Jurnal
Teknologi

Full Paper

SURFACE MORPHOLOGY AND FUNCTIONAL PROPERTIES OF BAMBOO CHARCOAL COATED POLYESTER-COTTON FABRIC

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Article history
Received
2 September 2025
Received in revised form
6 December 2025
Accepted
8 December 2025
Published Online
29 August 2026

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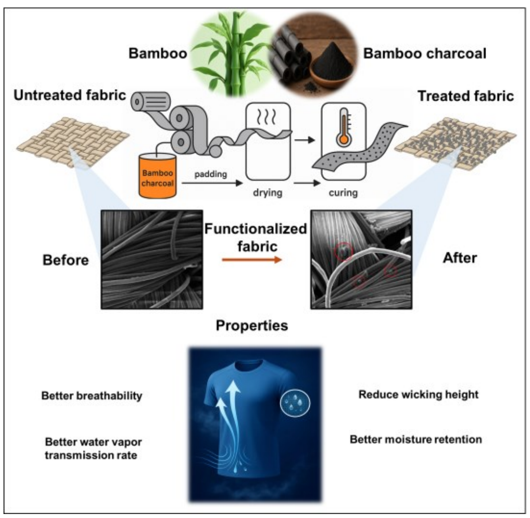
Graphical abstract



Abstract

The demand for multifunctional and sustainable textiles is growing in response to global concerns about comfort, durability, and environmental responsibility. Although bamboo charcoal is widely acknowledged for its adsorption capacity, antimicrobial activity, and eco-friendly nature, its properties after being coated onto fabric, especially the breathability, moisture regulation, and long-term durability, remain insufficiently explored. This study addresses this gap by coating bamboo charcoal microparticles onto polyester–cotton blended fabrics using the pad-dry-cure method and evaluating their structural, chemical, and functional performance. Scanning Electron Microscopy (SEM) showed strong particle adhesion on fiber surfaces, while Fourier Transform Infrared Spectroscopy (FTIR) confirmed the persistence of key functional groups after multiple washing and abrasion cycles. Functionality tests demonstrated an improved Water Vapour Transmission Rate (WVTR) of 2.2%, indicating enhanced breathability. Durability analysis revealed that the bamboo charcoal coating retained approximately 62.5% of its coating after washing and 5,000 of abrasion cycles. These findings revealed the potential of bamboo charcoal as a sustainable, low-cost, and effective coating for imparting multifunctional properties to fabrics. The work contributes to advancing functional textile engineering, offering applications in sportswear, healthcare, protective clothing, and eco-friendly apparel aligned with circular innovation goals.

Keywords: Bamboo charcoal, blended fabric, moisture management, durability, thermo-physiological properties

Abstrak

Permintaan terhadap tekstil multifungsi dan lestari semakin meningkat seiring kebimbangan global terhadap keselesaan, ketahanan, dan kelestarian alam sekitar. Walaupun arang buluh dikenali kerana kapasiti penyerapan, aktiviti antimikrob dan sifat mesra alamnya, sifatnya selepas disalut pada fabrik, terutama kebolehtelapan, pengawalan kelembapan, dan ketahanan jangka panjang, masih kurang diterokai. Kajian ini menangani kekurangan ini dengan menyalut mikropartikel arang buluh pada fabrik campuran poliester–kapas menggunakan kaedah *pad-dry-cure* dan menilai prestasi struktur, kimia, dan fungsinya. Mikroskopi Imbasan Elektron (SEM) menunjukkan lekatan partikel pada permukaan serat, manakala Spektroskopi FTIR membuktikan ketahanan kumpulan berfungsi selepas beberapa kitaran cucian dan geseran. Ujian fungsi menunjukkan peningkatan Kadar Pemindahan Wap Air (WVTR) sebanyak 2.2%, menandakan tahap kebolehtelapan udara yang lebih baik. Analisis ketahanan pula mendapati salutan arang buluh mengekalkan kira-kira 62.5% daripada salutannya selepas proses pencucian dan 5,000 kitaran geseran. Penemuan ini mendedahkan potensi arang buluh sebagai salutan yang mampan, kos rendah, dan berkesan untuk memberikan sifat multifungsi kepada fabrik. Kajian ini menyumbang kepada kemajuan kejuruteraan tekstil fungsional, menawarkan aplikasi dalam pakaian sukan, penjagaan kesihatan, pakaian pelindung, dan fesyen mesra alam sejajar dengan matlamat inovasi kitaran.

Kata kunci: Arang buluh, Fabrik campuran, Pengurusan lembapan, Ketahanan, Sifat termo-fisiologi

1.0 INTRODUCTION

The global textile industry is undergoing a transformative shift toward sustainability, driven by growing environmental concerns, the depletion of non-renewable resources, and consumer demand for eco-conscious products. Among the emerging bio-resources, bamboo stands out for its sustainability, rapid growth, carbon sequestration, and excellent mechanical properties, making it ideal for advanced textile applications [1, 2]. In Malaysia, where bamboo is abundantly available across tropical and hilly regions, its diverse species offer a strategic platform for advancing green textile technologies and bamboo-based innovations [3].

In textile applications, bamboo is increasingly seen as a sustainable alternative to wood and synthetic fibres because it is renewable, biodegradable, and capable of absorbing and storing carbon from the environment. It offers a significantly lower environmental footprint, along with a faster growth cycle and superior mechanical strength compared to traditional wood sources [4, 5]. In alignment with Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation and Infrastructure) and SDG 12 (Responsible Consumption and Production), research in this area promotes eco-friendly material innovation in textile engineering [6]. It also aligns with circular economy principles by encouraging the use of renewable resources, minimizing waste, and extending product life through functional material enhancements. The integration of bamboo-based materials into textile applications exemplifies circular material strategies, offering a sustainable approach to product design that reduces environmental impact and advances green manufacturing practices. Notably, bamboo exhibits natural antibacterial and UV-resistant properties, which further enhance its value in technical textile applications aimed at hygiene, comfort, and performance [7–9].

Bamboo charcoal is a carbonized derivative produced through high-temperature pyrolysis [10]. Previous studies have shown that bamboo charcoal possesses significantly higher absorption capacity and surface area compared to conventional wood pulp, enabling effective odor control, moisture adsorption, improving the warmth retention, antibacterial and UV protection [11, 12]. Nowadays, bamboo charcoal is widely used as a functional coating material to enhance textile performance and sustainability [10, 11]. Bamboo charcoal can be made from bamboo and the leftovers from processing bamboo at high temperatures in the presence of nitrogen [15]. Bamboo charcoal stands out for its high porosity, extensive surface area, and remarkable adsorption capacity, particularly for non-polar compounds [16]. Studies indicate that bamboo charcoal has four times the absorption rate and ten times more surface area than conventional wood charcoal, attributed to its porous structure and numerous microscopic holes [16, 17]. This allows it to efficiently absorb odors, moisture, and airborne pollutants [14, 15]. Structurally, it contains reactive functional groups including carbon–carbon double bonds (C=C), aliphatic C–H, and hydroxyl (–OH), which enable effective surface interactions with moisture, neutralize odors, and inhibit microbial growth [19].

Polyester-cotton blends are widely utilized in the textile industry for their balance of durability, comfort, and aesthetic appeal [13]. Polyester is known for its durability, resistance to wrinkles, and quick-drying properties, while cotton is valued for its breathability, comfort, and moisture-absorbing capabilities [14]. However, to meet contemporary performance requirements particularly in moisture management, thermal comfort, and hygiene additional surface functionality is needed. A sustainable approach is to apply value-adding finishes. In this context, bamboo charcoal engineered as a thin coating via pad-dry-cure or binder-assisted deposition can impart multifunctional benefits, including antimicrobial activity, deodorization, increased moisture absorption, and improved thermo-physiological comfort. Previous studies have shown that bamboo charcoal can enhance moisture absorption and improve thermal regulation. However, these findings are largely based on basic absorbency assessments and indirect thermal measurements. Therefore, a more comprehensive study is required, particularly focusing on surface morphology, thermo-physiological comfort, and washing durability as these areas are critical in determining real-world textile performance [20].

This study addresses this gap by investigating the impact of bamboo charcoal coatings on polyester-cotton woven fabric, focusing on surface morphology, comfort-related performance, and post-washing durability. The findings offer new insights into the multifunctional value of bamboo charcoal and its integration into sustainable textile systems.

2.0 METHODOLOGY

2.1 Materials

The bamboo charcoal powder extracted from Japanese White Bamboo with 3000 mesh size was sourced from Future food. The constructional parameters of the commercially available polyester-cotton woven fabric used in this study are shown in Table 1. The fabric was tested for weight, thickness and density in accordance with ASTM D3776 and ASTM D1777 standards.

Table 1 Constructional parameters of fabrics.

Fabric type	Ends per inch	Picks per inch	Grams per square meter (g/m^2)	Thickness
Polyester-cotton	113	69	95.76	0.212

2.2 Coating Preparation

The solution for the bamboo charcoal microparticles was prepared using 2% bamboo charcoal powder, 1% flexible acrylic binder, and 2% ionized water as the wetting agent, with a material-to-liquor ratio of 1:20. The total volume of ionized water and the mixed bamboo solution used was 2000 mL, with the weight of the fabric being 100 g. A homogenizer was used to blend the bamboo charcoal solution for 15 minutes at a speed of 2500 rpm to ensure uniform mixing.

2.3 Application of Bamboo Charcoal Particles

A pad-dry-cure method was employed to coat the bamboo charcoal particles onto the fabric. The fabric was soaked in the bamboo charcoal microparticles solution for 5 minutes before passing through the padding mangle. This process was repeated three times for each fabric sample to ensure uniform coating. The wet pick-up was determined by weighing the coated fabric as it emerged from the padding mangle. The padding roller applied a pressure of 2 kg/cm^2. The coated fabric was then dried at 100°C for 10 minutes and cured at 120°C for 4 minutes. Wet pick-up (%) was calculated using the formula:

$$\text{Wet pick-up (\%)} = [(W_{after} - W_{before}) / W_{before}] \times 100 \quad (1)$$

2.4 Fabric Characterization

The surface morphology of both uncoated and coated fabrics was examined using a COXEM EM-30AX scanning electron microscope (COXEM, Korea) at magnifications of x500 and x1000. The specimen was fixed on a specimen stub using double-sided adhesive tape and coated with sputtered gold. Fourier Transform Infrared Spectroscopy (FTIR) analysis was conducted to determine the chemical bonds that exist in the activated carbon by getting an infrared spectrum of the activated carbon. The wavenumber range was set from 4000 – 600 cm^{-1}. To obtain the spectrum, the samples were placed in the sample compartment. The spectra were measured using Varian Resolution Pro software.

2.5 Testing for Thermo-physiological Properties

Both the uncoated and coated fabrics were tested for thermo-physiological properties, including wicking and water vapor transmission rate (WVTR) using National Chinese Standard FZ/T01071-2008 and ASTM E96-95 standard test methods respectively.

2.5.1 Wicking

For the wicking test, fabric samples were subjected to the vertical wicking test to determine their longitudinal wicking properties [21]. The wicking behaviour of the fabrics was evaluated using the vertical wicking setup illustrated in Figure 1, where each specimen was suspended above a water reservoir, and the capillary rise was measured using a fixed ruler.

Fabric with the size of 30 cm × 2.5 cm were prepared. The test sample was suspended vertically in a beaker of distilled water, with one end immersed approximately 3 mm into the water as shown in Figure 1. The height of water conveyed along the sample was measured in cm using a ruler at 5 minutes intervals over a duration of 30 minutes (Figure 2). As the wicking height increased, the time intervals for water movement along the strip were recorded. The height of water transport is indicated by the red dashed line. This height is measured from the point where the fabric is immersed in the liquid up to the maximum level reached by the rising moisture along the fabric. The wicking area of the fabric reflects its overall moisture transport capability, and this area was determined using Equation 2.

$$\text{Wicking area (cm}^2) = c \times d \quad (2)$$

Where;

c = average height of water uptake (cm)
d = width of the sample (cm)

The averages readings for three samples were taken for each fabric and recorded as the vertical wicking characteristic of the fabrics.

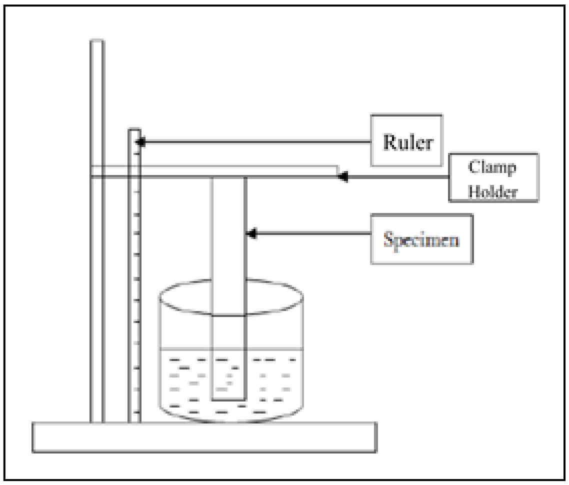


Figure 1 Wicking height measurement setup.

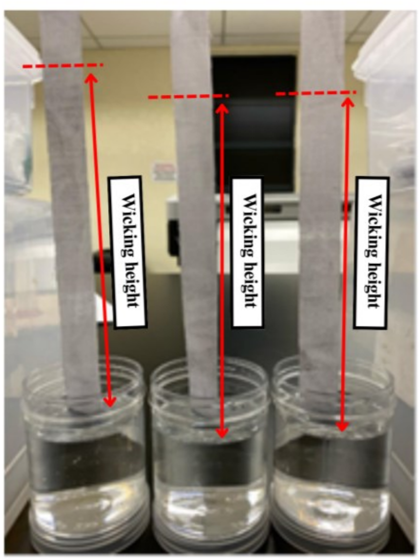


Figure 2 Demonstration of the wicking height measurement for fabric samples.

2.5.2 Water Vapor Transmission Rate (WVTR)

WVTR is carried out to measure the rate of water vapour transmission perpendicularly through a known area of the fabric in a controlled atmosphere. This test was measured in accordance with ASTM E96-95 which also known as the "traditional wet cup test". In this method, a sample covered in a cup containing water was placed in a controlled atmosphere of 20°C and 65% relative humidity. The cup was filled with water leaving 19 mm of gap. The initial weight of the cup was then measured. The weight of the cup was measured every hour for 7 hours, and WVTR in grams per hour per square meter, was calculated using the following Equation 3:

$$WVTR = G/tA \quad (3)$$

where G is the weight change of the cup with fabric sample in grams, t is the time during which G occurred in hours and A is the testing area in square meters.

2.6 Testing for Durability Properties

Durability testing was conducted to assess the ability of the bamboo charcoal coated fabric to withstand extended use under intended conditions. Washing fastness and abrasion resistance tests were conducted to assess the retention of the bamboo charcoal coating after multiple washing cycles and exposure to abrasion. The FTIR was used to analyse the functional group of samples before and after washing and abrasion exposure.

2.6.1 Washing Fastness Testing

Washing fastness testing was conducted following the ISO 6330 standard, in which the coated fabric was laundered using a top load washing machine, which is classified as type B. The samples were washed for 5 cycles. For every 2000ml of water, 100g of commercial liquid detergent was used. A total of 2.1 kg of samples, along with a dummy load, was prepared and laundered in a washing machine. The samples were dried using the flat drying method, where they were laid flat on a surface to prevent stretching, distortion, or wrinkles.

2.6.2 Abrasion Resistance

The Martindale Abrasion Test was performed to assess the abrasion resistance of the fabric in accordance with ASTM D4966-98 standards. Samples were rubbed against a standard fabric under low pressure for 5000 cycles with continuous directional alterations. Samples with diameters of 38 mm and 140 mm were prepared, and the 38 mm samples were weighed before and after the test to determine weight loss due to abrasion.

3.0 RESULTS AND DISCUSSION

3.1 Characterization of Fabrics

The surface morphology of both uncoated and coated polyester-cotton fabrics was analyzed using SEM at magnifications of x500 and x1000, as presented in Figures 3 and 4. For the uncoated samples (Figures 3(a) and 4(a)), the fiber surfaces appear smooth and clean, indicating no surface modification. The red circles in Figures 3(b) and 4(b) show the presence of bamboo charcoal microparticles attached to the fiber surfaces. The presence of these particles confirms the successful deposition of the bamboo charcoal microparticle solutions onto the fabric. Their attachment suggests good adhesion between the coating material and the polyester-cotton fibers. Based on direct measurements of the bamboo charcoal particles from the ×500 SEM micrographs and using the 100 µm scale bar for calibration (1 µm = 1.56 pixels), the adhered microparticles exhibited an estimated size range of approximately 5–13 µm. This is consistent with the expected particle size for 3000-mesh bamboo charcoal powders supplied by the manufacturer.

FTIR analysis was performed to identify the major functional groups present in the bamboo charcoal powder and to evaluate the chemical changes on the fabric surface before coating, after coating, and following five washing cycles. Table 2 presents the FTIR peak assignments and functional group identification of bamboo charcoal powder. Figure 5 shows the corresponding FTIR spectrum of the bamboo charcoal powder, while Figure 6 illustrates the comparative spectra of (a) uncoated fabric, (b) coated fabric before washing, and (c) coated fabric after five washing cycles.

Table 2 FTIR peak assignments and functional group identification of bamboo charcoal powder

Peak No.	Wavenumber (cm^{-1})	Functional Group	Interpretation
1	3350–3295	O–H stretching	Broad band from hydrogen-bonded hydroxyls in residual cellulose/lignin and adsorbed moisture.
2	2170–2080	C≡C or C≡N stretching	Weak triple-bond vibrations typical of carbonized materials.
3	2150–2100	C≡C/C≡N overtone region	Weak overtones from polyaromatic structures; not NH-related.
4	945–930	Aromatic C–H out-of-plane bending	Indicates aromatic ring formation and carbonization.
5	900–845	Si–O bending / aromatic C–H wagging	Reflects natural silica content in bamboo and aromatic structures.
6	845–800	Si–H wagging / aromatic deformation	Associated with siliceous phytoliths and aromatic carbon features.

Based on Table 2 and Figure 5, the FTIR spectrum of bamboo charcoal powder exhibits a broad absorption band at 3350–3295 cm^{-1}, attributed to O–H stretching from hydroxyl groups and residual moisture, indicating that hydrophilic sites remain present even after carbonization. This is consistent with findings reported in Chen *et al*., where bamboo charcoal shows a broad O–H stretching band around 3475 cm^{-1} due to surface hydroxyls and adsorbed water [20]. Weak bands in the 2170–2080 cm^{-1} and 2150–2100 cm^{-1} regions correspond to C≡C/C≡N triple-bond stretching and overtone transitions associated with polyaromatic carbon structures formed during biomass pyrolysis. The peak at 945–930 cm^{-1} represents aromatic C–H out-of-plane bending, confirming the formation of aromatic and graphitic domains. Prominent features between 900–845 cm^{-1} and 845–800 cm^{-1} are assigned to Si–O and Si–H vibrations originating from silica-rich phytoliths naturally present in bamboo and was supported from previous study [20]. Collectively, these functional groups suggest a heterogeneous surface rich in hydroxyl, aromatic, and siliceous structures, making bamboo charcoal suitable for surface interaction and adsorption-based applications.

The uncoated fabric 6(a) shows the characteristic aliphatic C–H stretching peak at 2903.60 cm^{-1}, typical of polyester–cotton fibers. For the coated fabric shows in Figure 6 (b), peaks at 3749.70 cm^{-1} and 3649.60 cm^{-1} correspond to free O–H stretching vibrations, indicating the presence of non-hydrogen-bonded hydroxyl groups. These may originate from exposed –OH functionalities in residual lignocellulosic structures of bamboo charcoal, consistent with previous FTIR studies [22]. The C–H asymmetric stretching of aliphatic methylene groups appears shift at 2959.51 cm^{-1}, typical of hydrocarbon chains introduced by the bamboo charcoal and align with previous study - C–H stretching in methyl and methylene group [7, 19].

A distinct peak at 1710.85 cm^{-1} in all coated samples is attributed to C=O stretching vibrations, indicating the presence of ketone or carboxylic acid functional groups, free carbonyl groups, stretching of acetyl or carboxylic acid (hemicelluloses) [20, 25]. This corresponds to oxidized carbon species formed during the pyrolysis of bamboo. The region between 1576–1557 cm^{-1} is associated with aromatic C=C skeletal vibrations, typically found in lignin structures within bamboo charcoal. Similarly, the peaks observed between 1321–1203 cm^{-1} correspond to C–O stretching, phenolic O–H bending, and C–H deformation in cellulose and hemicellulose. These oxygen-containing functionalities are crucial for increasing surface polarity, enabling moisture management and interaction with the surrounding environment.

After five washing cycles (Figure 6(c)), the spectra still showed most of the key functional groups, though with slight shifts in peak positions and intensities. Notably, the O–H stretching band broadened into the 2500–3100 cm^{-1} region, centered at 2966.96 cm⁻¹, indicating increased hydrogen bonding due to interactions with retained surface hydroxyls and moisture.

Additionally, a strong C=O stretching vibration was observed at 1710.85 cm^{-1}, corresponding to oxidized ketone structures typical of pyrolyzed bamboo align with previous study [22]. The persistence of peaks associated with C=O, C=C, and C–O stretching confirms the chemical stability of the bamboo charcoal coating after laundering. Although peaks near 1420 cm^{-1}often linked to carboxylic C–O stretching in oxidized lignocellulose were not distinctly visible, the spectral data between 1321–1203 cm^{-1} were sufficient to confirm the continued presence of bamboo-derived cellulose and lignin fragments.

The present of key functional groups after washing indicates the particles remain intact; implying strong mechanical anchoring and durability of the coating. This is essential for maintaining long-term functional properties such as antibacterial activity, odor absorption, and moisture regulation.

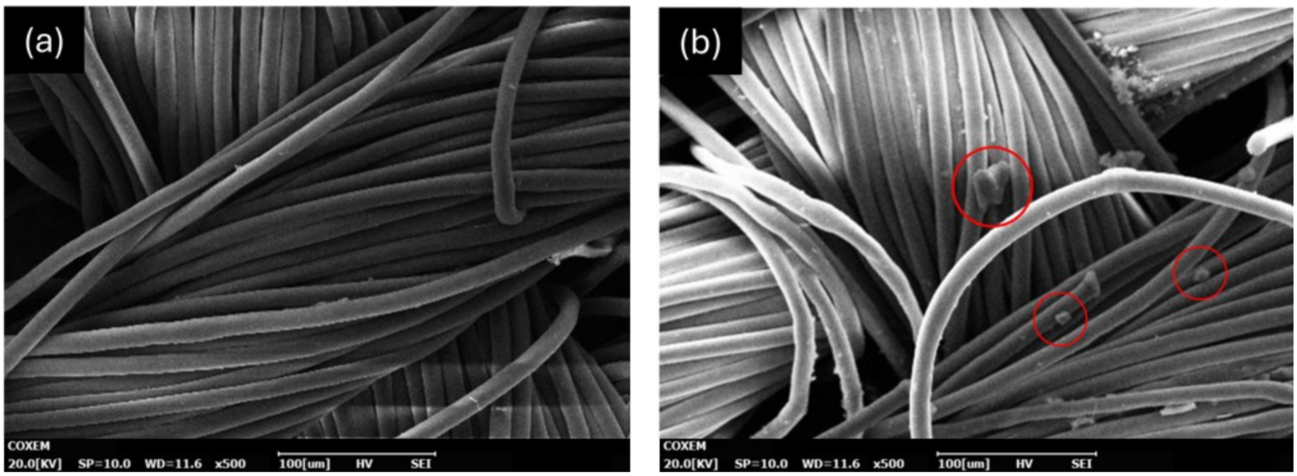


Figure 3 SEM images of (a) uncoated and (b) coated fabrics at x500 magnification.

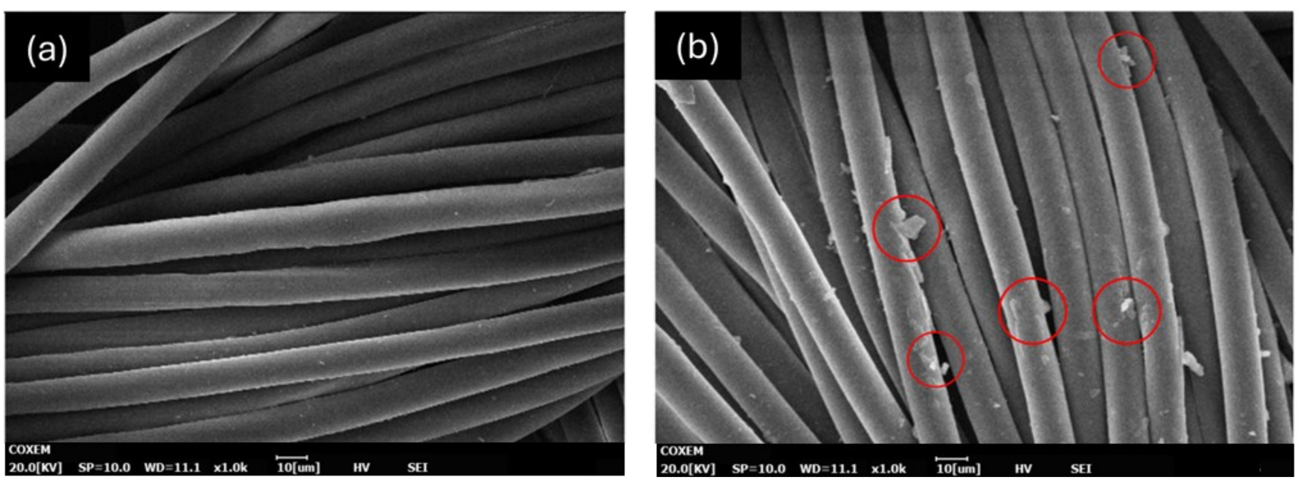


Figure 4 SEM images of (a) uncoated and (b) coated fabrics at x1000 magnification.

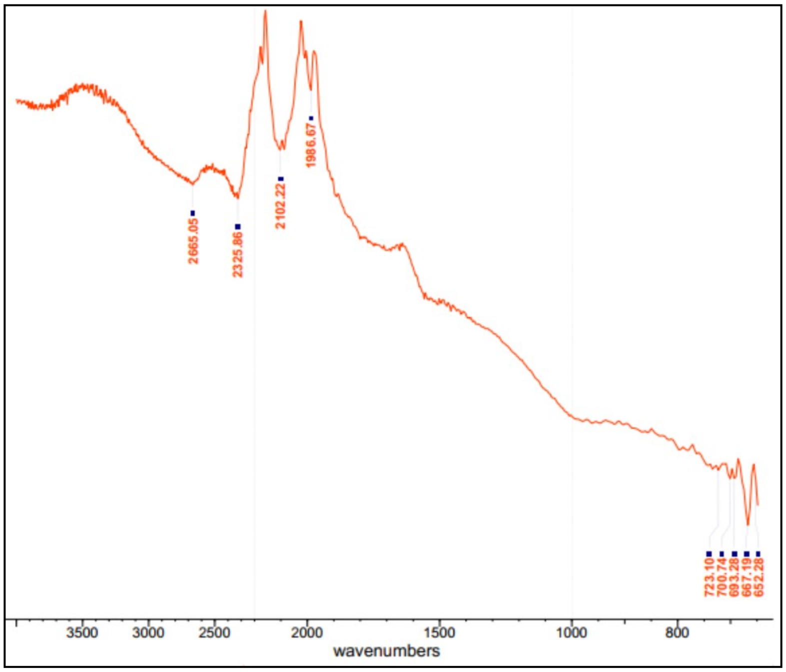


Figure 5 FTIR analysis of bamboo charcoal powder.

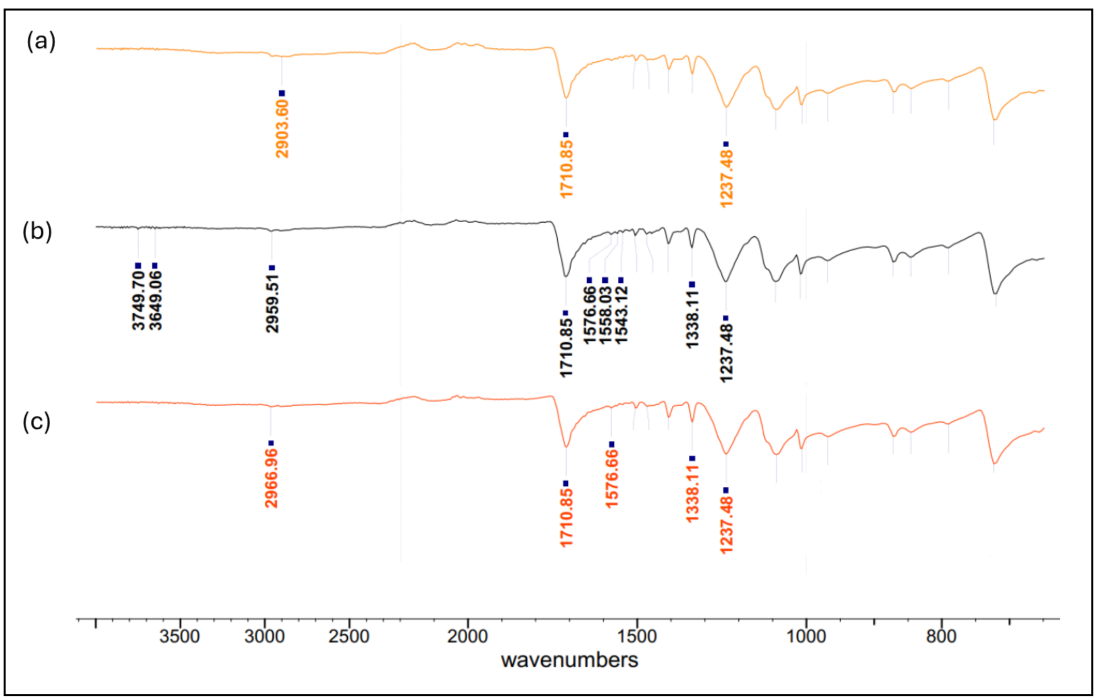


Figure 6 FTIR analysis of (a)uncoated fabric, (b)coated fabric before washing and (c)coated fabric after 5 washing cycles.

3.2 Investigation of Thermo-physiological Comfort Properties of the Fabric

Wicking performance is essential for fabrics designed for comfort, as rapid moisture transport improves drying rate and thermal regulation. Moisture-wicking fabrics are critical in enhancing thermal and moisture comfort by rapidly transporting sweat away from the skin surface, making them especially valuable for daily wear or applications such as activewear and sports applications [26, 27]. In this study, the treated fabric demonstrated a significantly higher wicking rate compared to the untreated sample, indicating that the coating effectively improved moisture management and would enhance wearer comfort in practical applications.

The wicking properties of both uncoated and coated fabrics were evaluated by measuring the height of water transferred at five-minute intervals over a 30-minute period. The wicking height for uncoated and coated materials is illustrated in Figure 7. In a 5-minute vertical wicking test, the coated fabric reached 4.8 cm compared to 5.2 cm for the uncoated fabric, indicating 7.6% lower absorptivity for the coated fabric at the same time point. This suggests the bamboo-charcoal coating slightly reduced the wicking rate. The decrease in wicking height is likely due to the interaction between the coating and the pore geometry [28].

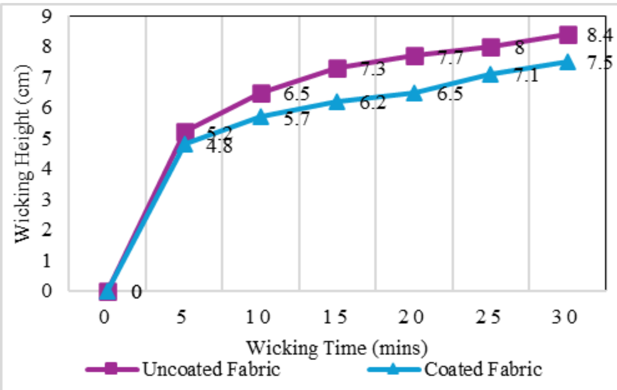


Figure 7 Wicking height (cm) for uncoated and coated fabrics.

Table 3 presents the Water Vapour Transmission Rate (WVTR) of the fabric samples. The coated fabric exhibited a slight improvement in WVTR compared to the uncoated sample. This enhancement can be attributed to the macro-porous structure of the fabric, which plays a significant role in vapour permeability and is largely influenced by the intrinsic properties of the fibres and yarns used [29]. In this study, the WVTR characteristics of fabrics were modified due to the application of bamboo charcoal coating. The porous nature of bamboo charcoal enhances the moisture vapor transmission properties of the coated fabric. This enhancement is evidenced by the data presented in Table 3 and Figure 8, which shows that the WVTR of uncoated fabric is 461.11 g/m²/day, while the coated fabric with bamboo charcoal exhibits a slight increase to 471.11 g/m²/day. The elevated WVTR values suggest the vapour management capabilities of the coated fabrics. The porous structure of bamboo charcoal, characterized by its microscopic cavities, likely facilitates efficient moisture absorption, thereby contributing to the increased permeability observed in the coated samples [17].

Table 3 *WVTR* of uncoated and coated fabric.

Mean value of *WVTR* (g/m²/day)	
Uncoated	461.11 (9.62)
Coated	471.11 (13.46)

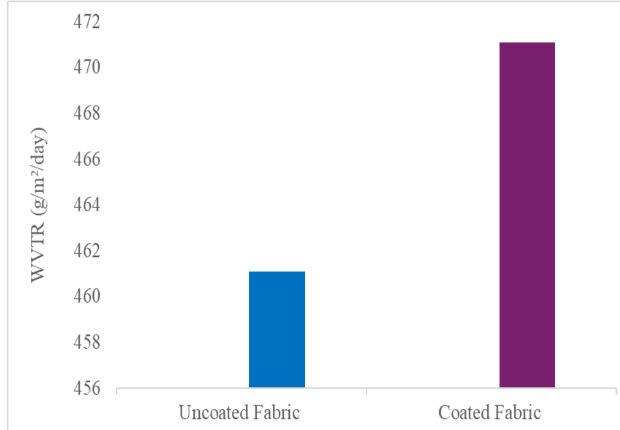


Figure 8 WVTR of uncoated and coated fabric.

3.3 Durability properties of fabric

The durability of the bamboo charcoal coated polyester-cotton fabric was assessed by 5000 cycles of mechanical abrasion, both before and after five washing cycles. The abrasion resistance data in Table 4 indicate that the coated fabric before washing experienced a weight loss of 0.02 g, corresponding to a 12.5% reduction in mass. After five washing cycles, the weight loss increased to 0.03 g. This minimal increase in weight loss suggests that laundering slightly reduces the mechanical integrity of the coating. However, the relatively small difference between the washed and unwashed samples also highlights that the coating retains a substantial portion of its physical structure and bonding strength even after repeated laundering. The retained coating performance is largely due to the porous microstructure of bamboo charcoal and its strong interlocking capability with the fabric surface. The material's micropores allow extensive interaction with textile fibers, promoting mechanical anchoring that strengthens the durability of the applied finish. Previous studies indicate that the flake-like, porous morphology of bamboo charcoal increases the number of contact and bonding sites, thereby improving the mechanical stability and wash resistance of treated fabrics and composite materials [12, 30, 31]. The pores of bamboo charcoal could not be visualized in the SEM images obtained in this study due to the resolution capability of the magnifications used (x500–x1000). Higher-resolution techniques such as Brunauer-Emmett-Teller (BET) surface area analysis or Transmission Electron Microscopy (TEM) are normally required to observe such fine pore structures. The "porous nature" of bamboo charcoal in this discussion refers to its intrinsic material property reported in previous literature, rather than pore features that can be directly resolved from the SEM images of the coated fabric.

Table 4 Abrasion analysis on fabric sample for 5000 cycles

Sample	Weight before (gram) (a)	Weight after (gram) (b)	Reduction of weight (gram) (a-b)	Percentage of weight loss (%) [(a-b)/a]x 100
Coated (Unwash)	0.16	0.14	0.02	12.5
Coated with 5 washing cycles	0.15	0.12	0.03	20

To further explore chemical stability, FTIR analysis was conducted on coated fabric under three conditions: (a) unwashed before abrasion, (b) unwashed after abrasion, and (c) washed after abrasion (Figure 9). Across all spectra, a consistent and strong peak at 1710.85 cm⁻¹ was observed, corresponding to C=O stretching of carbonyl groups such as ketones and carboxylic acids. These oxidized functionalities, derived from bamboo pyrolysis, are known to form stable hydrogen bonds and covalent interactions with the textile substrate, contributing to both functional and mechanical durability [26, 32]. Similarly, the band at 1576.66 cm⁻¹, previously associated with aromatic C=C skeletal vibrations in lignin-rich char structures, remained visible even after abrasion and washing, indicating the persistence of bamboo-derived aromatic functionalities. These rings are chemically stable and provide resistance to microbial degradation and UV-induced photodecomposition.

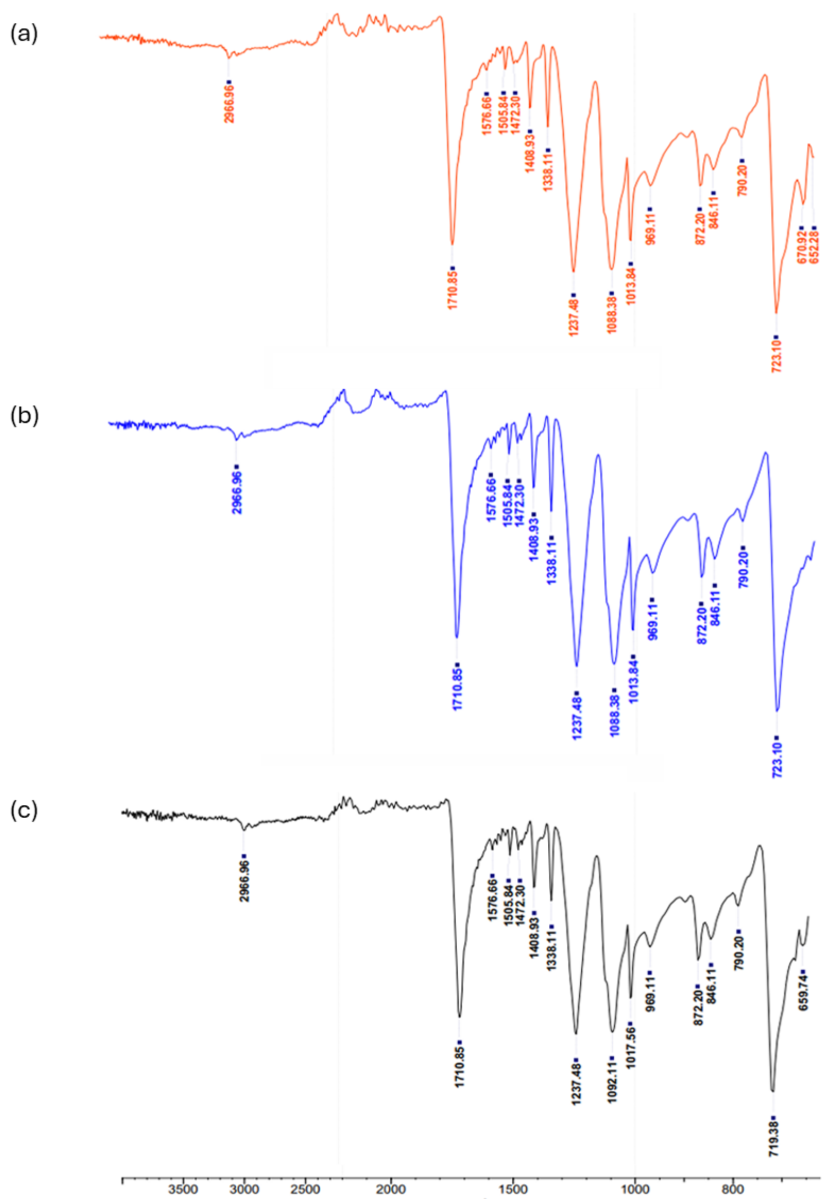


Figure 9 FTIR analysis of (a) coated unwashed fabric before abrasion, (b) coated unwashed fabric after abrasion and (c) coated fabric after abrasion for 5 washing cycle

Minor spectral shifts were observed in the region of 1000–1100 cm⁻¹ after abrasion. Specifically, the C–O stretching band shifted from 1092.11 cm^{-1} to 1088.38 cm^{-1}, and the peak at 1017.56 cm^{-1} shifted to 1013.84 cm^{-1}. These changes indicate a mild weakening of C–O bonds resulting from repeated mechanical stress. However, the retention of these peaks confirms that the backbone of oxidized cellulose and hemicellulose fragments remained intact. Moreover, key peaks such as 1277.48 cm^{-1} (C–O–C stretching), 1408.93 cm^{-1} (COO^- symmetric stretch), and 1338.11 cm^{-1} (phenolic O–H bending) were consistently detected in all samples, reinforcing the chemical robustness of the coating. Notably, the band at 670.92 cm^{-1} assigned to C–C skeletal vibrations unrelated to functional bamboo charcoal chemistry disappeared after abrasion in the washed sample. This suggests that abrasion primarily affected weakly bound or superficial molecular groups not critical to the functional performance of the coated fabric.

The persistence of key functional groups including carbonyls, aromatics, and phenolic oxygen-containing species under both washing and abrasion confirms that the bamboo charcoal coating possesses excellent chemical durability. These groups are known to contribute to long-lasting antibacterial activity, moisture regulation, and odour adsorption. Their ability to remain anchored after physical and chemical stress implies that the coating has not only mechanical adhesion but also chemical affinity to the textile fibers, likely via hydrogen bonding and Van der Waals interactions. This dual durability physical and chemical supports the potential application of bamboo charcoal-coated fabrics in performance textiles, including sportswear, medical apparel, and hygiene-related fabrics where long-term functionality is essential.

4.0 CONCLUSION

This study successfully demonstrated the functionalization of polyester–cotton fabrics with bamboo charcoal coating, offering an eco-friendly and sustainable approach to developing advanced textile materials. The SEM analysis confirmed particle adhesion on the fiber surface, while FTIR characterization revealed that the essential functional groups remained stable after multiple washing and even after 5000 abrasion cycles, highlighting the excellent chemical endurance of the coating. The coated fabrics maintained their structural integrity, underscoring their long-term durability against both laundering and mechanical stress. The WVTR increased from 461.11 $g/m^2/day$ in the uncoated fabric to 471.11 $g/m^2/day$ following the application of the coating, indicating a 2.2% improvement in breathability, likely due to the microporous characteristics of bamboo charcoal. Conversely, the wicking test showed a 7.6% decrease in wicking height, from 5.2 cm to 4.8 cm at the 5-minute mark, which can be attributed to partial blockage of fabric pores by the charcoal particles.

Durability analysis revealed that the coated fabric experienced a 12.5% weight loss after abrasion, whereas samples subjected to five washing cycles exhibited a 20% weight loss. This indicates a retention percentage of 62.5%. FTIR analysis confirmed the chemical stability of the coating, as the carbonyl and aromatic structures remained present after repeated laundering and abrasion. The persistence of these characteristic bands supports the presence of strong physicochemical interactions between the bamboo charcoal and the polyester–cotton substrate.

The significant contribution of this work lies in demonstrating how bamboo charcoal, a natural and sustainable resource, can enhance the thermo-physiological comfort and endurance of textiles under extreme wear conditions without compromising their mechanical stability. By integrating sustainable functionality with long-term performance, this research advances the field of functionalized textiles and contributes to the development of circular material innovation. The outcomes of this study open pathways for diverse applications, including sportswear and activewear requiring moisture management, healthcare textiles emphasizing hygiene and comfort, and protective or workwear garments where washing and abrasion durability are essential.

Acknowledgement

This research is supported by Universiti Tun Hussein Onn Malaysia (UTHM) through GPPS (vot Q809).

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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