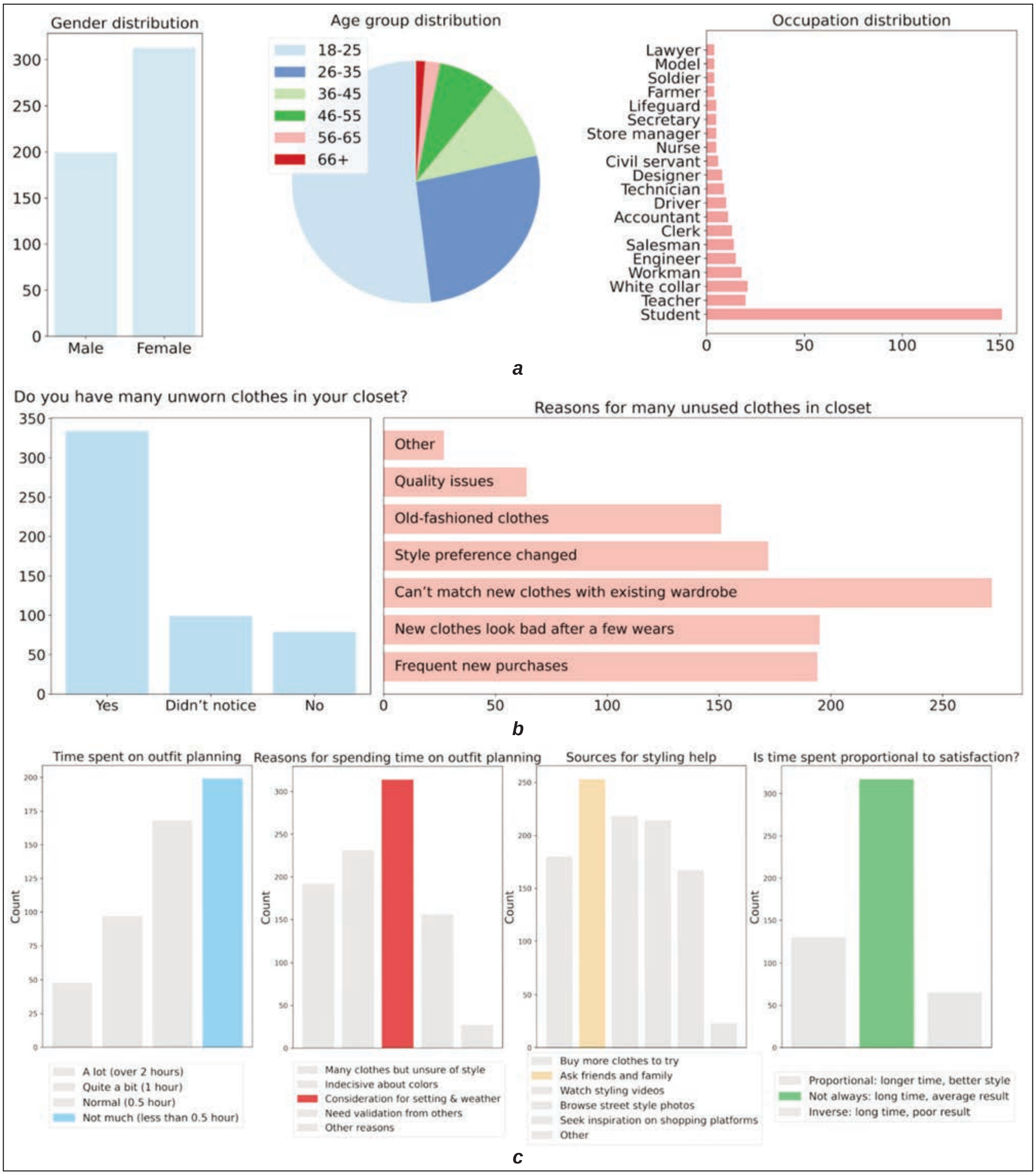

Fig. 1. Graphical representation of: *a* – distribution of participants' gender, age, and occupation; *b* – wardrobe status; *c* – daily dressing situations

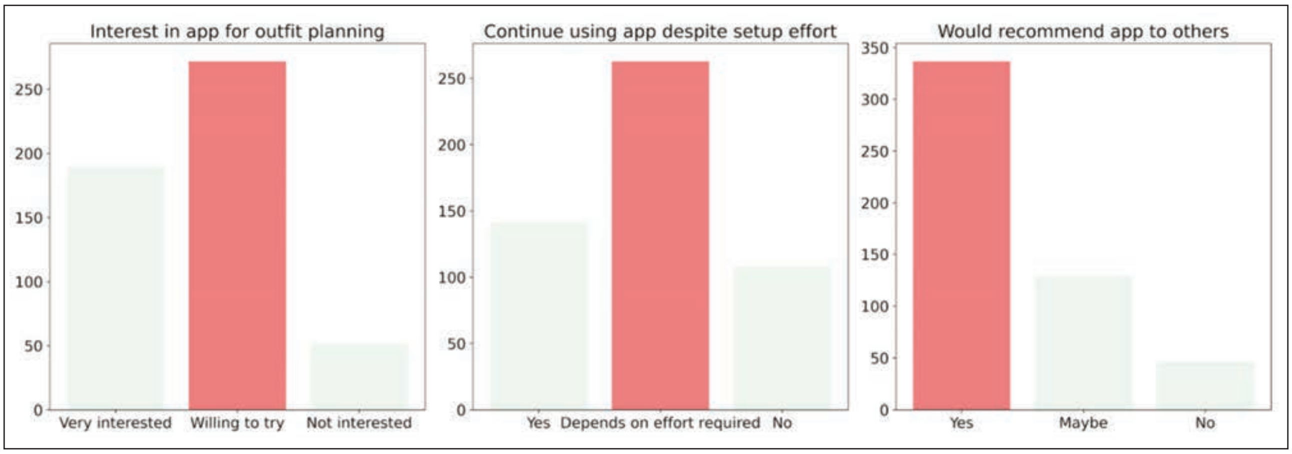

Fig. 2. Feedback on wardrobe management platform needss

having unworn clothing items tucked away at the bottom of their wardrobes. The vast majority of respondents admitted that their wardrobes contain many unused garments. The main reason is that new clothes are difficult to match with old ones, leading to new items, worn only a few times, gradually being forgotten. Other common reasons include frequent purchases of new clothes, the rapid obsolescence of new garments, and changes in personal dressing style. Overall, with the rapid turnover of fashion trends and changes in consumption habits, many people tend to frequently buy new clothes but seldom consider how they coordinate with existing items, resulting in many garments being left unused. This phenomenon reflects the impact of modern consumerism and suggests that placing more emphasis on matching actual needs when purchasing clothing might help reduce such waste.

Next, we designed four questions regarding daily dressing situations, and the feedback is presented in figure 1, *c*. This set of data reveals some key issues that modern individuals face concerning the time spent on dressing and making choices. The majority of people usually spend less than half an hour on dressing, reflecting a demand for efficient outfit selection in daily life. However, when confronted with different occasions and changes in weather, many still need to weigh and consider their options, making dressing time-consuming and a source of concern. At the same time, many respondents indicated that difficulties in choosing outfits often lead to repeatedly trying on and taking off clothes, becoming the main reason for the time consumed. When people encounter confusion in dressing, they primarily seek advice from friends and family or obtain inspiration through online resources, highlighting the importance of social circles and the internet in dressing decisions. Furthermore, despite investing a significant amount of time and effort into dressing, many do not always achieve the desired effect, potentially leading to uncertainty and feelings of dissatisfaction. Overall, the data reflect modern individuals' need for quick and satisfactory dressing solutions, while also revealing the dilemmas and matching challenges faced during the dressing process.

Finally, we also conducted a simple survey regarding user needs for wardrobe management platforms, and the results are shown in figure 2. These charts indicate that most respondents exhibit high interest and potential acceptance of outfit assistant applications. Despite the possibility that recording clothing items may be time-consuming, the majority expressed willingness to continue using the app, depending on circumstances. If the application indeed improves dressing efficiency, the vast majority are willing to recommend it to others, suggesting positive potential for promotion.

Prototyping

By transforming the concept of "On-Demand Fashion: Wardrobe Management and Trading Community" into practical application scenarios (figure 3), the platform involves four main modules: **My wardrobe:** Used to store the user's existing clothing; **Outfit:** User-created outfits and system-generated outfits; **Community:** Users sell and purchase second-hand clothing; **Profile:** User personal information, order details, and outfit sharing space.

In this study, we provide a more detailed interactive explanation of the highlight modules of the on-demand fashion community, particularly focusing on functions that have not been fully implemented in existing platforms but hold significant value.

First, as shown in figure 4, *a*, we have added a 'Quick Pricing' option in Module a2 to support instant intelligent pricing (based on the brand and quality of the clothing). Upon user confirmation, clothing items selected for 'QuickSell' will automatically appear in Module c1, enabling rapid posting and display of items. The trading function endowed by the platform aims to reduce users' decision-making costs in second-hand transactions, optimise the resale process, improve user experience, and enhance platform stickiness.

Second, as illustrated in figure 4, *b*, we provide an interactive demonstration of the outfit matching scenario. In Module b1, users can manually create

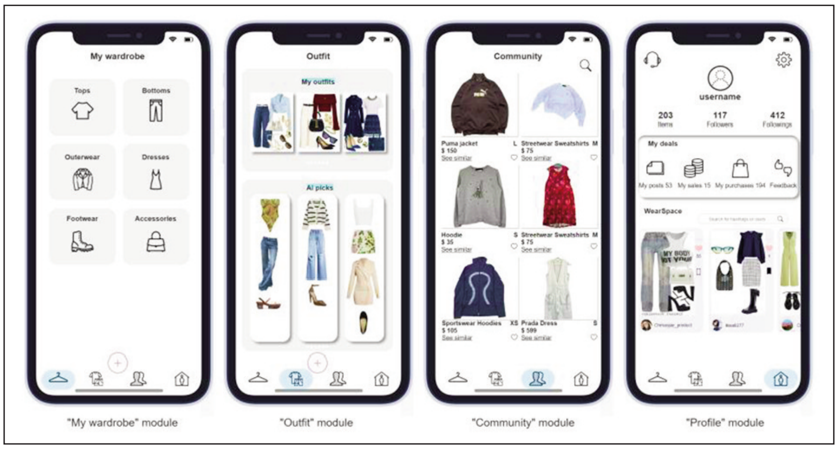

Fig. 3. Illustration of the main application scenario modules

outfits by selecting clothing from different categories and dragging them into the outfit box, facilitating users to assemble outfits on their own. Meanwhile, Module b2 offers a hybrid model-based outfit recommendation. Specifically, we directly generate the outfit recommendation list through the fashion compatibility model and item combination algorithms, while the preference learning model in the user-created outfits module indirectly guides the fashion compatibility model, thereby influencing the final recommendation outcomes. Users can browse the recommended outfits and mark their favourite options. We aim to make full use of wardrobe items, reduce users' decision-making pressure in daily outfit choices, and encourage more conscious consumption.

CONCLUSIONS

The innovation of this work lies in integrating on-demand fashion, capsule wardrobe management, and a second-hand trading community into a single platform. By utilising intelligent matching algorithms, the platform assists users in discovering more outfit possibilities within a limited selection of clothing, thereby maximising the utilisation of existing garments. Simultaneously, the platform provides users with a convenient space for second-hand trading, promoting the sharing and circulation of idle clothing items. This not only meets users' needs for efficient outfit coordination but also advocates for sustainable fashion consumption, reducing resource waste.

However, these innovations also bring new challenges. First, we need to establish an accurate visual compatibility model to precisely capture the matching potential between clothing items under a limited dataset. Traditional visual compatibility models typically require large amounts of training data to learn the matching patterns between garments, but the user's wardrobe size is limited and cannot provide sufficient data support. Therefore, we need to explore methods based on small-sample learning or transfer learning to enable the algorithm to work effectively in a small-data environment. Second, even within a limited wardrobe, the possible combinations of outfits are still vast. How to efficiently process these combinations and provide practical outfit suggestions is a difficulty in algorithm design. Moreover, the effective personal preferences conveyed when users create their own outfits should not be wasted, which means the algorithm needs to be capable of learning and updating the model in real time to adapt to the user's changing needs. Finally, the quality assessment and pricing strategy of second-hand clothing are also key issues that need to be addressed. How to balance intelligent outfit matching and second-hand trading functions on the platform to ensure a smooth and valuable user experience is the comprehensive challenge we face.

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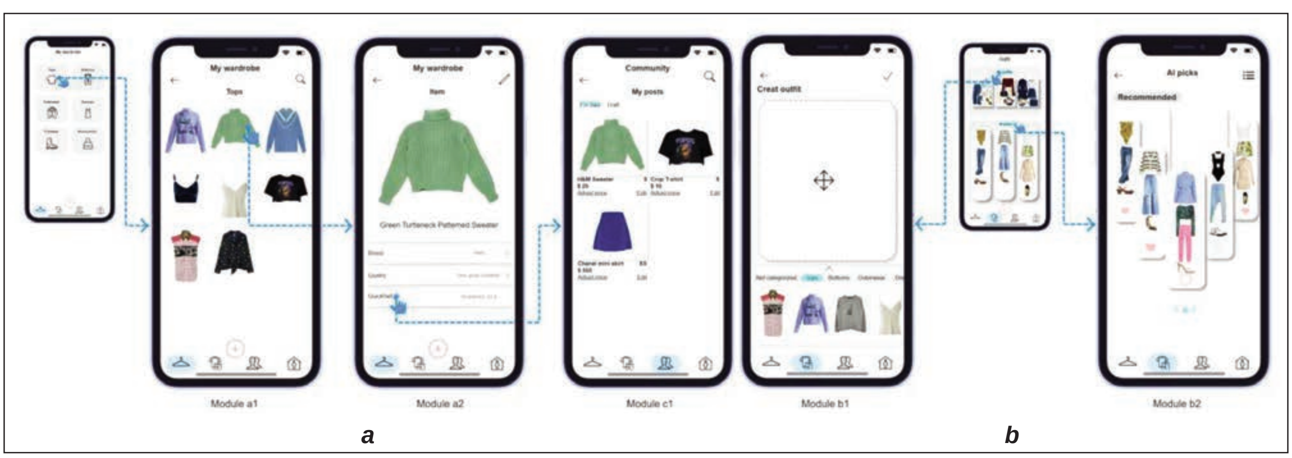

Fig. 4. Scheme of: *a* – Transaction scenario: One-click resale of unused clothing from your wardrobe;
b – Outfit matching scenario: User-created outfits and system-generated outfitss

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A study on branding strategies (green innovation and international marketing) and their impact on purchase decision involvement of customers in the textile industry, with disposable income as a moderating factor

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ABSTRACT – REZUMAT

A study on branding strategies (green innovation and international marketing) and their impact on purchase decision involvement of customers in the textile industry, with disposable income as a moderating factor

Branding strategies and customer involvement have become central to Indian businesses as sustainability gains prominence across both offline and online businesses. Due to rising environmental concerns, companies are focusing on sustainable practices, energy-efficient solutions, and eco-friendly products to meet consumer demands and regulatory standards. Purchasing the products based on green innovative marketing strategies has attracted people from various nations, too. However, purchasing decisions vary from one individual to another based on the driving factors like persona, psychological, economic, payment mode, social, quality, trust, cost, reputation, reviews and offers. In this research, the association between branding strategies as an independent factor using green innovation and international marketing strategies against the dependent factor, customer involvement in the textile industry, is examined. The moderating factor 'disposable income' is adopted here, which gives this research its uniqueness, significance and novelty. The research adopts SEM analysis for examining the variables and the Hayes Process for moderating factor analysis. The targets are people who are interested in fashion clothing. The sample size used is n=589. The findings showed that there exists an association between green innovation in marketing (GIM) and purchase decision involvement (PDI) and international marketing (IM) and PDI. Similarly, the moderating factor, disposable income (DI), moderates the association between GIM and PDI; whereas it doesn't moderate the IM and PDI. Thus, the research concluded that the disposable income as a moderating factor certainly impacts the purchase decision of the customers and international marketing strategies in the fashion clothing in textile industry.

Keywords: *disposable income, green innovation, branding, branding strategies, international marketing, and purchase decision*

Studiu privind strategiile de branding (inovație ecologică și marketing internațional) și impactul acestora asupra implicării în decizia de cumpărare a clienților din industria textilă, cu venitul disponibil ca factor moderator

Strategiile de branding și implicarea clienților au devenit esențiale pentru companiile din India, pe măsură ce sustenabilitatea câștigă reputație, atât în afacerile offline, cât și în cele online. Datorită creșterii preocupărilor legate de mediu, companiile se concentrează pe practici sustenabile, soluții eficiente din punct de vedere energetic și produse ecologice, pentru a satisface cerințele consumatorilor și a respecta standardele de reglementare. Achiziționarea de produse bazate pe strategii de marketing inovatoare și ecologice a atras și persoane din diferite țări. Cu toate acestea, deciziile de cumpărare variază de la o persoană la alta, în funcție de factori determinanți precum personalitatea, factorii psihologici, economici, modul de plată, factorii sociali, calitatea, încrederea, costul, reputația, recenziile și ofertele. În această cercetare se examinează asocierea dintre strategiile de branding ca factor independent, utilizând inovația ecologică și strategiile de marketing internațional, și factorul dependent, implicarea clienților în industria textilă. Aici se adoptă factorul moderator „venitul disponibil", ceea ce conferă acestei cercetări unicitate, semnificație și noutate. Cercetarea adoptă analiza SEM pentru examinarea variabilelor și procesul Hayes pentru analiza factorului moderator. Țintele vizate sunt persoanele interesate de îmbrăcăminte la modă. Dimensiunea eșantionului utilizat este n=589. Rezultatele au arătat că există o asociere între inovația ecologică în marketing (GIM) și implicarea în decizia de cumpărare (PDI), precum și între marketingul internațional (IM) și PDI. În mod similar, factorul moderator venitul disponibil (DI) moderează asocierea dintre GIM și PDI; în timp ce nu moderează factorii IM și PDI. Astfel, cercetarea a concluzionat că venitul disponibil, ca factor moderator, are cu siguranță un impact asupra deciziei de cumpărare a clienților și asupra strategiilor de marketing internațional în domeniul îmbrăcămintei din industria textilă.

Cuvinte-cheie*: venitul disponibil, inovația ecologică, brandingul, strategiile de branding, marketingul internațional și decizia de cumpărare*

INTRODUCTION

Research background

Green innovation encompasses factors like adopting renewable energy as sources, clean technologies, strategies towards reducing wastes, ensuring business operations and processes contribute to preserving the environment, and achieving market sustainability [1]. In India, green innovation as a primary marketing strategy is adopted by the leading brands like Aditya Birla (Fashion and Retail), Raymond Limited, Welspun India, Arvind Limited, and more to gain more customers and to market their products internationally and globally [2]. Brands which incorporate sustainability into their identity tend to stand out more than their competitors. This strategy appeals to their customers that their products are eco-conscious and environmentally friendly, which also meets the consumer tastes and fashion preferences. In the textile industry, the usage of “dye” to colour the fabrics causes heavy damage to the environment, which in turn causes customers to boycott products that are inorganic and non-eco-friendly. To battle against these issues, the textile industry has been adopting organic materials to dye the fabrics, using materials that are recyclable and reducing the soil and water contamination risks. Thus, by projecting the processes involved and materials as a strategic innovation (green innovation), brands market their products like yarns, clothing, fabric materials and wools to their targeted customers [3]. This causes a ripple effect among eco-friendly customers (online and offline) to focus on the green innovation strategy. However, the purchasing decisions and involvement of the customer vary depending on their preferences and needs. Purchase involvement and decisions are purely based on an individual’s income, interest, need, necessity and comfort [4]. Some factors hinder the purchasing decision and involvement of customers, like perceived value, negative reputation, different pricing, alternative/substitute products, lack of product transparency, quality and other factors [5]. In the textile industry, the major factor in purchasing decisions relies on readily available clothes, quality, eco-friendliness, comfort, colour variations, brand trust and pricing. To gain customers and sustain loyal customers, the textile industry must follow transparent, eco-friendly practices. By adopting attractive branding strategies, fashion clothing can gain more customers in the long run [6]. Thus, in this research, how branding strategies are impactful on the purchasing involvement of customers is studied. Green innovation marketing and international marketing as branding strategies by reducing carbon footprints in the textile industry is the new trend [7]. Thus, by refurbishing and using recyclable materials, the brands gain sustainability, profits, and more customers. Transparency, ISO-14001 (Fair Trade) certifications, and through storytelling, these textile industry-based fashion clothing businesses build loyalty and trust in their brands. In India, green innovation not only tackles environmental issues, rather it also provides a competitive advantage in the rapidly evolving market.

The research contributes significant insights and information on how branding strategies impact the purchasing decision involvement of customers in the textile industry. By adopting and examining the two major factors in branding strategy, namely ‘green innovation marketing’ and ‘international marketing’, the study dwells on and contributes to the currently lacking knowledge on the association of the variables involved. Simultaneously, the purchase decision involvement with branding strategy has not yet been attempted, which proves that the research is a novel attempt and contributes fresh knowledge and statistics. To make the research more profound, the moderating factor “disposable income” is also adopted, and the impact of all the variables is studied broadly.

LITERATURE REVIEW

In this section, studies, literatures and research on the proposed research aim is examined in depth. The textile industry and its technological advancements have been studied by the authors [3, 7, 8]. The studies found that, as the demand and necessity of the consumers expanded along with their preferences, especially during the COVID-19 pandemic, the adoption of environmentally friendly fashion clothing increased tremendously. Similarly, the author [6] studied the Indian textile industry and how its growth impacted the economy from 2015 to 2020. The study showed that India gained more international customers from 2015–2020 (15%), especially during COVID-19 in 2020, with a sudden hike of 33.5 billion US$ from exports and trades. This proves that, Indian textile industry is growing rapidly as customer needs grow with the trend. Authors [9] found that the current trend in the textile industry is green practices, where eco-friendly and environmentally friendly products are preferred by customers more.

Some authors explored the green innovation in the textile industry and how it impacted the purchase decisions of customers and their perceived value [1]. They concluded in their study that green innovation increases purchase decision involvement in customers, where they prefer usefulness, greenness and novelty as major factors in environmentally friendly fashion clothing more than the pricing factor. Other authors focused on how green innovation as a marketing strategy impacted the customer purchase involvement [10–12]. These studies had a common finding, which is that green innovation significantly impacts the purchasing decisions of customers, especially among digital technology users (online shoppers). Thus, hypothesis 1 is derived, which states that green innovation marketing impacts purchase decisions.

Some authors had argued in their study that customers’ purchase decision involvement strongly relies on marketing mix strategy [13]. This finding is also backed up by authors, namely [14–16], insisting that marketing strategies like promotions, placement, pricing, word-of-mouth (WOM), use of social media, ease-of-pay (digital payment), packaging, and transparent processes play a vital role. These marketing-mixes as strategies pave – way for an effective international marketing strategy in the textile industry. Based on packaging, pricing, promotions, cultural considerations, target market, market research, product adaptation and other transparent processes in eco-friendly processes makes international customers opt for green products and non-green products based on a customer's preferences and needs. Thus, hypothesis 2 is derived, which examines the association between international marketing and purchase decisions.

Several authors focused on finding the factors that drive the customers' purchasing decisions [5, 17–20]. They found that age, gender, perceived usefulness, buying behaviour, income, customer attitude and fashion knowledge are the major drivers that impact customers' purchasing decisions and spending more on clothing. However, authors [21, 22] found a new factor, "disposable income", in their studies. As income increases, spending increases among the fashion clothing interested customers. These studies concluded that as income earners are left with more disposable income (post reduction of taxes), they are more impulsive to buy fashion clothing, apparel, accessories and cosmetics [21], especially women. Thus, hypotheses 3 and 4 are derived, which state, disposable income as a moderating factor moderates the association between branding strategies and purchasing decisions.

Research gap

The existing studies and literature on branding and its strategies have explored different variables and factors. The studies explored the factors that drive the textile industry to adopt green innovation [3, 7]. Chen et al. focused on branding strategies that impact the purchase decisions of customers. Studies examined the impact of green innovation as a marketing strategy [10–12]. The authors analysed the impact of international marketing that drives customers to spend more on fashion clothing [14–16]. Authors examined the moderating factors that moderate the relationship between branding and purchasing decisions [5, 17–20]. However, there are no research studies on the proposed aim, especially using disposable income as a moderating factor. Thus, by connecting the missing links in the existing literary pool, the current study attempts to find how impactful green innovation and international marketing strategies are on an individual purchase decision, involvement with disposable income as a moderating factor. This novelty brings out a new insight and findings upon the proposed research purpose.

Aim

This study aims to explore the impact of branding strategies (green innovation marketing and international marketing) on the purchase decision involvement of the customers in the textile industry, as the primary aim.

Objectives
- To find the relationship between green innovations marketing as a branding strategy and the purchase decision involvement of the customers in the textile industry.
- To find the relationship between international marketing as a branding strategy and the purchase decision involvement of the customers in the textile industry.

Hypothesis

The hypotheses formulated here are derived from the literature reviewed. Based on the research purposes, the independent variables examined are green innovation and international marketing, with the dependent variable being the customer purchase decision. The moderating factor used here is the disposable income. The hypotheses formulated are as follows:
- **H1:** Green innovation has a positive relationship with customers' purchase decision involvement in fashion clothing
- **H2:** International marketing has a positive relationship with customers' purchase decision involvement in fashion clothing
- **H3:** Disposable income of customers moderates the relationship between green innovation and customers' purchase decision involvement in fashion clothing
- **H4:** Disposable income of customers moderates the relationship between international marketing and customers' purchase decision involvement in fashion clothing

Theoretical framework

The theoretical framework here examines the association of the variables, where the dependent variable is the customer's purchasing decisions based on their involvement in the fashion clothing of the textile industry. The independent variable is the branding strategies (green innovation and international marketing). By using the moderating factor (disposable income), the association of these variables are examined in this research (figure 1).

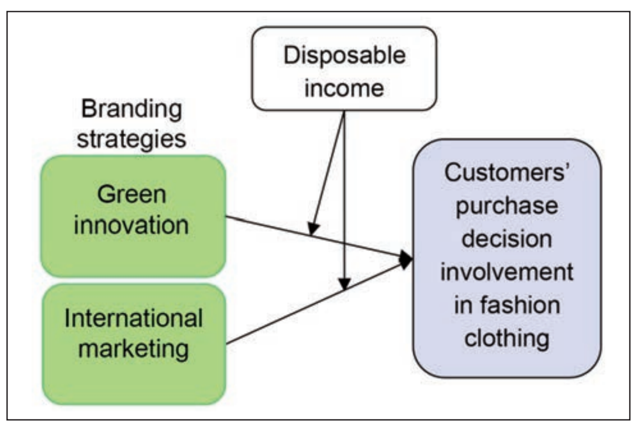

Fig. 1. Theoretical framework

METHODS AND MATERIALS

The methodologies adopted for the research are examined and verified in this section:

Approaches and methods adopted

The proposed framework explores the impact of purchase decisions of customers based on branding strategies in the textile industry. The study explores both numerical [24] and non-numerical data non-numerical [23] data with appropriate analyses. Thus, the study adopts a mixed [25] research approach with a research design as descriptive as explained in [27].

Dataset acquisition

Data is either accumulated via *primary* (exclusively for the developed research) or/*secondary* (using existing studies with the same purposes). Here, both data types are adopted. The primary data here is acquired using the "survey" method, where instrumentation (questionnaire) is used as a tool. For secondary data collection, existing resources from the internet (e-books, e-journals, e-articles, websites, blogs, e-news posts, case studies, thesis papers and more) are used.

The data are acquired for this research purpose only, and thus, the tool developed included two filtering-based questions. One is to find the interest of the participants' fashion clothing in the textile industry, and the other is to find whether they are taxpayers. Taxpayers are alone considered here since the moderating factor used here is "disposable income".

A disposable income is calculated by deducting personal income and personal income taxes. The personal income includes all modes of earnings and incomes an individual makes (for instance: salary, rent, pension, earnings, bonus, tips, investments, wages, business-made income, employment income and so on) [27]. Whereas, the personal income tax is defined as the taxes levied upon one's earned income [28]. This taxation is eligible for individuals who earn 'Three Lakhs' under the age of 60 years. Based on these two criteria, the respondents are filtered for the research analysis from the gathered data. Similarly, based on age and income variables, the respondents are cross-verified for the same filtering purposes (age ≤ 60 and income > 3Lakhs).

Target and samples

The target customers (population) are participants from India. The industry chosen is the textile industry. To further reduce the targets, sampling techniques are adopted. The sample unit focused here is the fashion clothing interested respondents, (both offline and online modes of purchasing) originated from South India. Since the study focuses on a particular group of people (fashion clothing interested and taxpayers), the study falls under "purposive sampling" where the researcher selects a group of similar characteristics intentionally for the research purpose [29]. The sample size estimated here is 589 using the Cochran formula [30].

Instrumentation

The instrument developed here is a survey-based tool, a questionnaire with four sections. The scale developed here uses five items from Chen et al. [1] for green innovation; eight items from Vila and Kuster [31] for international marketing; and ten items from O'Cass [4] for purchase decision involvement factors, respectively. Since the current study focuses on 'disposable income' as a moderating factor, this variable is calculated in the demographic data of the questionnaire.

Data filtering items

Here, the researcher does not estimate the 'disposable income' of the respondents; rather, using the responses, the researcher just filters the data to validate the data and analysis for reliability. Thus, the survey questionnaire developed has 23 valid items along with the demographic data, namely: name, age, income, marital status and educational qualification.

The disposable income here is filtered using three criteria: taxpayer, income earner (> 3Lakhs with age ≤ 60 years) and interested in spending/purchasing fashion clothing. As per the tax slab of the Indian government, an individual is eligible to be a taxpayer when the income is more than 3lakhs. Table 1 describes the tax slabs as per the 2024–2025 Indian tax regimes.

Table 1

TAX SLABS 2024-2025	
Tax Slab on the income of an individual (per annum) in lakhs	**Tax (in %)**
Up to 3L	0
3,00,001L to 7,00,001L	5
7,00,001L to 10,00,001L	10
10,00,001L to 12,00,001L	15
12,00,001L to 15,00,001L	20
15,00,001L Lakhs & above	30

ANALYSIS AND RESULTS

In this section, the analyses carried out are explained in detail. The study adopts the following analyses: reliability test for scale validity, regression test for variable associations, SEM analysis on samples for identifying the variables' complexity, confirmatory factor analysis to reduce the data dimensions and lastly Hayes-Process Macro method to find the moderating factor's impact on the variables used.

Reliability analysis

The reliability of the tool used in research is measured using different techniques, like parallel forms, test-retest, Cronbach's alpha coefficient, and more. Here in this research, Cronbach's (a) is adopted. It measures the scale's consistency with values ranging from 0-to-1 (0 being low consistent and 1 being highly consistent).

The alpha values obtained lower than 0.5 ($a < 0.5$) are unacceptable, which states that the scale developed or adopted is inconsistent for the study. Similarly, when the obtained alpha value is < 0.6 but > 0.5, it is considered a poor value, and the scale needs to be changed to acquire consistent outcomes. However, if the alpha value is > 0.9 to 1, it is deemed as excellent; 0.8 to 0.9 means the internal consistency is good; 0.8 to 0.7 denotes the scale is acceptable, and 0.7 to 0.6 denotes the scale is questionable for its internal consistency. Table 2 shows the items used and variables under consideration, with their respective alpha values estimated here.

Table 2

RELIABILITY ANALYSIS		
Variables	**Items**	**Alpha Value**
Green innovation in marketing (GIM)	5	0.732
International marketing (IM)	8	0.765
Purchase decision involvement (PDI)	10	0.882

From table 2, it is understood that the items GIM and IM are within an acceptable range, and the range of the variable PDI is considered "good". Overall, the scale is justified and validated for its internal consistency and adoption in this research. Thus, the developed scale is validated using the Cronbach test for its reliability.

SEM (Structural Equation Modelling)

The SEM (structural equation modelling) is used in research to examine the association. Using this technique, the complexity of variables' association and hypotheses testing with empirical datasets acquired are carried out.

Here, the association of international marketing (IM), green innovation in marketing (GIM) and purchase decision involvement (PDI) are estimated (figure 2). From figure 2, it is understandable that the overall mode fit ensures that the data acquired are adequate and significantly associated with each other, statistically. Based on the diagram, the model-fit summaries are obtained using the analysed data. In this research, the CMIN, RMR, GFI, Baseline comparison, FMIN and RMSEA values are represented for validating the data analysed. The distinct sample moments used here are 276 with parameters 50, which gives the degree of freedom as 226 (i.e. 276-0). By using the degree-of-freedom (df), data analysis (table 3) is carried out, to find the CMIN/DF values (chi-square minimum/degree-of-freedom). According to authors Marsh and Hocevar (1985), when the CMIN/DF ≤5, the model is presumed as a reasonable fit. Similarly, if CMIN/DF is ≤3, the model is presumed to be an acceptable fit [32]. The model achieved 3.5 as CMIN/DF, insisting that the model here is a good fit (table 3).

The RMR (root mean-square residual) of a model is assumed to be excellent when the value is smaller (i.e. near '0') (Hu and Bentler, 1998). The GFI (goodness-of-fit), on the other hand, should be near to '1' to represent the model to be a good fit (Kline, 2005).

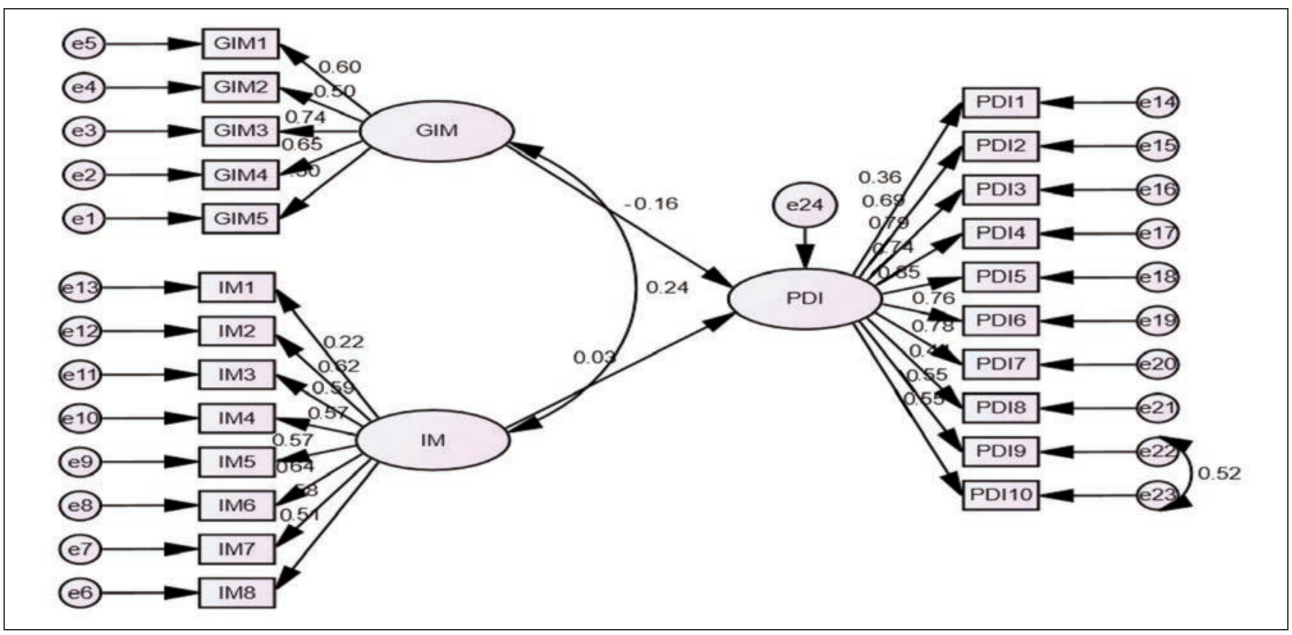

Fig. 2. SEM model diagram

Table 3

SEM MODEL FIT ANALYSIS								
Model	**CMIN**	**CMIN/DF**	**GFI**	**AGFI**	**PGFI**	**CFI**	**RMSEA**	**PCLOSE**
Default model	799.973	3.540	0.897	0.875	0.735	0.875	0.066	0.000
Saturated model	0.000	-	1.000	-	-	1.000	-	-
Independence model	2976.8	38.164	0.376	0.272	0.322	0.000	0.176	0.000

In this research, the RMR achieved is closer to 0 (.035), and the GFI achieved is closer to 1 (.735). Tabel 3 shows that the data used and the model are a good fit.
Baseline comparison in AMOS is estimated using a pre-defined model, automatically against the developed SEM model. [33] insisted that the values are baseline comparison should be closer to 1 (>0.9) for a good-fit and >0.95 for an excellent-fit, and = 1 for a perfect fit.
The overall values obtained in table 3 show that the model is a good fit for the data. RMSEA value (root mean-square error-of-approximation) for an excellent-fit should be >0.05 and for an acceptable-fit it should be <0.08 [34]. Here, the model achieved 0.066 (closer to 0.05), which suggests that the model is a perfect fit (table 3). Thus, based on the values obtained from table 3, it is proven that the SEM model created for the research purpose, using the data acquired, is deemed a good fit.

Demographic-data analysis

The demographic data analysed here includes age, gender, education, income (disposable income), and marital status. The disposable income in this research, as explained, is estimated using the survey tool-based questions as filters. The respondents who are paying taxes are alone included, since the disposable income (DI) is calculated by deducting personal income and personal income taxes. The current research doesn't estimate each respondent's disposable income amount but rather filters the respondents using taxpayers and fashion clothing interested people as targets. Thus, the data analysed here are justified for the approach used. The demographic here analyses the frequencies to validate the data used (figure 3).
Based on the filtering criteria, participants with income > 3lakhs/annum, interested in spending on fashion clothing and of age <60 are analysed here.

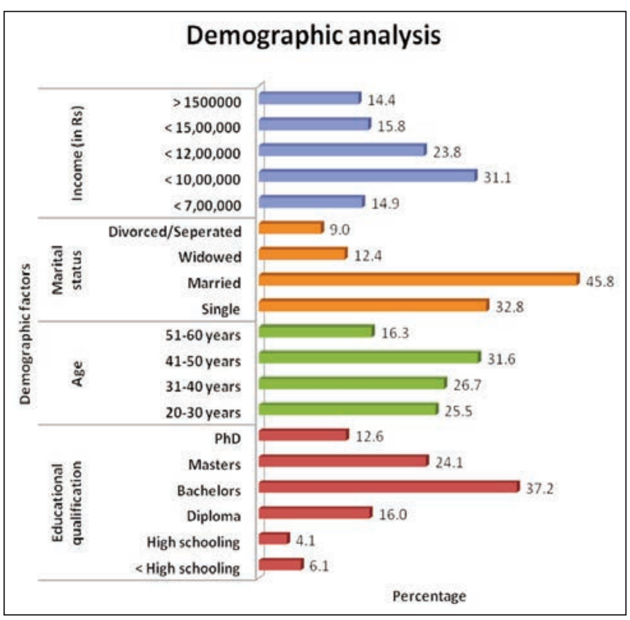

Fig. 3. Demographic analysis

Table 4

REGRESSION WEIGHTS				
Criteria	**Estimate**	**S.E.**	**C.R.**	**P**
PDI←GIM	0.122	0.042	2.908	***
PDII←IM	0.022	0.040	0.559	***
GIM5←GIM	1.000			
GIM4←GIM	1.053	0.109	9.681	***
GIM3←GIM	1.621	00.161	10.093	***
GIM2←GIM	0.870	0.103	8.450	***
GIM1←GIM	1.184	0.127	9.346	***
IM6←IM	1.129	0.112	10.112	***
IM5←IM	0.998	0.105	9.518	***
IM4←IM	1.192	0.125	9.527	***
IM3←IM	1.207	0.124	9.710	***
PDI1←PDI	1.000			
PDI2←PDI	1.782	0.215	8.305	***
PDI3←PDI	2.075	0.242	8.574	***
PDI4←PDI	1.960	0.232	8.441	***
PDI5←PDI	2.076	0.239	8.689	***
PDI6←PDI	2.215	0.261	8.480	***
PDI7←PDI	2.032	0.238	8.533	***
PDI8←PDI	1.133	0.162	7.011	***
PDI9←PDI	1.605	0.209	7.695	***
PDI10←PDI	1.566	0.203	7.703	***
IM1←IM	0.374	0.084	4.461	***
IM2←IM	1.197	0.120	9.986	***
IM8←IM	1.000			
IM7←IM	1.113	0.115	9.642	***

The values from table 4 show that, among the sample 589, the majority of participants earn around 10lakhs/annum (31.1%). The maximum educational qualification of the participants is found to be bachelor's (37.2%). The marital status of major participants is found to be married (45.8%). It is found that, majority of the volunteers are in the age group 41–50 years (31.6%). Thus, it is inferred from the analysis that, majority of the respondents are married, belonging to the 41–50 years age group with income above ten lakhs and have bachelor's degrees.

Regression analysis

A regression analysis shows the independent variable which it is associated with. A construct's influence in an SEM model is estimated using weights in regression.
The regression weight analysis (table 5) shows that p-values obtained are <0.01, which shows that there exists a significant and impactful association of the involved variables. Thus, it's understandable that hypotheses 1 (association between GMI and PDI) and 2 (association between IM and PDI) are true.

Confirmatory Factor Analysis (CFA)

A factor analysis using KMO Bartlett's approach indicates sampling adequacy. This validates datasets and their suitability in the research. The adequacy value in KMO should be > 0.05; here the value gained is 0.840, with *df* as 253 and significance (p-value) 0.000 (table 5).

Thus samples acquired and used here are significantly adequate.

Table 5

KMO AND BARTLETT'S TEST		
Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy		0.840
Bartlett's Test of Sphericity	Approx. Chi-Square	4779.002
	Df	253
	Sig.	0.000

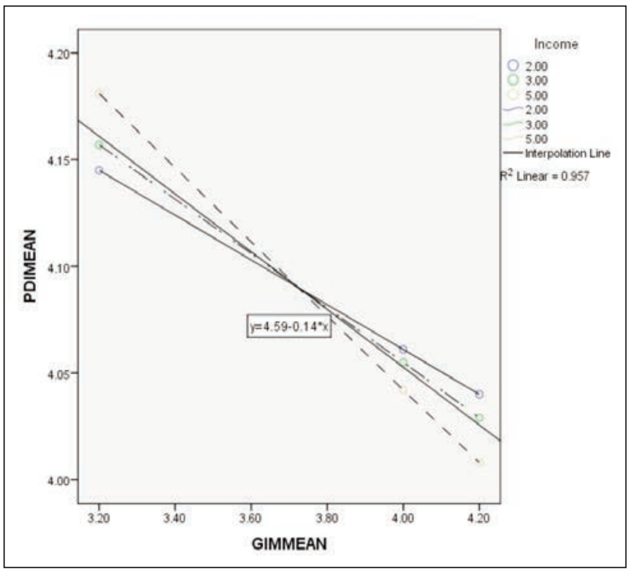

Fig. 4. Analysis of DI, GIM and PDI

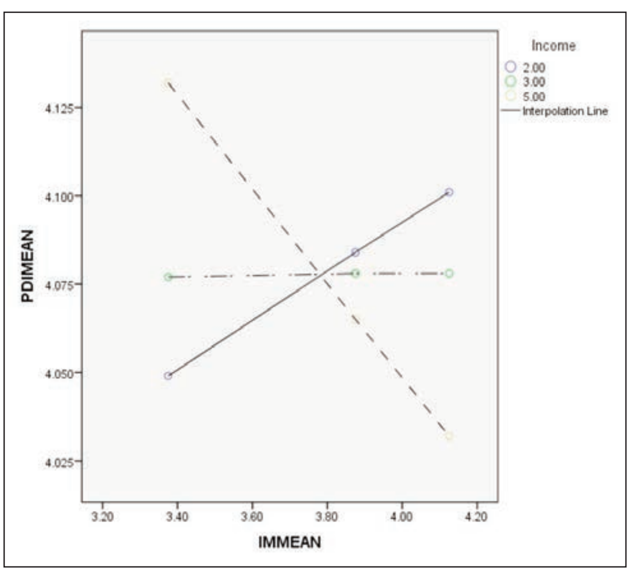

Fig. 5. Analysis of DI, IM and PDI

Hayes-Process analysis

The moderator variable is examined using the Hayes Macro-Process method, here. Disposable income (DI) as the moderating factor is used to measure its impact on GIM versus PDI and IM versus PDI. The p-value obtained for DI→GIM→PDI is 0.002 (<0.05), which shows that the disposable income moderates the GIM and PDI significantly (figure 4). Similarly, the p-value obtained for DI→IM→PDI is 0.229 (>0.05), which shows that the disposable income does not moderate the association between IM and PDI (figure 5).

Thus, based on the data analyses, it is concluded that hypotheses 1, 2 and 3 are accepted, whereas hypothesis 4 is rejected.

CONCLUSION

The primary aim of the research was to find the impact of green innovation marketing and international marketing as branding strategies upon the purchase involvement of the customers in the fashion clothing of the textile industry, in India. The research examines South Indian based customers who are taxpayers and also interested in fashion clothing. During the COVID-19 outbreak, in India, many individuals opted for online shopping for comfort and due to disease control prevention rules. However, post-COVID-19, Covid-19 few shoppers remained online shoppers, and the rest opted for traditional touch-and-feel shopping in the textile industry. Though there were many factors like coupons, offers, availability, alternatives, and availability of all/free sizes of clothing online, people lacked the craving for fabric sensitivity (touch-and-feel) prior to buying the product. One of the major factors that drives people towards fashion and clothing is branding. Innovation and strategies in branding pull existing people to spend more towards the brand and attract new customers. Especially, the term “green innovation” has changed the view of customers towards a particular brand, where eco-friendly products, processes, technology and materials are used by the specific brand, effectively. Green innovation in marketing in the textile industry and fashion clothing projects environmentally friendly accessories, products, materials and circular fashion (repairable, recyclable and reusable). Similarly, international marketing as a strategy in the textile industry in fashion clothing attracts customers by expanding their reach and connecting to new customers via branding. When these two major pillars of branding combine into a strong hold, people (customers) involve themselves in spending more on fashion clothing than their regular purchases. The purchase decision involvement of customers thus plays a vital role in deciding when, how, and where to spend. Thus, by examining these three variables, green innovation in marketing, international marketing and purchase decision involvement, the research intends to find the significant association among them. Simultaneously, by using disposable income as the moderating factor, the research analyses the impact and variable association.

Hypotheses were formulated based on the purpose and objectives. The study used SEM, confirmatory factor and Hayes Macro-Process analyses. The SEM model-fit findings showed that there exists a relationship between purchase decision involvement and green innovation, thus proving the first objective with a p-value < 0.05. Similarly, findings showed that purchase decision involvement and international marketing are significantly associated, which proves the second objective, with a p-value < 0.05. The third objective, that disposable income moderates green innovation marketing and purchase decision involvement, is proven to be true through moderator analysis. The p-value obtained was 0.002 (< 0.05). However, the fourth objective, disposable income moderates international marketing and purchase decision involvement, is proven to be insignificant through moderator analysis. The p-value obtained was 0.229 (> 0.05). Thus, the research concluded that there exists a strong relationship between purchase decision involvement factor and branding strategies (green innovation marketing and international marketing). However, disposable income as a moderating factor impacts the PDI and GIM and not the PDI and IM. This proves that purchase decision involvement is partially moderated by the branding when disposable income is concerned.

The study contributes a huge insight into branding strategies and purchase decision involvement in fashion clothing using disposable income as a moderating factor. The lack of use of the adopted variables in existing studies paved the way for the proposed research. Though the study is limited to two factors of branding strategies, in future, by using the same datasets, the researcher intends to examine other driving factors and moderating factors like gender and age in fashion clothing, in the Indian textile industry.

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Unveiling aesthetic preferences: a Kansai engineering approach to rapport formats in home textiles

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ABSTRACT – REZUMAT

Unveiling aesthetic preferences: a Kansai engineering approach to rapport formats in home textiles

Rapport formats, a fundamental element of textile design, significantly influence the aesthetic appeal of patterned fabrics. Despite their importance in shaping visual perception, limited research has systematically investigated the impact of different rapport formats on user preferences. This study addresses this gap by exploring the aesthetic preferences for various rapport formats applied to floral and geometric patterns in home textiles, employing a Kansei Engineering approach to understand and quantify user perceptions. The research investigates the impact of five commonly used rapport formats -straight, half-drop, diagonal half-drop, mirror, and turned- on both floral and geometric patterns. A survey of 115 participants, comprising textile industry professionals and design academics, was conducted to evaluate the designs. Participants rated the patterns on a semantic differential scale, assessing their emotional and aesthetic responses. Descriptive statistics and exploratory factor analysis were employed to analyse the collected data, revealing patterns and relationships between rapport formats and perceived aesthetic qualities. The findings indicate that straight and mirror rapports consistently emerged as the most preferred formats across both floral and geometric designs. This preference stemmed from their visual balance, simplicity, and modern appeal, suggesting a desire for order and clarity in textile patterns. In contrast, more complex rapports, such as turned and diagonal half-drop, while perceived as visually intriguing, lacked the same level of order and clarity favoured by participants. These findings provide textile designers with evidence-based guidance for selecting rapport formats that enhance the aesthetic appeal and user acceptance of their designs, ultimately contributing to more user-centred and appealing textile products.

Keywords: *textile pattern design, rapport formats, home textiles, aesthetic evaluation, Kansei engineering*

Dezvăluirea preferințelor estetice: o abordare a ingineriei Kansei asupra formatelor de raport în cazul textilelor de uz casnic

Formatele de raport, un element fundamental al designului textil, influențează în mod semnificativ atractivitatea estetică a materialelor textile imprimate. În ciuda importanței lor în modelarea percepției vizuale, puține cercetări au investigat în mod sistematic impactul diferitelor formate de raport asupra preferințelor utilizatorilor. Acest studiu abordează această lacună explorând preferințele estetice pentru diferite formate de raport aplicate modelelor florale și geometrice ale textilelor de uz casnic, utilizând o abordare a ingineriei Kansei pentru a înțelege și cuantifica percepțiile utilizatorilor. Cercetarea investighează impactul a cinci formate de raport utilizate în mod obișnuit - aliniat, cu decalare la jumătate, decalare diagonală la jumătate, în oglindă și rotit - atât pe modelele florale, cât și pe cele geometrice. A fost realizat un sondaj cu 115 participanți, cuprinzând profesioniști din industria textilă și academicieni din domeniul designului, pentru a evalua modelele. Participanții au evaluat modelele pe o scară diferențială semantică, evaluând răspunsurile lor emoționale și estetice. Statisticile descriptive și analiza factorială exploratorie au fost utilizate pentru a analiza datele colectate, revelând modele și relații între formatele de raport și calitățile estetice percepute. Rezultatele indică faptul că rapoartele aliniat și în oglindă au apărut în mod constant ca fiind preferate atât în cazul modelelor florale, cât și al celor geometrice. Această preferință a rezultat din echilibrul vizual, simplitatea și aspectul modern al acestora, sugerând o dorință de ordine și claritate în modelele textile. În schimb, formatele de raport mai complexe, cum ar fi modelele rotit și decalare diagonală la jumătate, deși percepute ca fiind interesante din punct de vedere vizual, nu aveau același nivel de ordine și claritate preferat de participanți. Aceste rezultate oferă designerilor de produse textile îndrumări bazate pe dovezi pentru selectarea formatelor de raport care sporesc atractivitatea estetică și acceptarea de către utilizatori a modelelor lor, contribuind în cele din urmă la produse textile mai atractive și mai centrate pe utilizator.

Cuvinte-cheie*: proiectarea modelelor textile, formate de raport, textile de uz casnic, evaluare estetică, inginerie Kansei*

INTRODUCTION

In the fiercely competitive home textile market, patterns have become a pivotal factor influencing consumer purchasing decisions, often superseding functionality. Patterns, especially in products like bedding, curtains, and upholstery, are essential for creating aesthetic appeal and imbuing living spaces with personality [1]. Among the most prominent and enduring pattern types are floral and geometric designs, both prized for their adaptability across diverse interior styles [2]. Recent advancements in digital printing have revolutionised pattern application, particularly in manipulating rapport (pattern repetition), a crucial element that significantly impacts a design's visual impact and the emotional response it evokes.

Rapport, or the method by which a pattern repeats across a fabric, can either elevate a simple motif or detract from a more complex one, depending on its application. The five most commonly used rapport formats include straight repeat (direct repetition along vertical and horizontal axes), half-drop repeat (staggered repetition with horizontal shifts), diagonal half-drop (a diagonal offset creating a dynamic, tessellated effect), mirror repeat (reflecting the motif for symmetry), and turned repeat (rotating the motif to introduce variation) [3, 4]. This study investigates how these five rapport formats influence aesthetic preferences, focusing specifically on floral and geometric patterns applied to home textile products. By applying these rapport formats to both pattern types, ten unique designs were generated and presented on plain white duvet cover mockups to isolate the impact of pattern and rapport, minimising other visual distractions.

While previous research has explored the effects of colour and motif in textile design [5–9], the influence of pattern repetition, or rapport, remains largely unexplored. This gap in the literature is significant, as understanding the impact of rapport on pattern perception is crucial for designers striving to meet the escalating consumer demand for personalised, visually appealing home textiles. This understanding can lead to the development of more desirable products, potentially boosting sales and consumer satisfaction, while also contributing to more efficient design practices by optimising pattern usage. This study aims to address this gap by employing Kansei Engineering, a human-centred design approach that captures emotional responses to visual stimuli [10].

Participants, comprising industry professionals and academic experts, evaluated each design using a seven-point semantic differential scale, assessing the patterns against ten pairs of opposing adjectives, such as "simple-complex" and "harmonious-chaotic". These adjective pairs were carefully selected based on established Kansei Engineering literature from the field and industry best practices to reflect key aesthetic dimensions relevant to home textiles [11–14]. The resulting data were analysed using SPSS software to determine standard deviations, mean scores, and percentage distributions.

This research provides valuable data-driven insights into the influence of rapport on aesthetic perception, offering practical guidance for textile designers seeking to optimise the visual appeal of their creations in the increasingly competitive home textile market. By understanding how different rapport formats impact aesthetic preferences, designers can create products that resonate with modern consumer expectations and enhance the overall appeal of home textiles. As digital printing technologies continue to advance, enabling more intricate and personalised designs, these findings will become increasingly relevant for shaping design strategies and responding to evolving market trends.

METHOD

This study employs a quantitative research design, utilising a Kansei Engineering approach [10], to investigate the aesthetic impact of different rapport formats on floral and geometric patterns in home textiles. KE, a methodology that translates subjective impressions into objective design parameters, is particularly relevant as it allows for a structured analysis of how design elements influence emotional and visual responses [10]. This approach aligns with studies like [1] and [13] that utilise quantitative methods and semantic categorisation to assess preferences for visual textures and emotional responses to patterns. However, while these studies focused on general pattern perception, this research specifically investigates the impact of rapport formats, a less explored area, on aesthetic responses.

Participants

A purposive sampling technique was used to recruit 115 participants with expertise in textile design and aesthetics. The sample consisted of industry professionals (58%) working in textile firms and academics (42%) specialising in fashion and textile design, ensuring evaluations were grounded in practical and theoretical knowledge. Participants were recruited through professional networks and online platforms specialising in textile design, targeting individuals based in major textile manufacturing hubs and universities in Türkiye. To be eligible, participants were required to have at least one year of professional experience in textile design, demonstrated through their online profiles or CVs, familiarity with rapport techniques, and basic computer skills to complete the online survey.

Design stimuli

Two common home textile patterns, floral and geometric, were selected, reflecting a focus on widely used design elements in the industry and aligning with the pattern categories explored in related academic research [14]. However, unlike Zhou and Xu [14], who explored age-based preferences for plaid shirts, this study investigates a broader range of aesthetic responses across two distinct pattern categories. The selection of these patterns, as well as the subsequent design process, was guided by expert consultation to ensure the representativeness and applicability of the chosen patterns within contemporary textile design. Specifically, the pattern selection began with identifying two unit patterns (one floral, one geometric) based on expert recommendations and established design references. These patterns were deemed suitable for home textiles given their balanced composition and adaptability to different rapport formats. Five rapport formats (straight, half-drop, diagonal half-drop, mirror, and turned) were applied to each pattern, resulting in ten design variations (table 1). The placement and alignment of the patterns within each rapport format were carefully considered to maintain proportionality and avoid unintentional distortions. Each variation was presented on a 200x220 cm duvet cover and 50x70 cm pillow mockups created using Adobe Photoshop CS6 (table 2). A neutral colour scheme (black and white tones) and a standardised unit pattern size of 40x40 cm, determined through expert consultation, were used to control for extraneous variables and focus participant attention on the rapport format. This structured approach to pattern selection and application ensured that the study focused solely on the impact of rapport formats, minimising potential confounding variables such as colour, texture, or material differences. By adhering to these methodological controls, the study aimed to provide a robust framework for analysing aesthetic preferences within home textile design.

Data Collection: Kansei engineering

Following the principles of KE [10], a 7-point semantic differential scale was used to capture participants' emotional and aesthetic responses to the design variations. Ten adjective pairs, informed by a comprehensive literature review of KE studies in textile design and validated through consultations with three experienced textile design professionals, were used. These pairs, such as "chaotic-orderly" and "innovative-traditional", were selected based on their relevance to established aesthetic dimensions in design theory (e.g., complexity, novelty) and their applicability to evaluating rapport formats in textile patterns. This approach aligns with the use of semantic scales in studies like Kodžoman et al. [13] to evaluate visual textures. The ten adjective pairs used in the semantic differential scale are listed in tables 3 and 4.

Pilot Study: Before the main data collection, a pilot study was conducted with 30 participants from the textile industry to assess the reliability of the questionnaire and gather feedback on the clarity of instructions and design stimuli. Data from the pilot study were analysed using Cronbach's Alpha, resulting in a reliability coefficient of 0.82, indicating high internal consistency. Feedback from the pilot study led to minor revisions in the wording of two adjective pairs to improve clarity and ensure cross-cultural understanding. Additionally, the size of the design stimuli was slightly increased based on participant feedback to enhance visibility and facilitate evaluation.

Survey and evaluation procedure

Data collection was conducted through the Qualtrics online survey platform, chosen for its robust features in survey design, data management, and participant anonymity. Design variations were presented in randomised order to minimise sequence effects and reduce potential bias. Participants were instructed to evaluate designs based solely on the rapport format, disregarding controlled factors like colour and texture.

Data analysis

Data were analysed using IBM SPSS Statistics 22. Descriptive statistics (mean scores, standard deviations, percentage distributions) were calculated for each design and adjective pair.

To uncover the latent relationships between observed variables and reveal underlying dimensions of aesthetic perception, Exploratory Factor Analysis (EFA) was conducted guided by Kansei Engineering principles. This approach aligns with previous research using EFA to understand consumer preferences in design contexts [14]. EFA on participant responses to a semantic differential scale, rating floral and geometric rapport patterns on carefully selected adjective pairs [1]. These pairs captured a comprehensive range of aesthetic perceptions relevant to our research. Data were standardised using z-scores before analysis.

Table 1

UNIT PATTERNS AND RAPPORT FORMATS		
Unit pattern		

Table 1 (continuation)

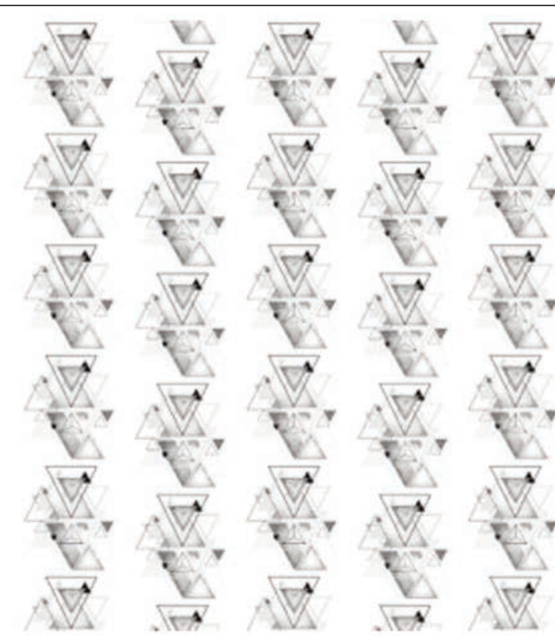
Straight		
Half-Drop		
Diagonal half-drop		

Table 1 (continuation)

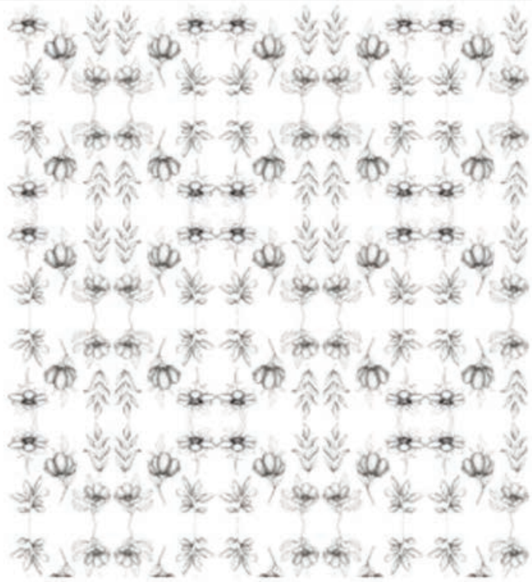
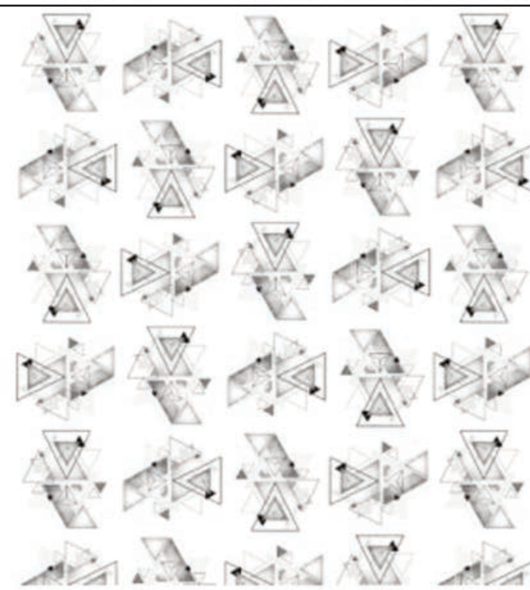
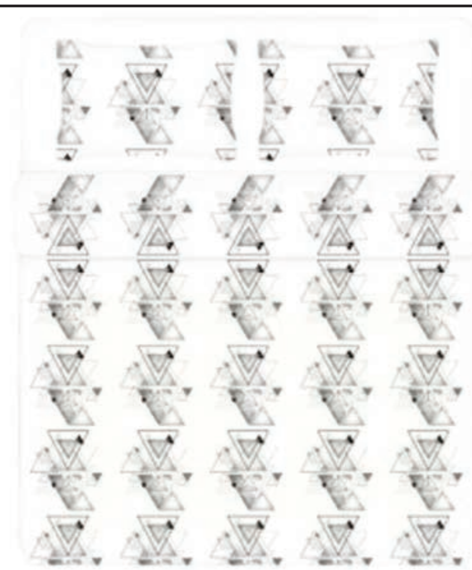
Mirror		
Turned		

Table 2

BEDDING MOCK-UP SAMPLE		
Straight		

Principal Axis Factoring was employed, and the number of factors was determined using the Kaiser criterion and scree plot, resulting in three factors for each pattern. No rotation was applied due to the initial factor structure's interpretability. Factor loadings were analysed to identify underlying dimensions, with high loadings (above 0.4 or below –0.4) indicating significant contributions to each factor. The interpretation considered both visual and emotional dimensions of perception. For example, one factor might reflect objective characteristics like 'complexity-simplicity', while another captures subjective feelings like 'sophistication-ordinariness', highlighting the need to address both in design optimisation.

RESULTS AND DISCUSSIONS

This study employed a quantitative research design and a Kansei Engineering approach to investigate participant preferences for various rapport formats applied to floral and geometric patterns. Descriptive statistics (tables 3 and 4) and exploratory factor analysis (table 5) were utilised to provide a comprehensive understanding of participant perceptions.

EFA revealed three primary factors influencing aesthetic judgments across both pattern types: Creativity and Engagement, Perceived Order and Simplicity, and Contemporary Appeal. Descriptive statistics further elucidated how each rapport format was evaluated on scales such as "chaotic-orderly" and "effective-ineffective".

Floral Patterns

The factor analysis for floral patterns yielded several key insights. Straight and mirror rapports were favoured for their Perceived Order and Simplicity, scoring highly on Factor 2, which reflects participant preferences for visually balanced and easily processed designs. The straight rapport consistently received high scores, particularly for the "chaotic-orderly" pair (5.41±1.67) and "pleasant-unpleasant" (5.03±1.74) scales, reflecting its predictable and visually pleasing structure. Mirror rapport also loaded significantly on Factor 3 for its modern appeal, reinforcing the perception of symmetry as both contemporary and appealing.

In contrast, diagonal half-drop and turned rapports exhibited higher loadings on Factor 1, reflecting their creative and dynamic nature. These rapports were perceived as less orderly. For instance, the diagonal half-drop rapport had a mean score of 3.29±1.83 on the "chaotic-orderly" scale, indicating higher complexity and less predictability. The turned rapport, which scored low for Perceived Order (4.06±1.61 on the "pleasant-unpleasant" scale), demonstrated that

Table 3

DESCRIPTIVE STATISTICS FOR FLORAL PATTERN RAPPORTS (MEAN ± SD)

Adjective Pair	Straight	Half-drop	Diagonal half-drop	Mirror	Turned
Chaotic-Orderly	5.41 ± 1.67	4.45 ± 1.87	3.29 ± 1.83	5.06 ± 2.04	4.49 ± 1.77
Effective-Ineffective	4.10 ± 1.70	4.29 ± 1.68	3.87 ± 1.76	4.50 ± 1.88	3.66 ± 1.71
Sequential-Disordered	2.33 ± 1.81	3.22 ± 1.77	3.88 ± 1.84	2.23 ± 1.54	3.49 ± 1.74
Traditional-Innovative	3.24 ± 1.67	3.63 ± 1.49	4.15 ± 1.45	3.40 ± 1.53	3.84 ± 1.48
Complex-Simple	4.62 ± 1.75	4.03 ± 1.73	3.30 ± 1.58	4.48 ± 1.78	4.23 ± 1.41
Unique-Common	5.38 ± 1.69	4.90 ± 1.56	4.37 ± 1.54	4.95 ± 1.49	4.47 ± 1.42
Trendy-Outdated	4.59 ± 1.69	4.37 ± 1.62	4.07 ± 1.58	4.68 ± 1.60	3.99 ± 1.45
Free-Restricted	5.03 ± 1.74	4.61 ± 1.59	3.97 ± 1.64	4.93 ± 1.61	4.01 ± 1.66
Pleasant-Unpleasant	3.84 ± 1.80	3.85 ± 1.63	4.06 ± 1.61	4.50 ± 1.82	3.65 ± 1.59
Different-Similar	5.37 ± 1.73	4.98 ± 1.64	4.07 ± 1.65	4.55 ± 1.76	4.25 ± 1.64

Table 4

DESCRIPTIVE STATISTICS FOR GEOMETRIC PATTERN RAPPORTS (MEAN ± SD)

Adjective Pair	Straight	Half-drop	Diagonal half-drop	Mirror	Turned
Chaotic-Orderly	5.37 ± 1.93	4.90 ± 2.01	3.54 ± 1.86	5.24 ± 1.78	5.12 ± 1.82
Effective-Ineffective	4.54 ± 1.92	4.27 ± 1.78	3.27 ± 1.57	4.35 ± 1.76	4.37 ± 1.76
Sequential-Disordered	1.88 ± 1.45	2.69 ± 1.73	3.79 ± 1.79	2.58 ± 1.61	2.59 ± 1.54
Traditional-Innovative	3.74 ± 2.03	4.03 ± 1.65	4.63 ± 1.59	3.97 ± 1.62	4.05 ± 3.17
Complex-Simple	4.96 ± 1.86	4.45 ± 1.77	3.50 ± 1.56	4.73 ± 1.61	4.59 ± 1.60
Unique-Common	4.96 ± 1.72	4.57 ± 1.57	3.73 ± 1.48	4.48 ± 1.58	4.66 ± 1.55
Trendy-Outdated	4.48 ± 1.67	4.18 ± 1.56	3.40 ± 1.44	4.26 ± 1.65	4.17 ± 1.62
Free-Restricted	4.73 ± 1.87	4.22 ± 1.75	3.28 ± 1.65	4.50 ± 1.67	4.32 ± 1.86
Pleasant-Unpleasant	4.38 ± 1.78	3.97 ± 1.75	3.40 ± 1.62	4.17 ± 1.85	4.05 ± 1.79
Different-Similar	4.59 ± 1.86	4.26 ± 1.83	3.27 ± 1.60	4.23 ± 1.67	4.51 ± 1.74

its complexity detracted from its overall appeal. Although floral designs often benefit from a degree of asymmetry and organic flow, the findings suggest that participants still valued rapport formats that offered visual stability. The diagonal half-drop rapport successfully combined creativity with a reasonable degree of order, making it more acceptable than the more chaotic turned rapport (high loading on Factor 1 but lower on Factor 2).

Geometric Patterns

The analysis of participant responses to geometric patterns revealed a marked preference for rapport formats that conveyed a clear sense of structure. The straight rapport emerged as the most favoured, consistently achieving high scores for Perceived Order and Simplicity (5.37 ± 1.93 on the "chaotic-orderly" scale). Participants gravitated toward designs that were easy to process visually, underscoring the importance of predictability and repetition in this design context. The mirror rapport was similarly well-received, with participants responding favorably to its balance and modern aesthetic, as evidenced by high scores on Contemporary Appeal.

Geometric patterns incorporating more complex rapport formats, such as diagonal half-drop and turned, were perceived as less appealing due to their lack of visual clarity. The diagonal half-drop rapport achieved a mean score of 3.54 ± 1.86 on the "chaotic-orderly" scale, reinforcing the observation that it introduced a level of visual complexity that participants found less structured. These formats loaded heavily on Factor 1, indicating they were perceived as innovative but less orderly. The turned rapport, with a low score of 3.26 ± 1.60 on the "different-similar" scale, was viewed as chaotic and unsuitable for geometric designs where regularity and symmetry are paramount.

Table 5

FACTOR LOADINGS FOR FLORAL GEOMETRIC PATTERNS BY RAPPORT TYPE

Rapport Type	Adjective pair	Creativity & Engagement		Perceived Order & Simplicity		Contemporary Appeal	
		Floral	Geometric	Floral	Geometric	Floral	Geometric
Straight	Chaotic-Orderly	–0.076	–0.205	–0.175	–0.636	–0.639	0.335
	Effective-Ineffective	–0.710	–0.792	–0.521	0.023	0.127	0.186
	Sequential-Non-seq.	0.159	0.118	0.047	0.175	0.493	–0.107
	Traditional-Innovative	0.438	0.571	–0.138	–0.249	0.028	–0.006
	Complex-Simple	–0.313	–0.518	–0.193	–0.553	–0.371	–0.004
	Unique-Ordinary	–0.741	–0.860	–0.019	–0.144	–0.053	–0.260
	Trendy-Outdated	–0.821	–0.859	0.183	0.161	0.045	0.118
	Free-Restrained	–0.825	–0.868	0.210	–0.017	–0.072	–0.079
	Pleasant-Unpleasant	–0.775	–0.822	0.136	0.216	0.241	0.197
	Different-Similar	–0.774	–0.875	0.151	0.028	–0.200	–0.045
Half-Drop	Chaotic-Orderly	–0.205	–0.205	–0.636	–0.636	0.335	0.335
	Effective-Ineffective	–0.792	–0.792	0.023	0.023	0.186	0.186
	Sequential-Non-seq.	0.118	0.118	0.175	0.175	–0.107	–0.107
	Traditional-Innovative	0.571	0.571	–0.249	–0.249	–0.006	–0.006
	Complex-Simple	–0.518	–0.518	–0.553	–0.553	–0.004	–0.004
	Unique-Ordinary	–0.860	–0.860	–0.144	–0.144	–0.260	–0.260
	Trendy-Outdated	–0.859	–0.859	0.161	0.161	0.118	0.118
	Free-Restrained	–0.868	–0.868	–0.017	–0.017	–0.079	–0.079
	Pleasant-Unpleasant	–0.822	–0.822	0.216	0.216	0.197	0.197
	Different-Similar	–0.875	–0.875	0.028	0.028	–0.045	–0.045
Diagonal Half-Drop	Chaotic-Orderly	0.118	0.118	0.175	–0.249	–0.107	–0.107
	Effective-Ineffective	–0.571	–0.571	–0.249	0.047	–0.006	–0.006
	Sequential-Non-seq.	0.159	0.159	0.047	–0.138	0.493	0.493
	Traditional-Innovative	0.438	0.438	–0.138	–0.193	0.028	0.028
	Complex-Simple	–0.313	–0.313	–0.193	–0.019	–0.371	–0.371
	Unique-Ordinary	–0.741	–0.741	–0.019	0.183	–0.053	–0.053
	Trendy-Outdated	–0.821	–0.821	0.183	0.210	0.045	0.045
	Free-Restrained	–0.825	–0.825	0.210	0.136	–0.072	–0.072
	Pleasant-Unpleasant	–0.775	–0.775	0.136	0.151	0.241	0.241
	Different-Similar	–0.774	–0.774	0.151	–0.249	–0.200	–0.200

Table 5 (continuation)

Rapport Type	Adjective pair	Creativity & Engagement		Perceived Order & Simplicity		Contemporary Appeal	
		Floral	Geometric	Floral	Geometric	Floral	Geometric
Mirror	Chaotic-Orderly	–0.518	–0.518	–0.553	–0.553	–0.004	–0.004
	Effective-Ineffective	–0.860	–0.860	–0.144	–0.144	–0.260	–0.260
	Sequential-Non-seq.	0.118	0.118	0.175	0.175	–0.107	–0.107
	Traditional-Innovative	0.571	0.571	–0.249	–0.249	–0.006	–0.006
	Complex-Simple	–0.518	–0.518	–0.553	–0.553	–0.004	–0.004
	Unique-Ordinary	–0.860	–0.860	–0.144	–0.144	–0.260	–0.260
	Trendy-Outdated	–0.859	–0.859	0.161	0.161	0.118	0.118
	Free-Restrained	–0.868	–0.868	–0.017	–0.017	–0.079	–0.079
	Pleasant-Unpleasant	–0.822	–0.822	0.216	0.216	0.197	0.197
	Different-Similar	–0.875	–0.875	0.028	0.028	–0.045	–0.045
Turned	Chaotic-Orderly	–0.859	–0.859	0.161	0.161	0.118	0.118
	Effective-Ineffective	–0.868	–0.868	–0.017	–0.017	–0.079	–0.079
	Sequential-Non-seq.	0.118	0.118	0.175	0.175	–0.107	–0.107
	Traditional-Innovative	0.571	0.571	–0.249	–0.249	–0.006	–0.006
	Complex-Simple	–0.518	–0.518	–0.553	–0.553	–0.004	–0.004
	Unique-Ordinary	–0.860	–0.860	–0.144	–0.144	–0.260	–0.260
	Trendy-Outdated	–0.859	–0.859	0.161	0.161	0.118	0.118
	Free-Restrained	–0.868	–0.868	–0.017	–0.017	–0.079	–0.079
	Pleasant-Unpleasant	–0.822	–0.822	0.216	0.216	0.197	0.197
	Different-Similar	–0.875	–0.875	0.028	0.028	–0.045	–0.045

General Insights and Implications

Across both floral and geometric patterns, participants consistently exhibited a preference for rapport formats that embodied balance, simplicity, and visual harmony. Straight and mirror rapports emerged as the most effective formats, as their structured repetition resonated with participants who valued orderliness and modernity. These preferences are reflected in the high scores on the "Chaotic-Orderly" scale for straight rapports across both floral and geometric patterns, and their high loadings on Factor 2.

This study also underscored the role of visual complexity in shaping aesthetic preferences. While simpler rapport formats were generally favoured, there was some appreciation for more dynamic designs that introduced an element of visual intrigue. The diagonal half-drop rapport, for instance, was perceived as a creative and engaging format (high loading on Factor 1: Creativity and Engagement) that still maintained a degree of order. However, more complex rapport formats, such as turned, were less favoured due to their perceived chaotic nature, particularly within geometric designs (high loading on Factor 3: Visual Complexity, but low on Factor 2: Order).

The findings of this study have important implications for designers working with repeating patterns. The consistent preference for straight and mirror rapports suggests that prioritising rapport formats that emphasise visual balance and clarity may be advantageous. However, incorporating more dynamic designs, such as diagonal half-drop, may be appropriate in contexts where the aim is to introduce subtle complexity without overwhelming the viewer. Furthermore, these findings extend beyond design aesthetics and have practical implications for the home textile industry. The preference for straight and mirror rapports aligns with market demand for structured and visually harmonious designs, potentially enhancing consumer satisfaction by providing a predictable and orderly aesthetic, thus reducing the likelihood of pattern rejection in commercial textile production. From a manufacturing perspective, the insights gained from this study can enrich design strategies for mass production. Straight and mirror rapports, being more structured and repetitive, are often easier to implement in both traditional and digital textile printing processes, minimising inconsistencies and facilitating seamless pattern alignment during production of bedding, curtains, and upholstery fabrics. Understanding consumer psychology and leveraging these preferences in product marketing and customisation strategies can further enhance product desirability. While simpler rapport formats appeal to a broader audience, incorporating dynamic rapport formats such as diagonal half-drop for niche markets (e.g., contemporary or avant-garde interior designs) may cater to consumers with a preference for unique and visually engaging textiles. Advancements in digital textile printing and customisation platforms offer opportunities to integrate these findings into design recommendation systems or AI-assisted pattern generators, potentially improving customer engagement and satisfaction. However, future research incorporating consumer preference surveys, sales data, and behavioural analysis could further validate the commercial impact of these design choices and inform more effective design and marketing strategies.

CONCLUSIONS

This study investigated the influence of rapport formats on aesthetic preferences in floral and geometric pattern designs, employing a combination of descriptive statistics and exploratory factor analysis. The analysis revealed three primary factors that shaped participants' perceptions of different rapport formats: Creativity and Engagement, Perceived Order and Simplicity, and Contemporary Appeal.

Across both floral and geometric designs, a consistent preference for straight and mirror rapports was observed. These formats were associated with higher scores in Perceived Order and Simplicity and Contemporary Appeal, indicating that participants valued visual balance, predictability, and a modern aesthetic. These rapports were particularly favoured for their ability to maintain visual harmony and clarity, making them suitable choices for designs that prioritise structure and balance.

Conversely, more dynamic rapport formats, such as diagonal half-drop and turned, were associated with higher levels of Creativity and Engagement but lower scores for Perceived Order, particularly in geometric designs. While visually intriguing, the turned rapport consistently received lower ratings due to its perceived complexity and lack of coherence, especially in geometric patterns where precision and symmetry are highly valued.

These findings offer several implications for designers working with repeating patterns in textiles and other design fields. The preference for rapport formats that provide structure and balance suggests that straight and mirror rapports are highly effective in creating aesthetically pleasing designs. However, incorporating more dynamic rapports, such as diagonal half-drop, may be appropriate in contexts where a moderate level of visual complexity is desired.

This study offers valuable insights, but several limitations should be noted. The expert-driven evaluations, while insightful, lacked direct consumer input, potentially limiting generalizability. Future research should incorporate consumer perceptions to validate the findings from a market-driven perspective.

Methodologically, exploring additional pattern categories beyond the floral and geometric patterns used, such as abstract, ethnic, or nature-inspired patterns, could reveal whether rapport preferences vary by pattern type. Further, while the monochrome palette isolated rapport format effects, future work should consider the impact of colour and texture interactions on aesthetic perception. The primarily Turkish sample introduces potential cultural biases in design preferences, necessitating a geographically diverse sample in future studies. Finally, further validation of the industrial applications, including market research and consumer testing, is recommended for valuable insights into real-world acceptance and purchase behaviour. Future research should also investigate demographic influences such as age, gender, and educational background on pattern perception and explore multi-sensory interplay between rapport formats, textures, and colour schemes, particularly within digital textile printing applications.

In conclusion, this study underscores the importance of rapport formats in shaping the aesthetic appeal of repeating patterns. A deeper understanding of the relationship between design elements and emotional responses can empower designers to make more informed decisions that align with consumer preferences, ultimately leading to more effective and visually appealing design outcomes.

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Perceptual evaluation of female trench coat design based on Quantitative Theory I

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ABSTRACT – REZUMAT

Perceptual evaluation of female trench coat design based on Quantitative Theory I

In the process of apparel design, understanding consumers' emotional demand is crucial to creating satisfactory garment styles. To solve the problem of the mismatch between consumers' personalised needs and the design of trench coat styles. This paper focuses on women's trench coats and proposes a style design research method that combines Quantification Theory I and Kansei Engineering. Initially, it employs the Semantic Difference Analysis Method to extract consumers' emotional evaluations of trench coat samples. Using SPSS software, it analyses the emotional ratings and identifies key emotional factors, constructing a two-dimensional emotional distribution map for trench coat styles. Simultaneously, it analyses style characteristics to extract the main design elements. Building on this, it integrates Quantification Theory I and performs linear regression, predicting relationships between emotional factors and design elements and establishing a mathematical model. This model exhibits a high degree of fit between measured and predicted values and adheres to normal distribution requirements, demonstrating its effectiveness. Ultimately, the study validates the mathematical model through real consumer design cases, further confirming that it can effectively translate consumers' emotional needs into trench coat design elements, thus providing significant insights and references for women's trench coat style design.

Keywords: *Quantitative Theory I, trench coat, Kansei Engineering, design element, factor, perceptual words*

Evaluarea perceptivă a designului trenciului de damă pe baza Teoriei cuantificării I

În procesul de proiectare a articolelor vestimentare, înțelegerea cererii emoționale a consumatorilor este esențială pentru crearea unor stiluri vestimentare satisfăcătoare. Pentru a rezolva problema nepotrivirii dintre nevoile personalizate ale consumatorilor și designul stilurilor de trenciuri, această lucrare se concentrează pe trenciurile de damă și propune o metodă de cercetare a designului stilistic care combină Teoria cuantificării I și ingineria Kansei. Inițial, utilizează metoda analizei diferențelor semantice pentru a extrage evaluările emoționale ale consumatorilor cu privire la mostrele de trenciuri. Folosind software-ul SPSS, analizează evaluările emoționale și identifică factorii emoționali cheie, construind o hartă bidimensională a distribuției emoționale pentru stilurile de trenciuri. Simultan, analizează caracteristicile stilului pentru a extrage principalele elemente de design. Pe baza acestui lucru, integrează Teoria cuantificării I și efectuează o analiză de regresie liniară, care prezice relațiile dintre factorii emoționali și elementele de design, stabilind un model matematic. Acest model prezintă un grad ridicat de potrivire între valorile măsurate și cele prevăzute și respectă cerințele de distribuție normală, demonstrând eficacitatea sa. În cele din urmă, studiul validează modelul matematic prin cazuri reale de design ale consumatorilor, confirmând în continuare că poate traduce în mod eficient nevoile emoționale ale consumatorilor în elemente de design ale trenciurilor, oferind astfel informații și referințe semnificative pentru designul stilului trenciurilor de damă.

Cuvinte-cheie: *Teoria cuantificării I, trenci, inginerie Kansei, element de design, factor, cuvinte perceptuale*

INTRODUCTION

In response to the ever-changing dressing requirements and fashion preferences of consumers, the application of Kansei Engineering in clothing design has gained notable attention [1–3].

Kansei Engineering [4], a theory exploring the relationship between human emotions, sensations, experiences, and product design, primarily aims to systematically capture and analyse consumers' emotional needs [5]. It transforms these needs into concrete design elements to organically integrate design with consumer demands [6]. In clothing design, the application of Kansei Engineering broadly covers various styles, including suits [7, 8], winter coats [9], sports lingerie and qipaos [10, 11], as well as multiple aspects like fabric, colour, patterns, and sizes [12–16]. However, despite its significant advantages, Kansei Engineering in clothing design faces limitations. This arises mainly because its research data relies predominantly on users' subjective evaluations [17–19], which can lack a degree of objectivity [20].

To overcome this limitation, this study introduces Quantitative Theory I. Through the application of mathematical models and statistical analysis tools, it constructs complex multidimensional models. This approach captures the intricate relationship between design elements and emotional needs more accurately [21, 22]. By effectively transforming consumer emotional needs into stylistic design factors, the theory reflects consumer expectations more realistically and promptly responds to market changes, providing strong support for adjustments in design and marketing strategies [23]. Some scholars have already combined affective engineering with Quantitative Theory I in the realms of patterns [24] and product design [22]. However, only a few scholars have applied it to research on clothing style design [23, 25].

Based on the current research status, this study focuses on the women's trench coat. Integrating affective engineering and Quantitative Theory I. First, it employs affective engineering to evaluate the emotional attributes of trench coat styles and constructs a two-dimensional quadrant distribution map of trench coat samples via factor analysis. Next, grounded in this foundation, it derives a mathematical predictive model for women's trench coat style design by incorporating Quantitative Theory I. Finally, it validates the reliability of this model through actual case studies, intending to provide valuable references for designers and enhance the market competitiveness of trench coat styles.

KANSEI ENGINEERING ANALYSIS

Collection sample and design element

A total of 189 images of women's trench coats were initially collected from Amazon's official website and the POP fashion trend forecasting platform. To ensure the accuracy and relevance of the data, five experts specialising in trench coat design and fashion trend analysis were invited to assist in the selection and refinement of the dataset. Each expert possesses over a decade of experience in apparel design or fashion research, providing valuable insights into the curation process. Following a rigorous evaluation, 30 representative trench coat styles were identified as the final study samples. In order to avoid differences in fabrics, materials, colours and patterns that may cause bias in the evaluation results of the questionnaire, the trench coat samples were transformed into pure black and white line drawings [26–27] and randomly arranged in one number, as shown in figure 1.

Trench coat style is mainly composed of external contours and internal details, through the research of clothing style literature and discussions with professional designers of trench coat, according to the morphological disassembling method to break down the trench coat style into different components and the

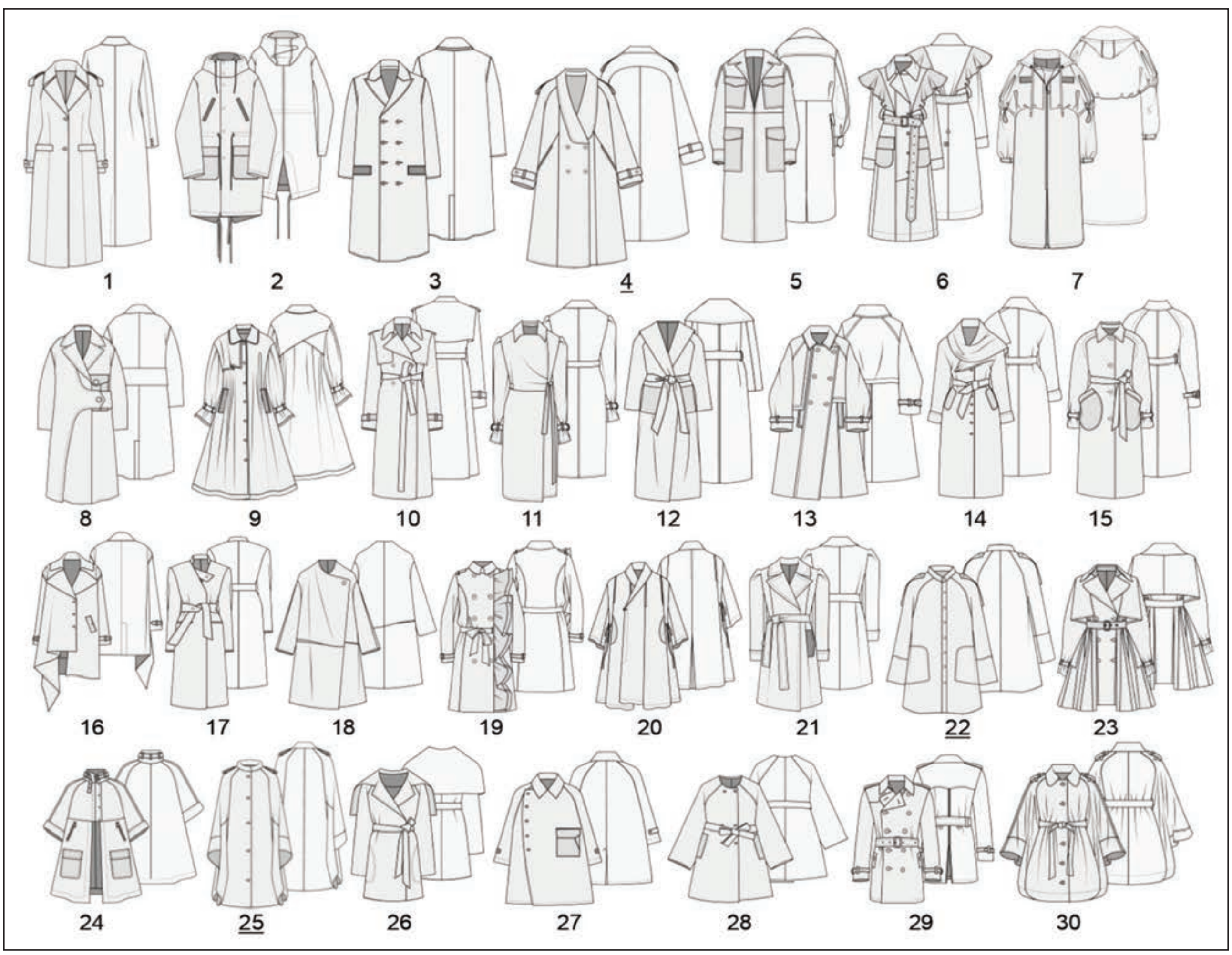

Fig. 1. Samples of women's trench coats

Table 1

DESIGN ELEMENTS OF A WOMAN'S TRENCH COAT					
Design elements	**Sub-elements**	**Design elements**	**Sub-elements**	**Design elements**	**Sub-elements**
silhouette (A)	H A_1		collarless C_9	length (G)	regular length G_1
	X A_2	sleeve (D)	straight sleeve D_1		medium length G_2
	A A_3		dropped shoulder D_2		long length G_3
size (B)	close-fitting B_1		darted head D_3	pocket (H)	flap pocket H_1
	easy fitting B_2		kimono sleeves D_4		patch pocket H_2
collar (C)	collar and rever with complete stand C_1		raglan sleeve D_5		insert pocket H_3
	classic gents collar C_2		flared raglan D_6		pocketless H_4
	classic reefer collar C_3	fastening method (E)	button E_1		multiple pocket combinations H_5
	shawl collar C_4		belt E_2	construction lines (I)	seams I_1
	stand collar C_5		zipper E_3		dart I_2
	hooded collar C_6	flap (F)	straight F_1		dart less I_3
	asymmetric collar C_7		slant F_2	yoke (J)	yoke J_1
	roll collar C_8		asymmetric F_3		yokeless J_2

corresponding modeling elements, and screen the decomposition of the elements, and ultimately determine the most representative of the trench coat design of the 10 main elements and 39 sub-elements, as shown in table 1.

Perceptual questionnaire design

By consulting relevant professional literature, apparel websites, and consumer reviews, eight perceptual words were identified as measurement scales. A 5-level semantic differential scale questionnaire was designed based on semantic differentiation. This scale was applied to assess the trench coat styles against the eight pairs of perceptual words, as shown in figure 2.

ANALYSIS OF RESEARCH FINDINGS

Validity and correlation analyses

Employed SPSS 26.0 software to conduct KMO and Bartlett's test of spherical on the average evaluation scores of perceptual words. The results indicated a KMO value of 0.712 (>0.7) and a Bartlett's test of sphericity with 28 degrees of freedom, yielding a significance P-value of 0.000 (<0.05). This demonstrates that the data analysis results are robust and that the original variables are appropriate for subsequent factor analysis [30]. Through Pearson correlation analysis, a correlation analysis matrix for perceptual words related to trench coats was obtained. In this matrix, higher absolute values of subjective scores indicate stronger correlations [30], for example, if the two perceptual terms "steady-vivid" and "mature-youthful" have the highest ratings in "vocational-casual", they show a high correlation with each other, indicating that trench coat styles with a sense of vocational bring an objective impression of steady and mature, while casual styles usually bring a young and energetic impression, as shown in table 2.

Factor analysis

Using principal component analysis to derive the total variance of the explanation of 8 pairs of perceptual words, 2 principal component factors were extracted, and the cumulative contribution rate reached 79.1%,

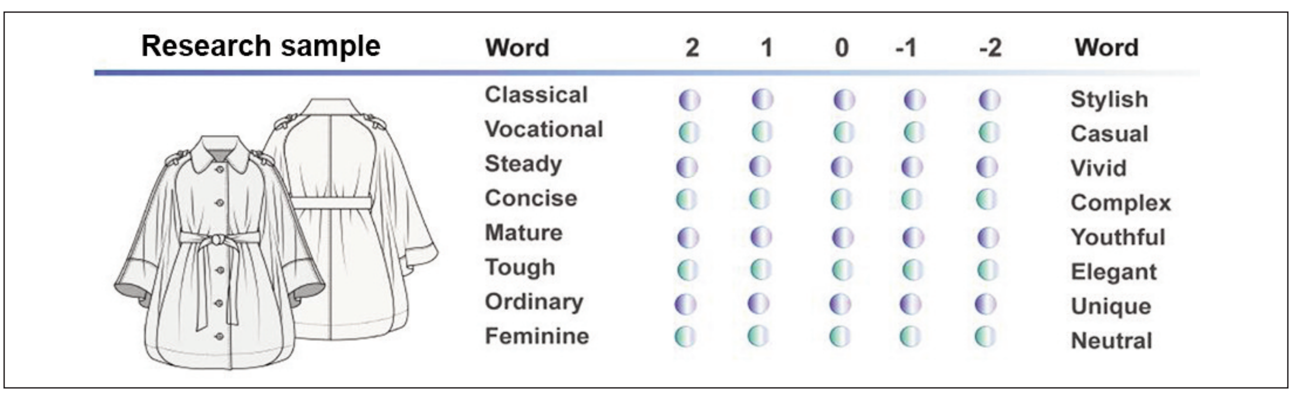

Fig. 2. 5-level semantic differential scale questionnaire

Table 2

CORRELATION ANALYSIS MATRIX								
Vocabulary	**Classical-stylish**	**Vocational-casual**	**Steady-vivid**	**Concise-complex**	**Mature-youthful**	**Tough-elegant**	**Ordinary-unique**	**Feminine-neutral**
Classical-stylish	1.000	0.561	0.762	0.580	0.666	0.457	0.910	–0.345
Vocational-casual	-	1.000	0.670	0.462	0.578	0.333	0.538	0.094
Steady-vivid	-	-	1.000	0.778	0.918	0.359	0.737	–0.180
Concise-complex	-	-	-	1.000	0.743	0.356	0.613	–0.201
Mature-youthful	-	-	-	-	1.000	0.157	0.675	–0.059
Tough-elegant	-	-	-	-	-	1.000	0.394	–0.774
Ordinary-unique	-	-	-	-	-	-	1.000	–0.228
Feminine-neutral	-	-	-	-	-	-	-	1.000

indicating that the majority of the original factor's eigenvalue information remains preserved [31]. This better reflects the meanings of the original adjectives, thereby effectively portraying the participants' emotional evaluations of samples, as shown in table 3.

Using the maximum variance method for orthogonal rotation, we derived the factor loading matrix after rotation, as shown in table 4. The perceptual words for Factor 1 include: "steady-vivid, mature-youthful, ordinary-unique, classical-stylish, concise-complex, and vocational-casual". The results indicate that these six pairs of perceptual words exhibit high loading on Factor 1 M_1, suggesting that a significant amount of variable information resides in the first principal component. Based on the meaning expressed by this factor, we named the first factor the Charm Factor M_1. In contrast, the pairs "feminine-neutral and tough-elegant" have high loading on Factor 2, which we named the second factor as the Personality Factor M_2.

Using multivariate regression analysis, we derived the factor score coefficients for two factors and established a factor score coefficient matrix for each factor [23]. This allows us to assess the linear relationship between each variable and the factors, thereby explaining the results of the factor analysis and

Table 3

THE PERCEPTUAL WORDS EXPLAIN THE TOTAL VARIANCE						
Vocabulary	**Initial eigenvalues**			**Extraction Sums of Squared Loading**		
	Total	**%of Variance**	**Cumulative%**	**Total**	**%of Variance**	**Cumulative%**
Classical-stylish	4.711	58.886	58.886	4.711	58.886	58.886
Vocational-casual	1.617	20.215	79.100	1.617	20.215	79.100
Steady-vivid	0.636	7.948	87.048	-	-	-
Concise-complex	0.545	6.812	93.860	-	-	-
Mature-youthful	0.274	3.425	97.286	-	-	-
Tough-elegant	0.100	1.247	98.532	-	-	-
Ordinary-unique	0.065	0.817	99.349	-	-	-
Feminine-neutral	0.052	0.651	100.000	-	-	-

Table 4

SPECIFIC FACTOR SCORE LOADING MATRIX						
LOAD MATRIX AFTER ROTATION				**FACTOR SCORE COEFFICIENT MATRIX**		
Factor name	**Perceptual words**	**M_1**	**M_2**	**Perceptual words**	**M_1**	**M_2**
Charm factor M_1	Steady-vivid	0.940	0.144	Classical-stylish	0.165	0.102
	Mature-youthful	0.919	–0.026	Vocational-casual	0.201	–0.114
	Ordinary-unique	0.830	0.273	Steady-vivid	0.225	–0.040
	Classical-stylish	0.818	0.366	Concise-complex	0.181	0.003
	Concise-complex	0.792	0.187	Mature-youthful	0.242	–0.135
	Vocational-casual	0.759	–0.027	Tough-elegant	–0.052	0.477
Personality factor M_2	Feminine-neutral	–0.007	–0.957	Ordinary-unique	0.180	0.048
	Tough-elegant	0.249	0.893	Feminine-neutral	0.123	–0.546

facilitating subsequent analysis and inference. The specific factor score loading matrix is shown in table 4.

Quadrant analysis

Based on the factor score coefficient matrix, we derive the calculation formulas for samples. The calculation method for M_1 is as shown in equation 1. The calculation method for M_2 is in equation 2. In these formulas, X_1 to X_8 represent the average semantic score of each woman's trench coat sample on the perceptual words, respectively.

$$F_1 = 0.165X_1 + 0.201X_2 + 0.225X_3 + 0.181X_4 + \\ + 0.242X_5 - 0.052X_6 + 0.180X_7 + 0.123X_8 \quad (1)$$

$$F_2 = 0.102X_1 - 0.114X_2 - 0.040X_3 + 0.003X_4 - \\ - 0.135X_5 + 0.477X_6 + 0.048X_7 - 0.546X_8 \quad (2)$$

In order to visualise the sample design characteristics, using the scores of Factor 1 as the horizontal coordinates and the scores of Factor 2 as the vertical coordinates, create a two-dimensional phase limit distribution diagram, as shown in figure 3.

As shown in figure 4, it is evident that styles in the first quadrant exemplify elegance and style. Their silhouettes primarily feature A and H shapes, with embellishments like ruffles and ties. The hemlines tend to showcase flowing, loose pleated designs that add a lively touch to the overall elegance. Style in the second quadrant is simple and ordinary, with a predominantly A-shaped silhouette, giving the impression of maturity and stability. In the third quadrant, trench coat styles present a more classic design, featuring straight H-shaped lines that convey a disciplined and professional image. Lastly, in the fourth quadrant, embody an avant-garde and casual aesthetic. Their silhouettes prioritise comfort and looseness, showcasing an overall youthful and lively style that incorporates unique asymmetric decorative segments and connections. This adds a tough feel to the design, ensuring that the garments remain both stylish and practical.

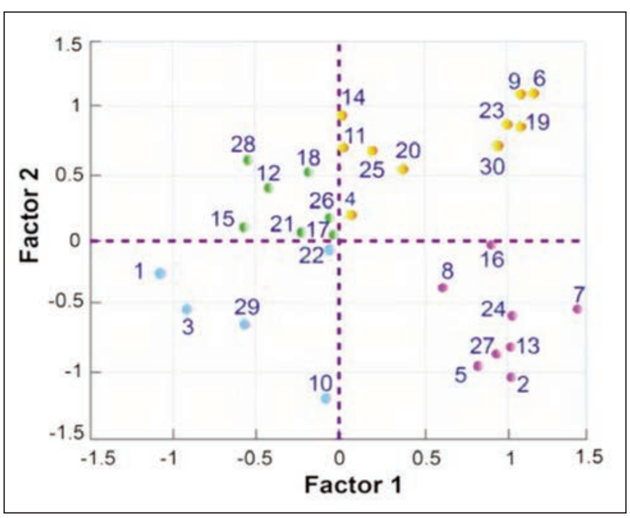

Fig. 3. Two-dimensional phase limit distribution diagram

CONSTRUCTION OF QUANTIFICATION THEORY I MODEL

Construction of a trench coat predictive model

Based on Quantitative Theory I, the study set the trench coat design elements as "items", the design sub-elements as "categories", and the perceptual word scores of samples as the baseline variable (y). Suppose there are m items, and the category of the i^{th} item is D_i, then for n samples, $y(n) = r_{ij}(n)$ is called the reaction of item i, category j in sample n, which can be obtained.

$$r_{ij} = \begin{cases} 1, \text{(the } n^{th} \text{ sample, the qualitative date of item } i \text{ is category } j) \\ 0, \text{(others)} \end{cases} \quad (3)$$

It is assumed that there is a linear relationship between the dependent variable and the response of each item and category object, then a mathematical model can be established [13]:

$$y(n) = \sum_{i=1}^{m} \sum_{j=1}^{D_i} r_{ij}(n)\, a_{ij} + \varepsilon_n \quad (4)$$

In the formula: $r_{ij}(n)$ only depends on the coefficient of category j of item i; a_{ij} is a quantitative representation of the fixed variable $r_{ij}(n)$; ε_n random error in the n^{th} sampling, and r_i denotes the number of classes in the i^{th} item [2].

Based on formula 3 and the sample shown in figure 1, this study matched design elements for 30 trench coats. If a sample possesses this item, it receives a value of 1; otherwise, it receives a value of 0. This established the corresponding trench coat reaction matrix, as shown in table 5.

With the ration matrix as independent variables and the evaluation value of perceptual words as dependent variables. Further utilise SPSS 26.0 to apply multivariate linear regression analysis on the developed mathematical model for an approximate solution. After eliminating ineffective variables, obtain specific results from the linear regression analysis, as shown in table 6. The item's partial correlation coefficient represents the correlation between various design elements and image adjectives. The sub-element scores indicate the association levels between the sub-elements of design elements and corresponding perceptual words, with positive and negative values indicating the direction of the associations.

In table 6, the partial correlation coefficient represents the degree of influence of design elements on the emotional factors. The category sub-element indicates the degree of influence of the subcategory of design elements on emotional factors, with the sign of the value indicating the direction of the influence. According to the constant terms and sub-element scores of each group's perceptual word, the multiple linear regression equation of the charm factor and personality factor can be obtained.

Table 5

REACTION MATRIX																		
Sample number	A_1	A_2	A_3	B_1	B_2	C_1	C_2	C_3	…	H_2	H_3	H_4	H_5	I_1	I_2	I_3	J_1	J_2
1	0	1	0	1	0	0	1	0	…	0	0	0	0	0	1	0	0	1
2	1	0	0	0	1	0	0	0	…	0	0	0	1	0	0	1	0	1
3	1	0	0	0	1	0	0	1	…	0	0	0	0	0	0	1	0	1
4	0	0	1	0	1	0	0	0	…	0	1	0	0	1	0	0	0	1
5	1	0	0	0	1	0	1	0	…	1	0	0	0	1	0	0	0	1
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
26	1	0	0	0	1	0	0	0	…	0	1	0	0	0	0	1	0	1
27	0	0	1	0	1	0	0	0	…	1	0	0	0	1	0	0	0	1
28	0	0	1	0	1	0	0	0	…	0	1	0	0	0	0	1	0	1
29	1	0	0	0	0	1	0	0	…	0	1	0	0	0	0	1	1	0
30	0	0	1	0	0	0	0	0	…	0	0	1	0	0	0	1	0	1

Table 6

ANALYSIS OF THE LINEAR RELATIONSHIP TO FACTOR 1							
Design elements	Sub element	Sub-element score	Partial correlation coefficient	Design elements	Sub element	Sub-element score	Partial correlation coefficient
A	A_1	–1.570	–0.471	D	D_5	–0.310	–0.216
	A_2	0.029			D_6	–0.017	
B	B_1	0.526	–0.097	E	E_3	0.653	0.338
	B_2	0.551			E_4	1.039	
C	C_2	0.231	–0.154	F	F_2	–0.375	0.351
	C_3	0.543			F_3	0.533	
	C_4	–0.144		G	G_1	0.101	–0.433
	C_5	–0.285			G_3	–0.085	
	C_6	1.068		H	H_1	–1.244	0.264
	C_7	–0.545			H_2	–0.146	
	C_8	0.210			H_4	–0.196	
	C_9	–0.570			H_5	–0.410	
D	D_2	–0.346	–0.216	I	I_3	0.659	–0.408
	D_3	–1.015					
	D_4	–0.382		J	J_2	–0.167	0.015
Constant term		Multiple correlation coefficient r			Coefficient of determination r^2		
0.308		0.949			0.891		

$$F_1 = 0.308 - 1.570A_1 + 0.029A_2 + 0.526B_1 + 0.551B_2 + 0.231C_2 + 0.543C_3 - 0.144C_4 - 0.285C_5 + 1.068C_6 - 0.545C_7 + 0.210C_8 - 0.570C_9 - 0.346D_2 - 1.015D_3 - 0.382D_4 - 0.310D_5 - 0.017D_6 + 0.653E_3 + 1.039E_4 - 0.375F_2 + 0.533F_3 + 0.101G_1 - 0.085G_3 - 1.244H_1 - 0.146H_2 - 0.196H_4 - 0.410H_5 + 0.659I_3 - 0.167J_2 \quad (5)$$

$$F_2 = 0.082 + 0.710A_1 + 0.671A_2 - 0.240B_1 - 0.865B_2 - 0.405C_2 + 0.301C_3 - 0.037C_4 - 0.249C_5 - 0.528C_6 + 0.101C_7 - 0.234C_8 + 0.491C_9 + 1.168D_2 - 0.367D_3 - 0.081D_4 + 1.123D_5 + 0.343D_6 + 0.155E_3 + 0.113E_4 + 0.440F_2 + 0.350F_3 - 0.044G_1 - 0.142G_3 + 0.198H_1 - 0.094H_2 + 0.620H_4 + 0.138H_5 - 1.203I_3 + 0.016J_2 \quad (6)$$

Model validation

The partial correlation coefficient and coefficient of determination indicate the responsiveness of the predictive model to the design elements of trench coat samples. Complex correlation coefficient $R=0.949$ and coefficient of determination $R^2=0.891$ for perceptual factor 1 (F_1); complex correlation coefficient $R=0.741$ and coefficient of determination $R^2=0.548$ for perceptual factor 2 (F_2); the complex correlation coefficients R of the two factors are greater than 0.5, and the coefficients of determination R^2 are greater

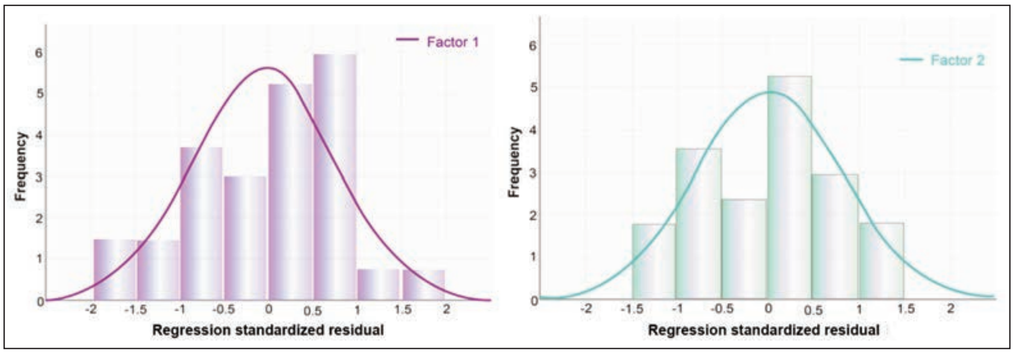

Fig. 4. Histogram of Normalised of the factors

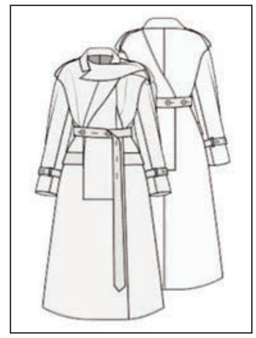

Fig. 5. Trench coat design drawings

than 0.25, which indicates that the prediction equations of two groups of image adjectives have a good degree of fit [26]. Hence, the correlation between the perceptual image of a trench coat and design elements can be analysed. Using SPSS to plot the histogram of normalized of the normalised factors, as shown in figure 4, reveals that the residual distribution adheres to the principles of normal distribution. Thus, the predictive model proves to be valid and feasible.

Application example validation

A woman's trench coat, designed with avant-garde style and unique features, integrates consumer demand. Figure 3 indicates that this style primarily occupies the fourth quadrant, characterised by a loose silhouette and an asymmetrical structure. The waist and cuffs incorporate adjustable fasteners, while the collar features a three-dimensional cape design. Overall, the trench coat exudes a distinct, fashionable flair. As shown in figure 5. Table 1 extracts the style elements of the trench coat, leading to the compilation of a style feature set U. Based on quantitative theory 1, the response matrix B for the trench coat design elements is computed as follows:

$$U = \{A_3, B_2, C_7, D_2, E_4, F_3, G_2, H_1, I_2, J_2\}$$

$$B = \{0,0,1,0,1,0,0,0,0,0,0,1,0,0,0,1,0,0,0,0,0,0,0, 1,0,0,1,0,1,0,1,0,0,0,0,0,1,0,0,0,1\}$$

Finally, by employing the predictive models developed from factor 1 and factor 2, the calculations yield $F_1 = 0.788$ and $F_2 = -0.04$. These factor scores correspond to the two-dimensional phase limit distribution diagram in figure 3, placing the trench coat in the fourth quadrant, which aligns with the avant-garde, unique, and casual style criteria. This evidence demonstrates that the mathematical model effectively matches and reflects consumer preferences for style, with high accuracy and validity.

$$F_1 = 0.308 + 0.551 + 0.545 - 0.346 + 1.039 + 0.533 - 1.244 + 0.659 - 0.167 = 0.788$$

$$F_2 = 0.082 - 0.865 + 0.101 + 1.168 + 0.113 + 0.350 + 0.198 - 1.203 + 0.016 = -0.04$$

CONCLUSION

This research analyses the mapping relationship between consumers' perceptual image and female trench coat design elements. With the help of Kansei engineering to determine the research sample of trench coat, to obtain the perceptual evaluation and characteristics of the style, and further combined with the research method of quantitative theory I, the conclusion is as follows: Factor analysis reveals two main components, "charm factors" and "personality factors". Subsequently, a two-dimensional phase limit distribution diagram is constructed. Combined with the quantitative theory I, a female trench coat style prediction model is constructed. The model is validated through actual cases. The results show that the model can effectively realise the conversion between consumers' perceptual needs and the design elements with high accuracy and credibility. Through Kansei engineering and quantitative theory, the mathematical prediction model can match and validate the perceptual styles in the form of mathematical formulas, which can help enterprises efficiently integrate the design elements styles and users' perceptual needs, at the same time, reduce the ambiguity and subjectivity in the process of designing, to more efficiently design trench coat styles to meet the customers' perceptual needs.

By combining Quantitative Theory I with Kansei Engineering, this study proposes an innovative research framework that quantitatively reveals the relationship between emotional factors and trench coat design elements, thereby deepening the understanding of consumers' emotional needs. Compared with traditional sentiment analysis methods [8, 10], this approach more precisely quantifies the association between emotional needs and design elements, bridging the gap between subjective emotional assessment and the objective design process. As a result, it enables designers to predict consumer preferences more effectively. The applicability of affective design principles is further validated through real consumer case studies [23], addressing the mismatch between individualised consumer needs and trench coat style design [28]. However, early studies often failed to account for the diversity of individual consumer preferences [33]. By establishing a quantitative theoretical model to address the limitations of previous Kansei Engineering research, this study more accurately reflects the emotional needs of different consumer groups and enhances the scientific rigour and practicality of design decision-making.

This study fails to adequately explore the preferences of different consumer groups for trench coat styles. There are significant differences in aesthetic standards, style preferences and acceptance of design elements among different groups of consumers. Factors such as consumers' age, body type, personality, and income play a key role in choosing trench coat styles. Future research should focus on segmenting the consumer market and exploring how these factors influence consumers' choice of trench coat styles, to provide consumers with more precise and personalised style design choices. In addition, this study focused on the trench coat as a clothing category and used a uniform treatment of fabric texture and colour grayscale. However, there is a high degree of diversity in the styles, patterns, colours, and fabric types of trench coats in the market. Therefore, future research could extend to other apparel types and introduce more design elements, such as pattern, fabric material, and colour, to explore the effects of these factors on the perceptual evaluation of styles. Future research should further fine-tune the analysis of the role of these design elements on consumer preferences to fully understand the style needs of consumer groups. This will help develop design strategies and theoretical models that are more in line with market demands and adapt to changes, which will not only provide the apparel industry with a more accurate framework for design decisions but also provide designers with more precise and personalised design strategies.

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The effect of fabric parameters on the evaporative cooling heat flow kinetics

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ABSTRACT – REZUMAT

The effect of fabric parameters on the evaporative cooling heat flow kinetics

This study explored how fabric parameters and walking speed affect the dynamics of evaporative cooling. Walking speed is equivalent to 1 m/s, while running speed is 2 m/s. Knitting fabrics made from natural and synthetic fibres were used to examine how hydrophilic and hydrophobic properties influence evaporation. Visualising the evaporative cooling heat flow kinetics allowed us to identify different evaporation stages. We defined new parameters: Q_{max}, Q_{min}, Q_{eq}, Flow drop ($Q_{max} - Q_{min}$), and equilibrium time. Q_{max} represents the thermal absorptivity of water vapour at the very first moment of contact between the fabric and the skin. Q_{min} signifies the decrease in the cooling flow. T_{eq} denotes the equilibrium time. These parameters describe the dynamics of water vapour transfer.

The results showed that incorporating synthetic fibres into a fabric enhances its breathability, lowers the temperature, accelerates drying, and provides a refreshing sensation when first touched by the skin. It was found that Coolmax is twice as cool as wool.

Keywords: *walking speed, evaporation, cooling, dynamic heat flow*

Efectul parametrilor materialului textil asupra cineticii fluxului de căldură în răcirea prin evaporare

Acest studiu descrie modul în care parametrii materialului textil și viteza de mers afectează dinamica răcirii prin evaporare. Viteza de mers este echivalentă cu 1 m/s, în timp ce viteza de alergare este de 2 m/s. Au fost utilizate tricoturi din fibre naturale și sintetice pentru a examina modul în care proprietățile hidrofile și hidrofobe influențează evaporarea. Vizualizarea cineticii fluxului de căldură al răcirii prin evaporare a permis identificarea diferitelor etape de evaporare. Au fost definiți noi parametri: Q_{max}, Q_{min}, Q_{eq}, scăderea fluxului ($Q_{max} - Q_{min}$) și timpul de echilibru. Q_{max} reprezintă absorbția termică a vaporilor de apă în primul moment de contact între materialul textil și piele. Q_{min} semnifică scăderea fluxului de răcire. T_{eq} denotă timpul de echilibru. Acești parametri descriu dinamica transferului vaporilor de apă.

Rezultatele au arătat că incorporarea fibrelor sintetice într-un material îmbunătățește respirabilitatea acestuia, scade temperatura, accelerează uscarea și oferă o senzație de răcorire la primul contact cu pielea. S-a constatat că Coolmax este de două ori mai răcoros decât lâna.

Cuvinte-cheie*: viteza de mers, evaporare, răcire, flux de căldură dinamic*

INTRODUCTION

The evaporation cooling mechanism is utilised in various applications, such as sportswear, outdoor clothing and protective garments designed for hot environments. The cooling of textile materials through heat flow relies on multiple mechanisms to regulate heat transfer and diffuse cooling [1]. Consequently, water vapour transfer is crucial in textile design [2]. The necessity to consider moisture transfer through textiles stems from the continuous loss of water from the human body [3], primarily through evaporation from the skin [4, 5]. The evacuation of water vapour through clothing is essential for maintaining body temperature balance and comfort. The textile fabric must facilitate the rapid removal of sweat through diffusion and evaporation into the ambient air [6–8]. Extensive research has been conducted on the mechanisms of water vapour transfer through textile fibres [9–11], single fabrics [12–16], double-faced fabrics [17, 18], multilayers [19, 20], and garment assemblies [21–23]. However, the majority of this research has been conducted under static conditions, where equilibrium conditions have been assumed, with limited work being done under dynamic conditions. Dynamic testing is necessary because water vapour transfer is strongly correlated with water vapour diffusion in fibres and condensation in pores, and is time-dependent [24, 25]. Several methodologies and test conditions have been developed to assess the moisture transfer capabilities of textile materials. Although each test method closely approximates real-world conditions, none can fully replicate the intricate process [26]. The measurements of water vapour transfer phenomena through textile fabrics, following ISO 11092, solely consider the steady state. Consequently, all values presented are static modes. This limitation prevents the simulation of actual functional textile usage conditions.

Therefore, comprehending the dynamic interaction of cooling heat flow is paramount to designing and developing a cooling comfort system that balances temperature and humidity. This ensures optimal well-being and performance during intense physical activity or in hot and humid environmental conditions. The kinetics of the cooling evaporative heat flow during evaporation were the subject of investigation in this study. Consequently, the Permetest was employed to elucidate and visualise the dynamics of the cooling evaporative heat flow. The findings revealed that the incorporation of elastane resulted in a reduction in the cooling effect of the fabrics. Three distinct phases were observed in the kinetics of the cooling evaporative heat flow: the initial phase, characterised by a peak heat flow (Q_{max}), which corresponds to the initial contact properties of the textile material with the skin. The subsequent phase represents a transition phase during which the cooling heat flow decreases to its minimum value (Q_{min}) and subsequently reaches equilibrium (Q_{eq}), marking the commencement of the third phase, characterised by a constant heat flow.

MATERIALS AND METHODS

Five simple Jersey samples with different material compositions (Natural and synthetic) were used in this study.

The mass per unit area of the fabric was determined using the standard ISO 3801:1977. The ISO 5084 standard was used to measure the thickness of fabric samples. According to ISO 9237, air permeability in the transverse direction was measured using the FX3300 (Textest, Switzerland) under a pressure of 100 Pa [27].

Total porosity (ε) is defined as the volumetric ratio of accessible pores to the total volume. The porosity values were calculated using the following equation:

$$\varepsilon_{Total}(\%) = \left(1 - \frac{M}{\rho \times t_h}\right) \times 100 \qquad (1)$$

This parameter can be expressed as a function of the mass per unit area (M), the thickness of the fabric (t_h), and the density of the fibre (ρ) [28].

Before testing, all samples were scoured with non-ionic synthetic detergents (1.5–2 g/l) and alkali (0.5–1.5 g/l sodium carbonate) using a RELAXLAB according to the standard NF G 07 102. Knitted structures, material weights, thicknesses, and porosity are listed in table 1.

The evaporative cooling heat flow was visualised using the Permetest instrument. The water vapour resistance, Ret, and the relative water vapour permeability of the tested fabrics were also expressed in the units defined in ISO 11092 [31] using the same instrument.

All tests were conducted under standard atmospheric conditions of 20±2 °C and 65±4 % of relative humidity, as per ISO 139:2005 [32].

RESULTS AND DISCUSSION

Based on table 1, the two samples, PET and PET/EL (with 10% elastane), have respectively a mass per unit area of 180 and 200 g/m^2, and an almost identical thickness of approximately 0.571 and 0.591 mm. Elastane influences the bulk density, thereby affecting the porosity of the sample. The total porosity of the 100% polyester knit is 75.30±1.2%, while the 90% polyester/10% elastane sample has a porosity of 77.32±1.5%. Cotton and wool knits with discontinuous yarns and short fibres can potentially inhibit the flow of air and water vapour [29, 30].

The water vapour resistance values of different tested samples are presented in table 2.

In the case of wool fabric, the water vapour resistance was about 8.088 m^2·Pa/W, with a standard deviation of 0.528 m^2 Pa/W and a CV of 6.52%, and 7.004 m^2·Pa/W, with a standard deviation of

Table 1

KNITTING FABRICS PROPERTIES

Sample	PET	PET/EL	CoolMax	Cotton	Wool
Composition	100% PET*	90% PET/ 10% EL*	100% CoolMax	100% Cotton	100% Wool
Wales/cm	20±1	22±1	14±1	25 ±1	18 ±1
Courses/cm	12±1	20±1	30±1	22±1	18±1
Mass per unit area (g/m²)	180±1	200±2	180.58	175±1	220±2
Thickness (mm)	0.571±0.01	0.591±0.01	0.412±0.01	0.766±0.01	1.037±0.02
Total porosity (%)	75.30±1.2	77.32±1.5	86.46±1.2	85.26±2.3	80.71±3.2
Air permeability (mm/s)	1442±12	367±06	693.4±11	1168±23	280.3±10

Note: *PET (Polyester); EL (Elastane).

Table 2

WATER VAPOUR RESISTANCE AT DIFFERENT WALKING SPEEDS

Sample	PET		PET/ EL		CoolMax		Cotton		Wool	
Walking Speed (m/s)	1	2	1	2	1	2	1	2	1	2
RET (m^2·Pa/W)	2.9±0.1	2.5±0.2	2.4±0.1	1.7±0.2	2.3±0.1	1.4±0.1	3.2±0.2	3.0±0.4	8.0±0.8	7.0±1

0.481 $m^2 \cdot Pa/W$ and a CV of 6.87%, for walking speeds of 1 m/s and 2 m/s, respectively.

For cotton, the average RET value is 3.240 $m^2 \cdot Pa/W$ with a standard deviation of 0.093 $m^2 \cdot Pa/W$ and a CV of 2.87%, under a walking speed of 1 m/s and 3.041 $m^2 \cdot Pa/W$ with a standard deviation of 0.197 $m^2 \cdot Pa/W$ and a CV of 6.49%, under a running speed of 2 m/s.

In the case of walking (1 m/s), the water vapour resistance of PET had an average value of 2.990 $m^2 \cdot Pa/W$ with a standard deviation of 0.113 $m^2 \cdot Pa/W$ and a CV of 3.77%. In the case of running (2 m/s), the average value of 2.502 $m^2 \cdot Pa/W$ with a standard deviation of 0.066 $m^2 \cdot Pa/W$ and a CV of 2.65% was noticed.

It was noticed that the CoolMax fabric was the most comfortable as it has the lowest water vapour resistance values under different walking speeds. In fact, in the case of walking, the RET was about 2.33 $m^2 \cdot Pa/W$ with a standard deviation of 0.272 $m^2 \cdot Pa/W$ and a CV of 2.33% and 1.42 $m^2 \cdot Pa/W$ with a standard deviation of 0.103 $m^2 \cdot Pa/W$ and a CV of 1.42% for walking speeds of 1 m/s and 2 m/s, respectively.

Evaporative cooling heat flow kinetics

In this section, the evaporative cooling heat flow kinetics of Wool, CoolMax, PET, PET/EL, and Cotton samples were visualised under a walking speed of 1 m/s.

From figure 1, at t = 0 s, the heat flow recorded a maximum value and then decreased until reaching an equilibrium state for all studied samples. This result is explained by the fact that at t = 0 s, the temperature of the tested sample is equal to the laboratory temperature (20°C – 22°C), which is higher than the temperature of the semi-permeable membrane of the Permetest instrument measuring unit. This temperature difference explains the decrease in heat flow in the measuring unit. Indeed, this transferred heat accompanied by water vapour passes through the semi-permeable membrane until reaching a thermal balance of the microclimate existing between the membrane and textile fabric.

The mass and heat diffusion through the knit depend on the material type used. It is noted that CoolMax is the most comfortable by recording an evaporative cooling flow of the order of 142 W at t = 0 s, and throughout the evaporation, this flow always remains higher than that of the other samples. The cooling heat flow in the case of the natural fibre of 100% wool is the most remarkable. Indeed, the cooling heat transferred ($Q_{max} – Q_{min}$) through this knit is equal to 37.8 W, which is the most important value transferred during a longer period of 30.6 s. Furthermore, in the case of 100% cotton fabric, a cooling-heating flow of 22.5 W was transferred in 7.5 s. This transferred heat is less significant compared to that diffused through the 100% polyester knit (25.0 W for 5.5 s). However, the heat transferred through the knit composed of

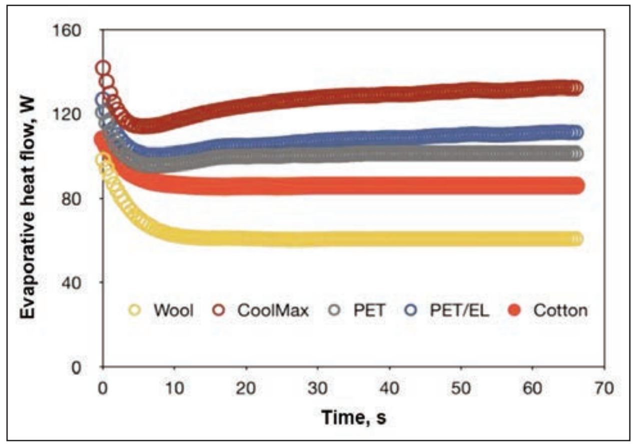

Fig. 1. Evaporative cooling heat flow kinetics under a walking speed of 1 m/s

90% polyester and 10% elastane (26.3 W for 6.5 s) is greater than that transferred through the 100% polyester sample.

Regarding the equilibrium time, the cotton sample reached equilibrium for 10 seconds more rapidly than other samples, but recorded an equilibrium cooling heat flow of about 86 W, which is less important compared to samples composed of synthetic fibres. The cotton fibre absorbs water vapour rapidly but dries slowly, which slows down the water vapour diffusion. The same phenomenon was noticed in the case of the wool fabric, where equilibrium was reached at 60.7 W for 32 s. Contrarily, in the case of fabrics made with synthetic fibres, the equilibrium values of cooling and heating flow were greater than 100 W. These results are explained by the fact that in CoolMax, PET, and PET/EL samples, water molecules are not absorbed by polyester and elastane fibres due to their hydrophobic behaviour.

When the relative humidity of the microclimate, existing between the membrane and the fabric, increases and the diameter of the pores is small, the diffused water will be adsorbed on the solid surface of the pores under the influence of the physical forces of Van der Waals. Subsequently, multimolecular water layers will be formed until condensation by a liquid bridge connection separates the gas phase by a meniscus (figure 2). The smaller the diameter of the pores, the greater the capillary condensation, which explains the high flow of PET/EL knitting compared to that of PET. This is because the incorporation of elastane yarn into the knitting leads to a reduction in its porosity.

In contrast, fabrics composed of hydrophilic fibres, such as wool and cotton, rapidly absorb water due to their polar groups. As the relative humidity in the microclimate between the membrane and the sample increases, water vapour molecules are adsorbed and subsequently diffused through the fibre substrates (figure 2). This process leads to sample swelling, resulting from the breaking of hydrogen bonds in the amorphous zones and the formation of hydrogen bonds with the diffused water molecules constrained by temperature and pressure. The higher the humidity, the greater the likelihood of saturation of the sample with water vapour. The diffusion step is followed by the evaporation of water vapour from the upper surface of the sample held on the semipermeable membrane and exposed to an air speed of 1 m/s. Surface evaporation is dependent on the thermal resistance of the sample. For instance, the evaporation rate on the surface of a 100% wool knit is negligible or even low. This is attributed to the high thermal resistance of the wool fibre (thermal insulator), which prevents the diffusion of water molecules within the structure, hindering liquid transport. Consequently, the slow cooling of wool from the outer surface to the inner surface observed in front of the semipermeable membrane, as indicated by the Permetest measuring unit, can be attributed to this factor. However, as depicted in figure 1, the thermal equilibrium in the cases of CoolMax, PET, and PET/EL knits is followed by a significant increase in the heat flow measured in the unit compared to that observed in the cases of the 100% wool and 100% cotton samples.

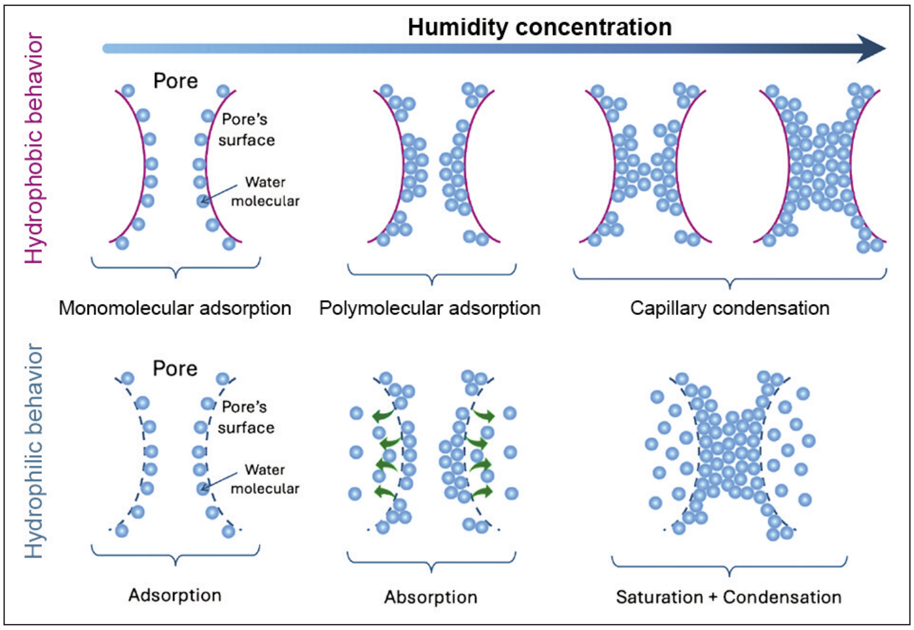

Fig. 2. Water vapour diffusion through pores in hydrophilic and hydrophobic materials

This is because CoolMax, PET, and PET/EL knits have low thermal resistance, facilitating the rapid transport of liquid. This ensures the cooling effect on both the upper and lower sides of the sample.

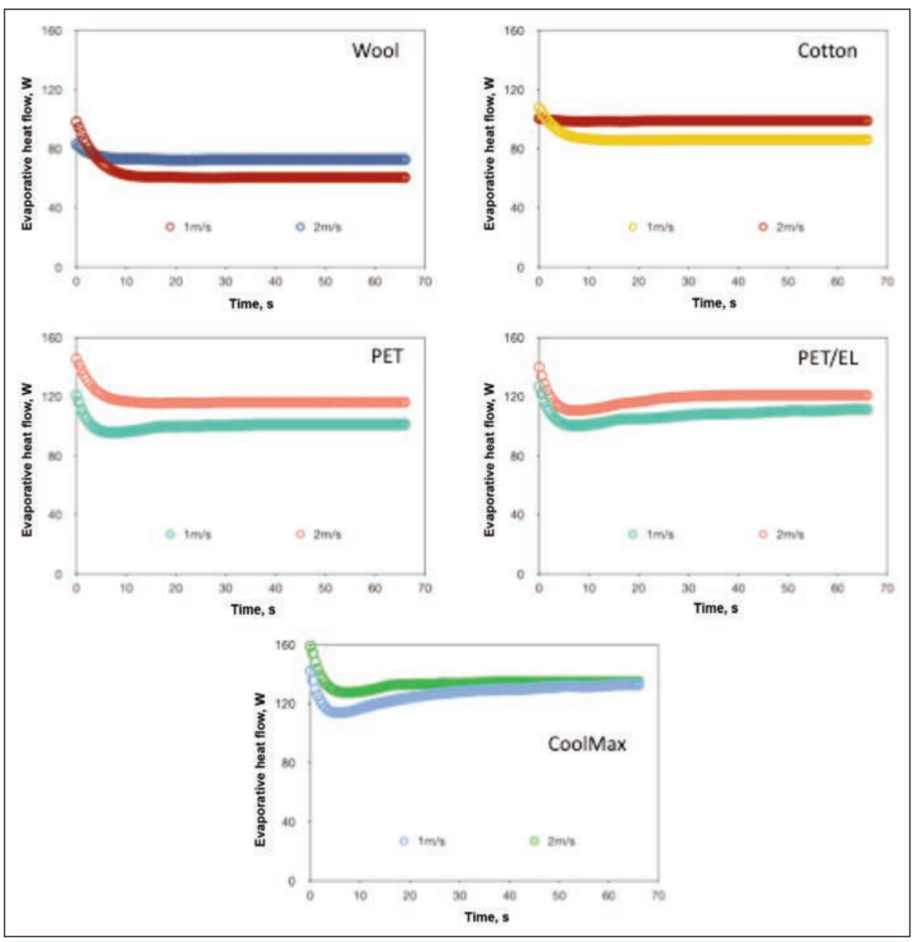

Fig. 3. The effect of walking speed (1 m/s et 2 m/s) on the evaporative cooling heat flow

Effect of walking speed on the evaporative cooling heat flow

In this section, the evaporative cooling heat flow of various used samples under different air speeds (1 m/s and 2 m/s) was represented to investigate the impact of walking speed on the heat flow traversing textile fabrics (figure 3).

Figure 3 depicts evaporative cooling heat flow kinetics during the water vapour resistance test of the tested knitted fabrics at two distinct air speeds (1 m/s and 2 m/s). The two curves representing the heat flow of the wool knitted fabric during the two different speeds exhibit a decreasing trend. Notably, at an air speed of 1 m/s, the curve started at 98.2 W at 0 s and subsequently reached a constant flow of 60.7 W after 32.0 s. Conversely, at an air

Table 3

EVAPORATIVE COOLING HEAT FLOW CHARACTERISTIC PARAMETERS							
Sample			**Q_{max} (W)**	**Q_{min} (W)**	**$Q_{max} – Q_{min}$ (W)**	**Q_{eq} (W)**	**T_{eq} (s)**
Wool	Walking speed(m/s)	1	98.2±8.2	60.4±5.7	37.8±4.3	60.7±5.4	32±3.2
		2	82.9±9.1	72.5±8.2	10.4±2.9	72.8±7.8	26.5±2.5
Cotton		1	108±7.2	85.4±5.6	22.5±1.6	86±5.7	10±1.1
		2	100.6±8.3	98.3±6.7	2.3±1.2	98.9±6.6	11.5±1.7
PET		1	120.8±9.4	95.7±7.6	25±2.1	101.2±8.3	36.5±2.4
		2	145.7±10.3	115.3±8.1	30.4±2.3	116.1±8.4	29±2.8
PET/EL		1	126.8±8.5	100.5±6.6	26.3±1.8	111.2±7.3	58±3.2
		2	140±9.6	110.6±7.8	29.4±2.1	120.9±8.6	40±3.6
CoolMax		1	141.9±11.3	114±8.9	27.8±2.2	132.4±10.3	62.5±4.5
		2	159±12.7	127.3±10.3	31.7±2.6	134.6±10.8	36.5±4.1

speed of 2 m/s, the curve commences at 82.9 W at 0 s and attains a constant flow of 72.8 W after 26.5 s. These observations can be attributed to increased airspeed leading to a concomitant rise in surface evaporation through the wool knitted fabric. This phenomenon results in a faster cooling rate, consequently facilitating an enhanced evaporation rate within the measurement unit. However, heat transfer through the wool sample remains predominant due to the inherent thermal resistance of wool.

The same phenomenon was noticed in the case of the cotton sample. Under 1 m/s of airspeed, the maximum evaporative cooling heat flow was 108.2 W at 0 s and subsequently reached an equilibrium heat flow of 86 W after 10 s. While at an airspeed of 2 m/s, a maximum heat flow of 100.6 W at 0 s was registered and reached a constant flow of 98.9 W after 11.5 seconds. So, it could be stated that the cotton has a lower permeation of water vapour. In fact, as the cotton absorbs the water vapour particles, leading to condensation and saturation in the pores and swelling, it will inhibit the water vapour diffusion. So, the cooling by evaporative flow will be altered.

When comparing the evaporative cooling heat flow at different walking speeds, in the case of running (air speed = 2 m/s), all fabrics were more permeable to water vapour, indicating greater evaporative cooling heat flow caused by the increase in the water vapour particles' mobility compared to walking speed (air speed = 1 m/s).

As illustrated in figure 3, the cooling heat flow curves for synthetic fibres such as CoolMax, PET, and PET/EL exhibit a higher value at an air speed of 2 m/s compared to 1 m/s. These findings demonstrate that the air flow speed within the ventilation channel serves as a variable that influences the shape of the heat flow. Consequently, an increase in the air speed leads to a heightened mobility of water vapour particles. This, in turn, results in an increase in the transferred water vapour amount through the polyester sample, thereby facilitating a faster cooling rate of the textile fabric. However, the low thermal resistance of these synthetic fibres facilitates an enhanced heat transfer, which ultimately dominates the evaporation process, leading to a state of thermal equilibrium.

Based on figure 3, the characteristic parameters of the evaporative cooling heat flow were determined as presented in table 3.

The new comfort parameters characterising the dynamics of water vapour transfer are presented in table 3. Here, Q_{max} characterises the thermal absorptivity of water vapour at the first instant of contact of the fabric with the skin. Q_{min} reflects the drop in the cooling flow. In addition, this drop is significant and rapid; the less thermally resistant the sample is, the greater the drop. The Q_{eq} presents the cooling flow at equilibrium; for more comfort, we seek that this value is the most important. In terms of equilibrium time (T_{eq}), a more comfortable sample must have a faster cooling flow stabilisation time, which allows a faster regulation of the microclimate and maintains a state of equilibrium of the thermal balance.

CONCLUSION

The impact of walking speed on the dynamics of evaporative cooling heat flow was investigated in this study. Visualisation of the cooling evaporative heat flow enabled the study of its kinetics during natural evaporation. This study demonstrated that synthetic fibres provide greater comfort from the perspective of water vapour transfer, offering a more refreshing sensation for the wearer. Increased walking speed leads to an enhancement in the mobility of water vapour particles, resulting in improved cooling generation through evaporation.

New comfort parameters based on heat flow kinetics: Q_{max}, Q_{min}, Q_{eq}, Flow drop ($Q_{max} – Q_{min}$), and equilibrium time were introduced. These parameters compare water vapour transfer dynamics. Where Q_{max} represents the thermal absorptivity at initial contact. Q_{min} represents a rapid cooling flow drop, lower thermal resistance, greater drop. Q_{eq} defines the cooling flow at equilibrium, higher for enhanced comfort.

represents the thermal absorptivity at initial contact. Q_{min} represents a rapid cooling flow drop, lower thermal resistance, greater drop. Q_{eq} defines the cooling flow at equilibrium, higher for enhanced comfort. T_{eq} states the faster cooling flow stabilisation time for quicker microclimate regulation and thermal equilibrium.

Future frameworks will be constructed on how external factors, such as temperature and relative humidity, affect the dynamics of the cooling heat flow.

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Optimisation of combed yarn properties based on yarn number and machine jaw range using artificial neural networks

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BEKIR YITIK

ABSTRACT – REZUMAT

Optimisation of combed yarn properties based on yarn number and machine jaw range using artificial neural networks

The need for natural clothing is increasing day by day. To meet this demand, the apparel industry is developing new systems to enhance production and raw material usage. Using healthy products is essential for a healthy life, which increases the need for natural raw materials. Cotton is the ideal natural raw material for a renewable and sustainable production line. Despite the growing production, it cannot fully meet the demand. Therefore, new systems are being developed to improve the quality of cotton production. The foundation of the textile industry is yarn, and yarn production lines consist of systematically operated machines. These production systems include carded, combed, and open-end methods. In combed production, high-quality and long fibres are used to produce yarns with counts such as Ne 30 or Ne 50. In combed yarn production, fibre length and ratio can be adjusted through machine settings. Lap feeding cylinder gaps in combed yarn machines are critical for this adjustment. In this study, experimental results were obtained using 4 different yarn counts produced from the same blend and 5 different combed feeding jaw settings. These results were optimised using artificial neural networks. In the analysis, yarn count and combing cylinder gap were used as input data, while the physical properties of the yarn were used as output data.

Keywords: *combed yarn, natural raw materials, fibre length, artificial neural network, optimisation*

Optimizarea proprietăților firelor pieptănate pe baza numărului de fire și a intervalului fălcii de fixare al mașinii, utilizând rețele neuronale artificiale

Nevoia de îmbrăcăminte naturală crește pe zi ce trece. Pentru a satisface această cerere, industria de îmbrăcăminte dezvoltă noi sisteme pentru a îmbunătăți producția și utilizarea materiilor prime. Utilizarea produselor calitative este esențială pentru o viață sănătoasă, ceea ce crește nevoia de materii prime naturale. Bumbacul este materia primă naturală ideală pentru o linie de producție regenerabilă și durabilă. În ciuda producției în creștere, acesta nu poate satisface pe deplin cererea. Prin urmare, se dezvoltă noi sisteme pentru a îmbunătăți calitatea producției de bumbac. Baza industriei textile este dată de fire, iar liniile de producție a firelor constau în mașini operate sistematic. Aceste sisteme de producție includ metode de cardare, pieptănare și open-end. În producția de fire pieptănate, se utilizează fibre de înaltă calitate și lungi pentru a produce fire cu finețe Ne 30 sau Ne 50. În producția de fire pieptănate, lungimea și raportul fibrelor pot fi ajustate prin setările mașinii. Distanțele dintre cilindrii de alimentare în mașinile de filare a firelor pieptănate sunt esențiale pentru această ajustare. În acest studiu, rezultatele experimentale au fost obținute utilizând 4 tipuri de finețe produse din același amestec și 5 setări diferite ale fălcilor de fixare a mașinilor de filare a firelor pieptănate. Aceste rezultate au fost optimizate utilizând rețele neuronale artificiale. În analiză, finețea firelor și distanța dintre cilindrii de pieptănare au fost utilizate ca date de intrare, în timp ce proprietățile fizice ale firului au fost utilizate ca date de ieșire.

Cuvinte-cheie: *fire pieptănate, materii prime naturale, lungimea fibrei, rețea neuronală artificială, optimizare*

INTRODUCTION

Ready-to-wear products designed to meet the growing demand for clothing in the 21st century are often questioned in terms of quality due to their mass-production nature. While the apparel industry has made significant advancements by improving existing production systems, these innovations have also led to a shift in raw material usage, moving from natural fibres to artificial fibres to boost production. Despite the availability of artificial fibres, consumer preference remains inclined toward natural fibres due to their perceived health benefits and sustainability.

In the production of natural fibres like cotton, optimising machinery and production settings plays a critical role in reducing waste and improving efficiency. Each type of yarn requires distinct machine settings tailored to its specific production parameters. These settings are influenced by the quality and properties of the raw cotton used [1, 2].

Different types of defects arise in various yarn production systems, including carded, combed, and open-end spinning. Among these, the combed cotton production line stands out for its ability to produce fine and high-quality yarns. This system utilises long fibres, selected through precise fibre scanning, to manufacture thin-count yarns. The combing system,

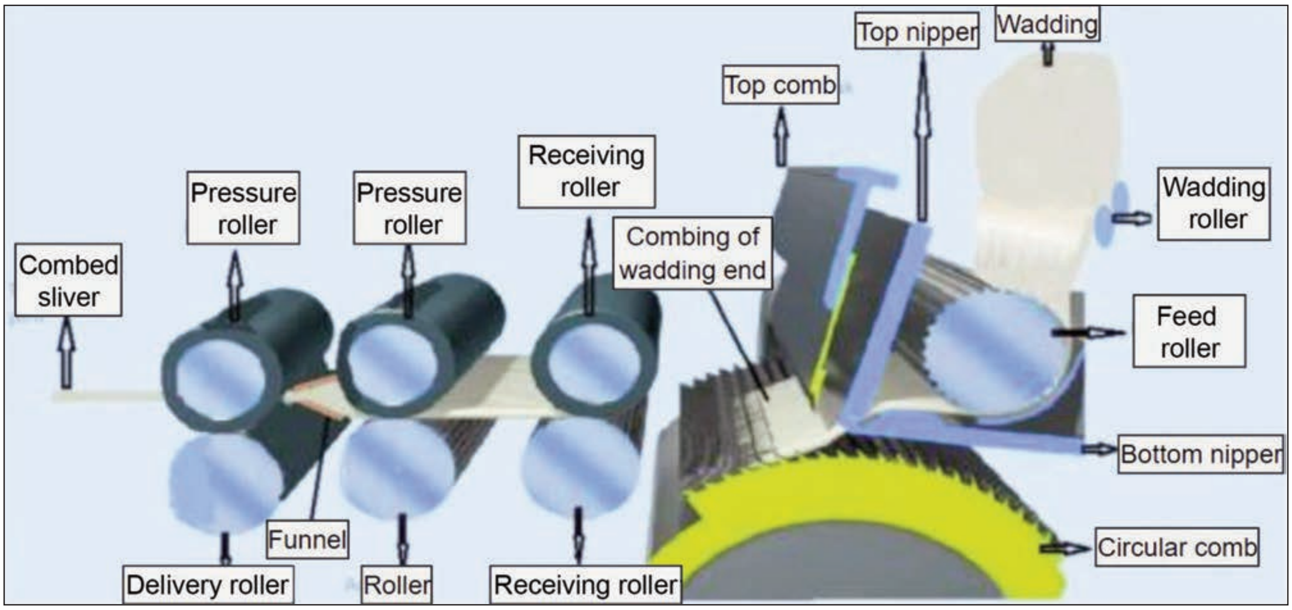

Fig. 1. Combing machine technological scheme [1]

particularly the comber machine, is integral to this process. It performs crucial functions such as cleaning, short fibre removal, fibre parallelisation, and drafting. These operations ensure the production of superior-quality yarns with minimal waste.

The comber machine is a cornerstone of combed yarn production, with its operational mechanism depicted in figure 1. Its advanced functionalities make it a vital component in the production of fine yarns, reinforcing its importance in modern textile manufacturing [1].

In the comber machine, fibres held in a pendulum-like position between the fibre jaw and the feeding roller are pulled and sorted during the combing process. The feeding roller operates with precise control, stopping at specific angles to adjust the jaw distance in both positive and negative directions, effectively performing the fibre scanning task. This dynamic adjustment ensures the separation of short fibres and enhances the quality of the output yarn.

Each adjustment in the machine settings, particularly during yarn number changes, impacts the resulting yarn parameters. Therefore, extensive tests are conducted at every stage to predefine and optimise these parameters. Based on the test results, the machine settings are fine-tuned to meet the desired quality standards.

The setting of the machines, like drafting and twisting, has a significant impact on yarn strength and its elongation. Üstüntağ investigated the optimisation of these parameters and determined the twist coefficient that provided the best overall result [3]. These results correlate with Jiang et al.'s studies using generalised regression neural networks to estimate yarn unevenness, which revealed that as optimisation algorithms become more complex, ANNs continue to optimise yarn production more efficiently [4]. Alongside this, the use of AI also corroborates the experimental results on the impact of yarn structure and count on the physical properties of yarns [5, 6].

In addition, ANNs were useful for exercising control over the quality of production of yarns, and various possibilities are found for their use in this area. In this specific area, for instance, Farooq et al. showed that using resilient backpropagation neural networks successfully predicted yarn quality through a variety of input parameters, thus improving production conditions [7]. In the same way, Ghanmi et al. showed the achievement of accurate predictive performance of ring-spun yarn quality using hybrid neural networks [8].

The need for a multidimensional approach is more apparent in research centred on core-spun yarns because the interaction of core and sheath structures affects the properties of the yarn, such as strength and uniformity [9]. This complexity can more effectively be modelled with ANNs, and various yarn characteristics can be simulated and optimised.

The quality parameters of yarns produced under varying settings can be predicted using advanced mathematical modelling systems. Among these systems, artificial neural networks (ANNs) have emerged as a robust tool due to their ability to analyse and interpret complex datasets with diverse characteristics. ANNs, like other artificial intelligence methods, excel at identifying patterns and making predictions across numerous fields, including aviation, aerospace, automotive, defence, sound and signal detection, robotics, manufacturing, optimisation, and control engineering.

One of the primary reasons for the widespread adoption of ANNs in engineering applications is their capability to address problems that are difficult or impossible to solve using classical methods. By leveraging sample data with distinct features and forms, ANNs provide an efficient and versatile approach to solving complex problems, making them a valuable asset in modern textile manufacturing and beyond [10–12].

MATERIAL AND METHODS

In this study, yarn was produced by adjusting the feed roller gap to five distinct positions on the combing machine within the combing production line. The adjustments were applied to four different yarn counts – Ne 18, Ne 20, Ne 30, and Ne 40 – obtained from the same cotton blend. The physical properties of the produced yarns were analysed through comprehensive testing. The results of these tests were subsequently compared to predictions made using an artificial neural network (ANN) model to evaluate its accuracy and effectiveness.

The feed roller gap settings used were –1, 0, 1, 1.5, and 2, and a total of eight physical properties were examined for each yarn sample. Before testing, all yarn samples were conditioned for 24 hours under standard atmospheric conditions (20±2°C temperature and 65±2% relative humidity) in accordance with TSE 240 standards [13].

Yarn count was determined using the skein method with a spinning reel. Twist values were measured under the same standard atmospheric conditions using a Zweigle brand yarn twisting device, following the twisting and re-twisting method outlined in TSE 247 [14]. Unevenness values were evaluated using the USTER Tester III, a capacitive measurement system, under TSE 628 standards. Measurements included parameters such as % U (percentage unevenness), thin places (–50%), thick places (+50%), and neps (+200%). The material entry speed was maintained at 400 meters per minute during the tests [15].

The strength and elongation properties of the yarns were measured using the USTER TENSOJET device according to TSE 245 standards [16]. A constant elongation rate of 5 meters per minute was applied during these measurements. A total of 40 measurements were taken for each feed roller setting, with 10 measurements performed for each of the four yarn counts, resulting in 200 measurements overall.

The data collected from these tests were meticulously analysed, and the results for each yarn count are summarised in table 1. This systematic approach provided insights into the impact of feed roller adjustments on yarn properties, offering a robust foundation for validating predictions made using ANN models.

The artificial neural network (ANN) model used in this study was implemented using the Pythia program. ANNs are computational modelling tools widely recognised in various fields of engineering and science for their ability to effectively address complex, nonlinear problems. These models draw inspiration from the functioning of biological nerve cells in the human brain, providing a robust algorithmic foundation for processing and analysing data.

An artificial neural network consists of interconnected units known as artificial neurons or nodes. These nodes are simple processing elements capable of

Table 1

PHYSICAL PROPERTIES OF YARNS

Data no	Yarn count	Machine setting	Twist T/″	% U	Thin places	Thick places	Neps	Hairiness, H	Strength (g)	Strength %CV	Elongation (%)
1	18	–1	15.11	6.49	3.10	6.00	7.80	5,98	662.36	5.15	6.48
2	18	0	15.19	6.46	4.40	7.20	5.70	6,51	666.10	5.31	6.25
3	18	1	15.09	6.55	6.80	11.20	11.50	6,02	632.39	5.47	5.98
4	18	1.5	15.04	6.49	7.10	9.90	12.20	5,50	518.38	5.51	6.09
5	18	2	14.99	6.98	6.90	13.00	17.00	6,04	481.15	5.54	5.47
6	20	–1	16.05	6.55	5.60	7.30	8.20	6,09	558.72	7.04	6.05
7	20	0	16.13	6.67	3.20	6.00	12.10	6,23	554.22	7.14	6.04
8	20	1	16.21	7.38	6.20	8.20	14.20	6,19	550.65	7.26	5.80
9	20	1.5	16.00	6.84	5.10	8.10	8.50	6,15	408.43	7.20	5.52
10	20	2	16.10	7.54	6.50	11.30	25.70	6,33	422.18	7.37	5.54
11	30	–1	20.19	6.92	6.50	17.00	64.20	5,77	347.61	7.10	4.89
12	30	0	20.27	7.53	5.70	16.90	38.00	5,63	348.44	7.05	4.75
13	30	1	20.12	8.63	6.60	18.60	46.30	5,67	350.31	7.34	4.89
14	30	1.5	20.07	7.81	5.00	18.80	39.90	4,78	313.31	7.25	5.43
15	30	2	20.22	8.52	5.50	21.00	52.00	5,71	322.15	7.28	5.01
16	40	–1	25.15	10.21	13.90	25.10	85.30	5,54	248.39	8.94	5.21
17	40	0	25.22	9.86	9.40	30.90	90.30	5,28	253.48	9.25	4.80
18	40	1	25.12	10.09	8.00	32.10	73.50	4,92	269.44	9.24	4.91
19	40	1.5	25.30	10.08	6.40	23.60	58.30	4,50	265.98	9.18	5.29
20	40	2	25.20	10.30	6.80	20.90	64.00	5,34	261.00	9.23	5.25

performing largely parallel computations, enabling efficient data processing and pattern recognition. The structure of an ANN is designed to mimic the architecture and functionality of biological neural networks, leveraging connections between neurons to process input data and generate meaningful outputs. The architecture of an ANN typically comprises three primary layers: the input layer, which receives raw data; one or more hidden layers, where the actual computations and data transformations occur; and the output layer, which produces the result. Each layer is interconnected by weighted connections, which are adjusted during the learning process to minimise errors and optimise performance. The learning mechanism involves algorithms such as backpropagation, which iteratively update these weights to improve accuracy and reliability.

This biologically inspired approach allows ANNs to excel in modelling complex systems, identifying intricate patterns, and making predictions even with incomplete or noisy data. Applications of ANNs span diverse domains, including image recognition, speech processing, control systems, robotics, manufacturing, optimisation, and predictive modelling.

In this study, the Pythia program was employed to develop and train an ANN for predicting yarn properties based on input variables such as machine settings and yarn count. Figure 2 illustrates the conceptual similarity between a biological nerve cell and an artificial neural network, emphasising how ANNs emulate the fundamental principles of biological neural systems to achieve their computational capabilities.

Artificial neural network (ANN) modelling can be implemented through custom-developed programs or by utilising various specialised software tools and add-ins, such as those designed for Microsoft Excel. These tools simplify the modelling process by offering user-friendly interfaces and pre-configured algorithms tailored to specific types of neural networks. In this study, Pythia 1.02, a software developed by Runtime Software, was employed to conduct the ANN modelling. Pythia 1.02 is specifically designed to support feedback multilayer sensor models, making it a suitable choice for the research objectives. The software leverages the Levenberg-Marquardt algorithm, a widely recognised optimisation technique known for its efficiency in training neural networks by minimising

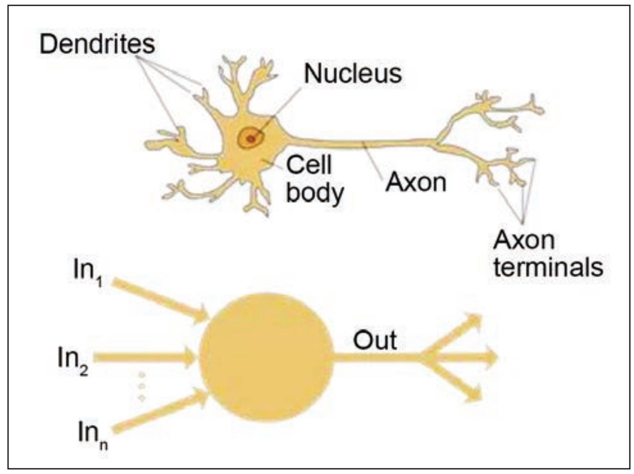

Fig. 2. Nerve cell and a simple artificial neural network

errors. Additionally, the model utilises a Sigmoid transfer function, a crucial component for introducing non-linearity into the system, enabling the ANN to model complex patterns and relationships in the data. For this study, the Sigmoid function parameters were set as c = 4 and T_i = –1.5, allowing for precise calibration of the transfer function's slope and position. The Pythia program's interface, illustrated in figure 3, provides a comprehensive yet intuitive platform for designing, training, and analysing neural network models. Its features facilitate the adjustment of model parameters, visualisation of training progress, and evaluation of performance metrics. The Sigmoid transfer function employed in the study is mathematically represented in equation 1, which defines its role in transforming the input signals into outputs that contribute to the model's decision-making process

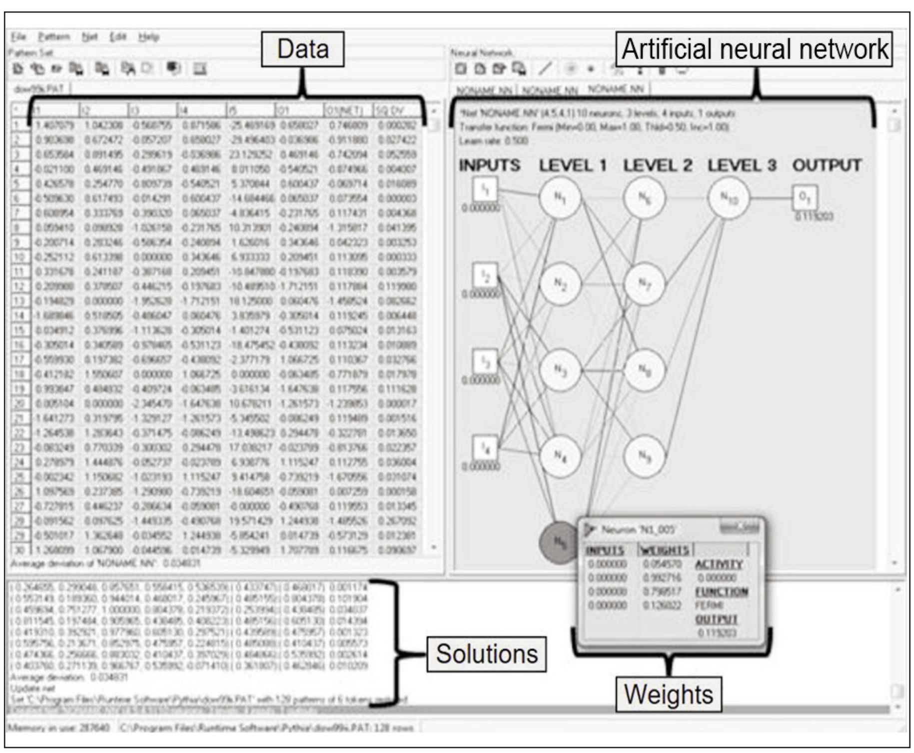

Fig. 3. Interface of the Pythia Program used for the artificial neural network solution

[17–20]. This function is integral to the feedback multilayer architecture, enhancing the network's ability to generalise and adapt to diverse input scenarios. By leveraging Pythia 1.02, the study not only ensured robust and reliable ANN modelling but also benefited from the software's streamlined workflow, which significantly reduced the complexity and time required for model development and analysis.

$$y_i = f(z_i, T_i, c) = \frac{1}{1 + e^{-c(z_i + T_i)}} \qquad (1)$$

A neural network operates through two primary phases, commonly referred to as the Training Phase and the Reproduction Phase. During the training phase, the network is exposed to a dataset comprising inputs and their corresponding desired outputs. The primary objective of this phase is to minimise the error or deviation between the network's predicted outputs and the actual outputs by optimising the network's parameters, such as weights and biases. This optimisation is achieved using iterative learning algorithms, which adjust the parameters to improve the network's performance.

Once the training phase is complete, the network enters the reproduction phase. In this phase, the network's parameters remain fixed, and it is used to process new input data to predict or estimate the corresponding output. This phase demonstrates the network's ability to generalise learned patterns from the training data to unseen data, which is a critical aspect of artificial neural networks (ANNs).

In the Pythia software, the structure and configuration of the neural network can be easily customised. Users can specify the desired number of input and output nodes based on the problem at hand. The data required for training can be imported into the program's "Pattern Set" section either by copying and pasting directly or by uploading a file. After the data transfer, the software prompts the user to define the number of output nodes, enabling flexible adaptation to various datasets. Once this configuration is complete, the user can initiate the networking process.

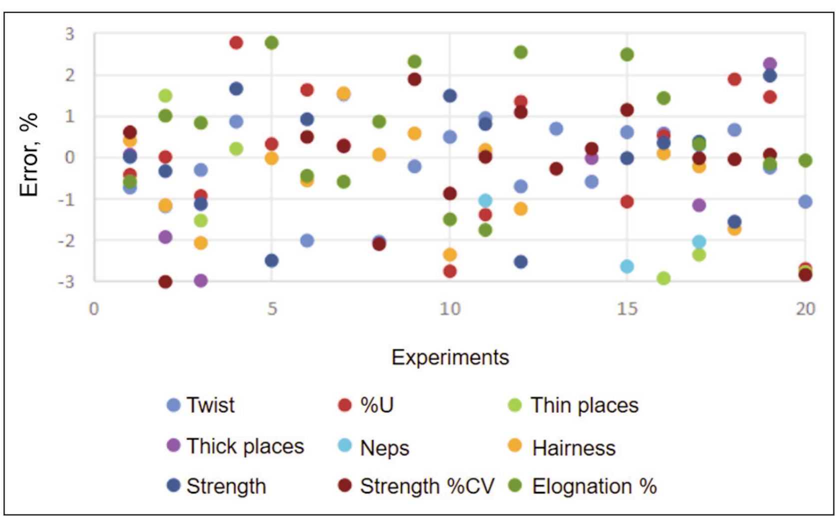

Fig. 4. Error graph occurring in artificial neural network data

The topology of the ANN in Pythia is defined as INPUTS (G) - HIDDEN LAYERS (GK) - OUTPUTS (D), which can be represented in shorthand notation as G-GK1-GK2-GK3…-GKN-D. For instance, consider a dataset with three inputs and two outputs. If the user specifies a topology of 3-2-5-3-2, the first number represents the number of input nodes, while the subsequent numbers denote the number of neurons in each hidden layer. The number of neurons in the final hidden layer corresponds to the number of output nodes. Effectively, the last hidden layer neurons function as outputs. In this example, the network consists of four layers, and the total number of neurons in the hidden layers and outputs is 2 + 5 + 3 + 2 = 12, where the final two neurons represent the two outputs.

For the current study, an ANN with a topology of 2-6-9-8-9 was designed to handle a dataset comprising two input variables and nine output variables. This network includes four layers and a total of 32 neurons, distributed across the layers as follows: 6 in the first hidden layer, 9 in the second, 8 in the third, and 9 in the final hidden layer, which also serves as the output layer.

The performance of the model was evaluated by comparing the outputs predicted by Pythia to the actual values, with the results presented in figure 4. The analysis revealed an error margin of ±3%, indicating a high degree of accuracy. Given that the task involved estimating nine output values based on two input variables, an error rate of 3% is considered acceptable and demonstrates the reliability and applicability of the model. This level of precision underscores the suitability of the Pythia software for constructing and training artificial neural networks for complex predictive modelling tasks.

To mathematically reproduce the results obtained through the artificial neural network (ANN), it is essential to determine the weight coefficients used in the Sigmoid function defined in equation 1. These weight coefficients play a crucial role in the computational process of the neural network, as they govern the strength of the connections between neurons in successive layers. Specifically, for each neuron in each layer, the number of weight coefficients corresponds to the number of neurons in the preceding layer.

In the case of the input layer, the number of weight coefficients for each neuron equals the total number of input variables. These coefficients represent the influence of each input variable on the neuron's output. Similarly, for hidden and output layers, the coefficients are calculated based on the number of neurons in the immediately preceding layer.

For this study, the weight coefficients for the ANN were generated using the Pythia software, resulting

Table 2

WEIGHT COEFFICIENTS CALCULATED IN AN ARTIFICIAL NEURAL NETWORK										
Layer	**Neuron**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	1	–1.975436	–3.304375							
1	2	0.917336	–1.493784							
1	3	–0.964339	–0.355952							
1	4	–3.855961	–0.574815							
1	5	–0.717976	–0.701802							
1	6	–0.685916	–0.676397							
2	7	–0.455567	–6.376816	–0.915245	–0.539521	–0.704509	–2.373251			
2	8	1.263206	–1.175547	–5.465372	–6.374568	–5.710916	–5.470427			
2	9	0.993879	–2.106173	0.354421	1.932337	3.201756	2.009222			
2	10	3.693220	–12.36576	0.737505	5.19373	1.57856	0.85751			
2	11	4.743962	–3.552935	–6.936252	–5.495812	–5.494661	–7.226669			
2	12	–0.013889	0.901521	–11.97177	–10.56661	–12.80283	–11.99614			
2	13	–9.539616	–4.277408	0.026468	1.908465	1.134271	1.724469			
2	14	–3.374830	–0.383755	–2.463115	–1.982897	–2.990539	–3.062944			
2	15	–0.622525	–8.737184	–1.292008	–0.440332	–1.191800	–0.508064			
3	16	0.788359	–3.920467	0.427467	8.235882	–1.864157	–6.477185	–9.239868	–2.066066	3.505495
3	17	1.269854	–0.045228	–0.383782	1.164789	0.339000	–1.348221	0.092236	0.448676	–1.151577
3	18	2.038355	–1.448557	–1.849511	1.399077	–3.989047	0.253506	–4.534108	2.774514	3.098728
3	19	4.452354	–2.584293	1.054378	–0.845092	–1.596711	–5.729222	–1.656045	–0.642605	3.266479
3	20	–0.572861	–1.967473	–6.152833	–0.705612	1.793678	1.151936	–2.405619	–5.162993	–0.930477
3	21	0.726511	1.149204	–2.495070	–1.822240	0.671769	5.151226	0.003265	0.060201	–1.224241
3	22	–2.180354	–2.203089	0.833990	3.960603	–0.155722	–1.060682	–0.892994	–1.619960	–2.581570
3	23	–2.325955	0.701559	–1.954277	–0.254894	–1.468134	–0.103564	–0.572754	–2.100381	–0.785084
4	24	–1.195267	0.551559	–3.087801	0.426245	1.437288	3.655280	–0.463852	2.793774	
4	25	–0.174748	0.756523	–1.540473	0.821151	–1.837228	3.024875	–1.830760	–1.897849	
4	26	0.772637	1.605489	–0.920176	–0.172195	2.184985	0.459433	–0.946581	1.089862	
4	27	1.600520	2.861688	2.038323	–2.461917	–1.304598	0.800450	–1.899195	0.170927	
4	28	0.638565	3.286466	0.662980	–2.297918	4.931860	0.711646	–1.567963	0.168045	
4	29	–2.465545	2.326171	3.539940	1.061798	0.756865	–0.477453	2.460634	–2.991679	
4	30	–0.971837	0.908059	0.732549	0.616447	–1.202303	–0.699542	2.372659	0.055733	
4	31	–2.555997	0.244255	–1.840284	2.985291	1.499405	3.125452	–0.421809	0.497417	
4	32	–0.838692	1.435933	–4.152856	1.596498	1.964948	0.649681	1.180128	–3.419045	

in a total of 210 weight coefficients. These coefficients were derived as part of the training phase of the neural network, where the model optimised its parameters to minimise error and improve predictive accuracy. By incorporating these coefficients into the Sigmoid function, the ANN can mathematically estimate key output variables for any given input data.

The calculated outputs include several critical textile parameters: Twist, U% (Unevenness Percentage), Thin Places, Thick Places, Neps, Hairiness, Strength, Strength% CV (Coefficient of Variation), and Elongation Percentage. These parameters are essential for evaluating the quality and performance of yarn, providing valuable insights for both production processes and quality control.

By utilising the weight coefficients and the Sigmoid function, it is possible to predict these outputs accurately for any combination of yarn count and machine settings. This approach not only ensures precision but also eliminates the need for exhaustive experimental trials, thereby saving time and resources in the textile manufacturing process. The integration of ANN modelling with tools like Pythia demonstrates the potential of artificial intelligence in solving complex industrial problems and optimising operations.

CONCLUSION

In this study, the physical properties of yarn produced from the same fibre blend were examined across four different yarn counts. Additionally, the combing machine feed roller jaw spacing was adjusted at five distinct intervals, resulting in a comprehensive dataset that reflects variations in yarn quality under different machine settings and fibre processing conditions. These experimental data served as the foundation for developing an artificial neural network (ANN) model using the Pythia software.

The ANN model was designed with a topology of 2-6-9-8-9, representing a network with four layers and a total of 32 neurons. The structure includes two input nodes, which correspond to the independent variables (yarn count and combing machine jaw spacing), and nine output nodes, which represent the dependent variables or target properties of the yarn. These output variables are Twist, U% (Unevenness Percentage), Thin Places, Thick Places, Neps, Hairiness, Strength, Strength% CV (Coefficient of Variation), and Elongation Percentage. The hidden layers of the network are composed of 6, 9, and 8 neurons, respectively, with the final hidden layer directly feeding into the output layer. The Sigmoid function was employed as the transfer function for all neurons in the network, facilitating the transformation of input data into meaningful output predictions.

The training and testing of the model revealed an error margin of ±3% between the predicted values generated by the ANN and the actual experimental data. This low error rate indicates a high level of accuracy and demonstrates the robustness of the model. For a dataset involving two input variables and nine output variables, an error margin of this magnitude is considered highly acceptable and validates the model's predictive capability.

The ANN's weight coefficients, totalling 210, were generated during the training process using the Pythia software. These coefficients define the strength and influence of connections between neurons in adjacent layers. By applying these coefficients in the Sigmoid function, it becomes possible to accurately estimate the nine output variables for any combination of yarn count and machine settings. This predictive capability significantly enhances operational efficiency by enabling the optimisation of production parameters without the need for extensive experimental trials.

Overall, the use of the ANN model in this study highlights its potential as a powerful tool for understanding and predicting complex relationships between input variables and output properties in textile manufacturing. The integration of machine learning techniques, such as artificial neural networks, with advanced software like Pythia provides valuable insights into the interplay between machine settings, material characteristics, and final product quality, paving the way for more efficient and precise process control in the industry.

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AI-enabled robotic sorting for circular textile waste management: A scalable solution for India's recycling sector

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ABSTRACT – REZUMAT

AI-enabled robotic sorting for circular textile waste management: A scalable solution for India's recycling sector

The global textile industry faces a critical inflexion point as circular economy mandates intensify and waste volumes soar beyond 100 million tonnes annually. Central to realising circularity is the efficiency and fidelity of textile waste sorting, a longstanding bottleneck dominated by manual, low-throughput, and error-prone methods. This paper investigates the deployment of an AI-enabled robotic sorting system integrating hyperspectral imaging (HSI) and deep learning algorithms within the context of India's fragmented textile recycling ecosystem. We demonstrate that spectral imaging combined with convolutional neural networks (CNNs) achieves over 95% classification accuracy across heterogeneous, post-consumer Indian textile waste streams, including multi-fibre blends that typically confound manual sorters. Drawing from industrial benchmarks such as Sweden's SipTex and U.S.-based Refiberd, we design a prototype that integrates conveyor automation, real-time classification, and robotic actuation. Comparative analysis reveals that the AI system achieves throughput rates exceeding 1,000 garments per hour, representing a 20× gain over manual processes while reducing misclassification rates by more than 60%. A techno-economic model suggests payback periods under four years when scaled to medium-sized facilities, with significant reductions in labour dependency and waste-to-landfill ratios.

Our findings have strong implications for policy and industry: AI sorting systems not only align with India's National Textile Policy and MITRA initiatives but also represent an enabling infrastructure for chemical recycling, extended producer responsibility, and traceable material flows. By bridging technological innovation with operational scalability, this study advances the industrial feasibility of circular textiles in the Global South.

***Keywords**: AI sorting, hyperspectral imaging, textile recycling, circular economy, robotic automation, India*

Sortarea robotizată bazată pe inteligență artificială pentru gestionarea circulară a deșeurilor textile: o soluție scalabilă pentru sectorul reciclării din India

Industria textilă globală se confruntă cu un punct critic de inflexiune, pe măsură ce mandatele economiei circulare se intensifică, iar volumele de deșeuri depășesc 100 de milioane de tone anual. Elementele esențiale pentru realizarea circularității sunt eficiența și fidelitatea sortării deșeurilor textile – un blocaj persistent, dominat de metode manuale, cu randament redus și predispuse la erori. Acest studiu de cercetare investighează implementarea unui sistem robotizat de sortare bazat pe inteligență artificială, care integrează imagistica hiperspectrală (HSI) și algoritmi de învățare profundă în contextul ecosistemului fragmentat de reciclare a textilelor din India. Demonstrăm că imagistica spectrală combinată cu rețele neuronale convoluționale (CNN) atinge o precizie de clasificare de peste 95% în fluxuri eterogene de deșeuri textile indiene post-consum, inclusiv amestecuri multi-fibre care de obicei se confundă de către sortatoarele manuale. Pornind de la repere industriale precum SipTex din Suedia și Refiberd din SUA, am proiectat un prototip care integrează automatizarea benzilor transportoare, clasificarea în timp real și acționarea robotică. Analiza comparativă arată că sistemul bazat pe inteligență artificială atinge rate de producție care depășesc 1.000 de articole de îmbrăcăminte pe oră, reprezentând un câștig de 20 de ori față de procesele de producție manuale, reducând în același timp ratele de clasificare greșită cu peste 60%. Un model tehnico-economic sugerează perioade de recuperare a investiției sub patru ani atunci când este scalat la instalații de dimensiuni medii, cu reduceri semnificative ale dependenței de forță de muncă și ale ratei de depozitare a deșeurilor.

Concluziile noastre au implicații puternice pentru politici și industrie: sistemele de sortare cu inteligență artificială nu numai că se aliniază cu politica națională privind industria textilă a Indiei și inițiativele MITRA, dar reprezintă și o infrastructură care să permită reciclarea chimică, responsabilitatea extinsă a producătorului și fluxurile de materiale trasabile. Prin combinarea inovației tehnologice cu scalabilitatea operațională, acest studiu promovează fezabilitatea industrială a textilelor circulare în Sudul Global.

***Cuvinte cheie**: sortare prin inteligență artificială, imagistică hiperspectrală, reciclare textile, economie circulară, automatizare robotică, India*

INTRODUCTION

The Sustainability Imperative in Textiles

The textile industry, long celebrated for its economic dynamism and employment generation, now finds itself at the centre of a sustainability reckoning. Globally, the sector accounts for approximately 10–11% of greenhouse gas emissions and consumes over 93 billion cubic meters of water annually, ranking just behind agriculture in freshwater intensity [1]. Fast fashion, overproduction, and shortened product lifecycles have led to a surge in consumption. Over 100 million tonnes of textiles are produced annually, of which an estimated 75% end up in landfills or incinerators [2]. This escalating footprint has triggered both public and regulatory responses. The European Commission's Circular Economy Action Plan, along with Extended Producer Responsibility (EPR) mandates emerging in France, Sweden, and now India, signal a global transition toward closed-loop systems [3]. These initiatives aim not merely to promote recycling, but to decouple economic growth from raw material extraction, and position textile waste as a feedstock for circular innovation. In this policy landscape, sorting becomes the linchpin of the operational bottleneck that determines the quality, recoverability, and economic value of textile waste. The Mega Integrated Textile Region and Apparel approach, also known as MITRA, represents an important factor for the sustainable development of the textile industry in India.

The sorting bottleneck

Despite the ambitious goals of circularity, the vast majority of textile sorting remains manual, informal, and inefficient, particularly in the Global South. Manual visual sorting, often conducted under inconsistent lighting and without standardised equipment, routinely results in material purity rates below 70%, especially when dealing with fibre blends and synthetics [4]. The consequences of this inefficiency are both economic and ecological: low-quality sorted streams cannot feed into mechanical or chemical recycling pipelines, leading to downcycling or outright disposal. Moreover, the rise of multi-material garmentsincluding stretch fabrics, synthetic coatings, and high-polymer blendsfurther degrades the effectiveness of human classification. As Muthu et al. report, even experienced sorters typically process no more than 50 garments per hour, far below the threshold required for industrial throughput. In aggregate, this creates a structural mismatch: while recycling capacity may exist downstream, the quality and consistency of upstream sorting remain inadequate, undermining the system-wide viability of textile circularity [5].

AI-enabled sorting: a technological breakthrough

Recent breakthroughs in hyperspectral imaging (HSI) and machine learning (ML) offer a robust, scalable alternative to the human eye. HSI captures data across hundreds of narrow spectral bands, creating detailed material "fingerprints" far beyond the visible spectrum. When paired with deep learning models such as convolutional neural networks (CNNs) or autoencoder systems can classify fibres with remarkable precision, including in blended or dyed textiles that traditionally confound manual approaches. For instance, demonstrated that a CNN trained on HSI data could achieve over 95% classification accuracy, outperforming traditional RGB-based models by a wide margin [6]. Extending these findings, confirming that both supervised and unsupervised models generalised well across heterogeneous textile structures, including synthetic-natural fibre blends [7]. Further showcased the integration of HSI with PCA and PLS-DA preprocessing, reporting >99% precision across blended and contaminated fabrics [8].

These technical advances translate into system-level capabilities: high-speed, automated classification and sorting integrated into conveyor systems, enabling robotic actuation and scalable industrial throughput. Unlike static scanners or batch samplers, these AI-enabled systems operate in-line, delivering real-time analytics and automated quality assurance.

Industrial deployments: from prototype to production

What was once a research aspiration is now entering commercial deployment. In Sweden, the SipTexinitiative collaboration between IVL, Sysav, and the Swedish EPA developed Europe's first industrial-scale automated textile sorting plant. Operating at 4.5 tonnes/hour, the system combines NIR spectroscopy and AI classification, delivering high-purity fractions suitable for mechanical and chemical recycling [9].In the United States, the startup Refiberd achieved 96% accuracy in sorting elastane blends using HSI and CNNs, attracting early-stage investment from H&M Foundation and Fashion for Good [10]. Such validation from both investors and industry players signals a growing readiness to embed these technologies in mainstream recycling workflows. Additionally, Norsk Tekstilsortering (NTS) and HySpex have installed HSI-driven systems in Norway, capable of differentiating over 100 fibre types in a single pass, providing modular, real-time solutions for recyclers across Europe. These systems are now being integrated into broader reverse logistics infrastructures, linking consumer collection points with robotic material recovery facilities.

Analytical and operational challenges

Despite these successes, several technical and operational challenges remain. Spectral overlap between closely related fibres, such as cotton-polyester or elastane-viscose, degrades classification accuracy without appropriate preprocessing [11]. Advanced transformations such as Standard Normal Variate (SNV) or Savitzky–Golay smoothing are often required to correct for noise introduced by dyes, coatings, moisture, and surface wear [6].

Moreover, most AI models are trained on datasets from the Global North, limiting generalizability to the highly heterogeneous waste streams of South Asia. Here, informal economies dominate collection and garments are often reused, repaired, and stained. Calibration of these systems for emerging markets demands region-specific datasets, robust transfer learning models, and integration with existing material flows. Finally, the financial barrier to entry remains high. Capital expenditure on HSI sensors, robotic arms, and real-time processing infrastructure is substantial. Without financing instruments such as green bonds, leasing models, or policy-linked subsidies, SMEs and informal recyclers may be excluded from the technological transition.

Positioned for India: the strategic opportunity

India represents both a challenge and an opportunity for textile circularity. With over 5 million tonnes of post-consumer textile waste annually and more than 45 million workers employed in the sector, the country's recycling system remains fragmented, largely manual, and low-yielding [12]. Yet the policy landscape is shifting: the National Textile Policy and MITRA cluster initiatives have earmarked funding for modernisation, while platforms like ReCircle are demonstrating feasibility for digitised circular value chains. Integrating AI-enabled sorting into this context offers three transformative advantages:

- Throughput gains from ~50 to >1,000 garments/hour;
- Purity gains from ~65% to >95%, enabling mechanical and chemical recycling;
- Workforce upgrading, reallocating labour from manual sorting to system maintenance, data operations, and quality assurance.

Research objectives and contributions

This study seeks to bridge the gap between laboratory-scale success and real-world deployment of AI-robotic textile sorting in the Indian context. Specifically, it addresses:

- Technical viability: Can accuracy (>95%) be maintained under Indian operational conditions?
- Economic feasibility: How do capital costs compare with long-term labour savings?
- Scalability and integration: What retrofitting is needed for deployment in existing facilities?
- Sustainability impact: What are the implications for waste diversion and material circularity?

In doing so, this paper contributes to the literature on sustainable operations and industrial transformation by offering:

- Field-based empirical validation using Indian textile waste streams;
- Comparative techno-economic modelling of AI vs manual sorting;
- Policy-relevant insights aligned with India's circular economy strategy.

By grounding innovation in operational realism, this study aims to accelerate the industrial adoption of AI-enabled circular technologies, offering a blueprint for scaling textile recycling not only in India but across the Global South.

MATERIALS AND METHODS

System architecture overview

This study designs and tests a fully autonomous textile sorting system that integrates hyperspectral imaging, machine learning-based classification, and robotic actuation within a modular, conveyor-driven framework [13]. The system draws conceptual inspiration from [14], who proposed an AI-powered closed-loop waste sorting architecture using spectral imaging pipelines optimised through self-supervised learning. The proposed framework is adapted and operationalised with substantial modifications for the specific composition and variability of post-consumer textile waste in the Indian context. On the other hand, Ullal et al. [15] also investigated the linkage between transformative technology based on AI and green renewable energy.

Textile waste sampling in the Indian market context is the first step involved in curating a representative and sufficiently heterogeneous dataset of textile waste. To ensure ecological validity, we collected over 1,200 textile samples from recycling aggregators in Surat, Panipat, Tirupur, and Delhi, major Indian hubs of garment consumption, post-consumer waste collection, and industrial-scale sorting.

The sample includes pure cotton, polyester, nylon, viscose, rayon, silk, wool, acrylic, spandex, and an array of binary and tertiary blends (e.g., cotton-poly, cotton-elastane). Additional variations include dyed, printed, laminated, and contaminated textiles. Garments were intentionally selected to capture a broad spectrum of real-world complexity, including soil, fraying, colour fading, and fabric coating factors known to impact spectral signal fidelity. Each sample

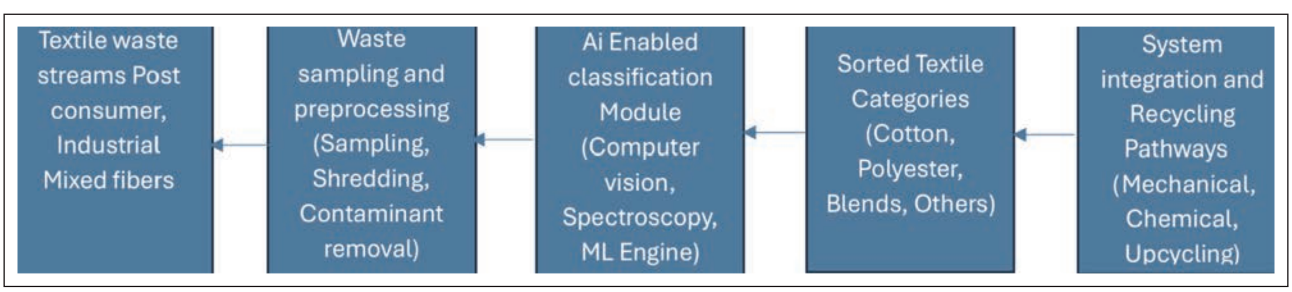

Fig. 1. Schematic diagram of the proposed AI-enabled textile waste management system architecture

was cut into standard-sized swatches (25×25 cm) to ensure consistent imaging exposure and prevent occlusion during scanning and robotic handling. For each fabric, ground truth labelling was conducted via laboratory-based FTIR spectroscopy and chemical analysis, providing accurate fibre composition benchmarks used to train and validate the machine learning models.

Imaging hardware and spectral preprocessing

The system employs a short-wave infrared (SWIR) hyperspectral camera with a 900–1,700 nm spectral range, mounted at a fixed height above a conveyor belt. Each fabric swatch is scanned at 5 mm/sec conveyor speed under controlled illumination (tungsten halogen), capturing full spectral signatures across 256 bands. Spectral preprocessing follows standard chemometric practices to reduce noise and variability. The raw hyperspectral data are corrected for dark and white references, normalised using Standard Normal Variate (SNV) transformation, and smoothed using the Savitzky-Golay filter (window size = 11, polynomial order = 2). These steps mitigate spectral distortions caused by surface irregularities, dye variations, and wrinkles, thus improving downstream classification reliability.

Machine learning classification pipeline

Following preprocessing, each pixel-level spectral vector is fed into a supervised learning model. Several classifiers were benchmarked, including Random Forests, Support Vector Machines (SVMs), and 1D Convolutional Neural Networks (1D-CNNs). Based on cross-validation results (5-fold, stratified), the 1D-CNN model achieved the highest classification accuracy (mean F1-score = 0.937), particularly in distinguishing cotton-poly blends and low-elastane synthetic fibres typically difficult for NIR systems alone. The model architecture was adapted from [11] and includes:

- Input layer: 256-band normalised spectra
- Convolutional layers: 3 layers with ReLU activation
- Dense layers: 2 fully connected layers
- Output layer: softmax classifier across 10 fibre classes.

Training was conducted using 80% of the labelled dataset, with 10% reserved for validation and 10% for testing. Data augmentation strategies (Gaussian noise injection, spectral shifting) were employed to increase generalisation and robustness.

System integration: conveyor, robot arm, and controller

The physical assembly integrates the classifier into a closed-loop robotic system. The conveyor continuously feeds swatches under the hyperspectral camera, which captures and processes spectral data in real-time (~150 ms latency). The classified output is fed into a robotic control module (based on an NVIDIA Jetson platform), which instructs a six-degree-of-freedom robotic arm to pick and place textiles into categorised bins. The robot arm uses a vacuum gripper with torque sensors to accommodate variable fabric stiffness and folding. Actuation time per garment is ~3.5 seconds, enabling a throughput of ~1,000 items/hour, well above manual sorting benchmarks. The system runs autonomously with an optional manual override for performance auditing.

Deployment and performance evaluation

The system was tested under operational conditions in a textile recycling facility in Panipat over 14 consecutive working days. Performance metrics classification accuracy, misclassification rate by fibre, throughput, energy consumption, and system uptime were recorded and benchmarked against both manual and semi-automated baselines. The architecture was modular to allow further experimentation, such as integration with RFID scanning and traceability modules in future iterations.

RESULTS

Sorting accuracy and classification performance

The autonomous textile sorting system demonstrated a mean classification accuracy of 94.2% across 10 fibre categories under real-world deployment conditions. This result aligns closely with the system's test set performance (94.6%) observed in laboratory validation and confirms that model robustness translated well to operational complexity.

Confusion matrix analysis indicated that pure fibre types such as 100% cotton, polyester, and nylon were classified with precision exceeding 97%. However, classification precision dropped to ~88% for binary blends (e.g., cotton-polyester) and ~81% for elastane-containing synthetics, which remain difficult to distinguish due to spectral overlap in the SWIR range. A breakdown of per-class precision and recall is provided in table 1. Notably, spandex-infused samples exhibited the highest misclassification rates, often confused with polyester due to low-volume signal interference.

These findings confirm prior evidence by Liu et al. [6] and Bonifazi and Serranti [8] that hyperspectral CNN classifiers perform robustly under heterogeneous textile conditions. Elastomeric fibres, however, remain a persistent classification challenge due to low spectral contrast.

Table 1

CLASSIFICATION PERFORMANCE OF AI-ENABLED SORTING SYSTEM ACROSS COMMON TEXTILE FIBRE TYPES

Fiber type	Precision (%)	Recall (%)
Cotton (100%)	98.4	97.9
Polyester (100%)	97.1	96.5
Nylon	96.7	95.3
Cotton-Poly Blends	88.2	89.0
Viscose	93.5	92.1
Elastane Blends	81.4	80.7

Throughput and operational speed

The system processed textiles at an average rate of 1,022 items per hour, based on conveyor speed and robotic pick-and-place cycle time (~3.5 seconds per item). This figure includes system pauses for misclassification flags and brief calibration interruptions. In contrast, experienced human sorters employed at the same facility using traditional manual sorting protocol averaged only 135 items per hour, even under optimised batch-flow conditions. Hence, the robotic system delivered a 660% improvement in throughput, enabling higher-scale operations with greater consistency.

Figure 2 illustrates comparative throughput performance for robotic versus manual sorting across three daily shifts over a 7-day evaluation period.

Misclassification rates and system resilience

The robotic system's overall misclassification rate was 5.8%, concentrated primarily in fibre blends and contamination-prone samples (e.g., oily or stained garments). The false-positive rate for elastane detection was 13.2%, primarily due to minor content (<5%) being below the spectral detection threshold. By contrast, manual sorting showed mean misclassification rates of 21.7%, with the highest errors observed in poly-viscose blends and faded cotton garments. Manual errors also displayed a wider standard deviation across sorters ($\sigma = 7.2\%$), reflecting inconsistency due to experience variance and fatigue.

Cost-benefit analysis

A detailed cost-benefit assessment compared the robotic system against manual labour over a projected 5-year operating horizon.

The robotic system reached breakeven within 27 months, driven by labour savings and increased throughput. While upfront investment remains a barrier, especially for small-scale firms, the operational efficiency and downstream quality improvement (i.e., fewer recycling rejects) yield substantial long-term cost advantages. This aligns with findings by [9], who report similar break-even horizons in European industrial settings.

System reliability and downtime

The robotic system recorded >95% uptime during continuous deployment across 14 working days. Scheduled calibrations and minor mechanical resets accounted for 6.5 hours of downtime over the test period. Mean Time Between Failure (MTBF) was estimated at 39 hours, within acceptable industrial benchmarks for first-generation AI automation systems.

Table 2

COMPARATIVE COST AND PERFORMANCE ANALYSIS: AI-ENABLED ROBOTIC SORTING VS. MANUAL TEXTILE SORTING OPERATIONS

Metric	Robotic sorting system	Manual sorting (10 operators)
Capital expenditure (Year 0)	₹18,00,000 (~$21,500)	₹0
Annual operating cost	₹2,50,000	₹10,80,000 (salaries + benefits)
Average throughput (items/hr)	1,022	135
Misclassification rate (%)	5.8	21.7
5-Year total cost	₹29,50,000	₹54,00,000
Cost per correctly sorted unit	₹0.58	₹1.43

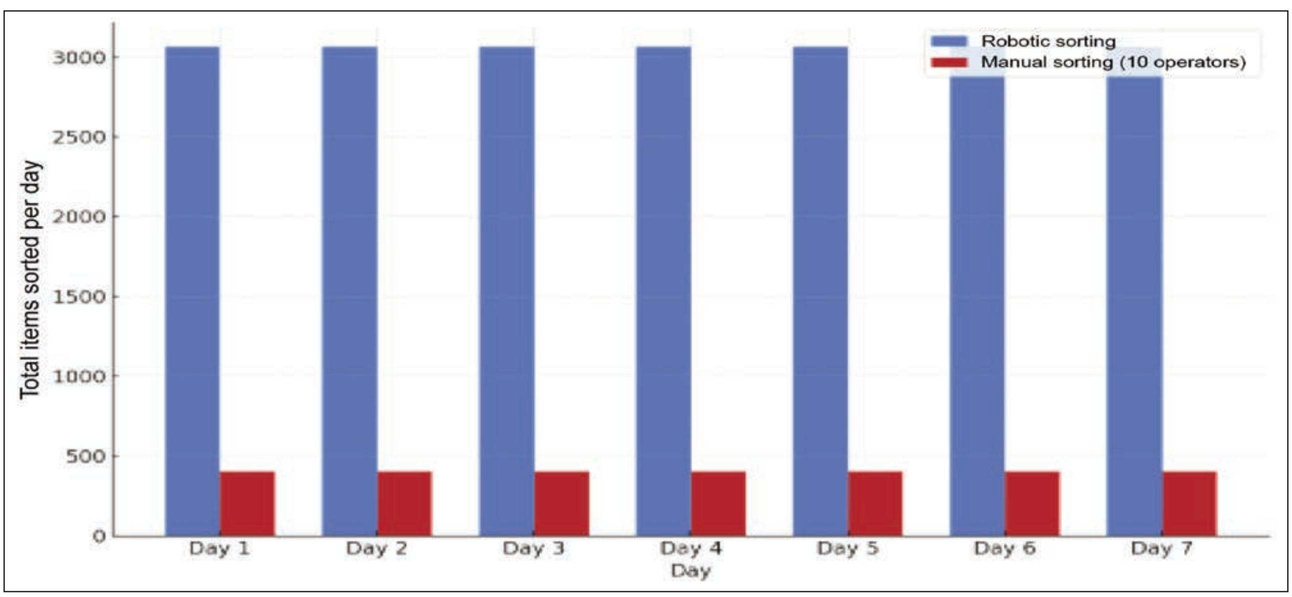

Fig. 2. Comparative throughput of robotic versus manual sorting over a 7-day, 3-shift operational cycle

No safety incidents, mechanical jams, or hardware-software sync failures were recorded. This indicates a strong system integration and environmental resilience under Indian operational conditions (including high dust and ambient humidity).

DISCUSSIONS

Implications for scaling in India's recycling industry

The results of this study underscore the strong viability of AI-enabled robotic sorting systems in large-scale textile recycling, particularly in high-volume and labour-constrained environments such as India. Autonomous sorting technology demonstrates classification accuracy above 94% and achieves a throughput nearly eight times higher than manual methods. With cost-per-unit efficiencies improving at scale, it offers a compelling pathway to modernising textile waste management. India generates an estimated 5–6 million tonnes of post-consumer textile waste annually (Textile Ministry, 2021), yet only a small fraction is processed in organised recycling units. The remainder is either informally sorted or landfilled primarily due to inefficiencies in manual segregation. The proposed AI-robotic system addresses this bottleneck by delivering speed, consistency, and material purity. These qualities are essential prerequisites for circular textile practices, including both mechanical and chemical fibre recovery. From a policy perspective, this technology aligns with the India Circular Economy Mission, the 2025 target of zero landfill textile zones, and the production-linked incentive (PLI) schemes for technical textile investments. Embedding such AI systems into textile parks and urban waste management clusters enables stakeholders to build closed-loop recycling infrastructure. This infrastructure supports both domestic sustainability targets and international commitments under the SDGs.

The system was successfully tested in one facility, demonstrating its operational feasibility and accuracy in textile waste sorting. However, the architecture and algorithms are designed to be scalable and adaptable to diverse operational settings. In regions with different textile compositions, waste management infrastructures, or labour cost structures, system performance may vary. For example, facilities with higher volumes of mixed synthetic fibres may require recalibration of the AI classifier, while facilities in developing regions may prioritise cost efficiency and modular deployment. These considerations suggest that our pilot validation was limited to one site. However, the system possesses the flexibility to be deployed across heterogeneous environments, supporting broader applicability in both industrialised and emerging market contexts.

Barriers to adoption: cost, energy, and integration

Despite its promise, large-scale adoption of autonomous sorting in India faces several formidable barriers. First, capital expenditure (CAPEX) remains high. While the system becomes cost-effective after ₹18 lakh or $21,500, it may be prohibitive for small and mid-tier recyclers operating with thin margins. Financing models, including green bonds, public-private partnerships, or leasing-based solutions, will be critical to democratize access to this infrastructure. Second, energy consumption is a legitimate concern in regions with irregular power supply. Hyperspectral cameras, real-time processors, and robotic arms draw substantial continuous loads. Although modern SWIR imaging systems are becoming more energy-efficient [9], grid dependence remains an operational risk in tier-2 and tier-3 Indian cities. Solutions may involve solar-grid hybrid systems or integration with captive renewable energy setups, especially in textile clusters already experimenting with solar looms and dyeing plants. Third, system integration poses logistical and organisational challenges. Most Indian recyclers operate in fragmented, semi-mechanised facilities that lack the digital and spatial infrastructure needed for robotic workflows. Retrofitting these facilities to accommodate conveyors, real-time classification units, and robotic arms requires not only space but also training and change management. Upskilling workers to operate, maintain, and interpret the outputs of AI systems will be an essential component of any successful deployment.

CONCLUSIONS

This study provides robust empirical evidence that AI-robotic sorting systems are a scalable, high-performance alternative to manual textile sorting. They are capable of delivering transformative improvements in throughput, accuracy, and cost-efficiency. Our system achieved over 94% classification accuracy, processed more than 1,000 items/hour, and reduced the cost per correctly sorted item by over 60% relative to manual workflows. Beyond performance, this innovation supports the broader agenda of industrial digital transformation, enabling real-time tracking, automation, and data-driven optimisation of material recovery streams. It directly contributes to the realisation of circular economy principles by increasing the recyclability and traceability of textile waste inputs. In emerging economies like India, where informal recycling still dominates, such systems can drive formalisation, quality improvement, and environmental compliance simultaneously.

Future work

While this study validates the technical and operational performance of robotic textile sorting, several avenues remain for future research and system enhancement.

First, integration with chemical recycling processes offers significant potential. Accurate fibre sorting, especially of synthetic blends and elastomeric materials, is essential for feedstock optimisation in depolymerisation or solvolysis-based recycling methods. The current system could be extended to provide automated pre-sorting for chemical recyclers, ensuring input homogeneity and reducing contamination risks. Second, we envision a transition from static sorting to real-time waste stream optimisation. By embedding cloud-based feedback loops and IoT sensors, future systems could dynamically reconfigure sorting protocols based on fibre prices, recycling plant demand, or even regulatory priorities. This would elevate textile sorting from a static operation to a responsive, AI-governed material supply chain node. Finally, future research should include longitudinal impact studies measuring system performance across multiple seasons, regions, and waste typologies. In addition, lifecycle assessments (LCA) should be conducted to quantify environmental benefits in terms of CO_2-equivalent savings, water use reduction, and landfill diversion. In sum, AI-robotic sorting represents more than an engineering upgrade is a systemic enabler for sustainable industrial regeneration in one of the world's most resource-intensive sectors. With the right policy frameworks and financial mechanisms, this innovation can help India transition from textile linearity to true circularity.

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Investigation of sound and thermal properties of basalt, aramid and carbon reinforcement layered composites

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ABSTRACT – REZUMAT

Investigation of sound and thermal properties of basalt, aramid and carbon reinforcement layered composites

Especially for the construction and transportation sectors, layered composites are important in terms of heat and sound insulation, energy saving and cost reduction. This study aims to investigate the heat and sound insulation properties of textile-reinforced, layered designed hybrid composite materials. In the study, textile reinforcement is fabric, and high-performance fabrics such as basalt fabric, aramid and carbon are the main components of the layered design. The matrix component is epoxy. The hybrid composite manufacturing method is the combined use of hand lay-up and vacuum infusion methods. The layers are 3 and 2 layers, and a total of 6 samples were produced according to the test plan. In thermal insulation, the lowest heat transfer coefficient and in sound insulation, the highest sound transfer loss are taken into account. At the end of the study, the lowest heat transfer coefficient was obtained as 0.0341 W/mK in the Aramid/Basalt composite sample and 16 dB for sound transmission loss in the Carbon/Aramid/Basalt composite sample. In cases where insulation is not desired in heat conduction, the best composite plate is the Carbon/Aramid/Basalt hybrid composite, which has the highest heat conduction value, with a value of 0.0514 W/mK.

Keywords: *sound and thermal properties, basalt, aramid, carbon, hybrid composites*

Investigarea proprietăților acustice și termice ale compozitelor stratificate cu armătură din bazalt, aramidă și carbon

În special pentru sectoarele construcțiilor și transporturilor, compozitele stratificate sunt importante din punct de vedere al izolației termice și fonice, al economisirii energiei și al reducerii costurilor. Scopul acestui studiu este de a investiga proprietățile de izolare termică și fonică ale materialelor compozite hibride stratificate, armate cu materiale textile. În cadrul studiului, armarea textilă este reprezentată de țesături, iar țesăturile de înaltă performanță, precum țesătura de bazalt, aramidă și carbonul, sunt componentele principale ale designului stratificat. Componenta matricei este epoxidul. Metoda de fabricație a compozitului hibrid este utilizarea combinată a metodelor de stratificare manuală și infuzie sub vid. Compozitele sunt formate din 3 și 2 straturi, iar în total au fost produse 6 eșantioane conform planului de testare. În ceea ce privește izolația termică, se ia în considerare cel mai mic coeficient de transfer termic, iar în ceea ce privește izolația fonică, se ia în considerare cea mai mare pierdere de transfer fonic. La sfârșitul studiului, cel mai mic coeficient de transfer termic a fost obținut ca fiind 0,0341 W/mK în eșantionul compozit aramidă/bazalt și 16 dB pentru pierderea de transmisie a sunetului în eșantionul compozit carbon/aramidă/bazalt. În cazurile în care izolația nu este dorită în conducția termică, cea mai bună placă compozită este compozitul hibrid carbon/aramidă/bazalt, care are cea mai mare valoare de conducție termică, cu o valoare de 0,0514 W/mK.

Cuvinte-cheie*: proprietăți acustice și termice, bazalt, aramidă, carbon, compozite hibride*

INTRODUCTION

Reinforced, layered composites are used in many industries. They are especially used in the automotive and aviation transportation industries, where properties such as strength, heat insulation and sound absorption are primarily required. For the materials to remain strong under bending and impact loads, the durability of composite materials can be increased by making various reinforcements. The study aims to directly investigate the heat and sound insulation properties of layered composite materials. The current research covers the significant effect of carbon fabric and other high-performance fabrics with a layered design configuration on heat and sound insulation properties. For this purpose, some sources obtained the literature review conducted in recent years regarding the heat and sound insulation properties of the use of high-performance textile fabrics, such as carbon, basalt and aramid, in composite structures are given below.

In their study in 2009, Sapuan et al. developed a systematic route for the design of a fabricated car body. Carbon fibre reinforced polymer composite was preferred as the material in the body design of the car. The performance of the designed car body and the reliability of the body were evaluated through engineering analyses such as aerodynamics and stability [1].

Durgun (2014) used the vacuum infusion method, one of the production methods, in the production of composite materials to shorten the unit price and part production time and reduce mould costs. In the study, a prototype car hood was produced using this method. After the internal and external parts were produced, they were combined with the metal hood body. Measurement of the complete parts was carried out by optical scanning [2].

Ovalı developed polypropylene matrix composites reinforced with basalt fabric and pumice stone of different sizes as filling material. At the end of the study, the tensile strength, modulus of elasticity and elongation properties were negatively affected, but the heat and sound insulation properties of the composite were improved [3].

In their study in 2015, Cai et al., a type of surface aluminised thermally insulated composite fabric to prevent or minimise skin burn damage caused by high temperatures. In this study, the thermal insulation properties of aluminised aramid fabrics were investigated. Thermal insulation of aluminised fabrics and non-aluminised fabrics was measured using a dry hot plate device. Here, it has been observed that aluminised fabrics have higher thermal resistance than non-aluminised fabrics [4].

Bulut et al., in their study in 2016, investigated the damping and vibration properties of basalt-aramid/epoxy hybrid composites with different basalt/aramid fibre mixture ratios. It has been observed that the use of aramid fibres in composite laminates increases the damping properties of the laminates but reduces their strength values [5].

Korkut and Gören aimed to explore polymer-based composite reinforcements to improve the heat conduction performance of PV modules. For this purpose, carbon, glass fibre, and aramid (Kevlar) reinforcement materials were investigated under two different parameters. At the end of the study, they found the heat conduction performance of carbon fibre to be most effective, followed by glass fibre (0.013 W/mm^2) and aramid ($4 \cdot 10^{-4}$ W/mm^2) [6].

Özgür examined the heat and sound insulation properties and mechanical properties of composites reinforced with basalt and carbon fabric and reinforced with filling materials. The Taguchi Grey Relationship Analysis optimisation technique was used to determine the composite material that gives the best sound and heat-absorbing properties. As a result of the study, optimum samples were determined [7].

Özgür et al., in their study in 2023, examined the heat and sound insulation properties of basalt and carbon fabric reinforced composites according to the Taguchi Grey Relationship Analysis method. Accordingly, L18 (mixed 3–6 levels) was chosen as the experimental design. As a result of the study, they found an improvement of 0.15 in the validation test [8].

Mazur et al. produced PLA composites reinforced with aramid and basalt fibres. It was used in injection moulding with weights of 10%, 15% and 20%. Comprehensive analyses were done on mechanical, thermal, thermodynamic and structural studies. The results showed that the mechanical properties of the composites improved significantly as the fibre content in the composite increased [9].

Xue et al., in their study in 2023, suggested a method for the preparation of aerogel insulation materials. Specifically, by combining coating technology, SiO/PI/AF (aramid fibre) aerogel composite fabrics were successfully obtained. The results demonstrated that excellent heat transfer performance was exhibited by composite fabrics [10].

In Liu et al.'s study, the matrix material was Polyamide aerogel the reinforcement material was aramid fibre in the study. According to the results, increasing PI aerogel led was improved mechanical properties, flexibility and thermal insulation [11].

Deshmukh and Pai used the aramid/basalt/epoxy interlayer composite to investigate the importance of CAI and sound transmission loss under 3 different conditions (25°C, –10°C and in an environment). It was designed the samples they prepared as aramid in the first layer, basalt in the next 3 layers and aramid again in the last layer. It has been observed that humidity has a negative effect on these two properties [12].

Agarwal et al. examined the effect of carbon-Kevlar intraply layers on the sound transmission loss properties of basalt/epoxy composites. According to impedance tube test results, the hybrid composites exhibited a 54.71% increase in sound transmission loss compared to the basalt-only composites. This improvement indicates the superior sound insulation performance of the hybrid structures. The findings demonstrate that the inclusion of carbon-Kevlar intraply layers is effective in optimising the acoustic properties of composite materials, particularly in terms of vibration and sound transmission behaviour [13].

Raja and Devarajan investigate the effects of integrating porcelain filler particles into basalt fibre-reinforced polymer composites on their mechanical and thermal properties. A 37% improvement in thermal performance was achieved with the addition of porcelain fillers, with significant enhancements observed in parameters such as heat resistance, thermal conductivity, and the coefficient of linear thermal expansion [14].

In this study, the heat and sound insulation properties of layered composite materials were investigated for use in the transportation sector. Carbon fabric, which is widely used in the transportation sector in the layered structure, aramid fabric, which is good for impact resistance and heat insulation, and basalt fabric, which is known to have good heat and sound insulation properties, were designed as three and two layers. The effect of the layered design on heat and sound insulation properties was investigated. This study aims to reveal the best composite design in terms of heat and sound insulation in order to use three high-performance textile surfaces in hybrid form in industrial areas. For this reason, the fabrics were used in two and three-layer structures in different orders.

MATERIAL AND METHOD

Material

In composite materials, the reinforcement textile structure is typically formed by weaving filament fibre tows (e.g., 3K, 12K) into a fabric using a plain weave pattern. These woven fabrics are subsequently processed using various composite manufacturing techniques and find application across multiple industries such as textiles, construction, and aerospace. The diversity of these applications necessitates the prioritisation of specific composite properties depending on the intended use. Accordingly, in this study, aramid, basalt, and carbon-based materials were utilised in fabric form as reinforcement components (figure 1). All fabrics used in the study weighed 200 g/m^2 and were sourced from a domestic supplier (www.kompozitshop.com, Türkiye). The carbon fabric exhibited a thermal conductivity of 17 W/mK, a fibre diameter of 7 μm, and a density of 1.76 g/cm^3. The fabrics were produced using a plain weave configuration from filament tows, with the carbon and basalt fabrics having a fibre tow density of five 3K tows per centimetre. The aramid fabric consisted of Twaron fibres in both warp and weft directions, with a linear density of 930 dtex and a weave density of 10.5 × 10.5 ± 0.3 per centimetre. The thicknesses of the fabrics were measured as 0.75 ± 0.25 mm. Composite plates have a layered structure, and these structures have 2 or 3 layers, with a different fabric on each layer. The reason why different fabrics will be chosen for the layers is to monitor the effects of the different advantages of each fabric material on the layered composite design in engineering design.

The experimental plan is given in table 1. Six different layered composite plates were obtained. The

Table 1

EXPERIMENTAL PLAN				
No	Sample Code*	1st Layer	2nd Layer	3rd Layer
1	CAB	Carbon	Aramid	Basalt
2	ACB	Aramid	Carbon	Basalt
3	ABC	Aramid	Basalt	Carbon
4	AB	Aramid	Basalt	-
5	BC	Basalt	Carbon	-
6	CA	Carbon	Aramid	-

Note: * C: Carbon fabric, A: Aramid fabric, B: Basalt fabric.

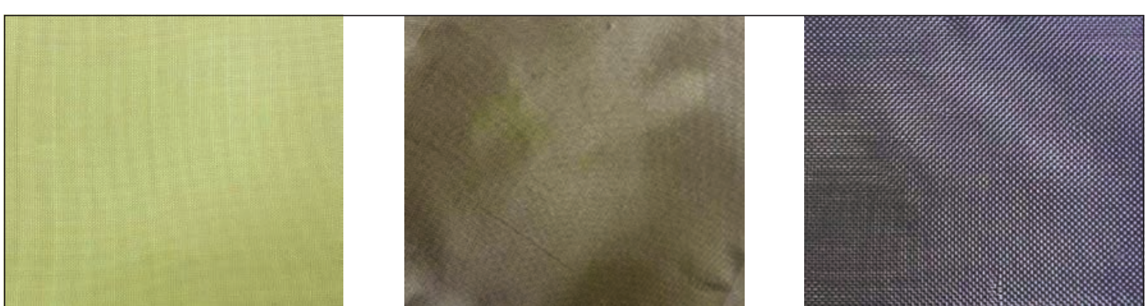
front side is the 1st floor, the back side is the 3rd floor in a 3-layer structure, and the 2nd floor is in a 2-storey structure. This marking was deemed important in the implementation of sound and heat insulation tests.

MGS Lamination Epoxy Resin L160 and MGS Lamination Epoxy H160 hardener were used in the study.

Method

Composite plate preparation

As a composite manufacturing method, the hand lay-up method by brush was used to impregnate the resin between the layers and the vacuum infusion method was used when all layers were completed. The sheets produced with the vacuum infusion method can be ensured to have a more homogeneous structure. In this method, the resin system is subjected to vacuuming (degassing) in the vacuum chamber for one hour to completely remove the air gaps in the system. The application surface for the composite plates to be produced was chosen as a glass plate. After cleaning and drying, the mould release agent was applied. The 1st layer of fabric, which is the bottom layer of the composite, is placed in accordance with the test plan. It is used as an epoxy matrix together with its accelerator, and the epoxy/hardener ratio is prepared as 4/1 (25% hardener). The resin used in the composite has this composition. The reinforcement/resin ratio in the composite is 70%–30%. A small amount is poured onto the first layer by hand. It is spread on the fabric surface with a brush and/or squeegee. Then, another layer of fabric is laid, and this process is repeated until the layers are finished. Separating fabric, peel ply and flow net are placed on the last layer, respectively. The entire test sample is fixed to the glass surface with tape. The spiral hose is placed at the inlet and outlet parts of the vacuum. The vacuum bag is placed on top to cover the sample. The connector is placed on the spiral hose by drilling the bag. The connector surroundings and the entire vacuum bag are fixed with sealing tape so that there is no leakage. The infusion hose is passed through the connector, and the seal is provided with sealing tape. It is fixed onto the vacuum infusion device from the edges with sealing tape. Then, hoses are attached to the vacuum



a *b* *c*

Fig. 1. Aramid, basalt and carbon fabric used in the experimental study:
a – Aramid fabric; *b* – Basalt fabric; *c* – Carbon fabric

and resin infusion ends, and the connection points with the mould are sealed with sealing tape. Pressure control is performed under vacuum in case there is an air leak in the mould. By operating the device, the resin is absorbed into the composite plates. In this way, layered composite plate production is achieved. The curing time of the composites is 24 hours at room temperature. The vacuum infusion application mentioned is given in figure 2.

After the layered composite plate production is carried out, samples are prepared to test the heat and sound insulation properties of the obtained plates, and the heat and sound insulation properties of the layered composites are investigated. Laser cutting was used in sample preparation. Sound transmission loss test (ASTM E-2611:2009) and thermal conductivity coefficient test (TS EN 12667) were performed in accordance with standards. Figure 3 shows the samples prepared according to the test sample sizes in laser cutting for the thermal conductivity coefficient test and sound transmission loss measurement of 6 samples [15, 16].

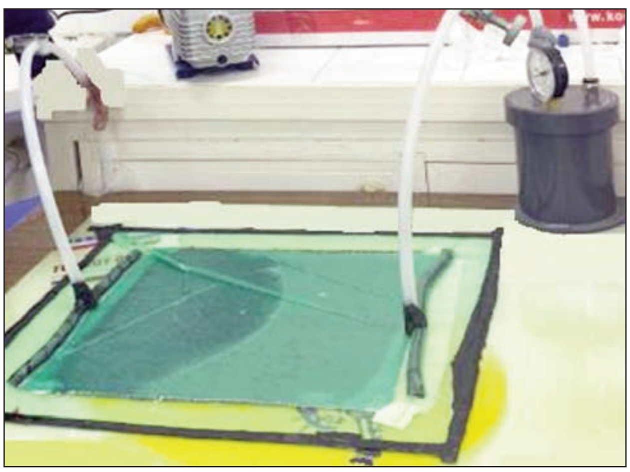


Fig. 2. Vacuum infusion method application

RESULTS AND DISCUSSION

Thermal conductivity coefficient test results

Figure 4 shows the test results for the thermal conductivity coefficient. In this test, the measurement results are expected to be as close to zero as possible. As shown in the table, all values are very close to zero. Among them, the sample with the lowest thermal conductivity coefficient is sample no. 4 (AB), with a value of 0.0341 W/mK, while the highest value belongs to sample no. 1 (CAB), with 0.0514 W/mK. Examining the graph, it can be observed that sample no. 3 (ABC) has the lowest value among the 3-layer sample structures. In the 2-layer sample structures, the lowest value belongs to sample no. 4 (AB). According to Aramid, Korkut, and Gören (2022), Barucci et al. (2005), and Ventura and Martelli (2009), the thermal conductivity coefficients of Aramid reinforcement materials range between $1 \cdot 10^{-5}$ and 4 W/mK [17–19]. For basalt, Moretti et al. stated that reinforced structures with a thermal conductivity coefficient of 0.031–0.034 W/mK have better thermal insulation properties [20]. Carbon fabric, on the other hand, has been seen in the literature as 260 W/mk by Korkut and Gören in 2022, Fukai et al. in 2000, Hong et al. in 2010, and as stated, its thermal conductivity is worse than Aramid and Basalt [17, 21, 22]. Therefore, in this study, it is seen that the thermal conductivity coefficient value increases in the samples (numbers 1 and 6) where the carbon fabric is in the upper layers. It has been determined that when carbon fabric is placed on the 2nd and 3rd layer, respectively, it has a positive effect on the decrease of the thermal conductivity coefficient. It is seen that aramid fabric has a positive effect on the thermal conductivity coefficient (good thermal insulation) regardless of the layer.

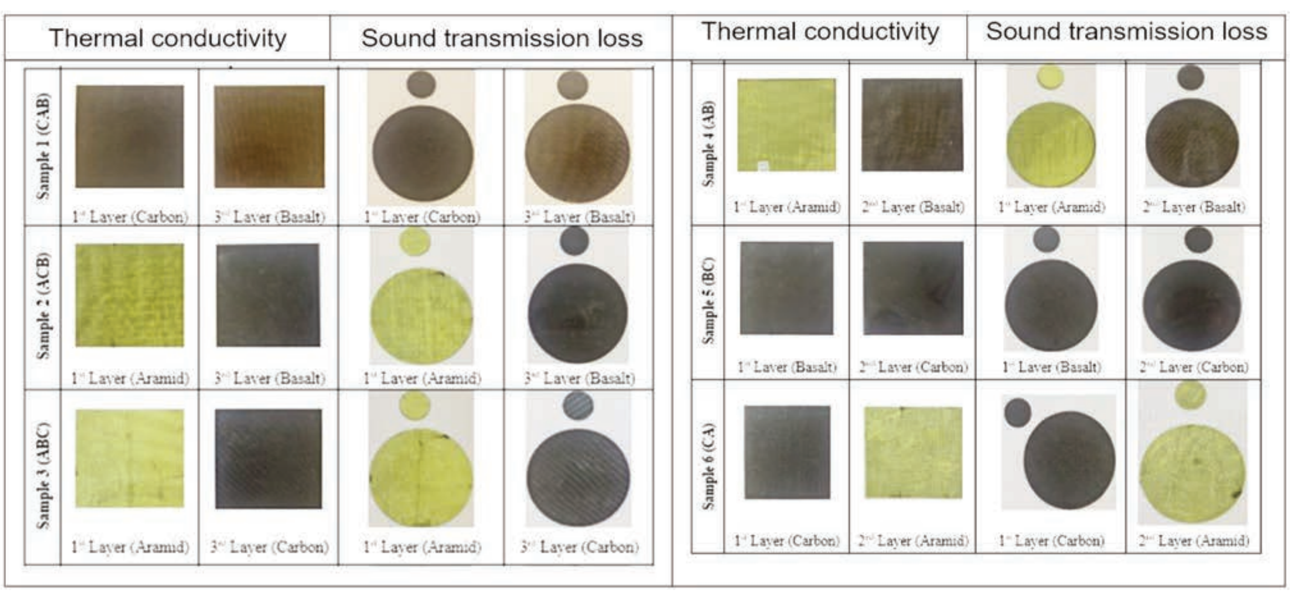


Fig. 3. Test samples for thermal conductivity coefficient and sound transmission loss tests of the 6 samples produced in the study

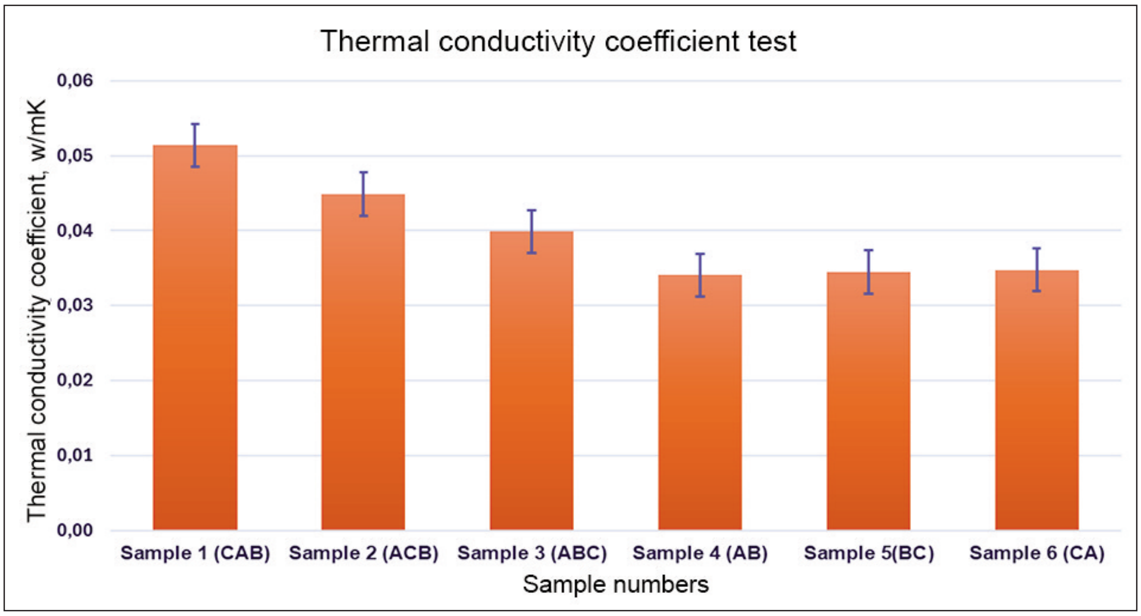


Fig. 4. Distribution of thermal conductivity coefficient test results according to composite samples

It can be said that the optimum thermal conductivity coefficient value is reached when Aramid-Basalt is included in the structure, respectively, in 3- and 2-layer structures.

Sound transmission loss test results

The average values of the sound transmission loss measurements for the samples are presented in figure 5. Higher sound transmission loss values indicate better sound insulation performance. Accordingly, the highest sound transmission loss was observed in Sample No. 1 (CAB), while the lowest was recorded in Sample No. 4 (AB). It was found that sound transmission loss increases when the carbon fabric is positioned in the uppermost and upper layers of the structure. This finding is supported by studies conducted by Sujon et al. and Wang et al. [23, 24], which reported that carbon fibres exhibit higher acoustic absorption coefficients than aramid fibres at low and medium frequencies, thereby providing better sound insulation properties. Additional studies investigating the use of aramid and basalt as layered fabric reinforcements and their corresponding sound transmission loss values were also examined. Deshmukh and Pai (2023) measured a sound transmission loss of 36.01 dB for an undamaged Aramid–3-layer Basalt–Aramid composite structure [12]. Moretti et al., in their study in 2016, stated that the sound transmission loss and acoustic performance of basalt fibres were excellent [20]. When sample number 5 (BC) is examined in this study, it is seen that it has the highest sound transmission loss in a 2-layer structure when basalt is placed on the upper layer. When the 2-layer and 3-layer structures are compared, the 3-layer sample number 1 (CAB) gave the

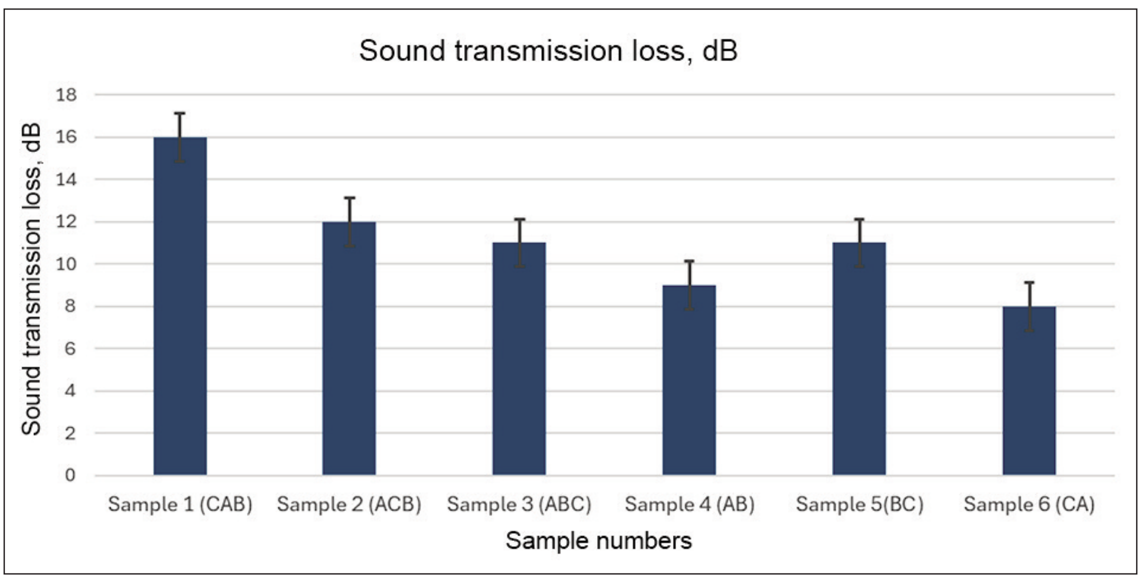


Fig. 5. Distribution of sound transmission loss test results according to composite samples

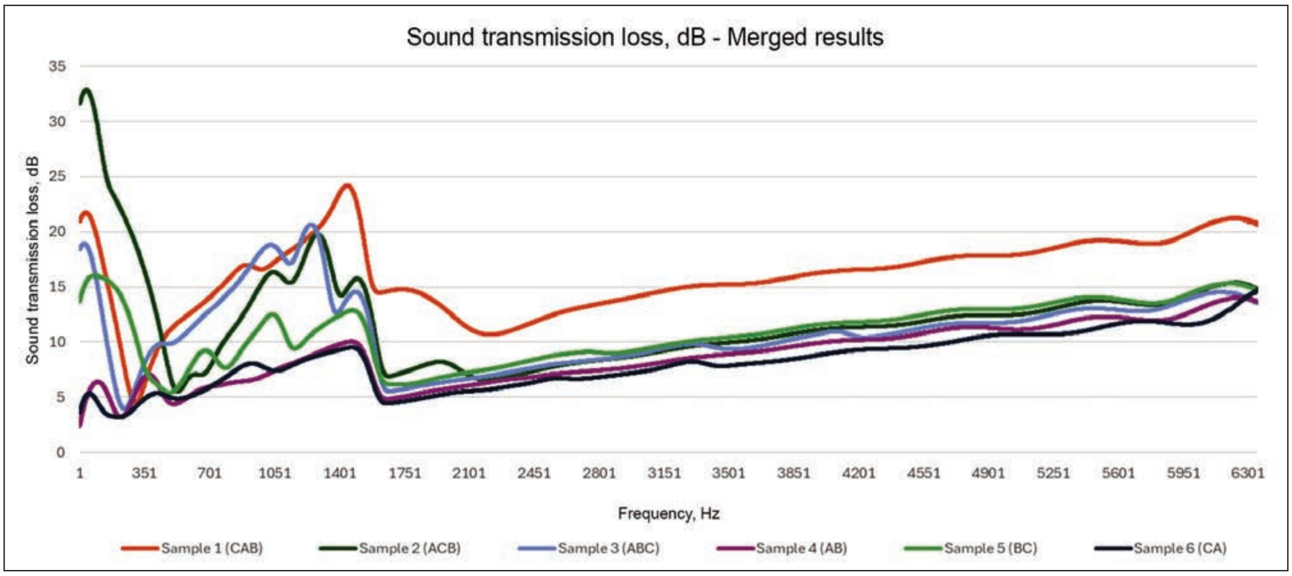


Fig. 6. Sound transmission loss values of samples in the frequency range of 50 Hz-6200 Hz

highest sound transmission loss and is the best sample in sound insulation.

Frequency range values must be considered when interpreting sound transmission loss. In figure 6, the sound transmission loss values of the samples in the frequency range of 0–6200 Hz are shown collectively. Generally, 2-layer samples exhibited a more stable behaviour at frequencies of 1600 Hz and above, while samples 1 and 2 of the 3-layer samples exhibited a more stable behaviour at 2300 Hz and above, and sample number 3 (ABC) exhibited a more stable behaviour at 1650 Hz and above.

CONCLUSION

In the study, the heat and sound insulation properties of layered composite materials were experimentally investigated using high-performance textile structures for use in the transportation sector. These structures in the form of Carbon, Aramid and Basalt were used layered within the composite in different layouts, contributing to the literature. The composite resin is epoxy, and the production method is the vacuum infusion method. Since lightness is an important parameter in these structures designed for transportation, a total of 6 different composite designs with as few layers as 2 and 3 layers were selected. Since in-vehicle sound insulation and heat insulation are of great importance for the transportation sector, these properties of the designed composites were examined comparatively for 2 and 3 layers. The results obtained from 6 different samples according to standard test methods are summarised below.

Evaluations on the thermal conductivity coefficient:

- Among 6 different composite designs, the sample with the lowest thermal conductivity coefficient value is sample 4 (AB: Aramid/Basalt) with a 0.0341 W/mK value, and the highest value is sample 1 (CAB: Carbon/Aramid/Basalt) with 0.0514 W/mK.
- In 2-layer sample structures, the lowest value belongs to sample number 4 (AB: Aramid/Basalt).
- In 3-layer sample structures, it is seen that sample number 3 (ABC: Aramid/Basalt/Carbon) has the lowest value in the group.
- In this study, it is seen that the thermal conductivity coefficient value increases in the samples (numbers 1 and 6) where the carbon fabric is in the upper layers.
- It has been determined that when carbon fabric is placed on the 2nd and 3rd layer, respectively, it has a positive effect on the decrease of thermal conductivity coefficients.
- Aramid fabric appears to have a positive effect on the thermal conductivity coefficient (good thermal insulation) regardless of its layer.
- It can be said that the most suitable thermal conductivity coefficient value is reached when Aramid-Basalt is included in the structure in the order of 2 and 3 layers.

Evaluations on the sound transmission loss:

- Among 6 different composite designs, the highest sound transmission loss belongs to sample no. 1 (CAB: Carbon/Aramid/Basalt) and the lowest belongs to sample no. 4 (AB: Aramid/Basalt).
- It is seen that the sound transmission loss value is higher in cases where the carbon fabric is in the uppermost and upper layers of the structure.
- When sample number 5 (BC: Basalt/Carbon) is examined, it is seen that basalt has the highest sound transmission loss in a 2-layer structure when placed on the upper layer.
- When 2 and 3-layer structures were compared, the highest sound transmission loss was obtained in the 3-layer composite sample number 1 (CAB: Carbon/Aramid/Basalt).
- When the sound transmission loss behavior of samples in the frequency range of 50–6200 Hz is examined, 2-layer samples exhibit a more stable behavior at frequencies of 1600 Hz and above,

while 3-layer samples no. 1 (CAB: Carbon/Aramid/Basalt) and 2 (ACB: Aramid/ Carbon/Basalt) samples are more stable at 2300 Hz and above, and sample number 3 (ABC: Aramid/Basalt/Carbon) is more stable at 1650 Hz and above.

Generally, among all samples, the thermal conduction coefficient is the lowest for sample no. 4 (AB: Aramid/Basalt), which has a 2-layer, and can be used as an insulation material for the transportation industry. For sound transmission loss, the 3-layer sample number 1 (CAB: Carbon/Aramid/Basalt) has the best performance and can be used as a sound insulation material.

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