

Article

Fabrication of Acacia-Waste-Charcoal-Printed Cotton Fabric for the Development of Functional Textiles—A Sustainable Approach

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Abstract

The textile industry is seeking alternative coloration methods to comply with the global demands for eco-friendly and non-hazardous dyes, as synthetic colorants are costly and substantially toxic in nature, having deleterious effects on the environment as well as ecosystems. This research aimed to develop a printed functional cotton fabric using a new bio-based pigment from acacia wood waste (*Acacia nilotica*) charcoal. Acacia charcoal was ground into fine powder and added into pigment paste with polyacrylic binder and screen printed on cotton fabric, followed by drying and curing. The printed fabric was tested for color strength (K/S), colorfastness, flame resistance, contact angle (for checking the hydrophobicity), thermal insulation, and tensile strength following standard testing protocols. Using different charcoal concentrations (in the range of 0.5–5%), the samples presented light to dark gray color and the K/S value gradually increased from 1.85 (0.5%) to 12.31 (5%), demonstrating stronger color depth. The printed fabrics revealed good results in terms of color fastness ratings (washing 3–5, dry rubbing 3–5, wet rubbing 3–5), satisfactory flame resistance, good thermal insulation, and excellent hydrophobicity. The obtained results contribute to sustainable and durable textile development for achieving better performance.



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1. Introduction

Textile scientists are continuously exploring sustainable sources to provide better solutions to the textile industry for the fabrication of highly durable textile substrates with sufficient hydrophobicity, flame retardancy [1], and thermal insulation and mechanical properties [2]. At the same time, conventional textile coloring techniques have been

increasingly criticized due to the rise in ecological awareness [3,4]. Globally, more than 200,000 tons of synthetic dyes are discharged into drainage systems every year, which directly affects plants and aquatic life [5,6]. In addition, several of these synthetic dyes are potent carcinogens and banned by the World Health Organization (WHO) [7]. Synthetic dyes can also cause skin diseases, respiratory issues due to inhalation of fumes, and eye irritation [8,9]. The European Union (EU) is imposing several strict regulations such as REACH certification systems and OEKO-TEX Standard 100 to control the use of hazardous chemicals in industries [10,11].

Natural pigments are becoming increasingly popular because of their biodegradability and reduced toxicity; nonetheless, problems like poor color strength, poor shade repetition, and inadequate fastness limit their industrial use [12,13]. A stronger substitute is provided by carbon-based pigments made from biomass pyrolysis [14,15]. In contrast to molecular dyes, carbon pigments provide deep black coloration with superior photostability by absorbing light widely over the visible spectrum [16]. High thermal stability, porous shape, and chemically active surfaces are some of the intrinsic characteristics that give these dyes their multifunctionality [17]. Biomass carbonization at 400–900 °C is usually followed by physical or chemical activation to generate activated carbon, which results in materials with high surface areas (600–2000 m²/g) and hierarchical pore structures [18,19].

Although agricultural leftovers, such as bamboo, and coconut shell, have been extensively studied as carbon sources, acacia-derived charcoal has not received as much attention for use in textiles. These materials have shown advantages in comfort characteristics, deodorizing capacity, antibacterial behavior, far-infrared emissivity, and thermal regulation [20]. Charcoal made from bamboo, neem, coconut, and oil palm shells can improve moisture management, breathability, UV protection, and deodorizing performance in cotton and synthetic fabrics, according to studies combining coating and printing techniques [21]. In one study, polyester nonwoven fabric was treated with acrylic resin and bamboo charcoal to give temperature regulation and infrared-ray emission capabilities, showing quantifiable increases in wearer comfort [22]. In a different study, cotton and polyester textiles were coated and pigment-printed with activated charcoal powders made from coconut and oil palm shells to improve functional performance [23]. Recent research on bamboo charcoal as a natural pigment demonstrated over 80% deodorizing efficiency, durable gray coloration, good fastness, and enhanced mechanical strength. These experiments used charcoal obtained from agricultural waste to promote circular economy goals [24]. There are still research gaps since acacia charcoal is understudied; most studies only evaluate a particular property, and the impact of charcoal concentration on morphology and performance has not been thoroughly examined.

Acacia wood (*Acacia nilotica*), a fast-growing leguminous tree abundant in tropical and subtropical regions, offers significant potential as a sustainable pigment source [25] and increases soil health [26]. The acacia plant wood is composed of 25–30% lignin content [27] which results in carbon-rich renewable, and carbon-neutral charcoal [28]. The charcoal contains 70–90% of carbon with some traces of oxygen, hydrogen, and ash [29]. Acacia charcoal's porous structure, which has micropores, mesopores, and macropores, traps air to provide thermal insulation and flame resistance [30]. While pigment printing increases sustainability through low water consumption, minimum effluent, and fiber-independent application, acacia charcoal's porous structure improves flame retardancy by restricting oxygen, absorbing heat, and diluting combustible gases [31]. Large liquor ratios (usually 10:1 to 30:1 bath-to-goods ratios), numerous rinse steps to eliminate unfixed dye, and thorough wastewater treatment are all necessary for conventional exhaust dyeing procedures [32,33]. Pigment printing uses insoluble particles fixed with a flexible, transparent, and environmentally friendly polyacrylic binder and only applies pigments to pattern areas,

saving up to 95% of water [34]. Strong adhesion, good pigment wetting, fabric softness, little yellowing, and low VOC emissions are all provided by polyacrylic binders, which create a long-lasting network that firmly retains charcoal particles [35,36]. The coloration, flame resistance, thermal insulation, mechanical qualities, hydrophobicity, and microscopic structure of *Acacia nilotica* charcoal as a multipurpose textile pigment are all assessed in this study. The study shows the potential of acacia charcoal as a sustainable, multipurpose pigment for technical fabrics using charcoal concentrations of 0.5–5% and standardized testing protocols for colorfastness, flame resistance, tensile strength, and contact angle.

2. Materials and Methods

2.1. Materials

The applied textile substrate was a plain woven 100% cotton fabric (purchased from Sapphire Textile Mills, Lahore, Pakistan) that was commercially scoured and bleached (150 g/m² 20.8/18.6 Ne warp/weft yarn count, 30 × 19 fabric count per cm). The acacia wood waste (*Acacia nilotica*) was purchased from nearby Rainbow Furniture Stores, Lahore, Pakistan.

Polyvinyl alcohol (PVA, >99% pure) applied as a thickening agent, cassava starch as a natural viscosity enhancer, gum arabic as an environmentally friendly binder, polyacrylic binder (Helizarin SFT liquor, >99% pure) for increased mechanical durability, Fixapret (ELF liquor C, >99% pure) as a cross-linking agent, and triethylamine (TEA, >99% pure) for pH maintenance and film coalescence were among the chemicals used in the formulation of print paste. Analytical-grade chemicals were acquired from Huntsman Supplier, Lahore, Pakistan. The study was conducted using double-distilled deionized water to avoid contamination.

2.2. Preparation of Acacia Charcoal Pigment

The raw material for making charcoal was acacia wood (*Acacia nilotica*), which was segregated and collected as waste from a furniture warehouse. To obtain constant weight, the wood was cut into small pieces (1–3 cm³), carefully cleaned with distilled water, and dried for six hours at 100 °C in a laboratory oven.

2.3. Pyrolysis Process

A covered stainless-steel crucible containing 100 g of dried wood samples was placed in a muffle furnace to undergo controlled pyrolysis. The furnace was heated from room temperature to 550 °C at a rate of 10 °C per minute, and it was kept there for two hours while the covered crucible produced oxygen-limited conditions [37]. The furnace was shut off and left to naturally drop to room temperature without being opened after the holding period. The yield was determined gravimetrically to be roughly 28% based on the initial dry wood weight after the resultant charcoal was thoroughly removed. The schematic presentation of acacia wood waste charcoal is shown in Figure 1.

The carbonized acacia wood was ground using an electric grinder (Coriander Crushing-Model: RT-34, Shanghai, China) in pulse mode for 15 min with 2000 (revolutions per minute) RPM. To separate fine particles from coarser and relatively larger ones, the ground material was subsequently sieved using muslin cloth (100% nylon). The homogeneous particle size required for proper dispersion in the printing paste was ensured by this sieving procedure. Before being used, the fine charcoal powder was collected and kept in a desiccator in an airtight container [38].

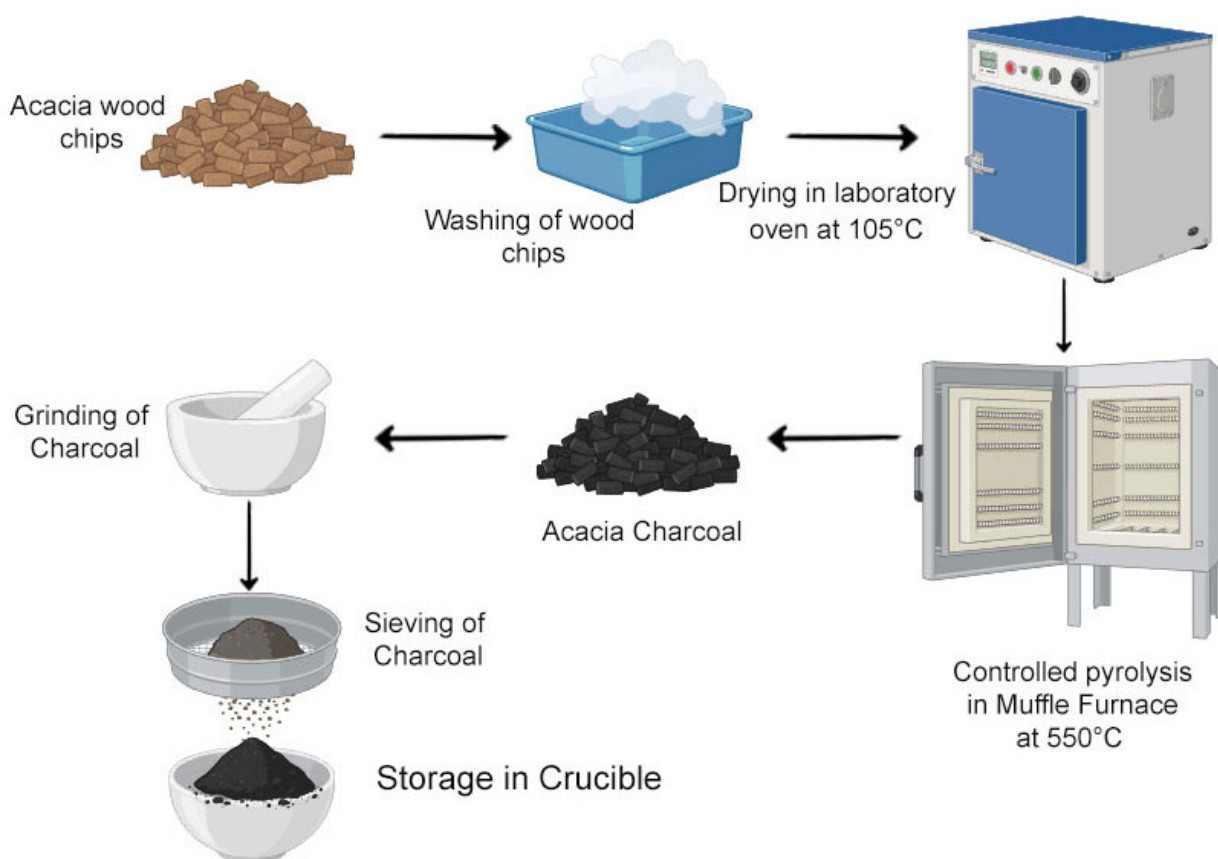


Figure 1. Schematic presentation of the preparation of acacia wood charcoal through controlled pyrolysis.

2.4. Printing Process

The 100% cotton fabric was subjected to cleaning in warm distilled water at 50 °C to remove contaminants and other impurities on the surface prior to the printing process. The cotton fabric samples were dried at 100 °C and then ironed to make sure that there were no creases. The pigment print paste was made in the form of a two-phase mixing method to avoid any aggregation.

In phase A, charcoal dispersion was made by adding 1 g of polyacrylic binder and heating to 50 °C for 30 min after progressively dispersing acacia charcoal powder in 25 mL of distilled water while continuously mixing with a digital magnetic stirrer. In order to make phase B (binder solution), 1 g PVA, 0.5 g cassava starch, 0.5 g gum arabic, 0.1 g Fixapret ELF liq C, and 0.5 g triethylamine were dissolved in 100 mL of distilled water at 50 °C while being continuously stirred until the mixture was completely dispersed. To create a uniform pigment paste, the two phases were then mixed at 45–50 °C while being continuously stirred for ten to fifteen minutes (Figure 2). For ten samples (S1–S10), ten formulations with different concentrations of charcoal (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, and 5.0%) were made while maintaining the same levels of polyvinyl alcohol (PVA), starch, gum arabic, polyacrylic binder, fixer, and triethylamine (TEA), as indicated in Table 1. This controlled design made it possible to clearly analyze the functional performance of the charcoal content on the printed textiles by ensuring that any changes in color, mechanical behavior, thermal performance, or surface qualities could be immediately linked to variations in charcoal concentration.

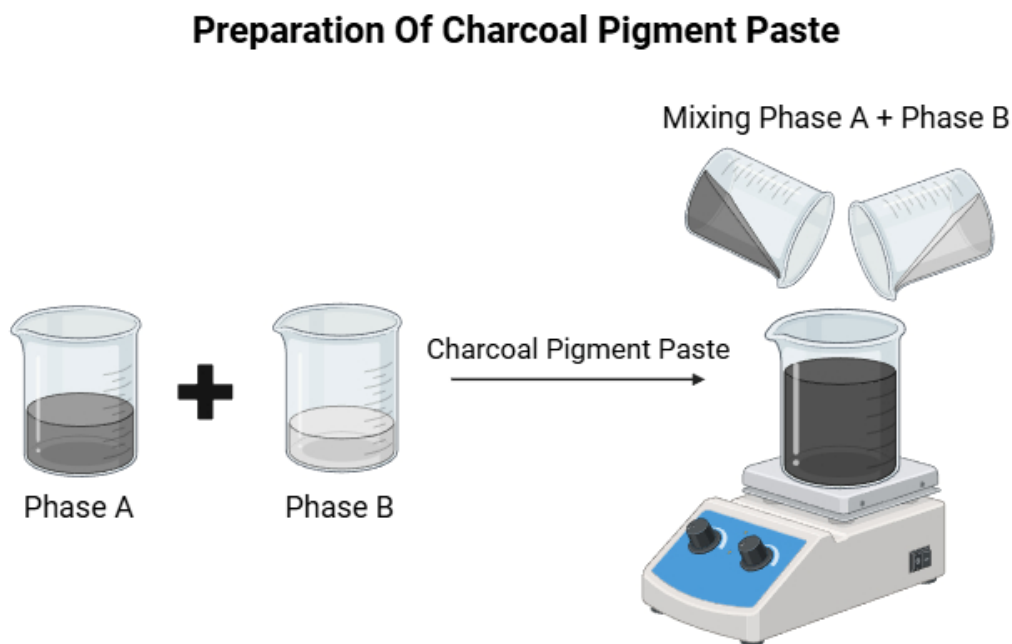


Figure 2. Preparation of acacia charcoal pigment printing paste by mixing phases A and B.

Table 1. Design of experiment (DOE) for screen printing using charcoal pigment paste, applying print–dry–cure route.

Sample #	Charcoal Powder Concentration (%)	Polyvinyl Alcohol (PVA)(g/L)	Starch (g/L)	Gum Arabic(g/L)	Polyacrylic Binder (g/L)	Fixer (g/L)	Triethylamine (TEA) (g/L)
S0	-	-	-	-	-	-	-
S00	-	1	0.5	0.5	1	0.1	0.5
S1	0.5	1	0.5	0.5	1	0.1	0.5
S2	1	1	0.5	0.5	1	0.1	0.5
S3	1.5	1	0.5	0.5	1	0.1	0.5
S4	2	1	0.5	0.5	1	0.1	0.5
S5	2.5	1	0.5	0.5	1	0.1	0.5
S6	3	1	0.5	0.5	1	0.1	0.5
S7	3.5	1	0.5	0.5	1	0.1	0.5
S8	4	1	0.5	0.5	1	0.1	0.5
S9	4.5	1	0.5	0.5	1	0.1	0.5
S10	5	1	0.5	0.5	1	0.1	0.5

Screen printing was performed manually using a 40-T mesh nylon screen mounted on a wooden frame using the print–dry–cure method. The pigment paste was applied using a wooden squeegee with 20 uniform strokes to ensure even distribution, as shown in Figure 3 [39]. Each sample received two printing passes with intermediate drying at 100 °C for 3 min to allow partial binder setting. After the second application, samples were cured at 150 °C for 3 min in an Auto Cure Pro machine (KraftCuring, Lindern, Germany) to promote cross-linking of the binder system. Post-curing, the samples were washed in warm distilled water (40–45 °C) containing 2 g/L neutral detergent for 5–7 min, rinsed thoroughly, dried at 60 °C for 20 min, and ironed to restore fabric smoothness.

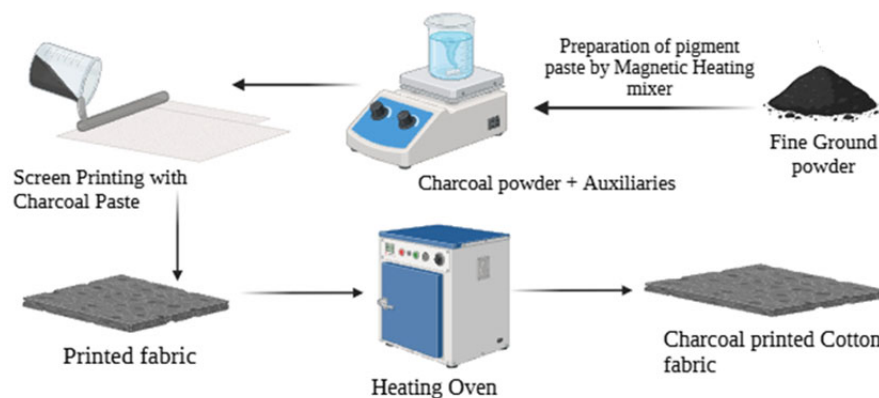


Figure 3. Schematic illustration of preparation of charcoal pigment print paste and application on cotton fabric using screen-printing method.

2.5. Testing

2.5.1. Color-Measurement and Color-Fastness Testing

A Datacolor 650 spectrophotometer (Suzhou, China) was used to assess color strength (K/S value) of the developed samples [40]. In accordance with the AATCC Test Method 61-1994, color fastness to washing was assessed by washing printed samples in a standard detergent solution for 45 min at 50 °C. AATCC Test Method 8 was used to measure color fastness to rubbing (crocking), evaluating both wet and dry rubbing resistance.

2.5.2. Vertical Flame Resistance Testing

The ASTM D6413 standard test procedure was used to assess the vertical flame resistance of cotton fabric printed with acacia charcoal by inhibiting the ignition process and limiting the spreading of flames in the testing materials. The printed samples were cut into 12 × 3-inch dimensions and conditioned for 24 h at standard atmospheric conditions (65 ± 2% relative humidity, 21 ± 1 °C) [41] to get real-time and error-free results in the flame test. The lower edge of each specimen was exposed to a controlled flame source while it was positioned vertically in a testing frame (Figure 4). In a controlled laboratory setting, the flame was administered for 12 s. As soon as the flame was exposed, measurements were taken of the flame height, after-flame duration, and char development. Each concentration of acacia charcoal was tested on all specimens, including the untreated sample, and the average flame height was recorded.

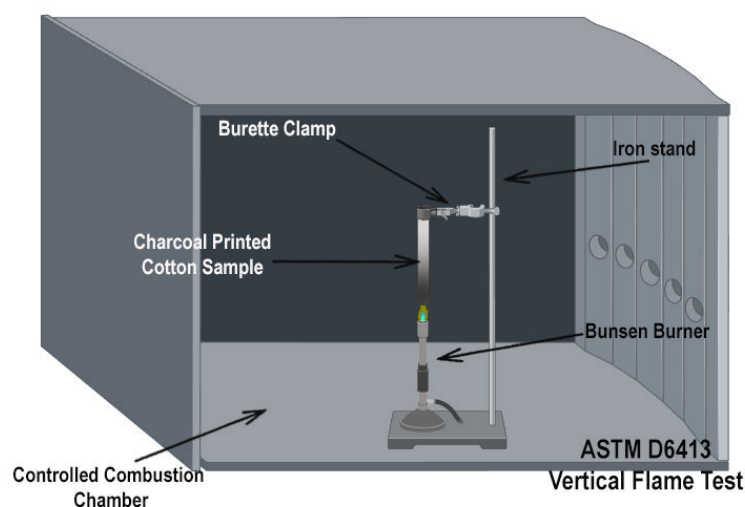


Figure 4. Testing equipment for vertical flame test of acacia-charcoal-printed cotton fabrics.

2.5.3. Thermal Insulation Testing

The thermal insulation of acacia-charcoal-printed cotton fabrics was evaluated using a hot-plate method (Figure 5) based on ASTM D1518 [42]. Four different temperatures were established on a lab hot plate: 37 °C, 45 °C, 55 °C, and 65 °C. A Fluke digital thermometer and forward-looking infrared (FLIR) thermal imaging camera were used to measure the surface temperatures of the printed fabrics. One untreated control (S0) and ten printed samples (0.5–5 g charcoal, 1 × 1 inch) were tested. Samples were positioned equally apart on the stabilized hot plate and left in still air for 25 min. At predetermined intervals, thermal imaging pictures were taken.

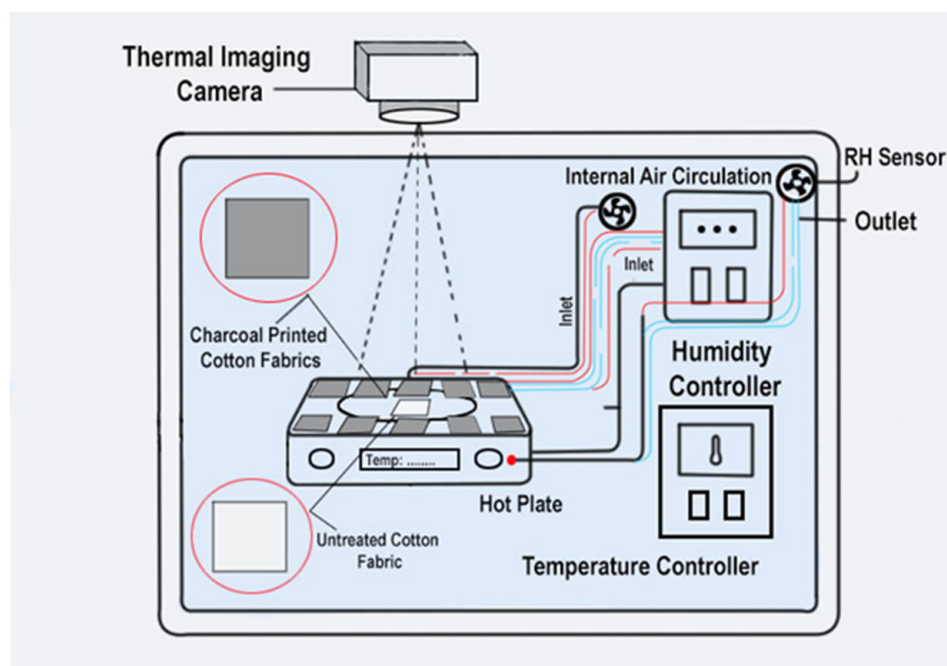


Figure 5. Schematic presentation of thermal insulation test of acacia-charcoal-printed cotton fabrics.

The relative insulation index (R') was calculated by applying Equation (1):

$$R' = \frac{T_{\text{plate}} - T_{\text{surface}}}{T_{\text{plate}} - T_{\text{ambient}}} \quad (1)$$

where T_{ambient} is the room temperature, T_{surface} is the fabric surface temperature that was recorded, and T_{plate} is the temperature of the hot plate. Greater thermal resistance is shown by a higher R' value, which means that the sample successfully prevented heat transmission. This normalized method made it possible to compare results under various temperature settings.

2.5.4. Tensile Strength Testing

Using universal tensile testing equipment (Instron Model 5566, New York, NY, USA), the tensile strength of cotton fabrics printed with acacia charcoal was assessed in accordance with ISO 13934-1 and ASTM D5035 standards [43]. The specimens were cut to a width of 60 mm and a thickness of 0.5 mm, resulting in a 30 mm² cross-sectional area (A). Before testing, samples were conditioned for a full day at 21 ± 1 °C and $65 \pm 2\%$ relative humidity. Until the cloth ruptured, the test was carried out at a steady extension rate of 100 mm/min.

The breaking load was recorded for each of the eleven samples (S0–S10) with different charcoal contents. The tensile strength (σ) was calculated using applying Equation (2):

$$\sigma = \frac{F \times 9.80665}{A} \quad (2)$$

where σ is the yield strength (MPa), A is the area of cross-section (mm^2), and F is the optimum breaking force (kg.f). The tests were performed in triplicate in the warp direction of the fabric, and the average values were recorded.

2.5.5. Contact Angle Measurement and Water Absorbency (Drop Test)

The contact angle was measured by the sessile drop technique to determine the wetting ability of the charcoal-printed cotton fabrics. The measurements were taken using an optical contact angle goniometer with image analysis software. A drop of distilled water (1 μL) was placed on the fabric surface with a carefully calibrated syringe under well-controlled conditions (25 $^{\circ}\text{C}$, 65 5% relative humidity). The contact angle was calculated as soon as drops were put. The samples were measured five times in various positions, and the average was calculated. The higher the contact angle, the higher the degree of hydrophobicity and moisture resistance. Only cotton printed materials were studied since untreated cotton is hydrophilic in nature and is quick to absorb water due to its approximately 8.5% moisture regain.

All the treated and untreated samples were tested for water absorbency by using AATCC test method 79. The fabric samples were placed on a plan table, and a water drop of the same size was dropped on the fabric from the same height. The time of absorption was recorded via stopwatch. The fabric samples with absorbency higher than 5 s correspond to hydrophobic materials.

2.5.6. Optical Polarized Microscopy Assessment

The morphology and surface features of cotton fabrics printed with Acacia charcoal were investigated using an optical polarized microscope (Nikon Eclipse LV1001POL, Yokohama, Japan) with polarized illumination for improved visibility of small surface details [44]. To preserve their original texture, small fabric specimens ($\approx 5 \times 5 \text{ mm}$) from samples S0–S10 were put on glass slides without any further processing. All the prepared printed samples were photographed three times to get an accurate evaluation of the charcoal's uniformity on the fabrics.

2.5.7. Fourier Transform Infrared (FTIR) Spectral Analysis

Attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectroscopy (KRÜSS, Berlin, Germany) was used to investigate the cotton samples with the presence of charcoal content [45]. The spectra were recorded with a resolution of 4 cm^{-1} at 32 scans and an internal reflection accessory in the transmittance mode from 500 to 4000 cm^{-1} .

3. Results and Discussion

3.1. Partical Size Distrubution of Powdered Material

The particle size of the prepared acacia-charcoal-powdered material was analyzed by a laser diffraction particle size analyzer (Malvern Mastersizer 2000, Worcestershire, UK), as shown in Figure 6. The average particle size of the powdered material was in the range of 10–12 μm which is appropriate for application in textile finishing and coating.

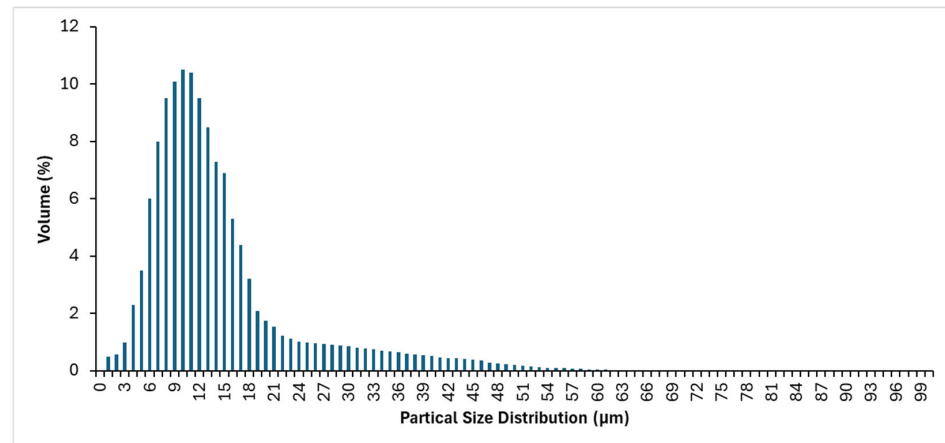


Figure 6. Particle size distribution of acacia charcoal recorded via Malvern Mastersizer 2000.

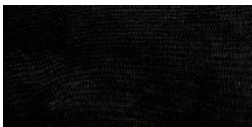
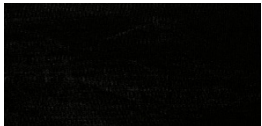
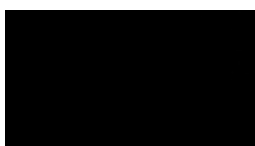
3.2. Effect of Charcoal Concentration on Color Strength K/S

The cotton printed samples developed were investigated for the color strength (K/S) values using a Datascolor spectrophotometer. The concentration of charcoal increased from 0.5 to 5 g in the print paste, the resultant printed fabrics color gradually changed from light gray to dark gray, and their K/S values ascended from 1.85 to 12.31 (Table 2). The typical gray coloration of the carbon-rich pigment was confirmed by the attached images in Table 2. A higher concentration of charcoal resulted in darker printed fabrics. In order to investigate the durability of the printed materials, the samples were checked for colorfastness to washing and rubbing following standard operating procedures.

Table 2. Cotton fabric printed with varying amounts of acacia charcoal in terms of color strength (K/S) and color fastness (washing and crocking).

Acacia Charcoal (%)	K/S	Color Fastness			Color Obtained After Printing with Charcoal
		Wash	Crock		
			Dry	Wet	
0.5	1.85	4–5	4–5	4–5	
1	3.42	4–5	4–5	4–5	
1.5	4.91	4	4–5	4–5	
2	6.28	4	4–5	4	
2.5	7.54	4	4–5	4	

Table 2. Cont.

Acacia Charcoal (%)	K/S	Color Fastness			Color Obtained After Printing with Charcoal
		Wash	Crock		
			Dry	Wet	
3	8.67	4	4–5	4	
3.5	9.73	4	4	4	
4	10.68	4	4	4	
4.5	11.52	4	4	4	
5	12.31	4	4	4	

Every printed sample showed color fastness to rubbing ranging from good to excellent. Dry rubbing fastness decreased to 4 for samples S7–S10, most likely because of increasing surface pigment buildup. The printed samples S1–S6 revealed 4–5 dry rubbing fastness ratings. Wet rubbing fastness followed a very similar pattern, with ratings of 4–5 for samples S1–S6, decreasing to 4 for S6–S10. The slightly reduced wet rubbing fastness at higher loadings is attributed to moisture loosening weakly bound surface pigment particles.

Washing fastness showed excellent ratings of 4–5 for samples S1–S2, and good ratings of 4 for S3–S10. The printed fabrics revealed a minor color loss in terms of shade change when applying higher concentrations of charcoal. Regardless of this trend, printed cotton specimen scores are all within acceptable limits when it comes to fastness (Table 2).

3.3. Flame Retardancy

Table 3 presents the results of the vertical flame test for the printed cotton fabrics using acacia charcoal via the print–dry–cure method. The control sample (S0) was completely burnt and surpassed the 12 inches limit of test specimen (see the S0 in Figure 7). The printed samples rendered significant flame retardancy, which improved with the increase in the concentration of charcoal. Sample S1, treated with 0.5 g charcoal, revealed 5.9 inches; at 5 g, it was 3.2 inches, which is a 73.3 percent decrease in the flame height (Figure 7). The charcoal-printed cotton fabrics present a sustainable approach towards the development of flame-retardant textiles. The results obtained are in considerable agreement with the developed bamboo-charcoal flame-retardant textiles [46,47]. To see the effect of binders and other auxiliaries on the flame-retardant properties of the substrate, another blank sample was developed without adding any charcoal to print paste containing other auxiliaries.

It was observed that these ingredients slightly enhanced the flame-retardant property, showing 2.3 inches flame height. The flame height for the blank samples is shown in Figure S1.

Table 3. Flame retardancy test results in terms of observed flame height of the charcoal-printed cotton fabric.

Sample No.	Charcoal Concentration (%)	Observed Flame Height (Inches)
S0	0	Burnt
S00	0	2.3
S1	0.5	5.9
S2	1	6.0
S3	1.5	5.9
S4	2	4.5
S5	2.5	4.8
S6	3	4.7
S7	3.5	4.2
S8	4	3.8
S9	4.5	3.6
S10	5	3.2

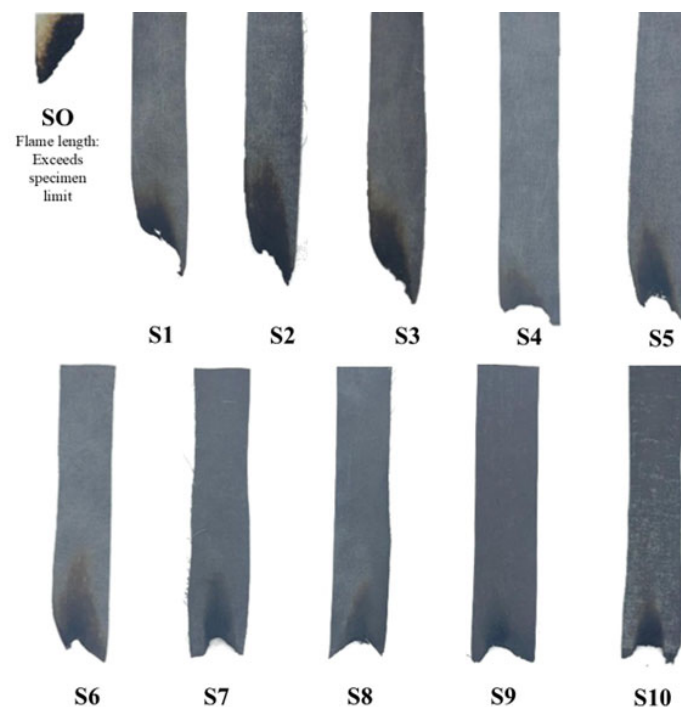


Figure 7. Vertical flame test images of the charcoal-printed cotton samples [48].

3.4. Effect of Acacia Charcoal Concentration on the Thermal Insulation of Cotton Fabric

Figures 8 and 9 present the thermal insulation performance of printed cotton fabrics at various hot plate temperatures in terms of decrease in surface temperature and thermal insulation index, respectively. The unprinted cotton sample (S0) had a 100 percent heat conduction and negligible thermal resistance ($R' = 0.000$) at all tested temperatures. The R' values increased from 0.033 to 0.583 at 37 °C by increasing the concentration of charcoal. Interestingly, the surface temperature also decreased significantly by 7.0 °C as compared to the unprinted sample (Figure 8). Similarly, at test temperature of 45 °C, the R' values

increased from 0.055 to 0.295 (Figure 9). Sample maximum R' with 5 g charcoal at 55 °C was 0.333 and at 65 °C it was 0.272, which is a range of 10–11 °C (Figures 8 and 9). The printing process resulted in improved thermal insulation; namely, the coating of charcoal was thick, forming a heat-reflective carbon barrier that prevented the conduction of heat and the trapping of air in the charcoal particles in their pores, which restricted air passage and conduction of heat [49]. The samples that contained 3.5 g and above of charcoal exhibited the best insulation properties at low temperatures with R' values that were always greater than 0.300, which is obvious from thermal imaging analysis at different temperatures (Figure 10).

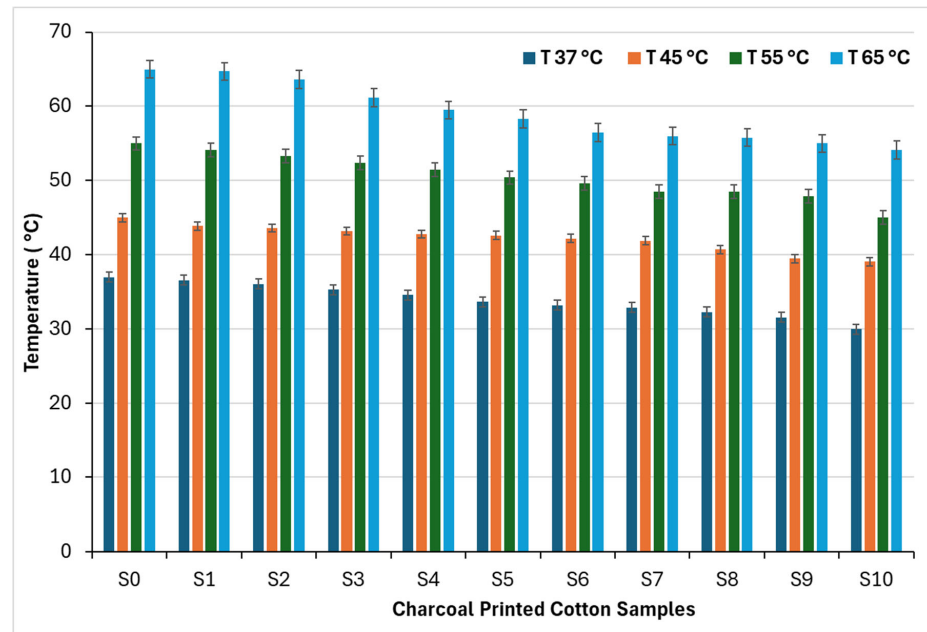


Figure 8. The thermal insulation performance in terms of decrease in surface temperature of all charcoal-printed samples.

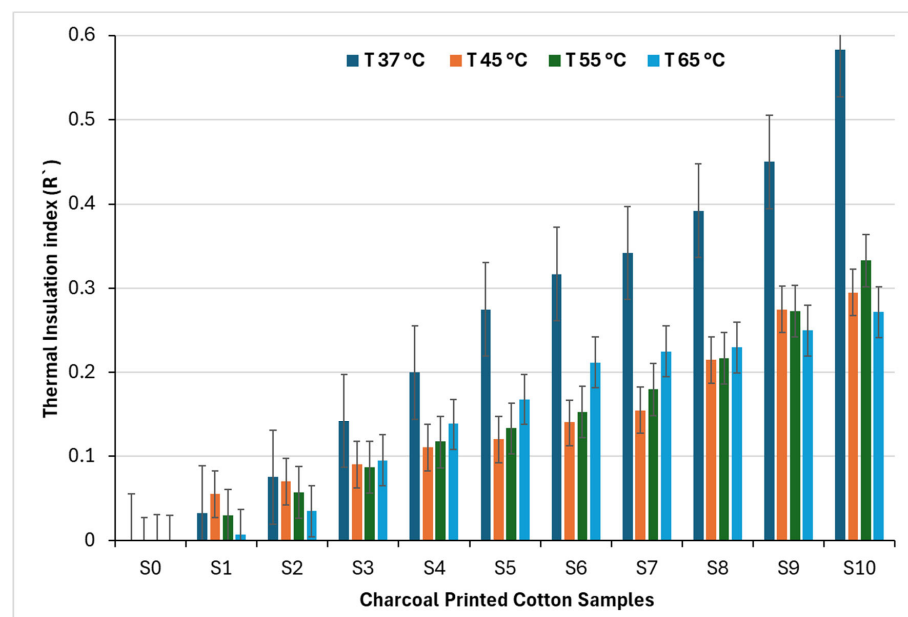


Figure 9. The thermal insulation performance in terms of increase in thermal insulation index of all charcoal-printed samples.

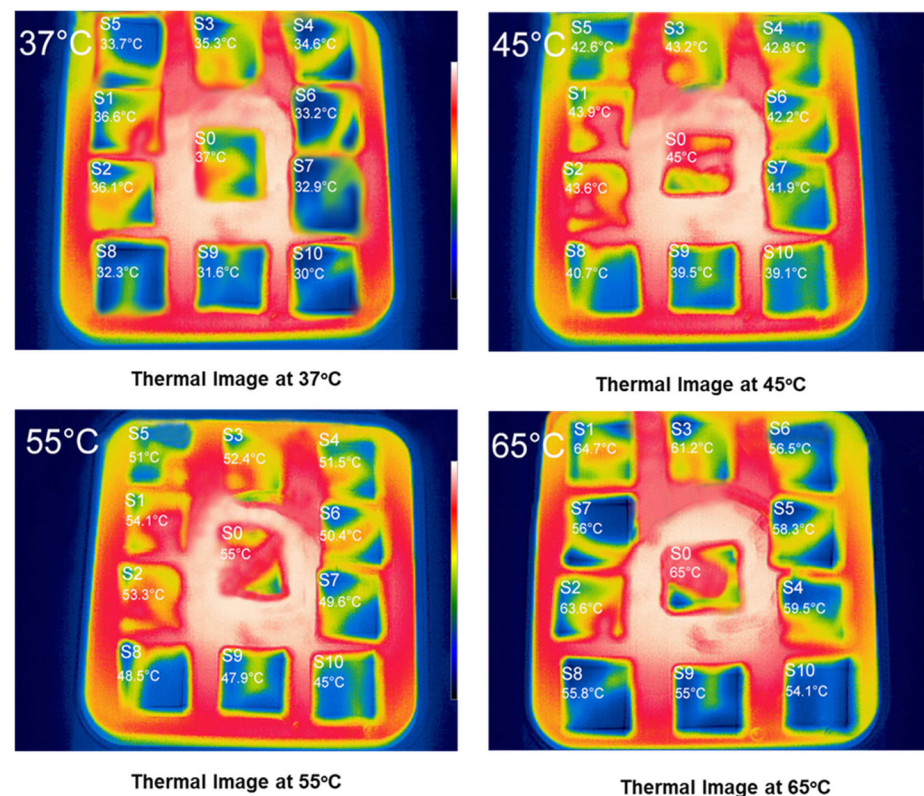


Figure 10. Thermal imaging analysis at different temperatures obtained via thermal imaging camera.

The results of this study show that the effect of charcoal in printing cotton fabrics provides great thermal insulation, and the performance depends on the concentration of charcoal. The findings confirm the possibilities of acacia charcoal as a useful ingredient to create environment-friendly fabrics that can be used as comfortable and protective fabrics.

3.5. Effect of Acacia Charcoal Concentration on Tensile Strength

Figure 11 shows the tensile strength values of cotton fabrics printed using acacia charcoal. Tensile strengths ranged from 5.21 MPa (S0) to 19.04 MPa (S10). As the baseline, the untreated sample (S0) showed the lowest tensile strength. The sample S00 printed with auxiliaries showed a very slight increase in tensile strength, showing the value of 5.74 MPa. Tensile strength increased gradually from 6.23 MPa (S1) to 19.04 MPa (S10) as the concentration of charcoal increased from 0.5 g to 5 g. More pigmented samples (S6–S10, 13.38–19.04 MPa) exceeded the plain cotton baseline by 4–27%, while less pigmented samples (S0–S5, 5.21–10.93 MPa) stayed below it. At 19.04 MPa, sample S10 showed a 27% improvement over standard plain cotton. A similar increase was observed with the application of eucalyptus wood charcoal content to cotton fabric [50].

The polyacrylic binder film, that embeds acacia charcoal microparticles within yarns, forming a reinforcing matrix that lessens fiber slippage and more evenly distributes stress throughout the fabric structure, is responsible for the increased tensile strength. This charcoal–binder system improves load-bearing capacity and fiber-to-fiber adhesion by acting as an internal interlocking mechanism. The printed coating greatly increases the fabric's strength while preserving its flexibility at the ideal concentration of 5%.

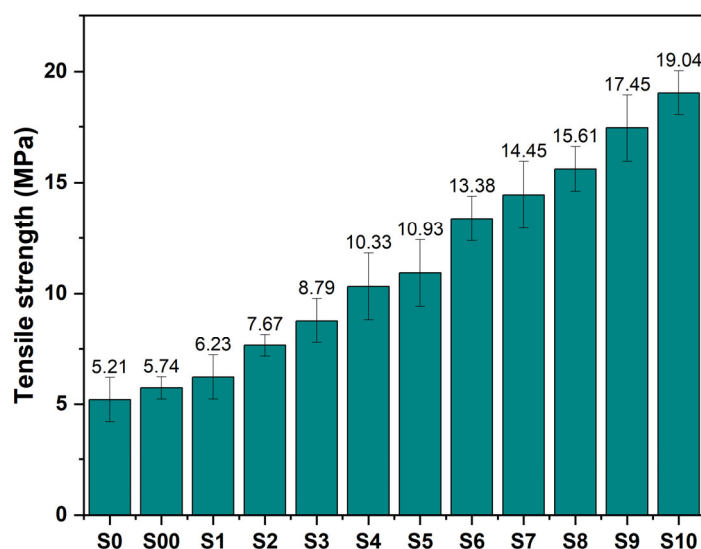


Figure 11. Gradual increase in tensile strength (MPa) with increase in charcoal concentration.

The findings demonstrate that acacia charcoal printing improves the mechanical performance of fabrics, with tensile strength rising in direct proportion to charcoal concentration. This demonstrates that acacia charcoal is a useful ingredient for creating long-lasting, environmentally friendly fabrics that are appropriate for uses that call for increased structural integrity.

3.6. Effect of Acacia Charcoal Concentration on Surface Hydrophobicity

Contact angle findings of cotton textiles printed using acacia charcoal are displayed in Figure 12. Water was quickly absorbed by samples printed with 0.5–2.0 g of charcoal, although there was no discernible contact angle. Low hydrophobicity was shown by the contact angle of 34.05° at 2.5 g concentration (S5). Contact angles grew gradually with increasing charcoal concentration (S6): 58.85° (3 g), S7 60.69° (3.5 g), S8 73.99° (4 g), S9 80.87° (4.5 g), and S10 84.86° (5 g). Samples containing more than 2 g of charcoal showed high hydrophobicity and stable droplet formation.

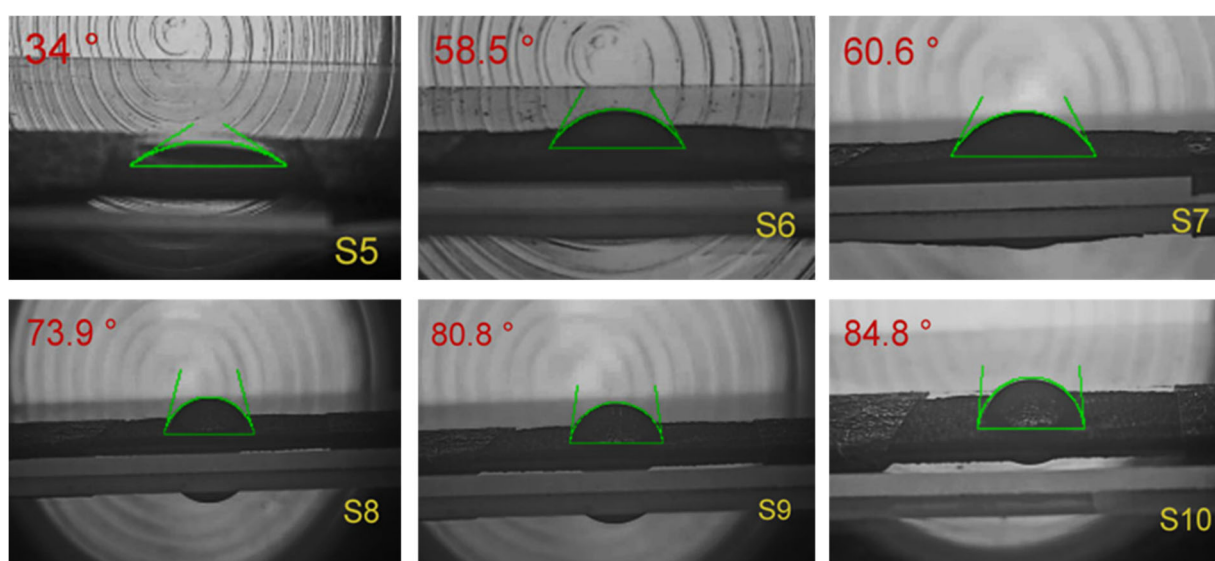


Figure 12. Contact angle measurement of the acacia-charcoal-printed cotton samples (S5, S6, S7, S8, S9, and S10).

The hydrophobicity was confirmed by water drop test according to AATCC 79 standard protocol. The control samples S0 and S00 absorbed the water droplet in 1–2 and 5–6 s, respectively. However, the samples printed with charcoal paste showed significant increase in the water droplet absorption time, ranging from 12–15 s (Table S1). The charcoal coatings impart hydrophobicity to cotton fabrics due to their water repellency nature. Cotton is hydrophilic in nature with approximately 8.5% moisture regain at standard conditions [51].

The development of a carbonaceous layer which lowers surface energy and forms a neutral coating on the fiber surface is responsible for improved hydrophobic performance. Charcoal particles' microporous nature adds to surface roughness, which increases water repellency by trapping air at the fabric–water contact. These results show that adding more acacia charcoal considerably improves surface hydrophobicity, making printed cotton materials good options for practical, moisture-resistant textile applications.

3.7. Effect of Acacia Charcoal Concentration on Fabric Porosity

With increasing charcoal concentration, the optical polarized microscopy pictures of charcoal-printed cotton fabrics (S0–S10) showed progressive fiber surface covering and inter-fiber gap filling (Figure 13). Visible inter-fiber spaces and an irregular fiber network characteristic of plain-woven cotton were present in the untreated cotton sample (S0). On the other hand, treated cotton samples showed charcoal particles gradually adhering to the fiber surfaces.

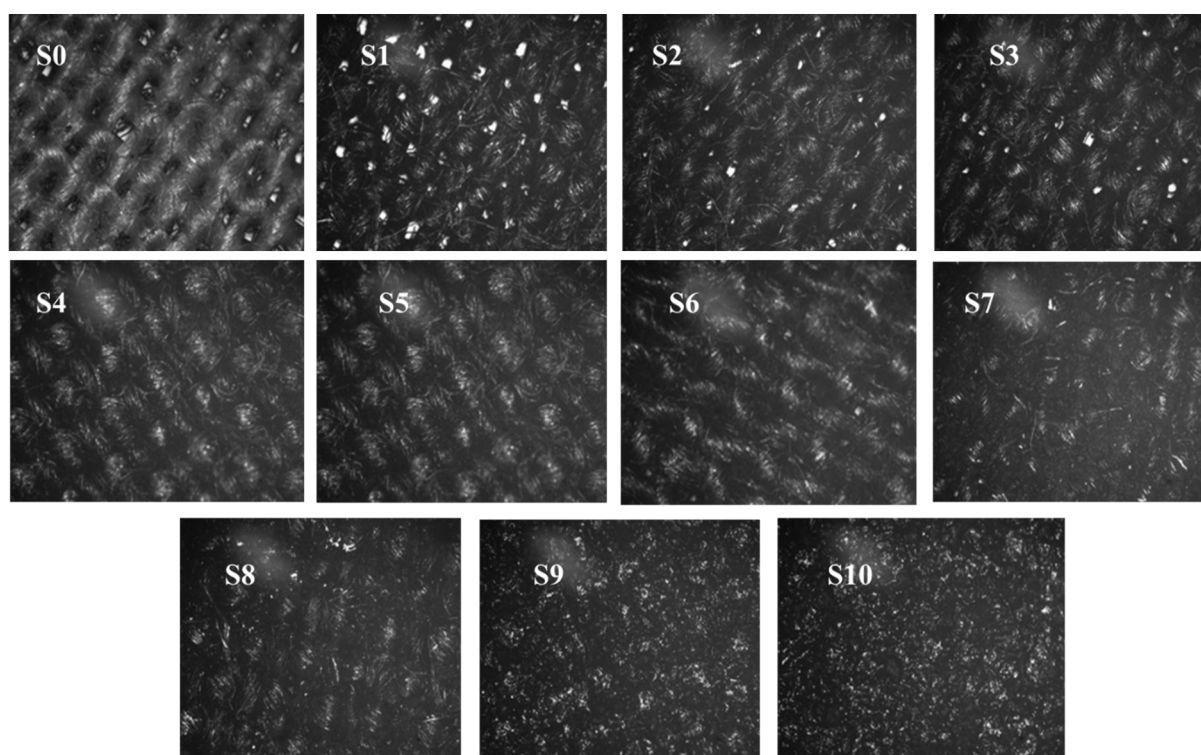


Figure 13. Morphological analysis of charcoal-printed cotton fabrics from S0 to S10 under polarized microscopy.

While voids were still evident, charcoal particles started to partially coat individual fibers and occupy inter-fiber spaces at lower concentrations (S1–S4). Particles formed a semi-continuous layer, and deposition became more noticeable as concentration rose (S5–S7).

Fiber surfaces showed nearly total coverage at highest concentrations (S8–S10), resulting in a continuous and uniform layer on the surface that significantly decreased visible

inter-fiber voids. Fewer air gaps enhance thermal insulation as they reduce heat transfers through convection, and subsequently, the hydrophobicity is improved. The samples that had an increased surface coverage with the charcoal (S8–S10) showed better thermal insulation ($R' = 0.230\text{--}0.583$ at 37°C) and increased contact angles ($73.99^\circ\text{--}84.86^\circ$) and tensile strength ($15.61\text{--}19.04$ MPa). The air permeability of cotton treated with eucalyptus wood charcoal showed a very similar decreasing trend [50]. These observations prove that the gradual deposition of acacia charcoal transforms the cotton fiber topography, which initially has an airy structure and porous texture, into a highly dense structure, which forms the basis of enhanced multifunctional activity in eco-friendly printed textiles.

3.8. FTIR Analysis and Interpretation

The successful deposition of charcoal on the cotton surface is confirmed by the FTIR spectra of the untreated cotton, acacia charcoal, and the S5 charcoal-printed cotton sample, which show distinct chemical differences (see Figure 14). A detailed comparison of peak assignments is given below.

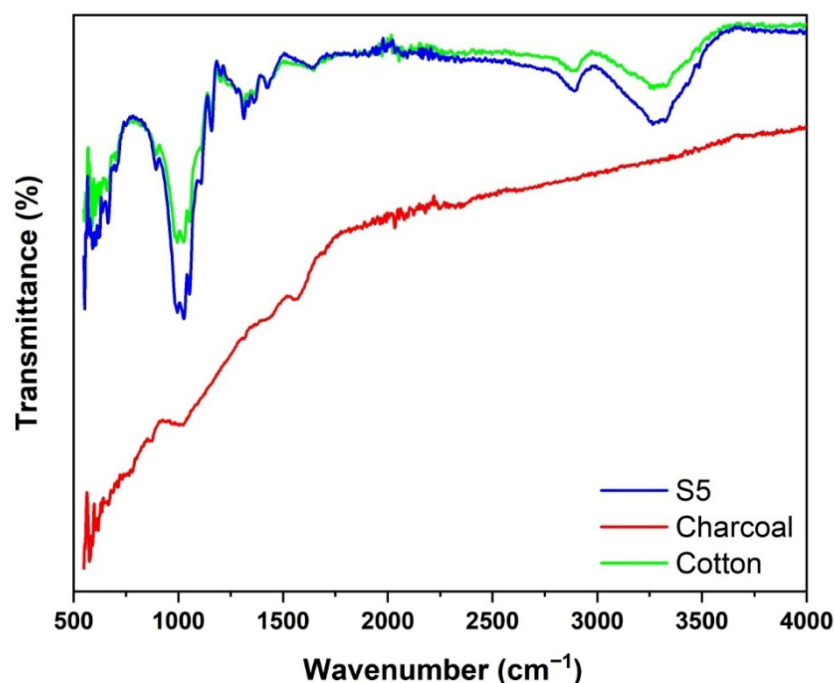


Figure 14. FTIR spectra of untreated cotton, acacia charcoal, and charcoal-printed cotton fabric (S5).

Cotton (Green Spectrum)

- There are distinctive cellulose absorption peaks in the untreated cotton fabric:
- Hydrogen-bonded hydroxyl groups in cotton are indicated by a broad and vigorous O–H stretching band at about $\sim 3330\text{--}3400\text{ cm}^{-1}$.
- $\sim 2890\text{ cm}^{-1}$: aliphatic --CH and --CH_2 groups' C–H stretching vibrations.
- $\sim 1640\text{ cm}^{-1}$: hydrophilic cellulose is characterized by O–H bends of absorbed water molecules.
- CH_2 bending vibrations at ~ 1425 and 1365 cm^{-1} .
- $\sim 1030\text{--}1050\text{ cm}^{-1}$: the cellulose backbone is represented by the strong C–O–C and C–O stretch peaks of polysaccharide rings.
- The predicted functional groups in pure cellulosic cotton are confirmed by these peaks.

Charcoal (Red Spectrum)

- The charcoal spectrum has a distinct profile that is typical of carbonaceous materials, with wider features and reduced transmittance:
- Weak/broad peak at $3300\text{--}3500\text{ cm}^{-1}$: surface O–H stretching due to adsorbed moisture and residual hydroxyls.
- Broad band around 1600 cm^{-1} : pyrolyzed carbon structures are characterized by C=C stretching of aromatic graphitic domains.
- There are few or no distinct peaks in the $1000\text{--}1200\text{ cm}^{-1}$ range: the full heat breakdown of cellulose into carbonaceous char is confirmed by the absence of polysaccharide C–O bands.
- This spectral pattern confirms that amorphous carbon with low surface oxygenated functionality makes up most of the charcoal.

S5 Printed Cotton (Blue Spectrum)

- The S5 sample (cotton printed with charcoal) exhibits a hybrid spectral profile that combines characteristics of charcoal and cotton cellulose, indicating that the surface treatment was successful. In particular:
- The C–H stretching peak ($\sim 2890\text{ cm}^{-1}$) linked to cellulose is still visible, indicating cotton structure is intact after printing.
- The O–H stretching band ($\sim 3330\text{--}3400\text{ cm}^{-1}$) is still present but slightly wider and altered, suggesting that there are bonds (hydrogen bonding or physical adsorption, respectively) between the cellulose hydroxyls and charcoal particles.
- Aromatic C=C vibrations from the accumulated charcoal, which are not noticeable in untreated cotton, are represented by an enhanced intensity or breadth about $\sim 1600\text{ cm}^{-1}$.

Charcoal particles were effectively fixed on the cotton surface despite weakening the cellulose backbone, as evidenced by the formation of new carbon-related bands and cotton-specific peaks.

4. Conclusions

This study presents acacia-charcoal-based screen printing of cotton fabrics using the print–dry–cure method. The color strength (K/S) of the printed fabrics gradually increased from 1.85 to 12.31 by increasing the charcoal content from 0.5 to 5% with satisfactory colorfastness to rubbing and washing (4–5 according to the gray scale). With an increase in the charcoal content in the print paste, the flame height decreased from 12 inches (unprinted cotton) to 3.2 inches, indicating a 73.3% improved flame retardancy. The thermal insulation property was further confirmed by an increase in the relative insulation index ($R' = 0.583$). Similarly, the tensile strength improved from 5.21 MPa to 19.04 MPa at 5% of charcoal content in the print paste. Higher concentrations of charcoal greatly increased surface hydrophobicity; contact angles reached 84.86° at 5% charcoal load, demonstrating excellent water-repellent qualities.

At larger loadings ($\geq 3.5\%$), optical polarized microscopy demonstrated full fiber coating and inter-fiber gap filling, confirming progressive fiber surface covering with increasing charcoal content. Higher concentrations of acacia charcoal ($\geq 3.5\%$) produced samples with the best multifunctional performance, including the darkest coloration ($K/S > 9.7$), maximum flame resistance (flame height < 5.2 inches), superior thermal insulation ($R' > 0.340$ at 37°C), improved mechanical strength (tensile strength > 14 MPa), and strong hydrophobicity (contact angle $> 60^\circ$). Therefore, cotton fabric printed with acacia charcoal powder might represent a promising option for functional textile applications such as water-resistant outdoor clothing, flame-retardant workwear, thermal-comfort clothing, and technical textiles.

needing improved mechanical durability. This would establish acacia charcoal as a practical eco-friendly substitute for synthetic pigments, while offering several performance advantages.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18052325/s1>, Figure S1: Vertical flame test result of sample S00 printed with auxiliaries without charcoal; Table S1: Absorbency Drop Test (sec)- AATCC 79.

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