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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GIZEM KARAKAN GÜNAYDIN
İREM ÇELİK
ERHAN KENAN ÇEVEN
HÜSEYIN GAZİ TÜRKSOY

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.

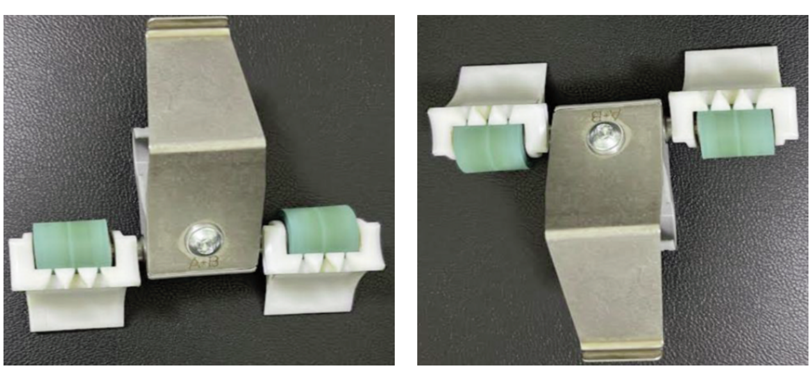
This study has been performed to make a comparative analysis of moisture management and thermal comfort properties of knitted fabrics made of ring, mechanical compact, Siro spun yarns of different fibre blends. Conventional ring, mechanical compact and Siro yarns produced from five different raw materials (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].



a *b*

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

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.

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).

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

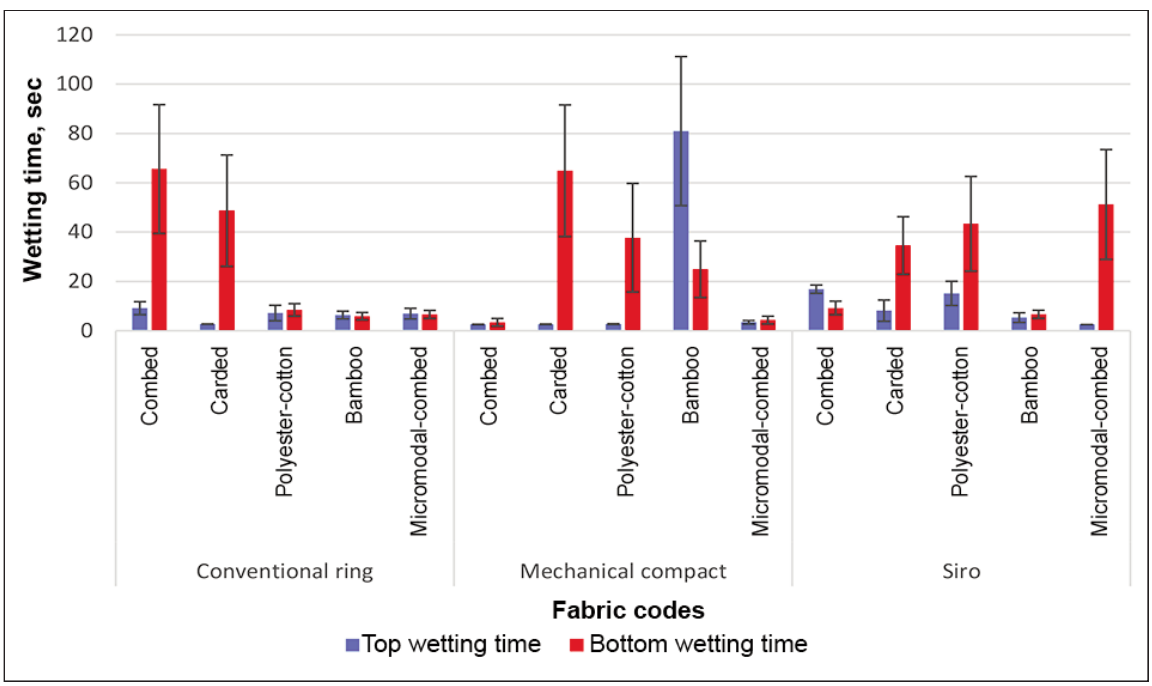


Fig. 2. Wetting time of knitted samples

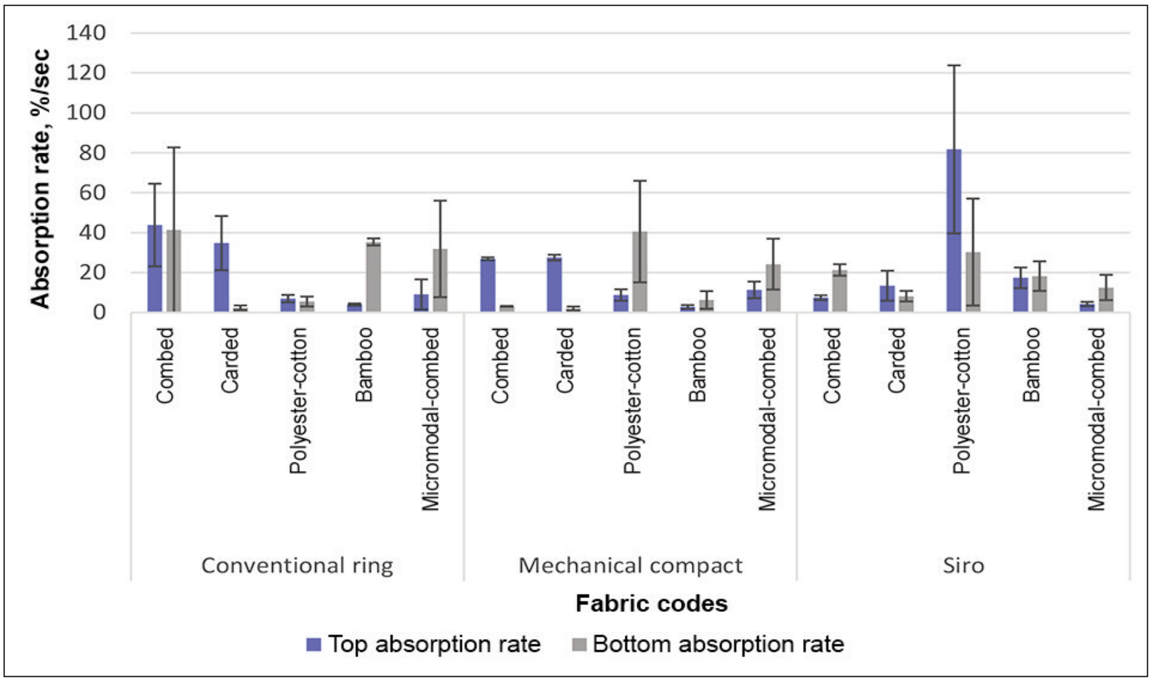


Fig. 3. Absorption rate (% /sec)

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

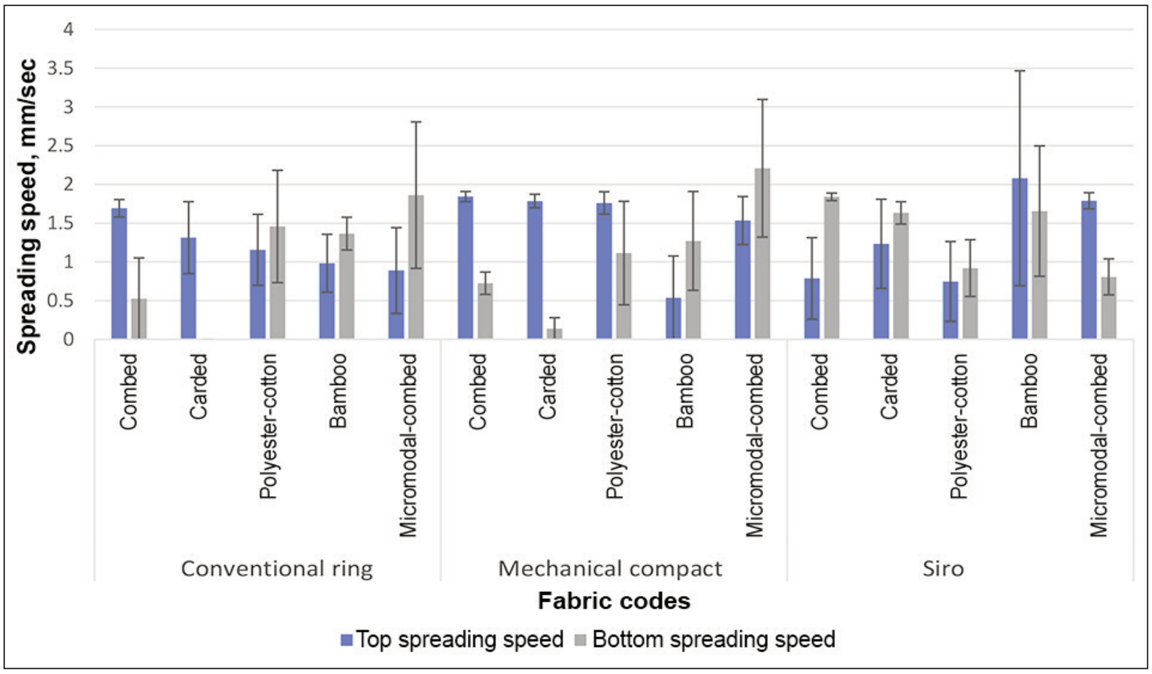


Fig. 4. Spreading speed (mm/sec)

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

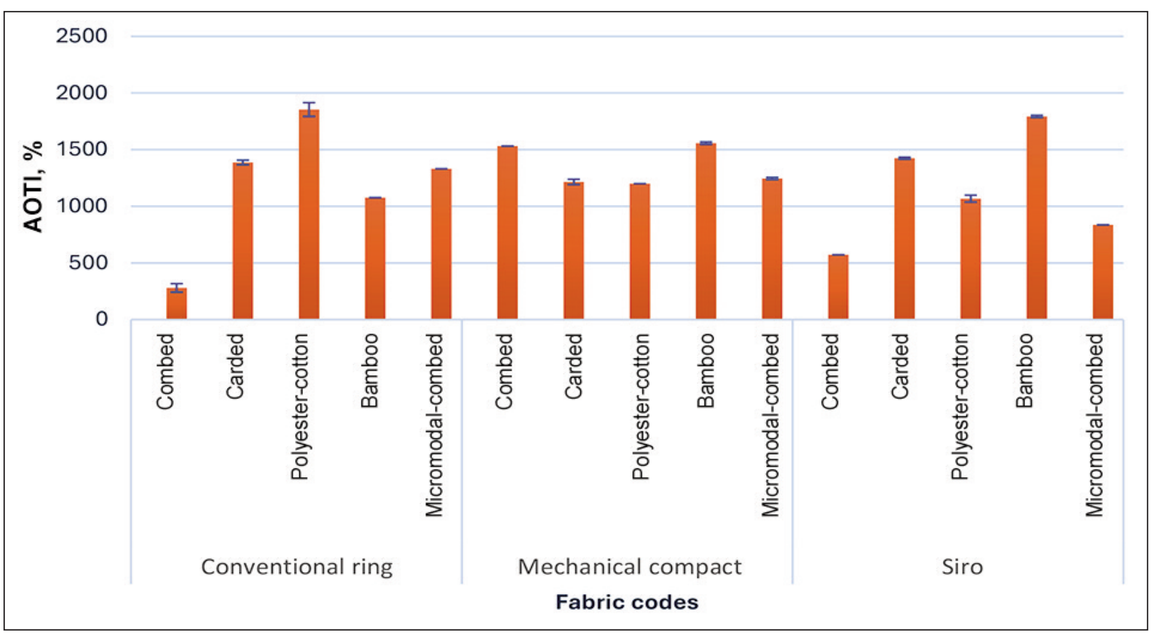


Fig. 5. Accumulative one-way transport index

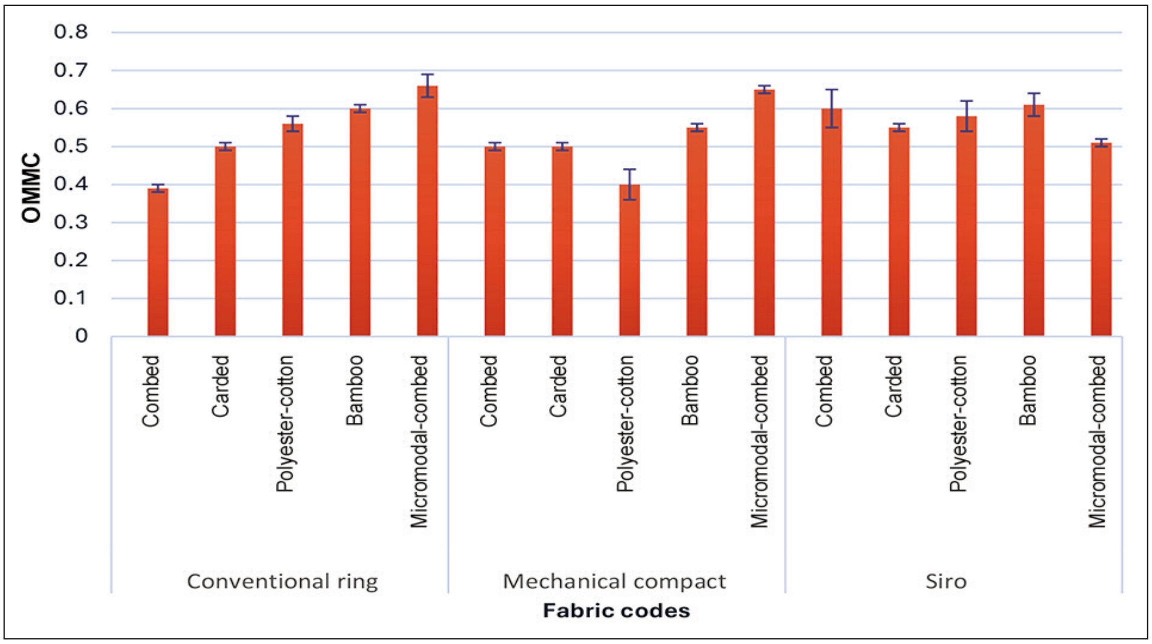


Fig. 6. Overall moisture management capacity (OMMC)

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).

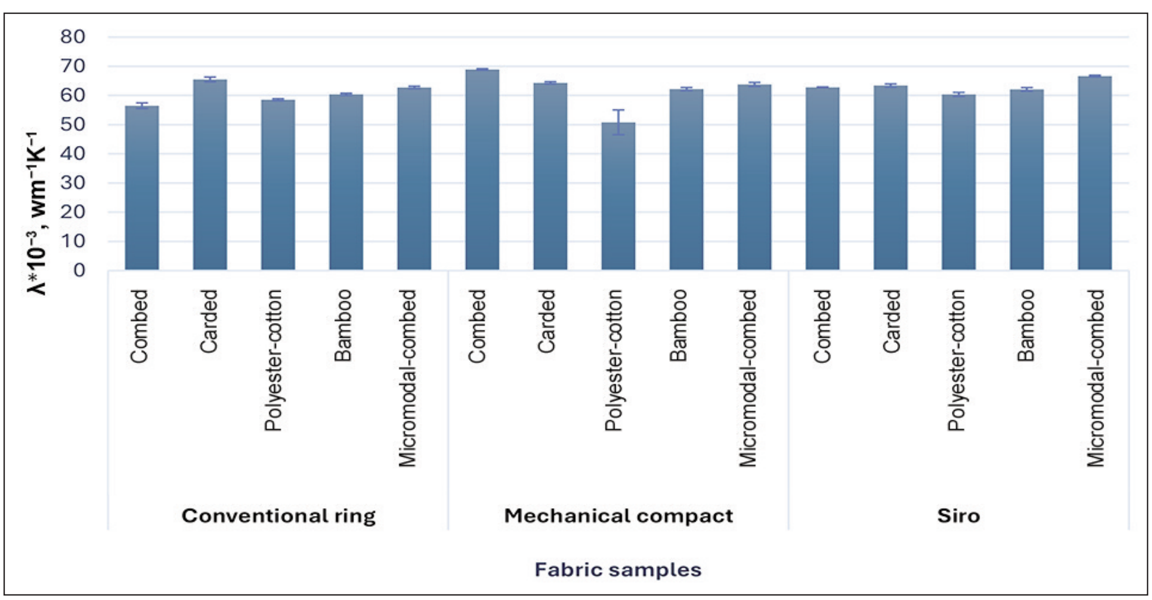


Fig. 7. Thermal conductivity

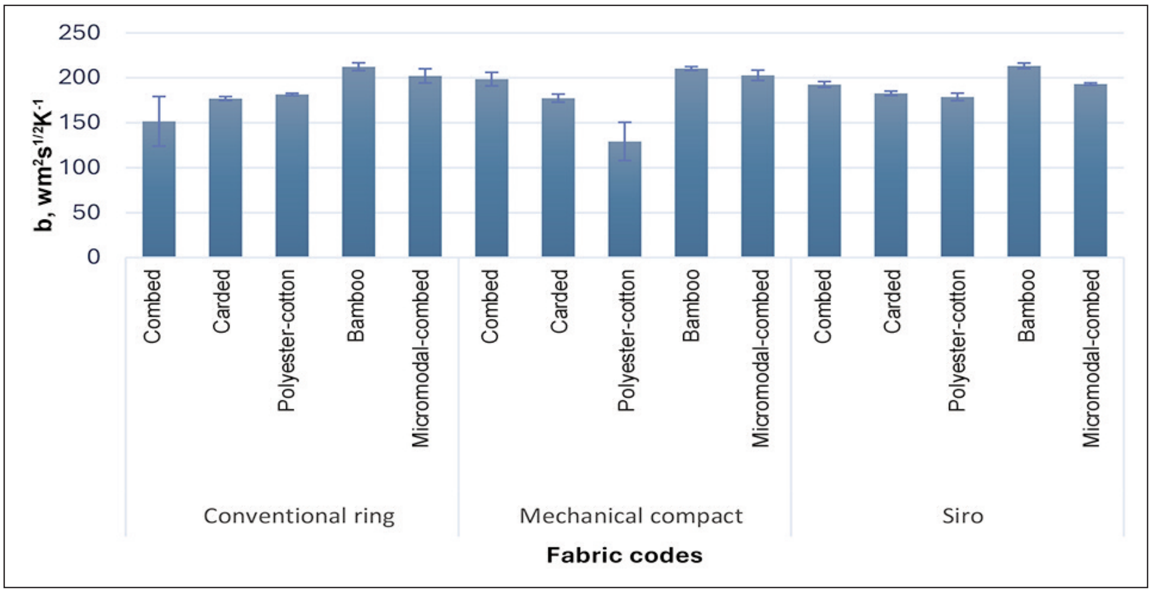


Fig. 8. Thermal absorptivity results

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

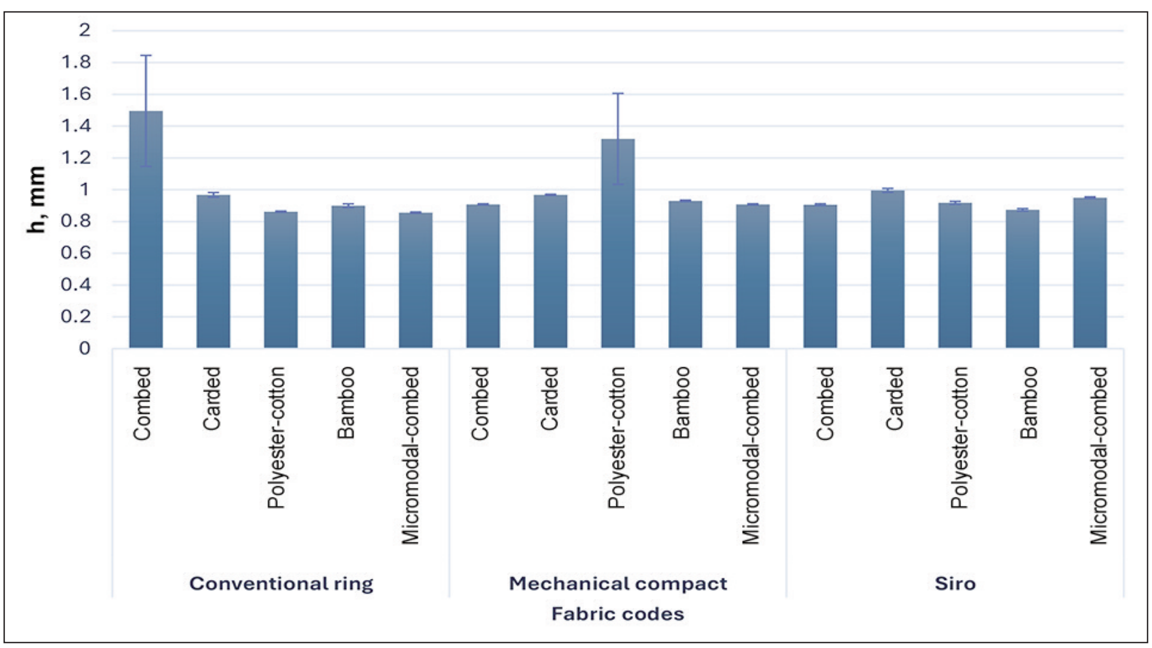


Fig. 9. Fabric thickness of fabrics

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

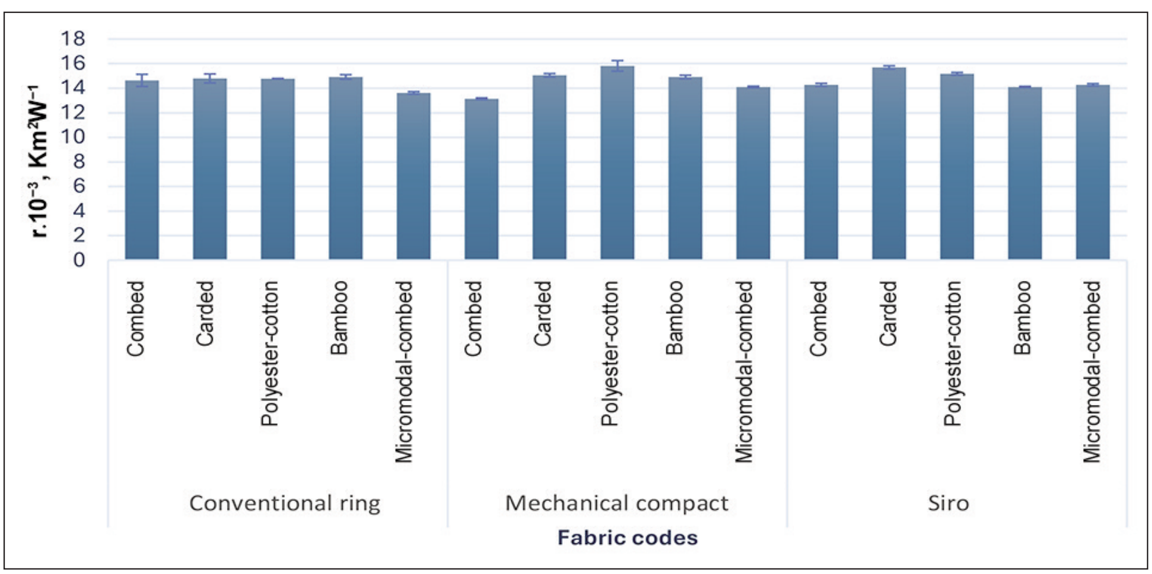


Fig. 10. Thermal resistance of fabrics

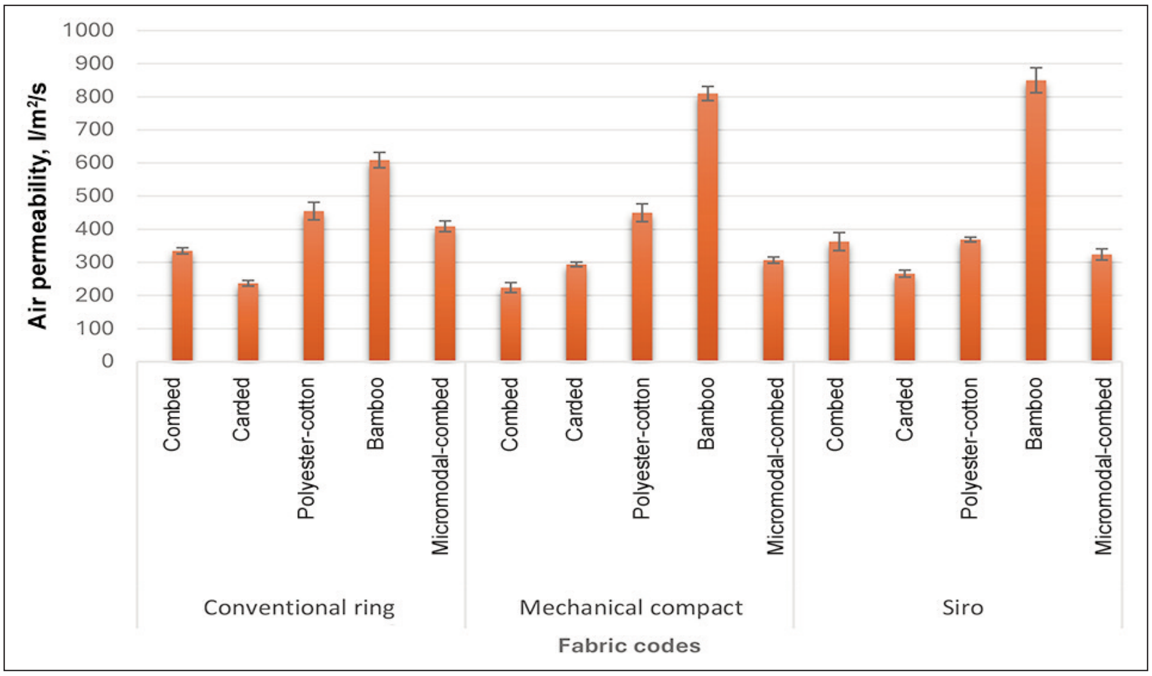


Fig. 11. Air permeability

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.

REFERENCES

[1] Gülsevincler, E., Usal, M.R., Yilmaz, D., *Effects of nozzle structural parameters on yarn hairiness in the jetring spinning system*, In: The Journal of the Textile Institute, 2020, 111, 11, 1567–1577

[2] Kaynak, H.K., Çelik, H.İ., *Thermophysiological comfort and performance properties of knitted fabrics produced from different spinning technologies*, In: The Journal of The Textile Institute, 2018, 109, 4, 536–542

[3] Altas, S., Kadoğlu, H., *Compact Spinning Research for Regenerated Cellulose and Synthetic Yarns*, In: TEKSTILEC, 2009, 52, 10–12, 306–311

[4] Örtlek, H.G., Kılıç, G., Okyay, G., Bilget, Ö., *Investigation of different ring spinning methods for producing core spun yarns containing stainless steel wire*, In: Textile and Apparel, 2011, 21, 3, 225–235

[5] Reiter, *COMPACTeasy*, available at: https://www.rieter.com/products/components/ring-and-compact-spinning/compacteasy [Accessed on March 2, 2023]

[6] Han, C., Wei, M., Xue, W., Cheng, L., *Numerical simulation and analysis of airflow in the condensing zone of compact-siro spinning*, In: Textile Research Journal, 2015, 85, 14, 1506–1519, https://doi.org/10.1177/0040517514561924

[7] Afroz, F., Islam, M.M., Akter, S., Ahmed, D.M., *Investigating tear strength in sustainable cotton-lyocell blend siro spun fabrics: twist multiplier and weave type effects*, In: Textile&Amp; Leather Review, 2023, 6, 718–741, https://doi.org/10.31881/tlr.2023.111

[8] Elrys, S., El-Habiby, F., Eldeeb, A., El-Hossiny, A., Elkhalek, R., *Comfort properties of knitted fabrics produced from dual-core and tri-core spun yarns*, In: Textile Research Journal, 2022, 93, 1760–1782, https://doi.org/10.1177/00405175221131056

[9] Gedilu, M., Santhanam, S., Bogale, M., Selvaraj, S., *Experimental analysis on the effect of ring and rotor spun yarns for comfort characteristics of weft knitted fabric structures*, In: Journal of Engineered Fibers and Fabrics, 2022, 17, https://doi.org/10.1177/15589250221078944

[10] Günaydın, G., Çeven, E., *Investigation of comfort properties of knitted fabrics made of core-spun vortex yarns*, In: Journal of Engineered Fibers and Fabrics, 2023, https://doi.org/10.1177/15589250231155622

[11] Özdil, N., Marmaralı, A., Kretzschmar, S., *Effect of yarn properties on thermal comfort of knitted fabrics*, In: International Journal of Thermal Sciences, 2007, 46, 1318–1322, https://doi.org/10.1016/J.IJTHERMALSCI.2006.12.002

[12] Manonmani, G., Vigneswaran, C., Chandrasekaran, K., Ramachandran, T., *Effect of Ring and Compact Cotton Spun Yarn characteristics on Physical and Comfort Properties of Knitted Fabrics*, In: Research Journal of Textile and Apparel, 2013, 17, 68–82, https://doi.org/10.1108/RJTA-17-03-2013-B008

[13] Kayabaşı, G., Yılmaz, D.A., *Comparative study about some of the knitted fabric properties of cotton and viscose vortex, OE-rotor and conventional ring spun yarns*, In: Tekstil & Konfeksiyon, 2015, 25, 246–255

[14] Barella, A.M.M.A., Manich, A.M., *Yarn hairiness update*, In: Textile Progress, 1997, 26, 4, 1–29

[15] EN ISO 139:2005. *Textiles – Standard atmospheres for conditioning and testing*, ISO Geneva, Switz, 2005

[16] American Association of Textile Chemists and Colourists, AATCC, T. 195: 2009. *Liquid Moisture Management Properties of Textile Fabrics*, 2009

[17] Hu, W., Li, J., Yeung, Y., Wong, K.-W., Xu, A.S.W., *Moisture Management Tester: A Method to Characterize Fabric Liquid Moisture Management Properties*, In: Text. Res. J., 2005, 75, 1, 57–62

[18] Frydrych, I.G., Dziworska, G., Bilska, J., *Comparative Analysis of the Thermal Insulation Properties of fabrics made of Neutral and Man-Made Cellulose Fibres*, In: Fibres&Textiles in Eastern Europe, 2002, 10, 4, 40–44

[19] Kayseri, G.Ö., Bozdoğan, F., Hes, L., *Performance properties of regenerated cellulose fibers,* In: J. Text. Apparel/Tekstil ve Konfeksiyon, 2010, 20, 3, 208–212

[20] Oğlakçıoglu, N., Marmaralı, A., *Thermal Properties of some knitted structures*, In: Fib.&Tex. in Eastern Europe, 2007, January / December, 15, 5–6, 64–65

[21] ISO 9237:1995. *Textiles – Determination of the permeability of fabrics to air*, Geneva, Switzerland

[22] Havlova, M., *Model of vertical porosity occurring in woven fabrics and its effect on air permeability*, In: Fibres Text in East. Europe, 2014, 22, 58–66

[23] Sarıoğlu, E., Babaarslan, O., *Porosity and air permeability relationship of denim fabrics produced using core-spun yarns with different filament finenesses for filling*, In: J. of Eng. Fibers and Fabrics, 2019, 14, 1558925019837810

[24] Elnashar, E.A., *Volume porosity and permeability in double layer woven fabrics*, In: AUTEX Res J, 2005, 5, 207–218
[25] Karaca, E., Kahraman, N., Omeroglu, S., Becerir, B., *Effects of fiber cross sectional shape and weave pattern on thermal comfort properties of polyester woven fabrics*, In: Fibres & Textiles in Eastern Europe, 2012, 3, 92, 67–72

Authors:

GIZEM KARAKAN GÜNAYDIN[1], İREM ÇELİK[2], ERHAN KENAN ÇEVEN[3], HÜSEYIN GAZİ TÜRKSOY[4]

[1]Pamukkale University, Faculty of Design and Architecture, Textiles and Fashion Design Department, Denizli, Türkiye

[2]Uğurlular Tekstil .San. ve Tic. A.Ş., Organiza Sanayi Bölgesi, Denizli, Türkiye

[3]Bursa Uludağ University, Faculty of Engineering, Textiles Engineering Department, Bursa,16059, Türkiye

[4]Erciyes University, Faculty of Engineering, Textiles Engineering Department, Kayseri, Türkiye

Corresponding author:

GIZEM KARAKAN GÜNAYDIN
e-mail: ggunaydin@pau.edu.tr