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REGULAR ARTICLE

Advancements in Cotton Textile Design: Addressing Temperature and Moisture Challenges

Zeynep Omerogullari Basyigit[1] · Cemre Nur Kuyucak[2] · Hatice Coskun[2]

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Abstract

The primary objective of this study is to alleviate discomfort arising from fluctuations in heat and humidity due to environmental and personal factors, aiming to develop functional textiles capable of effectively responding to these changes. To achieve this, systematic pattern designs were implemented on 100% cotton woven fabrics, incorporating hydrophobic characteristics through the application of a water-repellent agent to specific areas. The resulting compatibility of these hydrophobic features with hydrophilic elements endowed the fabrics with moisture management properties. Furthermore, the introduction of a phase-changing material agent to these fabrics imparted heat management capabilities. The rotation printing technique was employed to seamlessly transfer these agents onto the fabric. In assessing the durability of woven fabrics featuring distinct functionalities, a comprehensive examination was conducted, subjecting them to 30 repeated wash cycles within a single process step. The morphological structures of the fabrics produced were meticulously analyzed using SEM (scanning electron microscopy), SEM–EDX (energy-dispersive X-ray analysis) while their chemical compositions were scrutinized through FTIR–ATR (Fourier transform infrared spectroscopy–attenuated total reflectance). Additionally, a battery of tests, including physical, chemical, liquid absorption, liquid transfer assessments, and DSC (differential scanning calorimetry) analyses, were conducted in accordance with relevant standards. The outcomes of this study demonstrated that the fabrics not only met the criteria of the TS 866 standard, particularly with regard to a rapid response time of less than 10 s, but also exhibited resilience to repeated washings, affirming the enduring efficacy of the incorporated functionalities. According to tearing strength results, slight increase was also observed in treated cotton fabrics.

Keywords Functional textiles · Heat and moisture exchange · Moisture management · Heat management · Wash durability

1 Introduction

Textile surfaces play a crucial role as a protective interface between individuals and their environment, influencing well-being and physical performance based on environmental conditions [1]. The key determinant of such influence is the comfort provided by textile surfaces, as discomfort can lead to restricted movements, diminished metabolic activation, dissatisfaction, and a reduced quality of life [2–4]. Notably, the inadequacy of textile products in responding to changes in internal and external heat and humidity is a significant factor contributing to these negative effects, emphasizing the importance of achieving thermophysiological comfort [5].

Sweat on the skin is guided to the hydrophilic absorbent area by the hydrophobic segments, enabling rapid moisture removal from the skin. By ensuring that only specific areas of the fabric are wet, perceived wetness is reduced, and there is no adherence of the fabric to the skin. Furthermore, the fabric's region away from the skin is uniformly wetted, avoiding any restrictions in the individual's movements, discomfort, or performance loss during activities. A water-repellent agent is incorporated to facilitate these properties [6, 7].

Water repellents alter the surface tension between the fabric and air while increasing tension between the fabric and liquid, preventing liquid penetration and rendering the fabric water repellent [8, 9]. The study employs reversible thermal absorptivity/emissivity materials, specifically phase

✉ Zeynep Omerogullari Basyigit
zeynepbasyigit@uludag.edu.tr

1 Vocational School of Higher Education of Inegol, Textile, Clothing, Footwear and Leather Department, Textile Technology, ProgrammeBursa Uludag University, Bursa, Turkey

2 Agaoglu Textile Industry R&D Center, Uşak, Turkey

change materials (PCMs), to achieve effective heat management or thermoregulation [10–12]. PCMs store and release energy based on temperature changes, responding to ambient and body temperature fluctuations. High-temperature PCMs, with melting points close to skin temperature, are utilized to balance environmental and personal temperature changes [13–15]. These PCMs absorb excess heat during temperature increases, preventing discomfort, and release stored heat when temperature decreases, providing warmth [16, 17].

This study aims to address the issues by developing fabrics that offer dynamic thermal insulation, cooling, heating, and temperature regulation, along with effective moisture management within a singular structure. Additionally, the objective is to create ideal textile surfaces that eliminate discomfort and unwanted conditions resulting from fluctuations in heat and humidity due to internal and external factors affecting the individual. The integration of hydrophilic/hydrophobic characteristics and PCM application for moisture and heat management, respectively, is achieved in a single process step using rotary printing instead of conventional partial dyeing. To achieve targeted moisture management, this study introduces hydrophilic and hydrophobic zones in the fabric, strategically placed near the skin. This study presents a novel approach by synergistically combining two functional groups and utilizing the rotary printing technique to confer multifunctional properties to woven fabrics in a streamlined process, deviating from traditional methods of partial dyeing.

Table 1 Technical information about the functional agents

Functional agent	CrodaTherm ME29D	Rucostar E
Form	Dispersion	Liquid
Ionite	cationic	cationic
Active substance	50%	C6 fluorocarbon
Private point (°C)	28.8	–
Chris. Point (°C)	23.5	–
Heat storage (kj/kg)	183	–
Surface tension (dyne/cm)	–	15–20
Heat storage (kj/kg)	− 179	–

Fig. 1 Sample design (picture template)

2 Materials and Methods

In this study, woven fabric made from Ne 30/1 yarns, with a thickness of 30 picks/cm and 40 ends/cm, weighing 123 g/m^2, and consisting of 100% cotton, was utilized. The fabrics, sourced from Ağaoğlu İplik Dokuma in Turkey, underwent a scouring process at Ağaoğlu Tekstil using 0.1% Gensize LT 600 scouring enzyme (Genkim, Turkey) and 0.1% Erawet SWD wetting agent (ER-SA, Turkey) in an Osthoff-Senge 42,327 Wuppertal scouring machine. Subsequently, a combined desizing process was carried out with 0.8% Erawet MT desizing agent (ER-SA, Turkey), 2.5% NaOH (32 Bé) (Borkim Kimya, Turkey), and 3% H_2O_2 (Tempo Kimya, Turkey) in a Menzel continuous mercerizing machine, completing the pretreatment process. Functional agent applications were executed using the rotation printing technique on the woven fabrics, whose technical specifications were examined post these processes.

The heat management agent selected for this study was CrodaTherm ME29D (Croda Chemicals, UK), a microencapsulated phase change material in powder form that absorbs and releases thermal energy at a defined temperature. This agent, belonging to the organic material group, is based on polyethylene glycol (PEG). For water repellency (liquid protection), Rucostar E (Rudolf Duraner, Turkey), based on fluorocarbon, was employed. The technical information of the functional agents used in this study is presented in Table 1.

2.1 Rotary Printing Technique

One of the study's objectives is to effectively absorb moisture, specifically sweat, from the skin and maintain the dryness of hydrophobic areas by channeling it to hydrophilic sections on the fabric surface. This strategic approach prevents the fabric from becoming wet and adhering to the skin, thereby mitigating any restrictions on movement, discomfort, or performance loss during various activities. To achieve this, a systematic creation of diverse pattern designs on the fabric surface was implemented, establishing distinct hydrophilic and hydrophobic regions. The illustrated pattern designs, displayed as template visuals in Fig. 1, showcase the deliberate use of brown segments as hydrophilic areas and white segments as hydrophobic areas. A schematic representation highlighting the targeted characteristic features of these designed patterns for the fabrics is presented in Fig. 2.

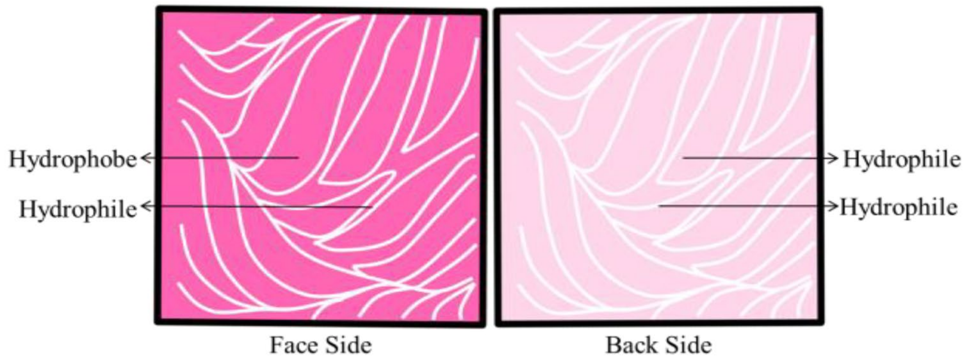


Fig. 2 Schematic representation of the fabric

Table 2 Pigment printing paste recipe

Chemical used	Chemical substance structure	Amount of chemical substance (g/kg)
Ammonia	25% ammonia solution	5
Foam cutter	Silicone based	5
Emulsifier	2-[(8Methyl nonyl)oxy]ethanol	5
Plasticizer	polysiloxane	10
Thickener	acrylic based	22
Urea	46% nitrogen	50

2.2 Application of a Water-Repellent Agent

In the context of the study, application recipes were developed by incorporating different quantities of Rucostar E into the printing paste containing pigment ink utilized in the printing technique. The templates and execution of the pattern designs under investigation were carried out using a Johannes Zimmer rotary printing machine located at Ağaoğlu Textile. Detailed formulations for the process applications are outlined in Tables 2 and 3.

2.3 Application of Thermal Regulators

In the study, application recipes were formulated by integrating the chemical substance CrodaTherm ME29D into a pigment printing paste devoid of ink for use in the printing technique. For moisture management, a second template for a lacquer (ful) surface print was introduced behind the selected template during the application process on the rotary printing machine, and the application was finalized. Subsequently, the textile surfaces underwent a fixation process at a temperature of 150 °C. Figure 3 provides a schematic representation of the sequential steps involved in the investigated printing technique application.

3 Experimental

3.1 Washing Process

Fabric samples underwent 30 repeated washings, denoted by adding 30Y to the fabric codes, utilizing an Altus brand household washing machine at Ağaoğlu Tekstil, following the EN ISO 6330–2012 standard. The drying process for the samples was carried out in a drum dryer for approximately 40 min (at 1000 rpm), leaving them with about 60% moisture content. Subsequently, the fabrics slated for

Table 3 Applied process recipes in printing technology

Recipe code	Paste information	Chemical used	Amount of chemical substance used (g/kg)	Template order	Pattern information
R01	Pigment paste containing paint	Rucostar E	200	1	Patterned template
	Unpainted pigment paste	Croda Therm ME29D	200	2	Lacquer template
R02	Pigment paste containing paint	Rucostar E	250	1	Patterned template
	Unpainted pigment paste	Croda Therm ME29D	250	2	Lacquer template
R03	Pigment paste containing paint	Rucostar E	300	1	Patterned template
	Unpainted pigment paste	Croda Therm ME29D	300	2	Lacquer template

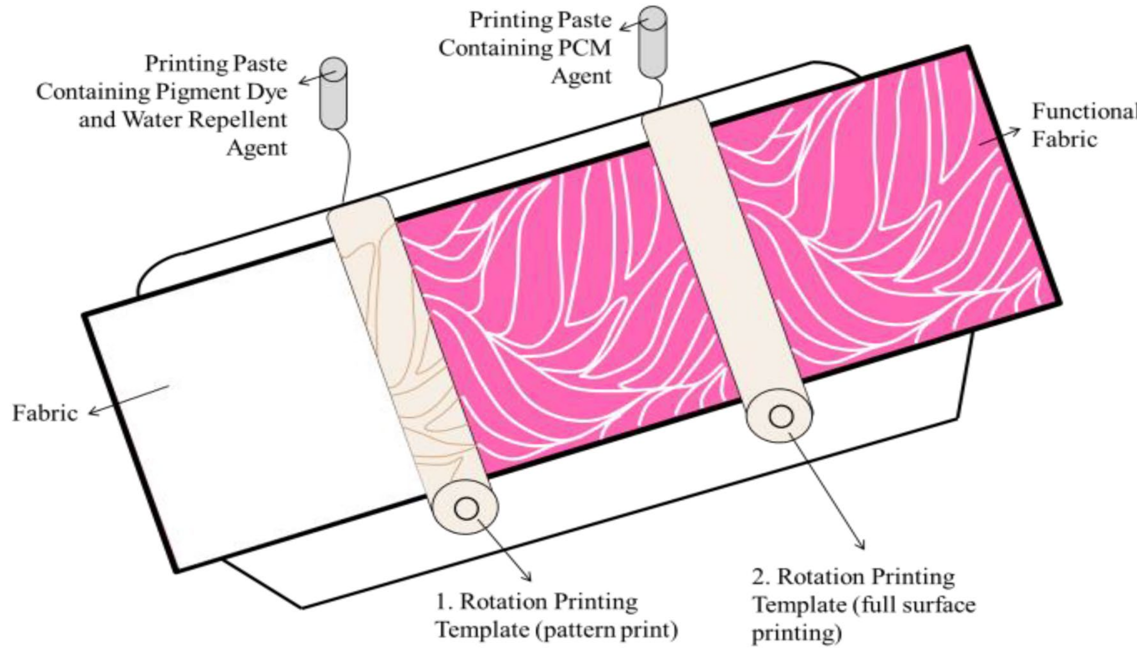


Fig. 3 Schematic representation of the application steps in the printing technology

Table 4 Performance tests standards

Test type	Standard	Devices used
Dry rubbing fastness	TS EN ISO 105-X12	Crocmeter
Wet rubbing fastness	TS EN ISO 105-X12	Crocmeter
Tensile strength	TS EN ISO 13934–2	James Heal Titan 2
Tear strength	TS EN ISO 13937–2	James Heal Titan 2
Pilling	TS EN ISO 12945–2	James H. Heal-Nu-Martindale 864
Abrasion resistance	TS EN ISO 12947–4	James H. Heal-Nu-Martindale 864

testing were conditioned for 24 h under standard atmospheric conditions, maintaining a temperature of 20 °C ± 2 and relative humidity of 65% ± 2.

3.2 Performance Tests

Physical tests and analyses of the fabric samples were conducted at Ağaoğlu Tekstil as part of the study. Comprehensive details about these tests and the corresponding standards can be found in Table 4.

3.3 Fastness Tests

Chemical tests and analyses of fabric samples were performed at Ağaoğlu Tekstil as an integral part of the study. A comprehensive breakdown of the details regarding these tests and the corresponding standards is presented in Table 5.

Table 5 Fastness tests and standards

Test type	Standard	Devices used
Washing fastness	TS EN ISO 105-C06	Perspirometer, stove
Acidic sweat fastness	TS EN ISO 105-E04	Perspirometer, stove
Alkaline sweat fastness	TS EN ISO 105-E04	Perspirometer, stove
Water fastness	TS EN ISO 105-E01	Perspirometer, stove

3.4 DSC Analysis

DSC analysis of textile surfaces was analyzed in PerkinElmer Jade device according to DIN SPEC 60015 standard.

3.5 Water Dropping Method

The liquid spreading properties of the functional textile surfaces generated in the study, both in their unwashed state and after undergoing 30 repeated washings, reflecting their moisture management functionality, were assessed using the water droplet method. Fabric samples, including those with recipe codes and untreated samples, were positioned on a flat surface. Subsequently, an equivalent volume of water (2 ml) was dispensed onto the face surface of the fabrics using a pipette. The examination covered aspects such as water distribution, distribution time, and water repellency performance on both the face and back surfaces of the fabrics.

3.6 Fluid Absorption and Transfer Tests

To assess the liquid absorption and transfer properties of the samples, vertical capillary absorption (TS 866) tests were executed. In the vertical capillary absorption test, a setup adhering to the standard was arranged, and the ascent of the liquid on the samples was measured over a duration of 120 s at 15 s intervals.

3.7 SEM and SEM–EDX Analysis

SEM and SEM–EDX analysis of textile surfaces after Pl–Au coating was performed with LEO 1430VP device at 1500 × magnification.

3.8 FTIR–ATR Analysis

Analysis of FTIR–ATR textile surfaces was carried out using PerkinElmer Spectrum 2 device with ATR apparatus in the range of 4000–500 cm^{-1}.

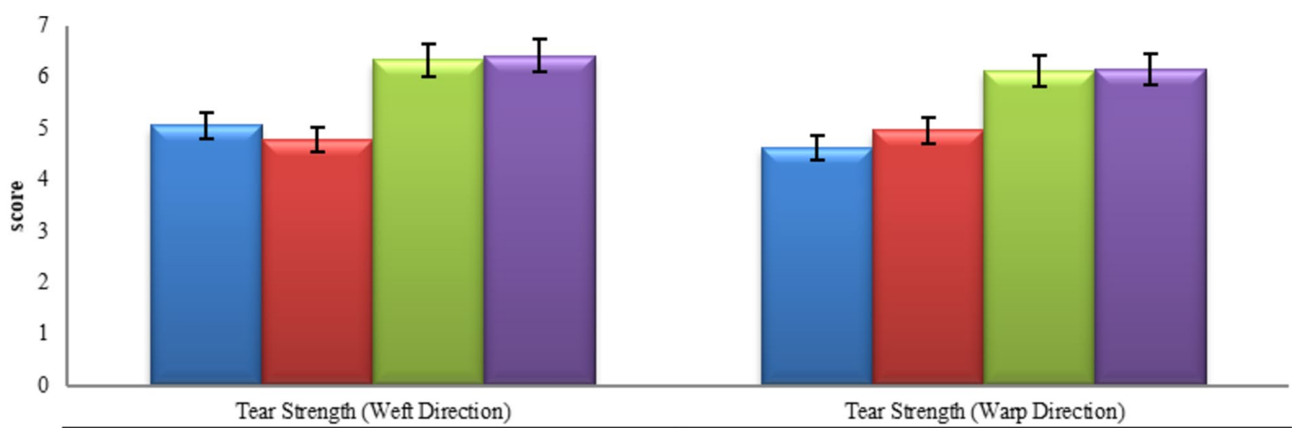
4 Results and Discussion

4.1 Performance Test Results

In Fig. 4, tear strength results were shown; according to this test result, a slight increase was observed both in warp and weft directions. The increase in tear strength is believed to be attributed to the inclusion of silicone-based materials in the recipe, in addition to the water-repellent agent used. The silicone-based foam cutter simultaneously enhances inter-fiber mobility, reducing the friction coefficient. Therefore, it is thought that the increase in tear strength is due to these factors. Figure 5, on the other hand, illustrates that the processed fabrics treated with the three different recipes exhibited the highest levels of resistance against pilling, abrasion, and rubbing, according to the test results.

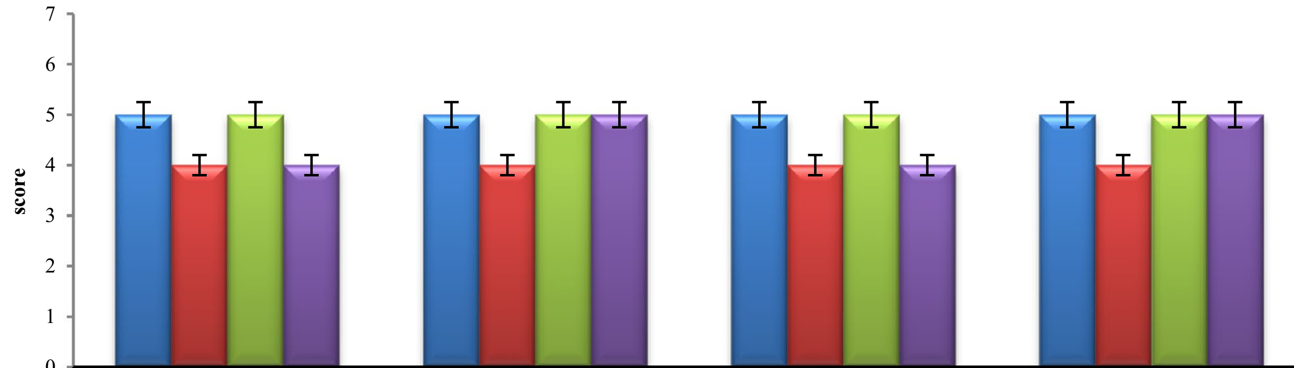
According to Fig. 6, after 30 repeated washings, tearing strength values of all fabrics in both warp and weft directions exhibited similarity. When compared to the test results of unwashed fabrics, there were insignificant decreases in tearing strengths. These decreases can be attributed to the increase in mechanical deformation of fabrics as the number of washings increases, leading to a gradual decrease in their mechanical strength [18]. Additionally, the tearing strength of fabrics is influenced by various factors such as fiber and yarn properties, fabric characteristics, and finishing processes.

As depicted in Fig. 7, after 30 repeated washings, no significant differences were observed in pilling resistance, abrasion resistance, and rubbing fastness test results among



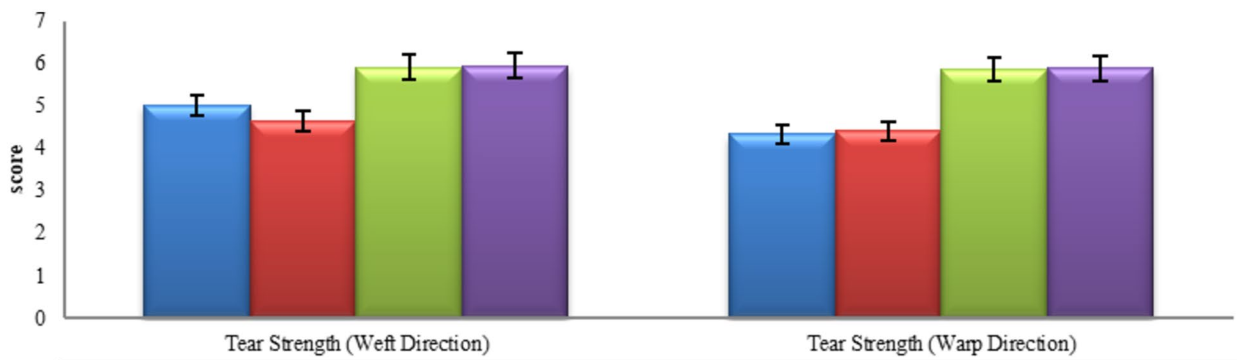
	Tear Strength (Weft Direction)	Tear Strength (Warp Direction)
R00	5.06	4.63
R01	4.78	4.96
R02	6.34	6.13
R03	6.42	6.16

Fig. 4 R00 (untreated), R01, R02, and R03 strength test results



	Pilling resistance	Wear resistance	Dry Rubbing Fastness	Age Rubbing Fastness
R00	5	5	5	5
R01	4	4	4	4
R02	5	5	5	5
R03	4	5	4	5

Fig. 5 R00, R01, R02, R03 pilling resistance, abrasion resistance, and rubbing fastness test results



	Tear Strength (Weft Direction)	Tear Strength (Warp Direction)
R00/30Y	5.02	4.33
R01/30Y	4.65	4.41
R02/30Y	5.92	5.87
R03/30Y	5.96	5.89

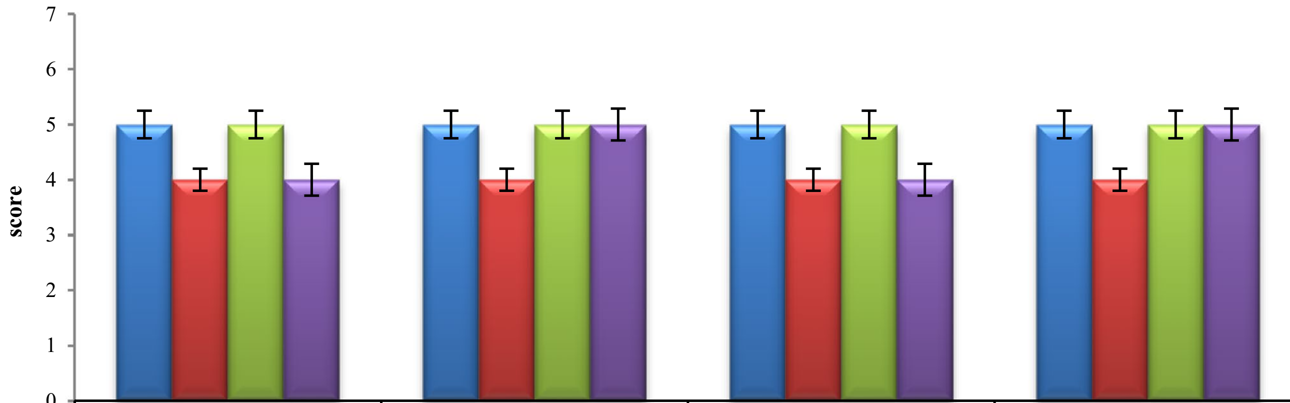
Fig. 6 R00/30Y, R01/30Y, R02/30Y, and R03/30Y strength test results

all fabrics. The results were closely aligned with each other, indicating consistent performance even after repeated wash cycles.

4.2 Fastness Test Results

In the study, Fig. 8 presents the test results of untreated fabrics alongside fabrics processed with three different recipes for fabrics that were not washed. In Fig. 9, the corresponding results are shown for fabrics that underwent 30 repeated washings.

As depicted in Fig. 8, all rubbing fastness values of both processed and untreated fabrics are consistently at the highest levels. Furthermore, Fig. 9 illustrates that there were no discernible changes in all rubbing fastness values of unwashed fabrics even after undergoing 30 repeated washings. Consequently, the study's evaluation suggests that the chemical components used in the process applications have no adverse effects on the performance and rubbing fastness values of the fabrics, as indicated by all test results.



	Pilling resistance	Wear resistance	Dry Rubbing Fastness	Age Rubbing Fastness
R00	5	5	5	5
R01	4	4	4	4
R02	5	5	5	5
R03	4	5	4	5

Fig. 7 R00/30Y, R01/30Y, R02/30Y, R03 pilling resistance, abrasion resistance, and rubbing fastness test results

	Acidic Sweat Fastness	Alkaline Sweat Fastness	Water Fastness	Washing Fastness
R00	5	5	5	5
R01	5	5	5	5
R02	5	5	5	5
R03	5	5	5	5

Fig. 8 R00, R01, R02, and R03 fastness test results

	Acidic Sweat Fastness	Alkaline Sweat Fastness	Water Fastness	Washing Fastness
R00/30Y	5	5	5	5
R01/30Y	5	5	5	5
R02/30Y	5	5	5	5
R03/30Y	5	5	5	5

Fig. 9 R00/30Y, R01/30Y, R02/30Y, and R03/30Y fastness test results

Table 6 DSC chemical analysis

Sample	Melting point Tm (°C) *	Heat capacity Tm (ΔH: J/kg)
R00	–	–
R01	26.4	330.2
R02	26.8	483.2
R03	26.5	550.6
R00/30Y	–	–
R01/30Y	28.7	1004.1
R02/30Y	28.9	1705
R03/30Y	29.1	1878.2

4.3 DSC Analysis

The melting point and heat capacity of the fabrics treated with the phase change material agent were determined using a DSC (differential scanning calorimetry) device. The test results of the fabrics utilized in the study are provided in Table 6.

The temperature levels corresponding to the heat stored and released by the cotton fabric samples are indicated beneath the melting and solidification peaks in the endothermic and exothermic directions, as illustrated in the DSC curves presented in the figures below (Figs. 10, 11, 12, 13, 14, 15, 16, 17).

According to the results extracted from the curve in Fig. 10, untreated cotton fabric (DA/R00) exhibited no discernible thermal properties, as microcapsules were not applied. Conversely, the microencapsulated cotton fabric sample with the code DA/R01, as depicted in Fig. 11, emitted 0.3302 J/g of heat at 26.37 °C. Similarly, the microencapsulated cotton fabric sample with the code DA/R02, as illustrated in Fig. 12, emitted 0.4832 J/g of heat at 26.85 °C. Lastly, based on the results from the curve in Fig. 13, the microencapsulated cotton fabric sample with the code DA/R03 emitted 0.5506 J/g of heat at 26.49 °C.

According to the results obtained from the curve in Fig. 15, the microencapsulated cotton fabric sample with the code DA/R03 emitted 1.0041 J/g of heat at 26.73 °C. Subsequently, based on the findings from the curve in Fig. 16, the same fabric sample emitted 1.7050 J/g of heat at 28.98 °C. Lastly, as indicated by the results from the curve in Fig. 17, the microencapsulated cotton fabric sample with the code DA/R03 emitted 1.8782 J/g of heat at 29.04 °C. It was observed that there is no significant difference between the

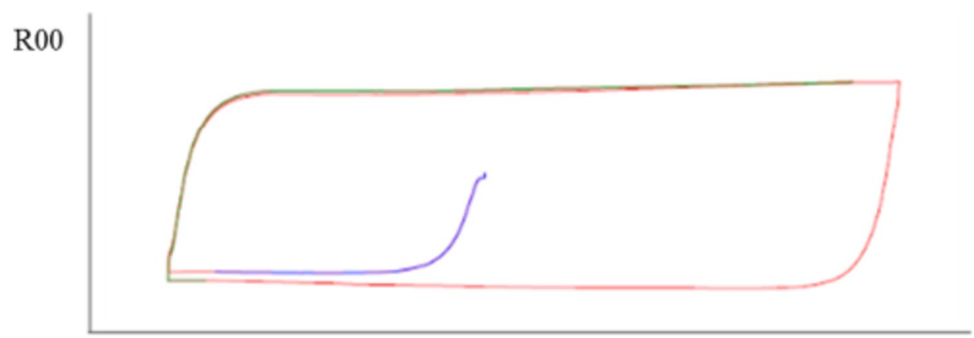


Fig. 10 DSC graph from R00

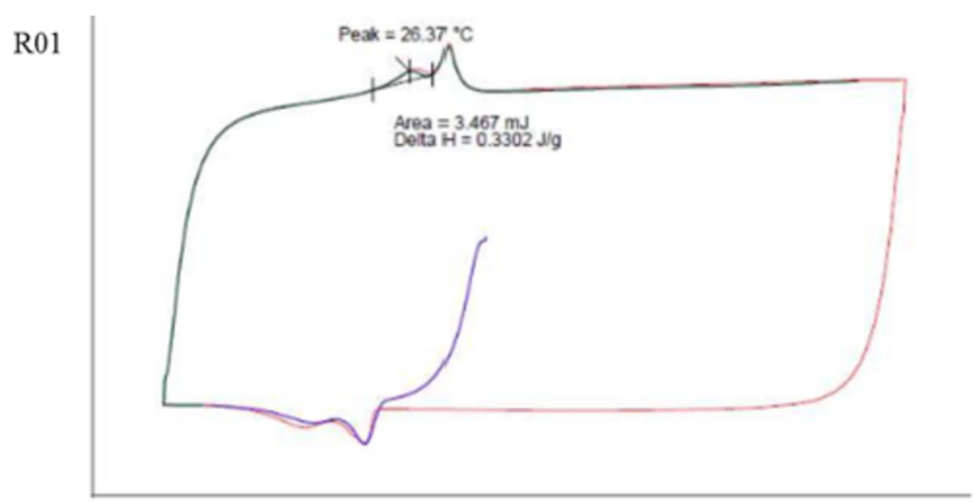


Fig. 11 DSC graph from R01

Fig. 12 DSC graph from R02

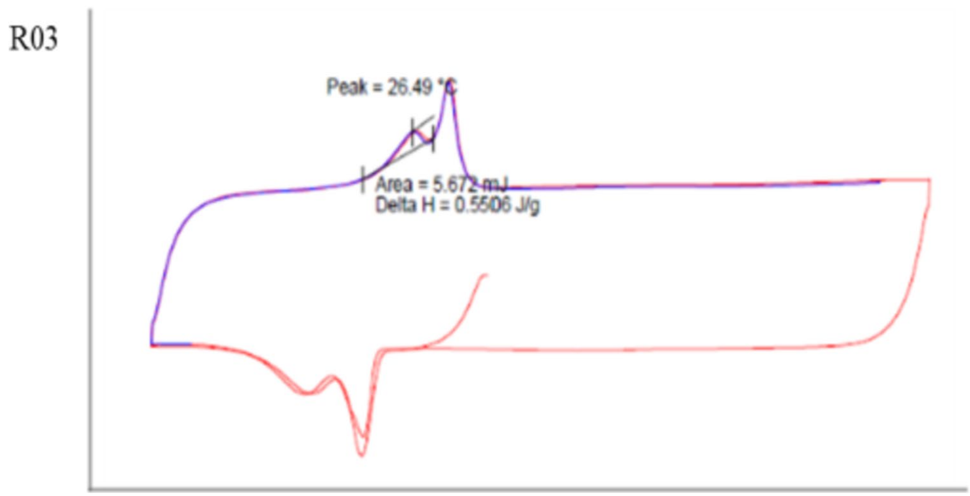


Fig. 13 DSC graph from R03

Fig. 14 DSC graph from R00/30Y

phase change temperatures of the R01, R02, and R03 recipes used in the study. However, varying results were obtained in terms of heat capacities. As the PCM microcapsule used in each recipe is the same and the usage amounts of the PCMs differ, it is suggested that significant variations in heat capacities arise. This demonstrates a direct proportionality between the amount of PCM and the energy absorbed and emitted. Notably, the recipe with the highest heat capacity was identified as R03, which utilized the highest amount of PCM. Therefore, fabrics of the R03 recipe were found to be crucial in terms of thermal comfort.

4.4 Water Drop Measurement Results

In the study, it is crucial that water dropped on the face side of the textiles is effectively transferred from the hydrophobic

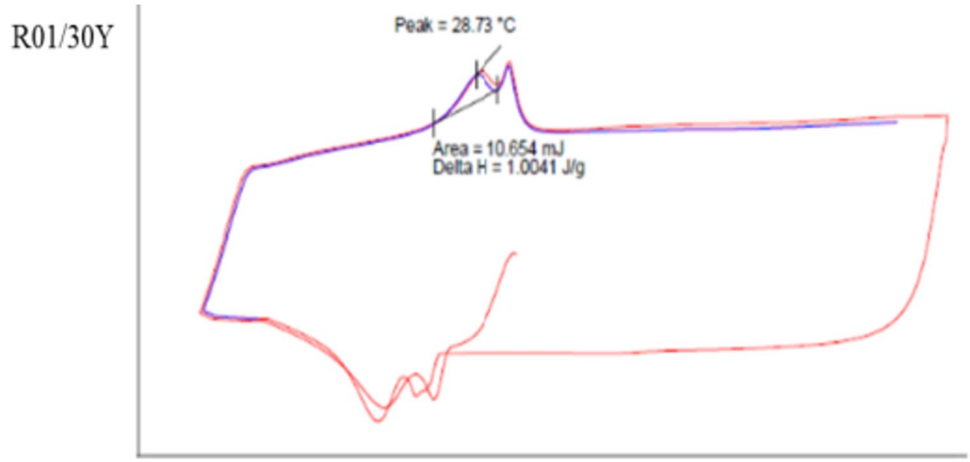


Fig. 15 DSC graph from R01/30Y

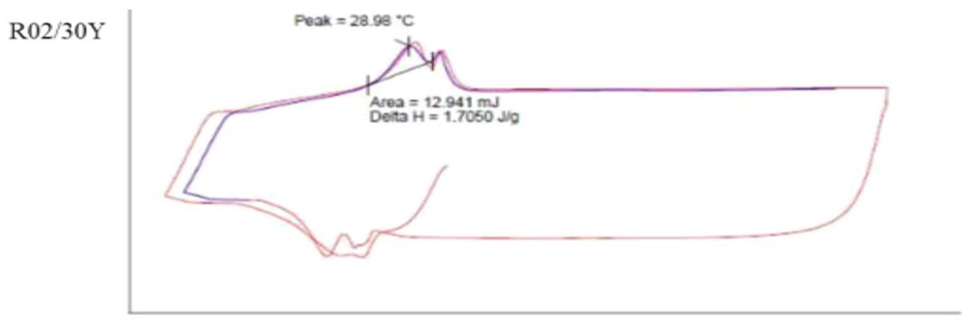


Fig. 16 DSC graph from R02/30Y

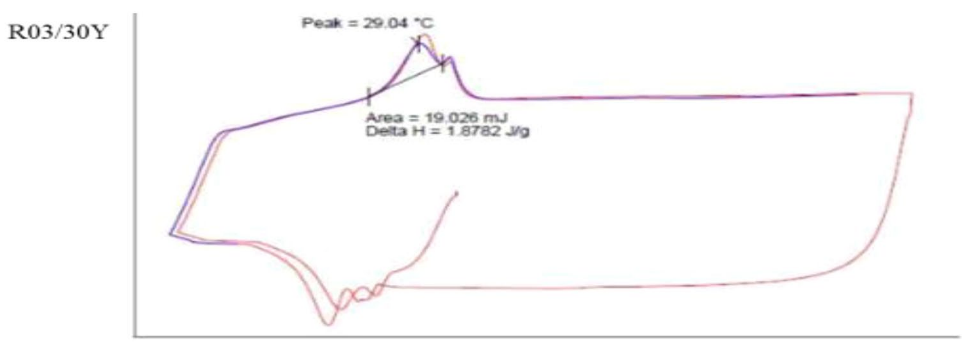


Fig. 17 DSC graph from R03/30Y

part (pink) to the hydrophilic part (white) and is absorbed in > 10 s. Additionally, it is anticipated that the back side of the fabrics is hydrophilic, ensuring complete dispersion of the transferred water. Liquid protection (water repellency), liquid absorption, and transfer in various directions (water distribution), along with the residence time of untreated products and products treated with three different formulations, were assessed using the water drop method. The procedures employed during the measurement and the fabric performances are visually represented in Figs. 18, 19.

In Fig. 18a, it is evident that both the face side and back side exhibit hydrophilic characteristics when water is applied to the fabric untreated with a functional agent. Moving to Fig. 18b, hydrophobic characters are noticeable on the face side (pink area) of the R01-encoded fabric, accompanied by partial hydrophilic characters on the back side. Due to the partial penetration of hydrophobicity from the face side to the back side, complete water diffusion across the entire surface is not achieved in this case. In Fig. 18c, the face side (pink area) of the R02 fabric appears hydrophobic, while the back side is hydrophilic, resulting in improved water distribution on both sides compared to R01. Finally, in Fig. 18d, water dropped on the face side of the R03 fabric is effectively transferred from the pink areas to the white areas, creating hydrophobic regions. The water distribution on the back side demonstrates the desired dispersion. Based on the measurement method, it

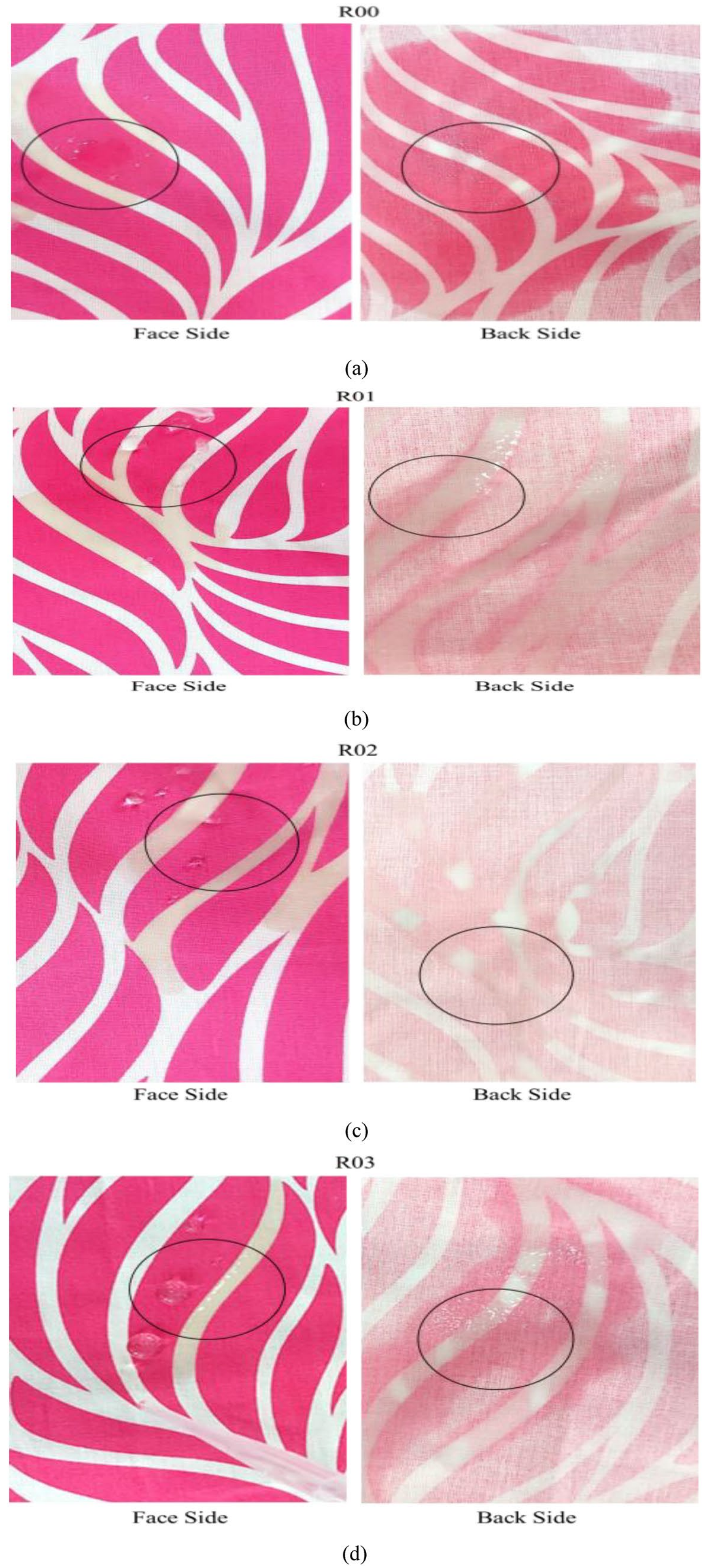


Fig. 18 **a** R00, **b** R01, **c** R02, and **d** R03 performance of the fabrics

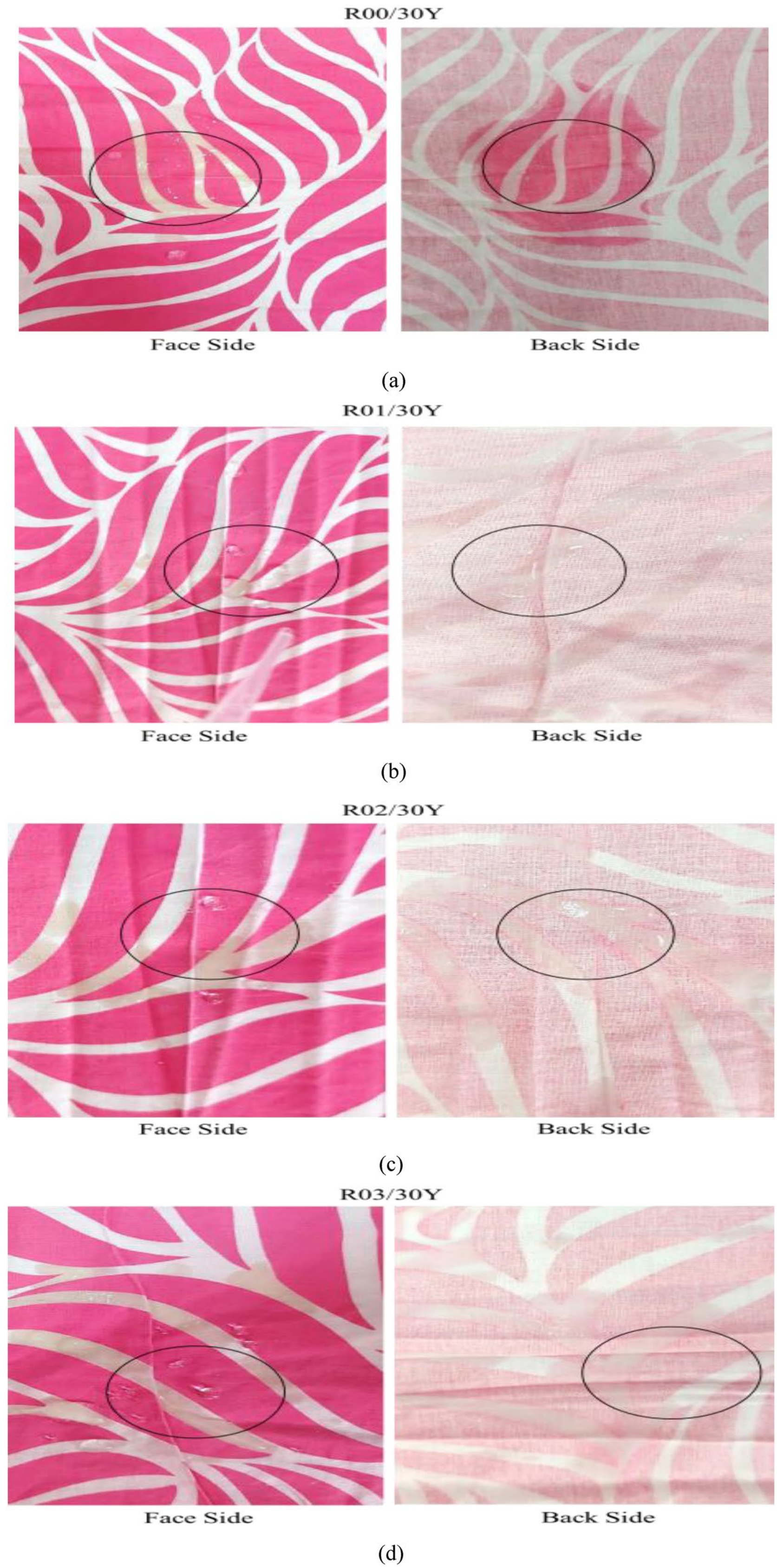


Fig. 19 **a** R00/30Y, **b** R01/30Y, **c** R02/30Y, and **d** R03/30Y performance of the fabrics

was determined that fabrics treated with formulations R02 and R03 exhibited the best performance.

In Fig. 19a, the untreated fabric was identified to possess a hydrophilic character. Moving on to Fig. 19b, it was observed that the hydrophobic properties on the face side of the R01 fabric were weaker than those of the unwashed fabric (Fig. 18b), and the impact of the functional agent on the fabric diminished with repeated washing. Conversely, in Fig. 19c (R02 fabric) and Fig. 19d (R03 fabric), it was noted that the hydrophobic properties on the face side (pink area) were well maintained even after repeated washing, with minimal difference compared to the unwashed fabric. According to the measurement method, fabrics treated with formulations R02/30Y and R03/30Y demonstrated the best performance against 30 repeated washings.

4.5 Test Results of Fluid Absorption and Transfer

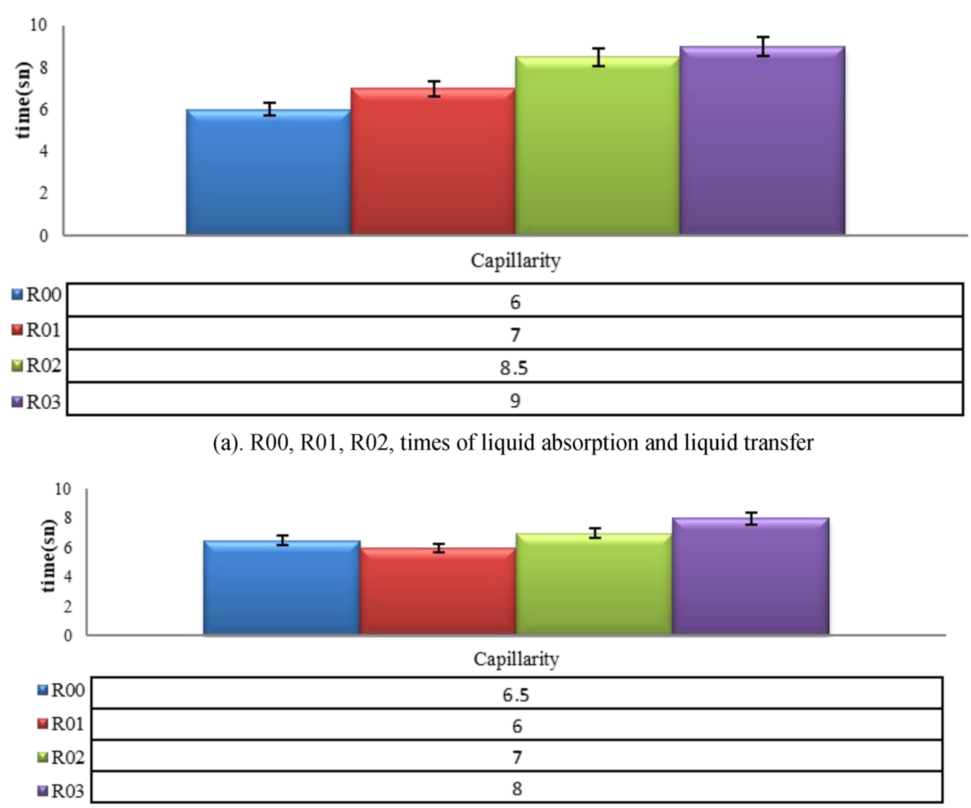
The measurement results of the liquid absorption and liquid transfer properties of the samples are shown in Fig. 20a, b

In the measurements, it was observed that the liquid progresses more slowly on fabrics treated with three different recipes compared to the R00 fabric. This deceleration is attributed to the water-repellent properties conferred by the use of fluorocarbon in the process applications. No significant differences were noted between untreated fabrics and those subjected to repeated washings. The key factors influencing the liquid flow in capillary measurements, described as the progression of liquid on the fabric, include the shapes, speeds, and directions of the surfaces. Managing these measurements can be challenging. However, it is hypothesized that improvements in capillary measurements in the processed fabrics subjected to repeated washings may be linked to the removal of fluorocarbon from the fabric after washings.

4.6 SEM and SEM–EDX Analysis

The SEM microscopic images of the R00, R01, R02, and R03 fabric samples prepared during the study are displayed in Fig. 21, while the images of those subjected to 30 washes are presented in Fig. 22. SEM–EDX analyses of the R00, R01, R02, and R03 fabric samples are depicted in Fig. 23, and the analyses after 30 repeated washes are illustrated in Fig. 24.

In Fig. 21, no chemical particles were observed on the R00 fabric. However, in Fig. 21b–d, microcapsules of PCM were identified on the surface of the fibers. Notably, the presence of microcapsules was more prominent in Fig. 21d. This is assumed to be a result of the high utilization of PCM in the R03 fabric sample.



(b). R00/30Y, R01/30Y, R02/30Y, R03/30Y times of liquid absorption and liquid transfer

Fig. 20 **a**. R00, R01, R02, times of liquid absorption and liquid transfer. **b** R00/30Y, R01/30Y, R02/30Y, and R03/30Y times of liquid absorption and liquid transfer

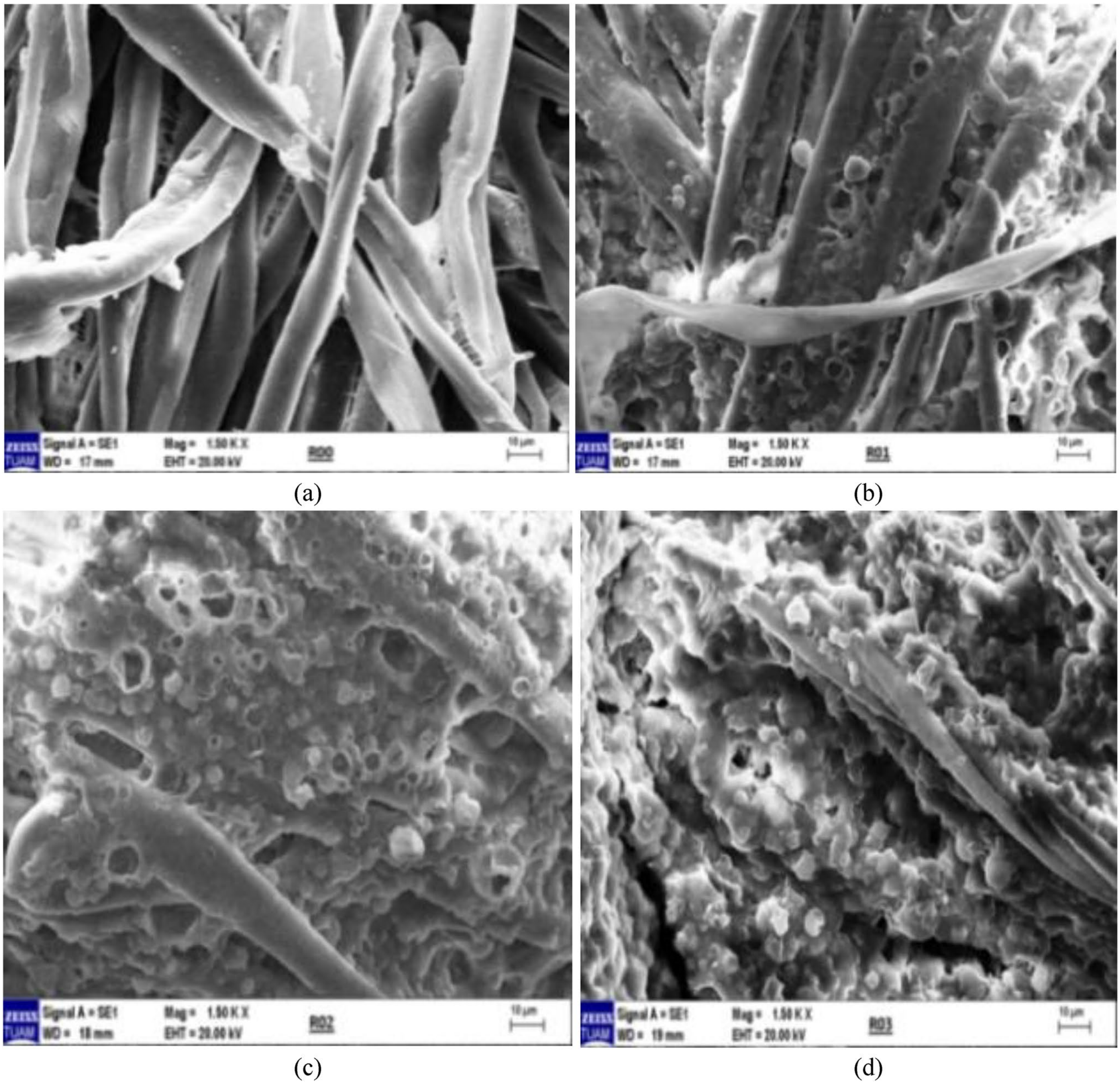


Fig. 21 **a** R00, **b** R01, **c** R02, **d** R03 microscopic SEM images

It is evident from Fig. 22 that the number of microcapsules in the fabric sample decreased after 30 washes. In comparison to fabrics R01/30Y and R02/30Y, more microcapsules belonging to PCM were observed in R03/30Y. The continued presence of microcapsules in the fabric samples after washing indicates their resistance to the washing process.

It is apparent from Fig. 22 that the number of microcapsules in the fabric sample decreased after 30 washes. In comparison to fabrics R01/30Y and R02/30Y, more microcapsules belonging to PCM were found in R03/30Y. The continued presence of microcapsules in the fabric samples after washing indicates their durability to washing.

In Fig. 24, C (carbon) and O (oxygen) elements are observed in the samples due to the characteristic properties of the cotton in the fabrics, and Au elements are visible in each of the fabrics due to the gold coating. No other chemical elements were detected in the R00/30Y fabric (Fig. 24a). Fluorine was identified in SEM–EDX analyses of R01/30Y, R02/30Y, and R03/30Y. The presence of fluorine in the fabric samples after washing indicates that the functionality is durable through repeated washings.

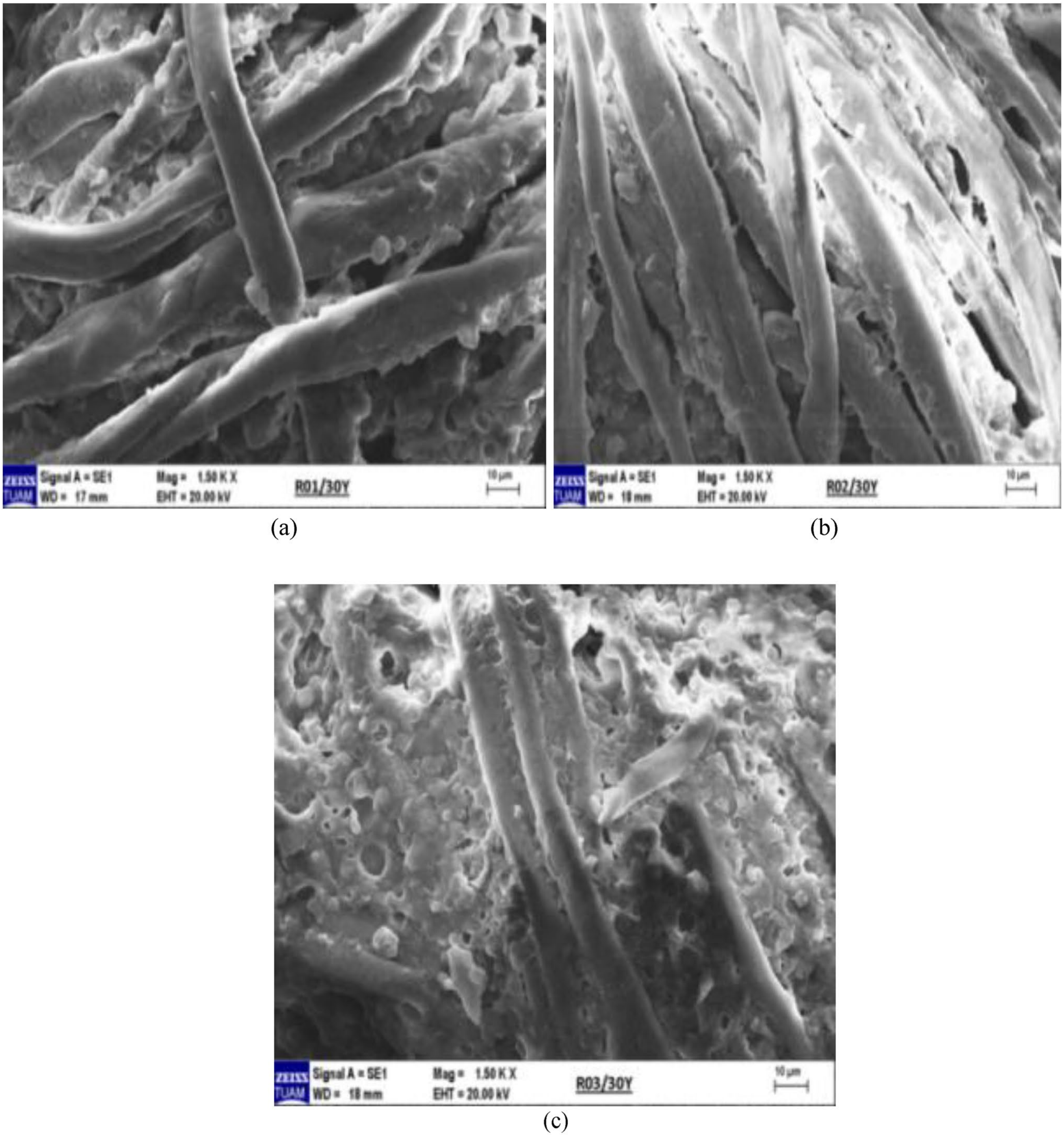


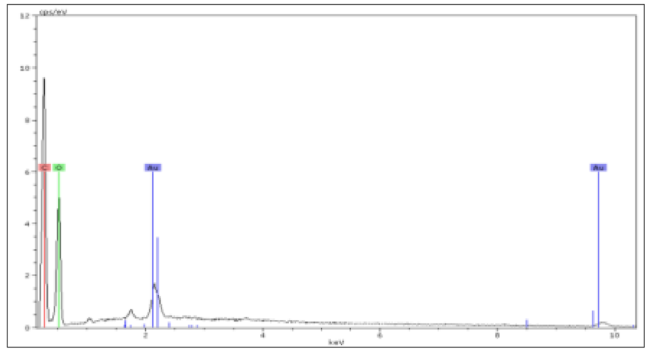
Fig. 22 **a** R01/30Y, **b** R02/30Y, and **c** R03/30Y microscopic SEM images

4.7 FTIR–ATR Analysis

The FTIR–ATR spectra of the untreated (R0) fabric and the fabric samples prepared as part of the study with codes R01, R02, and R03, along with the fabric samples subjected to 30 repeated washings, are illustrated in Fig. 25.

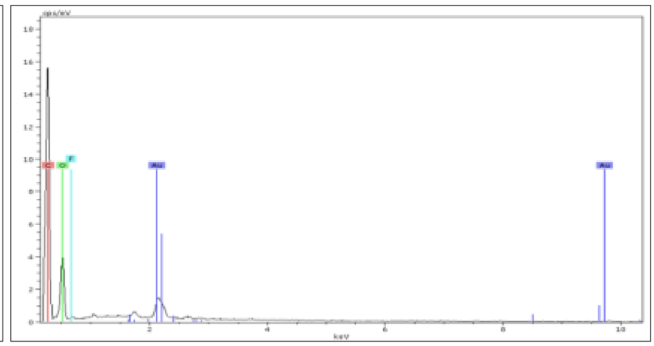
As depicted in Fig. 25, the spectra overlap in all recipes due to the use of the same chemicals. Furthermore, FTIR–ATR analysis was conducted on the R03 recipe, where the amount of chemicals used was the highest. The presence of characteristic peaks, including the OH vibration of cotton fiber at 3300 cm^{-1}, the CO vibration at 1030 cm^{-1}, the CH

Element	Series	Net	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Carbon	K series	49734	38.40	38.40	45.37
Oxygen	K series	27356	61.60	61.60	54.63
		Total:	100.0 %		



(a)

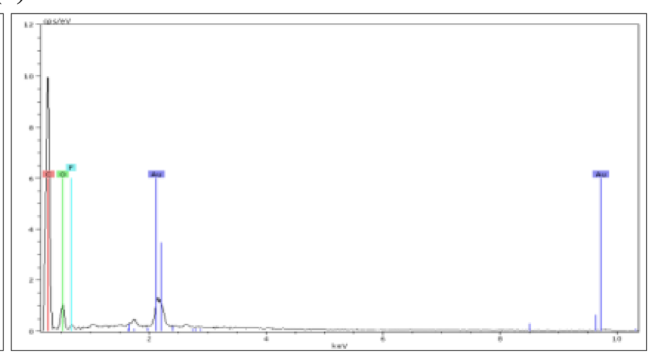
Element	Series	Net	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Carbon	K series	48682	44.00	44.00	52.20
Oxygen	K series	13297	41.16	41.16	36.66
Fluorine	K series	1301	14.84	14.84	11.13
		Total:	100.0 %		



(b)

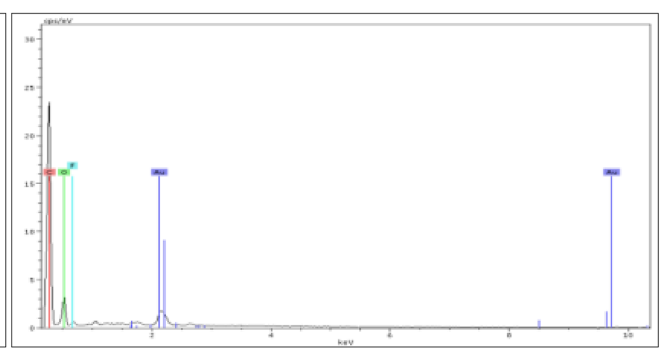
Spectra: object

Element	Series	Net	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Carbon	K series	40589	55.70	55.70	63.86
Oxygen	K series	4508	29.73	29.73	25.59
Fluorine	K series	1021	14.56	14.56	10.55
		Total:	100.0 %		



(c)

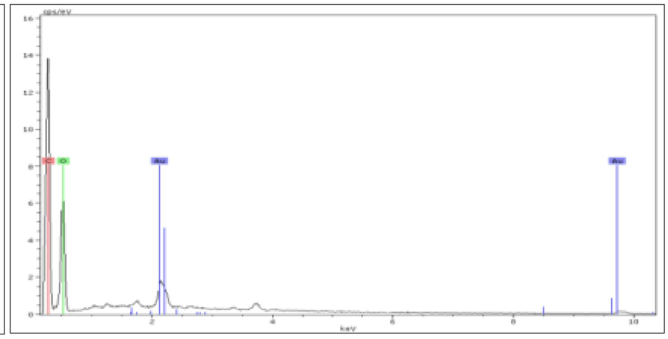
Element	Series	Net	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Carbon	K series	85662	50.96	50.97	59.45
Oxygen	K series	12728	31.71	31.72	27.77
Fluorine	K series	2903	17.32	17.32	12.77
		Total:	100.0 %		



(d)

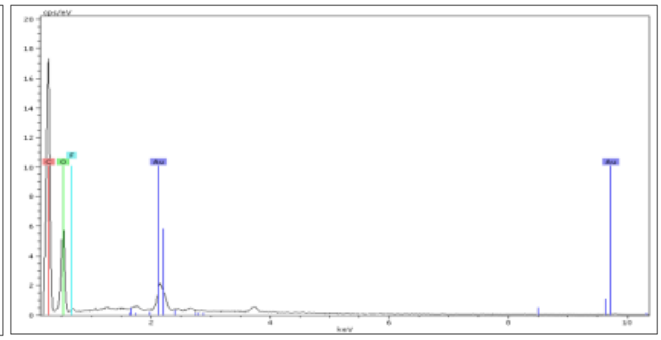
Fig. 23 **a** R00, **b** R01, **c** R02, and **d** R03 image of SEM–EDX analysis

Element	Series	Net	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Carbon	K series	75344	40.19	40.19	47.24
Oxygen	K series	36514	59.81	59.81	52.76
		Total:	100.0 %		



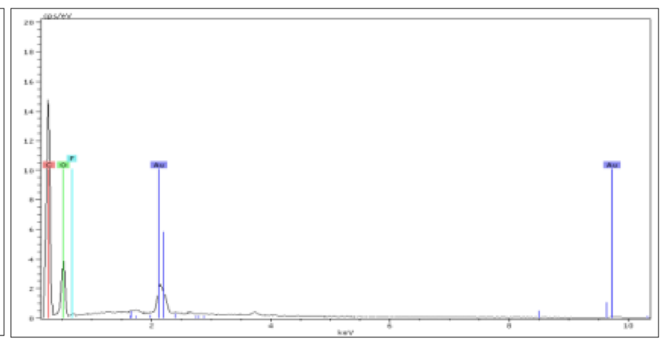
(a)

Element	Series	Net	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Carbon	K series	63492	40.70	40.70	48.74
Oxygen	K series	22481	44.86	44.87	40.33
Fluorine	K series	1655	14.44	14.44	10.93
		Total:	100.0 %		



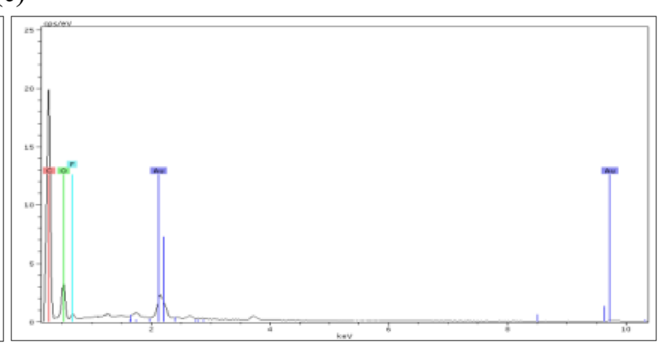
(b)

Element	Series	Net	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Carbon	K series	74640	44.56	44.56	52.53
Oxygen	K series	21206	44.05	44.05	38.99
Fluorine	K series	1315	11.39	11.39	8.49
		Total:	100.0 %		



(c)

Element	Series	Net	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Carbon	K series	190971	47.06	47.06	55.76
Oxygen	K series	35390	32.65	32.65	29.05
Fluorine	K series	8711	20.28	20.28	15.19
		Total:	100.0 %		



(d)

Fig. 24 **a** R00/30Y, **b** R01/30Y, **c** R02/30Y, and **d** R03/30Y image of SEM–EDX analysis

vibration at 2900 cm^{-1}, and the CH bending at 1310 cm^{-1}, was observed [19]. The peak intensity of the PEG bands belonging to the PCMs used in the study is recognized at the O–H vibration at 3400 cm^{-1} of the hydroxyl group.

In the spectrum of the cotton fabric with microcapsules applied, in addition to these peaks, the appearance of peaks at 2926 cm^{-1} and 2857 cm^{-1} is attributed to the C–H stretching peaks of paraffin in the microcapsule structure,

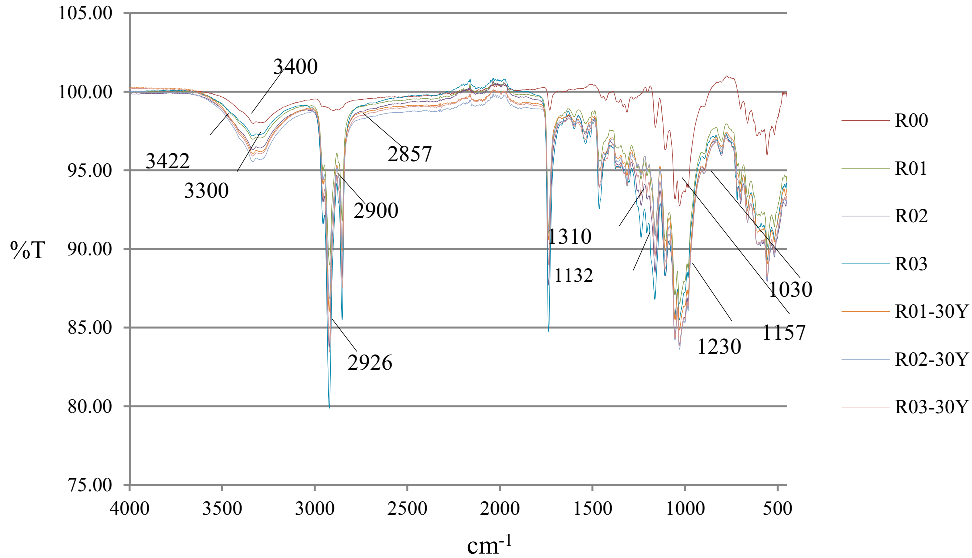


Fig. 25 FTIR–ATR spectra of fabric samples

indicating the presence of microcapsules in the fabric structure. The characteristic peaks of the C–F bond of the fluorocarbon used in the study were observed at the wave number of 1230 cm^{-1} [12, 20, 21]. Additionally, the characteristic peak of the C–F bond marking the fluorocarbon-containing R03 fabric was observed at 1157 cm^{-1} and 1132 cm^{-1} [22].

5 Conclusion

The primary source of discomfort on textile surfaces arises from changes in heat and moisture due to environmental factors like rain or personal factors such as sweat [14]. Fluctuations in temperature and humidity lead to textiles becoming wet, resulting in discomfort such as sticking to the body, feeling heavy, experiencing cold sensations, and sweating. The objective of this study is to develop textile products that eliminate these uncomfortable situations caused by temperature and humidity changes without compromising people's quality of life or restricting their activities.

To achieve this goal, a systematic approach was employed to create hydrophilic and hydrophobic features on the surfaces of textile products that come into contact with the skin. Hydrophilic characters were incorporated on the surfaces not in contact with the skin. This design ensures that moisture (sweat) on the skin is directed toward the hydrophilic part by the hydrophobic section, and the hydrophilic area rapidly removes moisture from the skin. Consequently, as the area where moisture is absorbed does not wet the entire surface, individuals perceive less wetness, and uncomfortable situations like the textile product sticking to the skin are avoided.

Various pattern designs were utilized to impart partial hydrophobic characters to woven fabrics using water-repellent finishing materials. The remaining fabric surface was made hydrophilic, creating a combination that facilitates moisture management. For heat management, treatment was applied with PCMs with high temperatures, employing traditional printing techniques. The chemical components used were carefully analyzed to ensure no negative impact on textile surfaces, as indicated by relevant physical and chemical performance tests. FTIR–ATR analysis was conducted for chemical components, while SEM–EDX was employed for morphological analyses. The textile surfaces' capacity to manage heat changes was determined through DSC analysis. The water-repellent performance and water distribution times of the fabrics were evaluated using the water droplet method.

Upon evaluating the results of all conducted tests, multifunctional single-layer 100% cotton woven fabrics resistant to 30 washes, with diverse functional properties, were successfully produced. Notably, the recipe with the highest heat capacity was identified as R03, which utilized the highest amount of PCM. Therefore, fabrics of the R03 recipe were found to be crucial in terms of thermal comfort. Based on the measurement method, it was determined that fabrics treated with formulations R02 and R03 exhibited the best performance. Furthermore, tearing strength results were imporved after these innovative finishing recipes. Importantly, these fabrics were created using traditional methods without relying on new technologies or newly synthesized materials. With this study, it is anticipated that the developed cotton fabrics will not only find applications in the apparel sector but also offer opportunities for use in various home textile areas such as bed linens, sheets, and pillowcases.

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Data Availability The authors declare that the data supporting the fndings of this study are available within the paper.

Declarations

Conflict of Interest No potential conflict of interest was reported by the authors.

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