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Flaxseeds gel as a bio-hosting material for organic PCM to improve the thermoregulating properties of cotton fabric

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Abstract
Flaxseed gum (FSG) comprises neutral and acidic polysaccharides. Research shows that flaxseed gums with high arabinoxylan concentration have shear thinning and weak gel-like properties, whereas those with high acidic monosaccharides have decreased rheology. FT-IR and DSC tests described a bio-PCM composite made from flaxseed gum and fatty acid anhydrides. The study examined how fatty acid type affects bio-synthesized composite materials made from flaxseeds and various fatty acids with and without octadecane as phase transition materials. In the final composite structure, the fatty acid backbone lengthened, increasing the host material's latent heat. As phase transition material, 20% octadecane yielded best results. Polymer-based materials (PCM) are used to make bio-synthesized composite materials from flaxseeds and stearic acid. Latent heat of host materials increases with PCM content, optimum at 20% octadecane. The treated cotton cloth regulates temperature better than the untreated. The study shows that PCM composite material treatment creates a homogenous thin coating on cotton fiber surfaces, improving thermal characteristics and heat retention.

Keywords Flaxseeds gel · Bio-hosting material · Organic PCM · Thermoregulating properties · Cotton fabric

Introduction

Smart fabrics have received a lot of interest in recent years because of their potential to provide more functionality than conventional textiles. One of the most interesting advances in this sector is using phase change materials (PCMs) to give thermal regulation characteristics in textiles. PCMs absorb and release heat during phase changes, such as from solid to liquid and vice versa, allowing them to effectively regulate temperature. When incorporated into fabrics, PCMs can assist maintain thermal comfort [1–4].

Cotton is one of the most extensively utilized natural fibers because of its breathable and comfortable properties [5, 6]. However, it lacks adequate temperature regulation, especially in harsh environments. So, the integration of PCMs with cotton fabric offers a novel method to generating textiles with superior thermal regulating characteristics while maintaining cotton's natural comfort and breathability [7, 8].

However, integrating PCMs into textiles poses challenges, notably the danger of material leakage during the liquid phase and the possible influence on the fabric's mechanical properties [9, 10]. To tackle these difficulties, researchers have investigated embedding PCMs in different host materials that stabilize the PCM and prevent leakage [11]. Traditionally, synthetic polymers have been utilized as host materials, but their environmental effect and lack of biodegradability have sparked interest in employing natural, renewable, and biodegradable materials [12].

Several research have investigated the use of biopolymers including pectin, sodium alginate, and chitosan as hosting materials for PCMs in textiles, with excellent results in terms of thermal regulation and environmental sustainability [13–16]. Flaxseeds, with their own unique composition and structure, present an attractive choice as a bio-hosting material for organic PCMs. Flaxseeds, originating from the flax plant (*Linum usitatissimum*), have long been also recognized for their nutritional and environmental benefits [17]. They are a renewable resource, distinguished by their low environmental effect in processing [18].

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People have been very interested in organic phase change materials (PCMs) in the last few years because they could make cotton fabrics better at keeping heat in and putting out fires. Organic PCMs, like paraffin waxes or fatty acid derivatives, absorb and store heat when they melt and release it when they solidify. This lowers the peak heat release rate during combustion. This thermal buffering effect can make it take longer for a fire to start and slow the spread of the flames. Also, when these PCMs are properly microencapsulated and applied to cotton by coating or impregnation, they can create a protective barrier that slows down the transfer of heat and oxygen to the fiber surface. Research indicates that the amalgamation of organic phase change materials (PCMs) with additional flame retardant substances, including phosphorus- or nitrogen-based compounds, can significantly improve fire resistance by facilitating char formation and diminishing flammable volatiles [19]. So, combining organic PCMs is a promising way to make cotton textiles both more comfortable to wear and better at stopping fires [14, 19, 20].

Flax is a primary source of the plant-based lignan precursor secoisolariciresinol diglucoside (SDG), comprising 75 to 800 times more than other diets [21]. Figure 1 illustrates the chemical structure of SDG. Lignans are phenolic compounds created by the combination of monomeric units derived from hydroxyl- and hydroxy-methoxy derivatives of cinnamic and benzoic acids [21]. Flaxseed has garnered interest mostly because to its high content of polyunsaturated fatty acids, including α-linolenic acid. Furthermore, it includes dietary fiber and lignan compounds, which may potentially mitigate the risk of cardiovascular disease in humans [22–24]. Flaxseed also contains proteins rich in arginine, lysine, and branched-chain amino acids [25–27]. Consequently, it may serve as value-added byproducts in many industrial fields.

This study seeks to investigate the usage of flaxseeds extraction as a bio-hosting material for organic PCMs (octadecane) to increase the thermoregulating capacities of cotton textiles without losing flexibility, durability, or sustainability. Thermal characteristics, and durability of treated cotton textiles will be analyzed using different approaches such as differential scanning calorimetry (DSC) and scanning electron microscopy (SEM).

Experimental

Materials

100% Gabardine cotton fabric (Twill weave (3/1); 265 g m^{-2}) was purchased from Al-Qasas Company, Egypt. Three different fatty acids, namely Stearic acid, palmitic acid, and myristic acid, were supplied from Alpha Chemika**,** India. Octadecane provided from Sigma-Aldrich Co. Reactive dye (Reactive blue 19) was purchased from DyStar Co., Egypt. Flaxseeds purchased from Harraz market, Egypt. Tween 80, sodium chloride, and sodium hydroxide were provided from El Nasr Pharmaceutical Chemicals Co., Egypt. All the reagents and chemicals were used without any purification.

Methods

Extraction of flaxseeds gel

The naturally flaxseeds were washed and cleaned using water to remove dust and particulate matter, then dried over night at 30 ℃. 100 g of dried flaxseeds were boiled in 1000 mL of distilled water for 60 min, then the extract was filtered and concentrated using rotary evaporator,

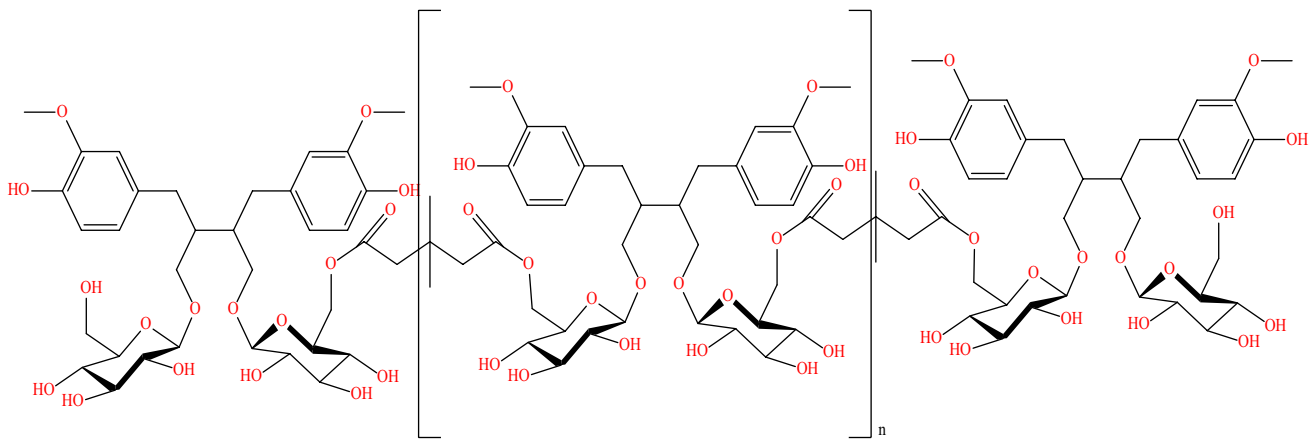

Fig. 1 Chemical structure of the lignan macromolecule from flaxseed [secoisolariciresinol diglucoside (SDG; 2,3-bis[(4-hydroxy-3-methoxyphenyl) methyl])-1,4-butane-diglucoside)]

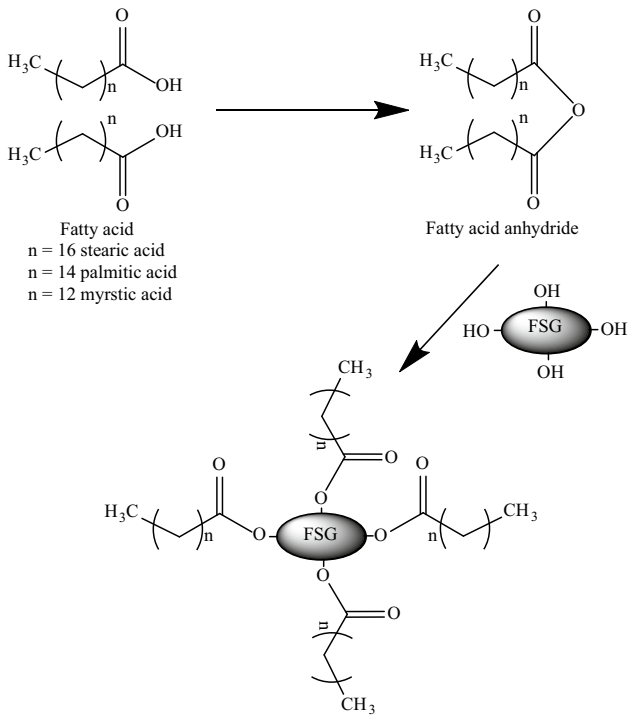

Fig. 2 Scheme for modification flaxseeds gum with fatty acids

then stored at 277.15 K. There was no further purification applied to the filtrate.

Synthesis of fatty acid anhydrides

100 mmol of fatty acid was solubilized in 20 mL of dichloromethane and agitated quickly in an ice-water bath under argon environment. 50 mmol of dicyclohexylcarbodiimide (DCC) was solubilized in dichloromethane. Subsequently, soluble DCC was included into the mixture and agitated at ice bath temperature for a further 2 h. The precipitate was isolated using filtration, followed by the evaporation of the solvent from the filtrate under vacuum to yield the anhydride. Chemical reaction is illustrated in Fig. 2. To optimize the best condition of synthesis, different fatty acids (stearic acid, myristic acid, and palmitic acid) were used.

Synthesis of flaxseeds gum (FSG)-fatty acid esters

According to the modified procedure previously reported by Hassabo et al. [28], flaxseed/fatty acid ester was prepared, briefly, 30 g flaxseeds gum, 2.5, 5, 7.5, and 10 g fatty acid anhydride and K_2CO_3 (0.1 eq.) (Fig. 2). The solution was kept under constant stirring for 60 min at 160 ℃. The mixture was left at room temperature to cool. The finished product was dialyzed in deionized water for one day, then lyophilized for two days.

Synthesis of PCM composite based on flaxseeds gel (FSG)-fatty acid ester

PCMs composites were prepared according to previous work [28, 29] as follow: by mixing flaxseeds gel (FSG)-fatty acid ester with paraffin compound (n-octadecane; (C18)) in varying ratios (10, 20, and 30% (w/w) PCM material: polymer) at 263.15 K for 2 h, and then the PCM composite was used for further investigation and application.

Pretreatment of fabrics

Cotton fabric was immersed in a solution containing 10 g L^{-1} citric acid and 5 g L^{-1} sodium hypophosphite at 40 ℃ for 15 min, then squeezed at 80% wet pickup, and then dried in the oven at 100 ℃ for 3 min. (see Fig. 3).

Application of PCM composite to cotton fabric

The treatment solution was made up of various concentrations (30, 50, and 100 g L^{-1}) of PCM composites that were dispersed in water with Tween 80 (2 g L^{-1}) as a surfactant. The solution was homogenized for 10 min at 20,000 rpm with a homogenizer. The cotton fabric was treated with PCM solution using the pad-dry-cure procedure; cotton fabric was immersed in the treatment bath at 343.15 K for 15 min. and squeezed with 100% wet pickup. The fabrics were then dried in an oven at 377.15 K for 5 min. After that the fabrics were cured at 423.15 K for 3 min. (see Fig. 3).

Dyeing cotton fabric with reactive dye

There were two procedures used for dyeing. (a) In the first approach, the fabric was pretreated with PCM composite and then dyed with reactive dye solution, whereas in the second way, the fabric was dyed with reactive dye solution and then treated with PCM composite (see Fig. 3).

The dyeing technique was carried out using (3%) reactive dye, 10 g L^{-1} NaCl, and 5 g L^{-1} NaOH at 333.15 K for 30 min. The fabrics were then dried in an oven set at 377.15 K for 3 min. and thermofixed at 413.15 K for 3 min. Finally, the fabrics are immersed for 15 min at 323.15 K in a soaping solution containing non-ionic detergent.

Characterization

Fourier transform infrared (FT-IR)

A JASCO FT-IR spectrometer (ATR) was utilized to record FT-IR spectra and evaluate the untreated and treated material's spectra. The tester measures infrared transmittance in films between 400 and 4000 cm^{-1}.

Scanning electron microscopy (SEM)

Fabric surface morphology was studied using a scanning electron microscope HITASHI S-3000 S at a voltage of 15 kV.

Differential scanning calorimetry (DSC)

DSC measurements were performed using the Netzsch DSC 204. 7 mg massed samples were sealed in aluminum pans, and an empty aluminum pan was utilized as a reference. Throughout the procedure, the pans were heated, cooled, and heated. Temperatures varied from 0 to 343.15 K at a rate of 287.15 K min^{-1}. The melting temperature and the enthalpy (ΔH) of the peaks measured during the second heating.

Duration index (DI) and total resistance to dry heat transfer

Duration index (DI) (J cm^{-3} K−1) is a parameter that describes the material and the temperature at which it is intended to work. It measures how long a PCM will remain at a consistent temperature throughout the phase transition. [30]

$$\mathrm{DI} = \frac{\Delta H \times \rho}{\Delta T}$$

where ΔH is the enthalpy of PCM change of state, $\rho$is the PCM density, and ΔT is the temperature difference between measured and the temperature of interest (ambient or body temperature).

The total resistance to dry heat transfer (R) is the insulating value of clothing systems and is proportional to the textile material on which PCM is placed.

$$R = \frac{\Delta T \times A}{H}$$

In this equation, A represents the material's area, ΔT represents the temperature differential between its two sides (TF—TR), and H represents the heat flow. The unit of measurement for garment insulation derived from hygienic comfort research is "clo" (m^2 °C W^{-1}), in which 1 clo = 0.155 m^2 °C W^{-1} (A person wearing a standard business suit is represented by zero (0) clo, whereas a person wearing nothing at all is represented by one (1) clo.) [31–33].

Thermal conductivity measurements

Thermal conductivity refers to a fabric's ability to transfer heat. Thermal conductivity was determined in this study using the KES-F7 Thermo Lab standard. The thermal conductivity of a fabric may be determined using the following formula: [34]

$$k = (W \times D)/(A \times \Delta T)\left(W\,m^{-1}\,k^{-1}\right)$$

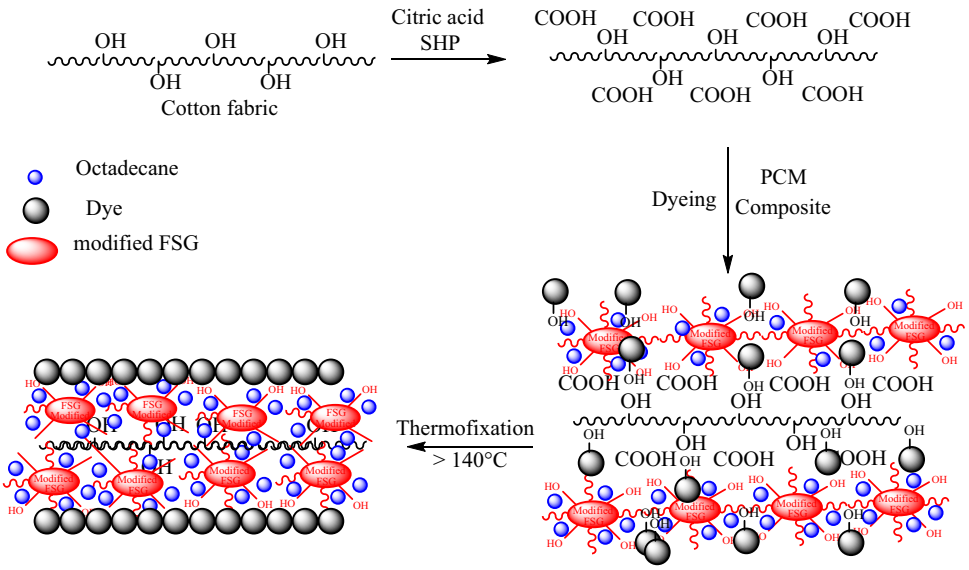

Fig. 3 Scheme for treatment and dyeing of cotton fabric with PCM composite

where A is the heat plate's size (25 cm^2), k is the thermal conductivity (W cm^{-1} $°C^{-1}$), W is the heat flow (W), D is the average thickness of the samples, and ΔT is the temperature difference (heat plate temperature (307.15 K)—the cooling base temperature (297.15 K) = 287.15 K.

Qmax measurement (feeling hot or cold)

The Qmax index evaluates how warm or cool an area of skin feels when it contacts fabric. It is determined by the quantity of heat transferred from the skin to the garment.

Measurement of color strength

The CIE Lab parameters (a*, b*, L*, and ΔE) and the color of the textile materials were determined using a Data Color International 500 reflectance spectrophotometer. The color strength (K/S) was calculated using the Kubelka–Munk equation: [35–38]

$$K/S = \frac{(1-\boldsymbol{R})^2}{2\boldsymbol{R}} - \frac{(1-\boldsymbol{R_o})^2}{2\boldsymbol{R_o}}$$

where R refers to reflectance, K to absorption, and S to scattering. coefficient.

Color fastness properties

The washing fastness characteristics of colored samples were evaluated using the standard ISO 105-C01:2006 test method [39]. Laundry was done in the Launder-O-Meter (Atlas Electric Co., USA) at 307.15 K using soap. The washed samples were graded using a visual gray scale.

The term "fatness to rubbing" refers to the amount of color transmitted by rubbing a colored textile material's surface against another surface The AATCC crock meter is used to perform the test in accordance with AATCC Test Method 8-2016 [40]. Wet and dry rubbing fastness test were conducted.

The test specimens were assessed using a visual gray scale, and the rubbing fastness rating was assigned a five-point scale [41]. Acidic and alkaline perspiration were measured using the AATCC 15-2013 and ISO 105-EO4 (2013) test methods [42, 43].

The color fastness to light measurements was made using the AATCC Test Method 16-2014 [44].

Mechanical properties

Tensile strength and elongation at break were measured using a tensile strength apparatus type FMCW 500 (Veb Thuringer Industriewerk Rauenstein 11/2612 Germany) at 298.15 K and 65% relative humidity, according to ASTM test method D5035-2011 [45]. The AATCC test method 66-2014 was used to determine the dry crease recovery angle (CRA) [46]. The roughness of the fabric was measured using ASTM test method D 7127-13 using the surface roughness measuring equipment SE 1700 [47]. The cantilever equipment was used to perform stiffness tests according to ASTM test method D 1388-14e1 [48]. The sample's air permeability was determined in accordance with ASTM standard D 737-2018 [49]. The water vapor permeability of fabric samples was evaluated using Permetest at the National Institute for Standards in accordance with ISO 11092 and ATSM (E96/E96M-16) [50, 51].

Results and discussion

Optimization and characterization of synthesized bio-PCM

The hosting materials were synthesized through the reaction of flaxseeds gum (FSG) with fatty acid anhydrides (stearic, palmitic, and myristic anhydrides) and characterized via FT-IR and DSC analyses.

FT-IR analysis

FSG-fatty acids were characterized using FT-IR, IR spectra for FSG; fatty acids, fatty acid anhydride, and FSG-fatty acid are illustrated in Fig. 4. The FT-IR spectra of the FSG exhibited six distinctive bands accompanied by several peaks. The absorption peak at 3277 cm^{-1} was broad and can be ascribed to the stretching vibration of non-free hydroxyl (OH) groups forming hydrogen bonds with one another [52, 53]. The asymmetric stretching vibration of the carbonyl (C=O) group at 1601 cm^{-1} indicates the existence of uronic acid or bound water in FSG. The features observed around 1416 and 1601 cm^{-1} can be ascribed to the symmetric and asymmetric vibrations of the carboxylate (COO) group, respectively [54]. Additionally, the region between 800 and 1200 cm^{-1} is recognized as the carbohydrate fingerprint area, which may indicate variations in the gum structure [55]. The extensive range between 1000 and 1200 cm^{-1} corresponds to a characteristic polysaccharide peak, whereas the peak at 1146 $cm.^{-1}$ can be ascribed to the existence of glycosidic linkages, specifically C–O C–C and C–OH (Fig. 5) [56].

Figure 4 confirms the chemical modification of FSG with acid anhydride. For FSG-fatty acid IR band is reprehensive the chemical modification as follow: FSG-stearate: 3431 cm^{-1} for O–H, 2926 and 2852 cm^{-1} for C–H, 1722 cm^{-1} for C=O (methyl ester), 1701 cm^{-1} for C=O

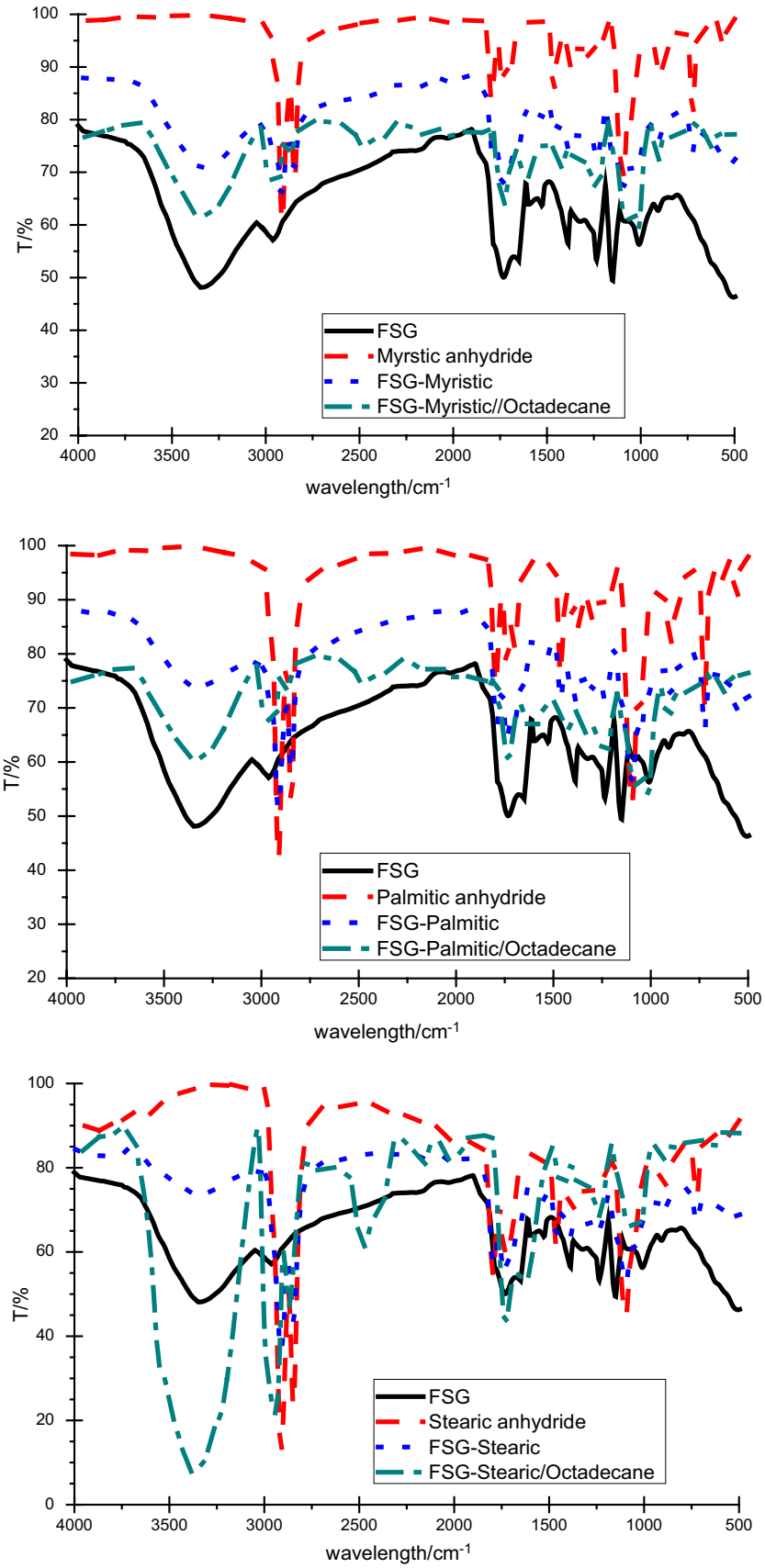

Fig. 4 FT-IR spectra of hosting materials with/without octadecane

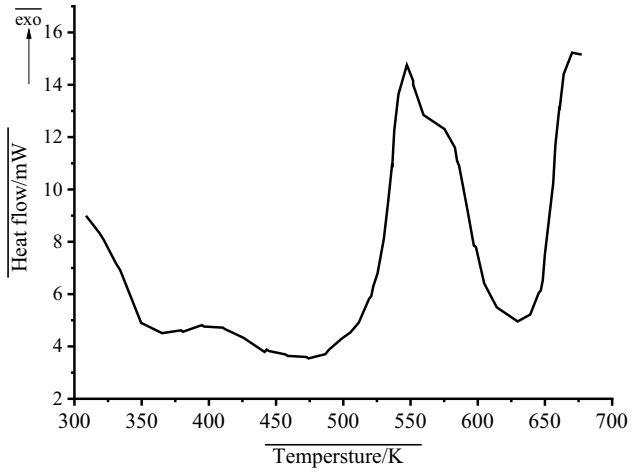

Fig. 5 DSC measurement for flaxseeds gum

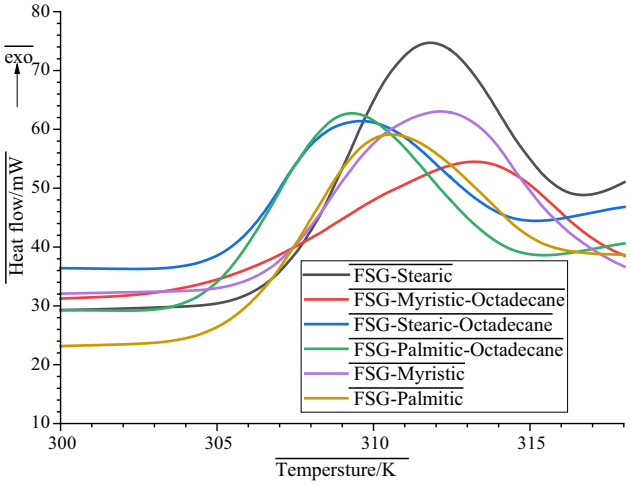

Fig. 6 DSC curves of covered cotton fabrics with pectin-fatty acid with/without octadecane from 2nd heating

Table 1 DSC data for hosting materials with/without octadecane from 2nd heating

Hosting materials		2nd heating		
		T_o/K	T_p/K	ΔH/J g^{-1}
FSG	–	408.85	410.25	132.12
Stearic acid [29]	–	332.62	344.36	288.39
Palmitic acid [29]	–	346.75	349.95	184.93
Myristic acid [29]	–	343.35	346.75	143.21
Octadecane [29]	–	302.45	306.55	241.44
FSG -stearic	Without Octadecane	305.35	311.82	210.26
	With Octadecane	305.55	310.36	220.65
FSG-palmitic	Without Octadecane	305.25	310.75	158.52
	With Octadecane	304.45	309.31	186.16
FSG-myristic	Without Octadecane	306.12	312.07	137.67
	With Octadecane	304.55	312.45	172.26

Hosting material: 5 g fatty acid acid + 30 mL flaxseed. PCM material: 10% octadecane

T_o: Onset Temperature, Tp: Keeping Temperature, ΔH: Enthalpy

(fatty acid ester), 1628 and 1433 cm^{-1} for COO−, 1199 and 1118 cm^{-1} for C–O; FSG-palmitate: 3433 cm^{-1} for O–H, 2911 and 2844 cm^{-1} for C–H, 1741 cm^{-1} for C=O (methyl ester), 1699 cm^{-1} for C=O (fatty acid ester), 1617 and 1431 cm^{-1} for COO−, 1201 and 1137 cm^{-1} for C–O; and FSG-myristate: 3431 cm^{-1} for O–H, 2922 and 2851 cm^{-1} for C–H, 1757 cm^{-1} for C=O (methyl ester), 1690 cm^{-1} for C=O (fatty acid ester), 1624 and 1401 cm^{-1} for COO−, 1200 and 1136 cm^{-1} for C–O.

Effect of fatty acid type

The molecules of flaxseed gum readily formed a three-dimensional network, resulting in a denser structure and increased gel strength. Consequently, increased energy was required to disrupt the ordered network, leading to a higher melting temperature. The exotherm had a peak temperature between 98 and 427.15 K which represent the removal of water from the FSG, whereas a melting peak temperature was between 493.15 and 523.15 K. The ΔH was 133.65 ± 13.79 (J g^{-1}).

The DSC results for bio-synthesized composite materials made from flaxseeds and various fatty acid (myristic acid, palmitic acid and stearic acid) in presence and absence of octadecane as PCM materials are shown in Table 1 and Fig. 6. Table 1 clearly illustrates that the latent heat of the hosting materials rises as the fatty acid backbone increases in the finished composite form. The greatest results were obtained with stearic acid since it has the most carbon atoms in its backbone, resulting in a high melting point and heat storage capabilities. So, the DSC values of the FSG-fatty acids with octadecane indicate that the optimal composite, exhibiting the highest latent heat, corresponds to the fatty acid with the greatest molecular mass (stearic acid > palmitic acid > myristic acid).

Effect of fatty acid concentration

The influence of stearic acid concentration was examined to determine if the combination of stearic acid with flaxseed gum could achieve a eutectic state, considering stearic acid (melting temperature: 344.36 K, ΔH: 288.39 J g^{-1}) and octadecane (melting temperature: 344.36 K, ΔH: 288.39 J g^{-1}). 2.5, 5, 7.5, and 10 g of stearic acid were added to 30 g

Table 2 DSC data for hosting materials using various concentration of stearic acid with/without PCM material from 2nd heating

PCM material			2nd heating			
			T_o/K	T_p/K	T_{end}/K	ΔH/J g^{-1}
Octadecane only			302.45	306.55	316.38	241.44
Flaxseed			408.85	410.25	419.4	132.12
Stearic acid			332.62	344.36	357.68	288.39
stearic acid conc	308.36	Without	308.36	309.7	321.68	173.25
	307.5	Octadecane	307.5	313.27	318.97	188.34
	306.31	Without	306.31	311.82	316.72	210.26
	304.95	Octadecane	304.95	309.6	315.2	220.65
	305.5	Without	305.5	309.95	320.83	215.12
	303.27	Octadecane	303.27	311.47	321.594	238.99
	307.4	Without	307.4	313.03	316.03	237.75
		Octadecane	304.41	312.58	317.25	251.04

Hosting material: 2.5, 5, 7.5 and 10 g stearic acid + 30 mL flaxseed. PCM material: 10% octadecane

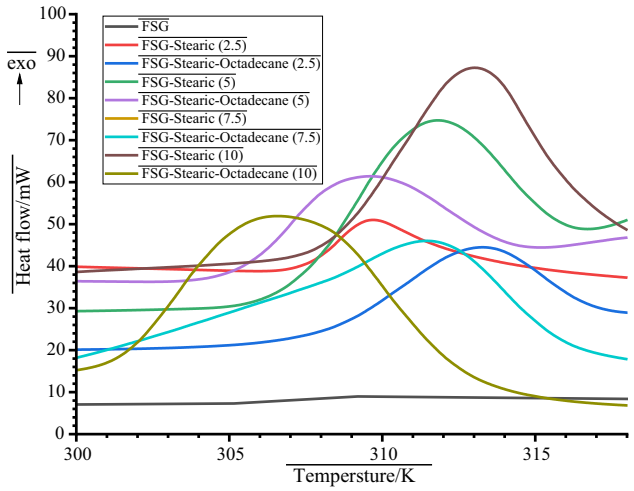

Fig. 7 DSC chart for various concentrations of stearic acid with FSG with and without octadecane from 2nd heating

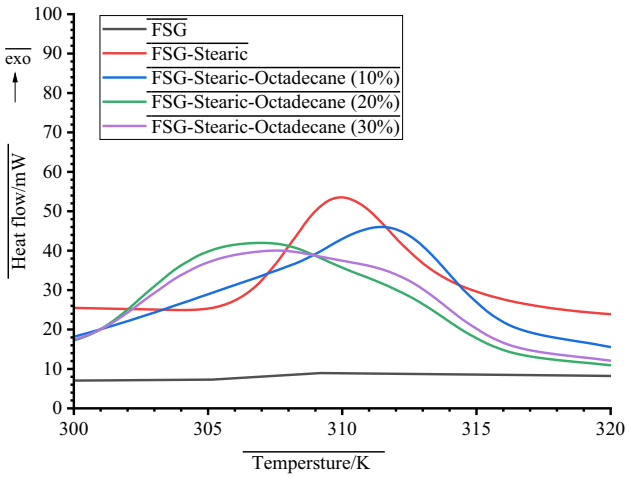

Fig. 8 DSC chart for hosting materials using stearic acid with octadecane concentration from 2nd heating

Table 3 DSC data for hosting materials using different concentration of PCM materials from 2nd heating

PCM material		2nd heating			
		T_o/K	T_p/K	T_{end}/K	ΔH/J g^{-1}
Octadecane only		302.45	306.55	316.38	241.44
Flaxseeds		408.85	410.25	419.4	132.12
St. only		332.62	344.36	357.68	288.39
Without PCM		307.4	313.03	316.03	237.75
10%	Octadecane	304.41	312.58	317.25	251.04
20%	Octadecane	300.54	306.47	316.48	259.96
30%	Octadecane	300.54	307.5	316.49	269.96

Hosting material: 10 g stearic acid + 30 mL flaxseeds. PCM material: 10, 20 and 30% octadecane

of flaxseeds. Table 2 and Fig. 7 illustrate the DSC values for PCMs following a second heating. The initial results from the second heating cycle reveal that PCM-polymer composites derived from flaxseeds and stearic acid, utilizing octadecane, exhibit an increase in enthalpy with a higher concentration of stearic acid in the host materials. Furthermore, heat storage enhances when the concentration of stearic acid rises to 10 g; therefore, sufficient heat storage is attained without increasing the concentration of stearic acid in the host materials beyond this point.

Effect of octadecane concentration

The DSC results for bio-synthesized composite materials prepared from flaxseeds and stearic acid in the presence

Table 4 DSC, duration index, and total resistance results of covered cotton fabric with PCM composite material (flaxseeds/Stearic with Octadecane composite)

Sample description		Thickness/cm	T_o/K	T_p /K	ΔH /J g^{-1}	DI * /J cm^{-3} K^{-1}	R/clo	Q_{max}/W cm^{-2}	Thermal conductivity /W m^{-1} K^{-1}
Blank		0.05	307.85	311.54	0.88	0.31	0.025	0.096	0.033
PCM composite	30 gm L^{-1}	0.053	304.35	309.67	115.38	16.05	0.035	0.097	0.024
	50 gm L^{-1}	0.054	308.75	311.8	131.55	76.82	0.020	0.098	0.044
	100 gm L^{-1}	0.045	309.35	312.83	133.84	142.76	0.022	0.100	0.033

Hosting material: 10 g stearic acid + 30 mL flaxseeds. PCM material: 30% octadecane

Duration index: based on ΔT from melt point to body temperature (310.15 K) and average density of 0.8 g cm^{-3}

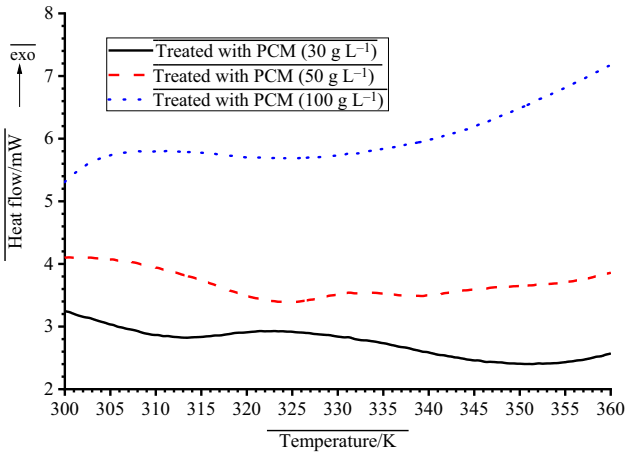

Fig. 9 DSC chart for hosting materials using stearic acid with PCM (octadecane) concentration from 2nd heating

and absence of octadecane as PCM materials with various concentrations (10, 20, and 30%) are shown in Table 3 and Fig. 8**.** Table 3 clearly illustrates that the latent heat of the hosting materials increases as the concentration of PCM material increases in the finished composite form. Table 3 shows that DSC curve for hosting materials utilizing stearic acid at different concentrations of PCM (octadecane) from the second heating, and it was found that using 30% of octadecane gives the best result.

Characterization of treated fabric

Differential scanning calorimetric

Table 4 presents the results of the DSC analysis performed on cotton fabric that has been treated with flaxseeds, stearic acid, and octadecane. It has been discovered that the treated cotton fabric with this composite imparts a thermoregulating capability in comparison with the fabric that has not been treated (Blank). The amount of latent heat that is produced by coated cotton fabric with 100 g L^{-1} flaxseeds, stearic acid, and octadecane is more than that produced by coated cotton fabric with other concentrations (30–50 g L^{-1}) and by uncoated fabric.

Furthermore, total resistance to dry heat transfer was computed and confirmed that cotton fabric treated with FSG–stearic acid–octadecane composites makes the fabric more comfortable than those untreated. This was the conclusion reached after the calculations were undertaken.

At long last, it is possible to draw the conclusion that PCM composites may be used to cover cotton fabric, and that the covered fabric delivers superior results than the uncoated cotton fabric (Fig. 9).

Table 5 DSC, duration index, and total resistance results of treated fabric using PCM before and after dyeing

Sample description		Thickness/cm	T_o/K	T_p/K	ΔH/J g^{-1}	DI * /J cm^{-3} K^{-1}	R/clo	Q_{max}/W cm^{-2}	Thermal conductivity W m^{-1} K^{-1}
Blank		0.05	307.89	311.54	0.88	0.31	0.025	0.096	0.033
Dyed		0.058	307.27	309.34	18.55	5.15	0.014	0.097	0.068
PCM (100 g L^{-1})	T	0.041	300.43	309.4	133.8408	11.02	0.059	0.098	0.011
	TD	0.053	300.44	317.4	115.2908	9.50	0.088	0.125	0.010
	DT	0.053	300.44	317.51	130.3908	14.28	0.066	0.168	0.013

T: Treated, TD: Treated then dyed, ΔT: Dyed then treated

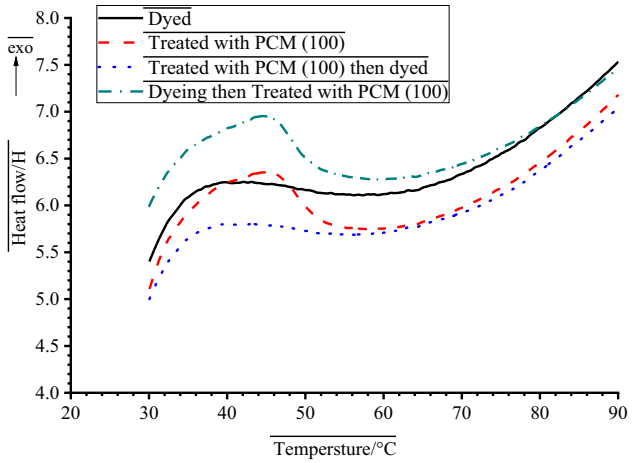

Fig. 10 DSC chart for treated fabric using PCM before and after dyeing

Dyeing performance

Cotton fabrics treated with flaxseeds/stearic acid/octadecane were dyed and tested for thermal storage and thermal conductivity. Furthermore, cotton fabric was dyed, then treated with flaxseeds/stearic acid/octadecane, and tested for thermal storage performance and thermal conductivity.

Table 5 and Fig. 10 show the thermal storage properties and thermal conductivity of treated fabric (T), treated then dyed fabric (TD), and dyed then treated fabric (ΔT). The data in Table 5 clearly show that dyed then treated fabric with flaxseeds/stearic acid/octadecane provides greater thermal storage than treated then dyed fabric. It is possible that after dyeing the functional groups on the surface of cotton fabric did not react completely with dye molecules, and upon treatment, PCM composite material formed a thin film on the surface of dyed cotton fabric, allowing the PCM materials to react and produce thermoregulated fabrics during curing stage. From another point of view, dyeing treated fabric allows the dye molecules to react with free functional groups on the surface of cotton fabric. It is also possible that the treated then dyed fabric did not give good results because the dyeing process proceeded at 333.15 K that convert the PCM from solid to liquid phase and causing them to fall out from the surface, resulting in decreased thermoregulated performance.

Table 6 shows that dyeing the treated fabric results in higher color strength properties than dyed then treated cotton fabric, which could be attributed to the formation of a thin film from the pretreatment, which activates the surface with functional groups and allows the fabrics to absorb more dye molecules, while dyed then treated fabrics produces approximately same color strength to the blank dyed cotton

and also demonstrates the fastness properties of treated then dyed fabrics and dyed then treated fabrics. All fabrics exhibit extremely good to excellent fastness characteristics. The light fastness characteristics of all treated textiles were good, showing that the PCMs composite is suitable for dyed thermoregulated fabrics due to chemical linkages between the dyed fabrics and the PCMs composite.

Durability measurement

Table 7 and Fig. 11 show the DSC chart for dyed then treated fabric using PCM-based composite (flaxseeds/stearic acid/octadecane) after different washing cycles (5 and 10) washing cycles. It is obvious that the general properties of dyed

Table 6 Color strength (*K/S*) and fastness properties of different treated dyed fabrics

Sample description		*K/S*	Fastness properties								
			Washing		Rubbing		Perspiration				Light
							Acidic		Alkaline		
			Alt	St	Dry	wet	Alt	St	Alt	St	
Dyed blank		7.63	4	4	4	3–4	4	3–4	4	4	5
PCM(100 g L^{-1})	TD	8.41	4	4	4	4	4	4	4	4	5
	DT	7.41	4	4	4	4	4	4–5	4–5	4	5

Table 7 *K/S*, DSC, Duration index, and Total Resistance results of treated dyed cotton fabric after different washing cycle

Sample description		*K/S*	T_o/K	T_p/K	ΔH/J g^{-1}	Percentage loss of ΔH/%	DI * /J cm^{-3} K^{-1}
PCM (100 g L^{-1})	DT	7.41	300.44	317.51	130.39	–	14.28
	5 WC	6.92	300.1671	317.42	128.77	12.4	14.3
	10 WC	6.75	300.11252	317.38	121.68	6.68	13.46

WC: washing cycle

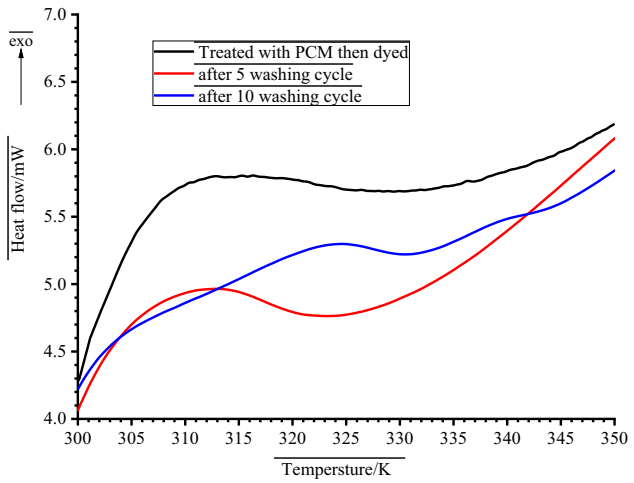

Fig. 11 DSC chart for dyed treated fabric using different PCM after different washing cycle

treated cloth (thermal insulation) reduced slightly after 5 washing cycles, and this loss grew when the washing cycle increased to 10. Although the fabric's properties decrease with each washing cycle, the fabric has the capacity to store heat and it outperforms the blank fabric without treating.

3.2.4. Morphological properties

The morphological behavior of cotton textiles was investigated after being treated with PCM composite material (see Figure 12). It is obvious that treatment with composite results in the existence of a homogenous thin coating on the cotton fiber surface. This thin coating causes uniformity in the filling of the gabs in the surface of cotton fiber, which is responsible for the increase of thermal characteristics and heat storage.

Evaluation of comfortability

Textiles are a material that is widely utilized in everyday life. On the other hand, surface treatment or multilayer approaches are required for direct outdoor use of textiles, especially natural ones such as cotton, in order to preserve them [57, 58].

Figure 13 illustrates water vapor permeability of treated and untreated fabrics, and the data sources demonstrate that evaluated values decreased after treatment but remained within acceptable limits.

According to the sources of the data, the air permeability of the treated and colored textiles rose somewhat after treatment (Fig. 13). The fact that the treatment and dyeing methods did not have any impact on the degree of comfort provided by the cloth is obvious.

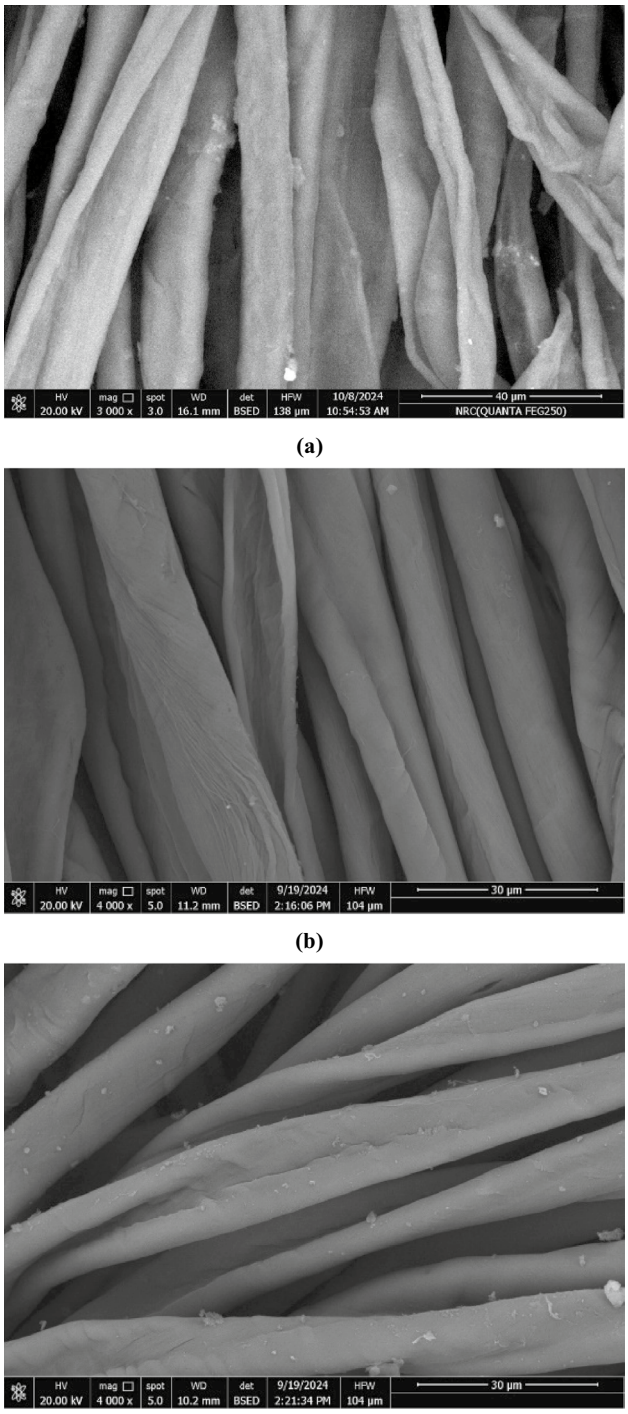

Fig. 12 Morphological behavior of treated cotton textiles **A** untreated, **B** treated dyed, and **C** dyed

It was proved that the mean values after treatment recorded the greatest values compared to the values recorded before treatment, as shown in Fig. 13, which is based on the mean value of the samples. As a means of conducting analyses on samples prior to treatment, based

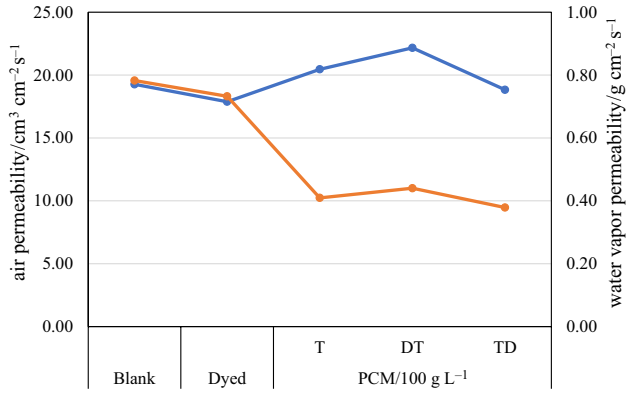

Fig. 13 Air permeability and water vapor permeability of treated and untreated fabrics

on the results, it was determined that there was a considerable difference between the treated dyed cotton textiles and the dyed treated cotton fabrics that were made using the manufactured PCM composites.

Mechanical and physical properties

For cotton textiles before and after treatment, tensile strength, elongation at a break, air permeability, roughness, and crease recovery angle have been observed and the data are listed in Table 8. From Table 8, it was clear that the crease recovery angle (CRA) increases dramatically as the roughness of the surface, air permeability, tensile strength, and elongation at break slightly decreased after treatment with three prepared PCM composites. This reveals that the host material containing the prepared PCM materials in core was deeply absorbed into the microstructure of the textiles, leaving a thin coating layer on the surface of the fabric that caused the changes that were seen.

Further investigation was going for investigation the crease recovery angle for treated fabrics in both warp and weft direction. The results provide that the crease recovery angle of all treated fabrics has increased values compared with the untreated. These results confirm that the biopolymer materials play an important role in enhancing the mechanical or physical properties. The substantial rise in the crease recovery angle was probably caused by the covalent chemical connection, which also resulted in the formation of an intense network with a high degree of cross-linking using citric acid and sodium hypo phosphite.

Conclusions

Flaxseed gum (FSG) is a type of gum with two different polysaccharide fractions: a neutral fraction and an acidic fraction. Studies have shown that flaxseed gums with higher levels of arabinoxylans exhibit pronounced shear thinning and weak gel-like characteristics, while those with higher concentrations of acidic monosaccharides display diminished rheological properties. A bio-PCM composite was synthesized by reacting flaxseed gum with fatty acid anhydrides and characterized via FT-IR and DSC analyses. The study examined the effect of fatty acid type on the performance of bio-synthesized composite materials made from flaxseeds and various fatty acids in the presence and absence of octadecane as PCM materials. The results showed that the latent heat of the hosting materials rises as the fatty acid backbone increases in the finished composite form. The best results were observed when using 20% of octadecane as PCM materials.

The study focuses on the use of polymer-based materials (PCM) in the production of bio-synthesized composite materials made from flaxseeds and stearic acid. The latent heat of the hosting materials increases with the concentration of PCM material, with the best results observed when using 20% of octadecane. The treated cotton fabric imparts a thermoregulating capability

Table 8 Mechanical and physical properties of treated and untreated fabrics

Sample description		Air permeability/ cm^3 cm^{-2} s^{-1}	Water permeability/g cm^{-2} s^{-1}	Tensile strength/N	Elongation at a break/%	Roughness/μm	CRA
Blank		19.197	0.779	155.50	51.0	17. 45	114
Dyed		17.819	0.725	154.68	49.1	17.20	121.8
PCM (100 g L^{-1})	T	20.06	0.4	152.95	44.79	17.31	242.21
	DT	21.73	0.43	152.41	40.47	17.24	227.56
	TD	18.46	0.37	153.71	50.46	17.48	276.4

T: Treated, TD: Treated then dyed, DT: Dyed then treated

compared to the untreated fabric. The study also investigates the morphological behavior of cotton textiles after being treated with PCM composite material, showing that treatment results in a homogenous thin coating on the cotton fiber surface, increasing thermal characteristics and heat storage.

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Data availability The authors declare that all the required data are listed in the text.

Declarations

Conflict of interest The authors declare that there is no conflict of interest.

References

1. Mondal S. Phase change materials for smart textiles–an overview. Appl Therm Eng. 2008;28(11–12):1536–50. https://doi.org/10.1016/j.applthermaleng.2007.08.009.
2. Huang X, Zhu C, Lin Y, Fang G. Thermal properties and applications of microencapsulated PCM for thermal energy storage: a review. Appl Therm Eng. 2019;147:841–55.
3. Lima F, Costa S, Costa S, Oliveira A Application and evaluation of the properties of nanoencapsulated pcms in textiles. In: 2025 https://doi.org/10.56238/sevened2025.021-011
4. Dirlik Uysal C, Minguez D, Bou-Belda E, Gisbert J, Bonet-Aracil M. Thermo-regulated cotton: enhanced insulation through PVA nanofiber-coated PCM microcapsules. Appl Sci. 2024. https://doi.org/10.3390/app14114725.
5. Koh J Dyeing of cellulosic fibres. In: Handbook of textile and industrial dyeing. Elsevier, 2011 p 129–146
6. Wang J, Zhong B, Chen W. Research on the comprehensive properties of cotton/silk fiber grinding knitted fabrics. Fibers Polym. 2025;26:1–13. https://doi.org/10.1007/s12221-025-01008-w.
7. Prajapati DG, Kandasubramanian B. A review on polymeric-based phase change material for thermo-regulating fabric application. Polym Rev. 2020;60(3):389–419.
8. Rahimi E, Biabani A, Ghaljahi M, Golbabaei F. A systematic review on the improvement of thermoregulating properties of cotton fabrics with nanocapsules of phase change materials. J Health Saf Work. 2025. https://doi.org/10.18502/jhsw.v14i3.18320.
9. Jamekhorshid A, Sadrameli S, Farid M. A review of microencapsulation methods of phase change materials (PCMs) as a thermal energy storage (TES) medium. Renew Sustain Energy Rev. 2014;31:531–42.
10. Heniegal A, Ibrahim O, Frahat N, Sherif M. Thermal and mechanical properties of mortar incorporated with phase change materials (PCMs). Key Eng Mater. 2022;921:259–69. https://doi.org/10.4028/p-f0qyby.
11. Sarier N, Onder E. Organic phase change materials and their textile applications: an overview. Thermochim Acta. 2012;540:7–60. https://doi.org/10.1016/j.tca.2012.04.013.
12. Onder E, Sarier N, Cimen E. Encapsulation of phase change materials by complex coacervation to improve thermal performances of woven fabrics. Thermochim Acta. 2008;467(1–2):63–72.
13. Herchi W, Bahashwan S, Sebei K, Saleh HB, Kallel H, Boukhchina S. Effects of germination on chemical composition and antioxidant activity of flaxseed (*Linum usitatissimum* L) oil. Grasas Aceites. 2015;66(1):e057–e057.
14. Demirbağ S, Aksoy SA. Encapsulation of phase change materials by complex coacervation to improve thermal performances and flame retardant properties of the cotton fabrics. Fibers Polym. 2016;17(3):408–17.
15. Khan B, Tanha J, Amin J, Fahim T, Islam MR. Thermal regulation in textiles: phase change materials and sustainability. Sustain Finish Tech Text. 2025. https://doi.org/10.1007/978-981-96-4860-3_10.
16. House R, Sasikala R, Bindu J 2025 Chitosan and sodium alginate: the potential of natural biopolymers of marine origin in development of biodegradable packaging material: natural biopolymers in biodegradable packaging material. Fish Technol. https://doi.org/10.56093/ft.v62i1.153493
17. Pramanik J, Kumar A, Prajapati B. A review on flaxseeds: nutritional profile, health benefits, value added products, and toxicity. eFood. 2023;4(5):e114.
18. Stavropoulos P, Mavroeidis A, Papadopoulos G, Roussis I, Bilalis D, Kakabouki I. On the path towards a "greener" EU: A mini review on flax (*Linum usitatissimum L.*) as a case study. Plants. 2023;12(5):1102.
19. Liu Y, Tao Y, Wang B, Li P, Xu Y-J, Jiang Z-M, et al. Fully bio-based fire-safety viscose/alginate blended nonwoven fabrics: thermal degradation behavior, flammability, and smoke suppression. Cellulose. 2020;27(10):6037–53. https://doi.org/10.1007/s10570-020-03162-1.
20. Parsamanesh M, Shekarriz S, Montazer M. Enhancing cotton fabric flame retardancy with eco-friendly graphene oxide and PCM microcapsules. Fibers Polym. 2025. https://doi.org/10.1007/s12221-025-00888-2.
21. Mazur W. 11 phytoestrogen content in foods. Baillieres Clin Endocrinol Metab. 1998;12(4):729–42.
22. Dodin S, Cunnane SC, Mâsse B, Lemay A, Jacques H, Asselin G, et al. Flaxseed on cardiovascular disease markers in healthy menopausal women: a randomized, double-blind, placebo-controlled trial. Nutrition. 2008;24(1):23–30.
23. Griffin B. How relevant is the ratio of dietary n-6 to n-3 polyunsaturated fatty acids to cardiovascular disease risk? Evidence from the OPTILIP study. Curr Opin Lipidol. 2008;19:57–62. https://doi.org/10.1097/MOL.0b013e3282f2e2a8.

24. Shinde Y, Shaha A, kolte N, Talele D Flaxseeds as a potential herbal functional food: nutritional benefits and bioactive compounds. 2023
25. Hall AV, Parbtani A, Clark WF, Spanner E, Keeney M, Chin-Yee I, et al. Abrogation of MRL/lpr lupus nephritis by dietary flaxseed. Am J Kidney Dis. 1993;22(2):326–32.
26. Reggiani R, Russo R (2015) Protein concentration and amino acid profile in hempseed and flaxseed meal. https://doi.org/10.13140/RG.2.1.4079.5048
27. Ambroszkiewicz J, Chelchowska M, Mazur J, Grażyna R, Klemarczyk W, Strucińska M, et al. Interplay Between Diet, Branched-Chain Amino Acids, and Myokines in Children: Vegetarian Versus Traditional Eating Habits. Nutrients. 2025;17:834. https://doi.org/10.3390/nu17050834.
28. Hassabo AG, Mohamed AL. Enhancement the thermo-regulating property of cellulosic fabric using encapsulated paraffins in modified pectin. Carbohydr Polym. 2017;165:421–8. https://doi.org/10.1016/j.carbpol.2017.02.074.
29. Hassabo AG. New approaches to improving thermal regulating property of cellulosic fabric. Carbohydr Polym. 2014;101:912–9. https://doi.org/10.1016/j.carbpol.2013.10.006.
30. Mottinger B. Space Hardware Design Final Project, ASEN 4512. USA: University of Colorad; 1999.
31. Doerr DF Heat stress assessment and a countermeasure. Biomed Lab Kennedy Sp Cent, West Melb, FL 1997 32912–0642
32. McCullough EA, Jones BW A comprehensive data base for estimating clothing insulation. The american society of heating refrigerating, and air-conditioning engineers, Inc., 1984
33. Shim H, McCullough EA, Jones BW. Using phase change materials in clothing. Text Res J. 2001;71(6):495–502. https://doi.org/10.1177/004051750107100605.
34. Fathallah AI, Youssef BY, El-Sadek H, Amin MG, Abd El-Kader BM, El-Kambashawy YM, et al. Alginic/Stearic/Octadecane as Phase Change Material (PCM) for enhancing the thermal Comfort-ability of Different Polyester Fabrics Constructions. Egy J Chem. 2023;66(4):167–77. https://doi.org/10.21608/ejchem.2023.188010.7468.
35. Kubelka P, Munk F. Ein Beitrag zur Optik der Farbanstriche. Z Tech Phys. 1931;12:593. https://doi.org/10.1007/978-3-642-27851-8_300-1.
36. Mehta KT, Bhavsar MC, Vora PM, Shah HS. Estimation of the Kubelka-Munk scattering coefficient from single particle scattering parameters. Dyes Pigm. 1984;5(5):329–40. https://doi.org/10.1016/0143-7208(84)80027-3.
37. Waly A, Marie MM, Abou-Zeid NY, El-Sheikh MA, Mohamed AL Process of single–bath dyeing, finishing and flam–retarding of cellulosic textiles in presence of reactive tertiary amines. In: 3rd international conference of textile research division, NRC; textile processing: State of the art & future developments, Cairo, Egypt, 2 –4 April 2006 P. 529–543
38. Waly A, Marie MM, Abou-Zeid NY, El-Sheikh MA, Mohamed AL. Flame retarding, easy care finishing and dyeing of cellulosic textiles in one bath. Egy J Text Polym Sci Technol. 2008;12(2):101–31.
39. ISO 105-C01: Textiles tests for colour fastness. Part C01: colour fastness to washing: Test 1. Deutsches institut fur normung E.V. (DIN), 2006
40. AATCC Test method (8–2016) Colorfastness to crocking, crockmeter method. Technical manual method vol 86. American association of textile chemists and colorists, 2018
41. Wei W, Zhou Y-H, Chang H-J, Yeh J-T. Antibacterial and miscibility properties of chitosan/collagen blends. J Macromol Sci, Part B. 2015;54(2):143–58. https://doi.org/10.1080/00222348.2014.987097.
42. ISO 105-E04:2013 Textiles tests for colour fastness. Part E04: colour fastness to perspiration. Deutsches institut fur normung E.V. (DIN), 2014
43. AATCC Test Method (15–2013) Colour fastness to perspiration. Technical manual method vol 86. American association of textile chemists and colorists, 2017
44. AATCC Test Method (16.1–2014) Colour fastness to light: outdoor. Technical manual method vol 16.1. American association of textile chemists and colorists, 2015
45. ASTM Standard test method (D5035–11 (Reapproved 2019)) Standard test method for breaking force and elongation of textile fabrics (Strip Method). ASTM international, 2019
46. AATCC Test Method (66–2014) Wrinkle recovery of fabric: recovery angle method. Technical manual method. American association of textile chemists and colorists, 2017
47. ASTM Standard test method (D7127−13) Standard test method for measurement of surface roughness of abrasive blast cleaned metal surfaces using a portable stylus instrument1. ASTM international, West Conshohocken, PA 2016
48. ASTM Standard test method (D1388−14e1) Standard test methods for stiffness of fabrics. ASTM international, West Conshohocken, PA 2016
49. ASTM Standard Test Method (D 737-18) Standard test method for air permeability of textile fabrics. ASTM international, West Conshohocken, PA 2018
50. ISO 11092 : 2014 Textiles-physiological effects-measurement of thermal and water-vapour resistance under steady-state conditions (Sweating Guarded-Hotplate Test) 2014.
51. ASTM Standard Test Method (E 96/96M-16) (2016) Standard test methods for water vapor transmission of materials. https://doi.org/10.1520/e0096_e0096m-16
52. Li H, Su L, Chen S, Zhao L, Wang H, Ding F, et al. Physicochemical characterization and functional analysis of the polysaccharide from the edible microalga *Nostoc sphaeroides*. Molecules. 2018;23(2):508.
53. Skwarek E, Goncharuk O, Sternik D, Janusz W, Gdula K, Gun'ko VM. Synthesis, structural, and adsorption properties and thermal stability of nanohydroxyapatite/polysaccharide composites. Nanoscale Res Lett. 2017;12:1–12.
54. Razmkhah S, Razavi SMA, Mohammadifar MA, Koocheki A, Ale MT. Stepwise extraction of *lepidium sativum* seed gum: physicochemical characterization and functional properties. Int J Biol Macromol. 2016;88:553–64.
55. Sherahi MH, Fathi M, Zhandari F, Hashemi SMB, Rashidi A. Structural characterization and physicochemical properties of *Descurainia sophia* seed gum. Food Hydrocoll. 2017;66:82–9.
56. Ren X, He H, Li T. Variations in the structural and functional properties of flaxseed gum from six different flaxseed cultivars. Food Sci Nutr. 2021;9(11):6131–8. https://doi.org/10.1002/fsn3.2566.
57. Xue C-H, Bai X, Jia S-T. Robust, self-healing superhydrophobic fabrics prepared by one-step coating of PDMS and octadecylamine. Sci Rep. 2016;6(1):1–11. https://doi.org/10.1038/srep27262.
58. Wang H, Xue Y, Ding J, Feng L, Wang X, Lin T. Durable, self-healing superhydrophobic and superoleophobic surfaces from fluorinated-decyl polyhedral oligomeric silsesquioxane and hydrolyzed fluorinated alkyl silane. Angew Chem. 2011;123(48):11635–8. https://doi.org/10.1002/anie.201105069.