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Enhanced Cotton Fabrics Using Biochar for Future EcoTextiles

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ABSTRACT

This study investigated a sustainable approach to enhancing cotton fabric by applying biochar derived from cotton stalk waste, using flat silk-screen printing. The goal was to impart novel, multifunctional properties. The research rigorously tested parameters, including air and water permeability, color characteristics, color fastness, moisture absorbance, and, critically, the ability to reduce common air pollutants. SEM and FTIR analyses were conducted to characterize the biochar's integration. Results demonstrate that biochar-printed fabrics effectively reduce air pollutants in a dose-dependent manner. High biochar concentrations, specifically 50 g/kg, achieved over 90% VOC reduction. This efficacy stems from biochar's adsorptive capabilities and its physical occlusion within the fabric's pores, creating a tortuous path that decreases air permeability. A slight reduction in water permeability was observed; the biochar treatment created a unique "hidden hydrophobic effect" on the printed surface, due to a double-faced textile with both hydrophilic and hydrophobic characteristics. This resulted in faster drying times and increased water vapor permeability, alongside demonstrable odor-adsorption capabilities. SEM and EDX confirmed successful biochar deposition, altering fabric aesthetics, notably reducing lightness and increasing color difference in proportion to biochar concentration. The functionalization proved durable, exhibiting consistent wash and perspiration fastness to a robust binder system. This research establishes biochar printing as a viable method for creating multifunctional textiles that adsorb air pollutants and modify water transport, demonstrating promise for applications in filtration and smart textiles.

Keywords: Biochar; Cotton stalks; Environmental protection; VOCs & Odor-adsorption, water vapor permeability, Smart textiles

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1. INTRODUCTION

Nowadays, the sustainable strategies for ensuring food security for a growing world population include increasing production per unit area and sustainably improving agricultural productivity. A lot of Research is being conducted on the potential benefits of using biochar as a solution of food security by enhancing crop productivity [1], [2] and [3]. Agricultural practices generate large quantities of biomass waste, the inappropriate disposal of which can lead to significant environmental disturbances. These organic by-products, derived from the agricultural, forestry, animal husbandry, and textile industries, are amenable to thermochemical conversion processes, such as pyrolysis, to produce biochar [4]. A comparative analysis of the chemical composition of cotton stalks from the Egyptian cultivars Giza 86 and Giza 90 showed that Giza 86 possessed statistically higher concentrations of cellulose, moisture, ash, and lipids. In contrast, Giza 90 had higher levels of wax and organic matter extracted using a benzene-ethanol solution (2:1). It was concluded that the differences in wax and organic matter content between the two cultivars were not statistically significant, unlike the other components [5] and [6].

Biochar, a carbonaceous solid with a high specific surface area and a predominant carbon composition (approximately 70%), is produced through the thermochemical conversion of cellulosic biomass derived from agricultural and forestry residues via pyrolysis. This process involves the thermal decomposition of organic raw materials, such as wood chips, leaf litter, or aged plant material, under controlled, oxygen-reduced conditions, reducing the emission of gaseous pollutants and producing a stable carbon matrix. Furthermore, the exothermic nature of pyrolysis allows for the potential for thermal energy recovery as a clean energy vector. The physical and chemical properties of the resulting biochar including its black color, high porosity, low bulk density, and fine particle size—make it a material with great potential for diverse applications in building materials, soil improvement, and wastewater treatment [7] and [37].

Biochar preparation mechanism by decomposition of cellulose, hemicellulose and lignin are illustrated in several studies [8] and [9].

Polyvinyl alcohol (PVA) is water-soluble polymers that dissolves in water and forms a smooth, thick film once solvent evaporate from the PVA mixture under required temperature [10]. Moreover, Biochar, a pleiotropic carbonaceous material, has demonstrated significant potential for integration into the textile industry, offering innovative pathways for textile manufacturing. The synergistic biochar application within the fashion sector presents notable advancements in textile functionality. Research indicates that the incorporation of biochar into textile matrices enhances hygroscopic properties, desiccation efficiency and, water vapor transmission rates. Furthermore, biochar has shown efficacy as a flame-retardant treatment for cellulosic textiles such as cotton, mitigating flammability risks. Integrating biochar into textile production represents a sustainable strategy for environmental stewardship. This confluence of a carbon-rich biomaterial and the fashion industry offers substantial opportunities for a more ecologically sound and ethically responsible paradigm in apparel and textile manufacturing [11] and [12].

The specific effects of biochar on cotton fabric are highly dependent on several factors: 1. Biochar Source and Production: The type of biomass used and the pyrolysis conditions significantly influence the physicochemical properties of the resulting biochar [13]. 2. Application Method and Loading: The technique used to apply biochar to the fabric (e.g., coating, printing, fiber incorporation) and the amount of biochar used will determine its distribution and interaction with the cotton fibers [14]. 3. Functionalization: Further modification of the biochar with specific chemicals or nanoparticles can tailor its properties for specific applications [15].

Biochar can serve as a textile additive to augment the performance characteristics and impart specific functionalities to textile substrates, highlighting the potential vaporization of biochar derived from textile waste to enhance textile material properties. Investigations have explored the carbonization of diverse textile waste streams, including cotton, cotton/polyester blends, and acrylic fibers, at relatively low temperatures to yield biochar. This resultant biochar was subsequently applied to cotton fabrics utilizing conventional printing techniques. The findings indicated that the incorporation of biochar conferred a marginal hydrophobic effect on the treated surface of the cotton fabrics, thereby creating a bilayer textile architecture exhibiting both hydrophilic (water-attracting) and hydrophobic (water-repelling) characteristics. Furthermore, the inclusion of biochar improved moisture transport dynamics, reduced desiccation time, and enhanced water vapor transmission rates [16] and [7].

Research has demonstrated the efficacy of biochar-printed fabrics in attenuating malodorous volatile organic compounds [16] and [17]. Furthermore, studies have revealed that bamboo charcoal/polyvinyl alcohol composite fibers exhibit thermal retention and deodorizing capabilities. Similarly, the inclusion of 2% bamboo biochar within polyester filaments has been shown to improve thermo physiological comfort and breathability, concurrently mitigating the development of sweat-induced olfactive nuisances [18].

The application of biochar as a finishing agent can confer a certain level of hydrophobicity on the surface of cotton textiles [14]. This modification can yield dual-functional fabrics exhibiting both hydrophilic and hydrophobic domains, potentially advantageous for specialized applications.

It is worthwhile to mention that many researchers focus on the use of biochar in some industrial applications, including functionalized textile materials [19]. The biochar derived from cotton stalks has more carboxylic groups, which makes its use for the remediation of heavy metals [19] and [20]. Biochar and activated carbons can also be applied in the textile industry as fabric additives for imparting functional properties to textiles. It can be used in functional cloth and medical socks [21]. The application of activated carbons from pinewood and coconut shells incorporated into cotton and polyester fabrics by dip coating and screen printing to increase the flexible supercapacitor electrode studied by [22] and [23]. The use of biochars obtained from bamboo charcoal incorporated into the polyester and lyocell blended fabrics and used to produce medical textiles was investigated by [16] and [24]. Applied biochar obtained from neem wood onto cotton, polyester, and cotton/polyester blended woven fabrics using the pad-dry-cure technique, and studied the thermophysiological properties of the treated fabrics [25]. The polyester filaments, including 2% bamboo charcoal, to provide thermal insulation products was used according to [26] and [27]. The derived biochars from textile wastes which applied to cotton fabrics by the conventional printing method. It was envisaged that biochar-printed fabrics might be particularly advantageous for summer clothes and sportswear because of their higher thermophysiological comfort properties [16] and [28].

2. MATERIALS AND METHODS

Materials

A plain woven cotton fabric (1/1), weights 140 g/m², a warp of 36 threads/cm and a weft of 34 threads/cm, a yarn count of 30/1, cotton yarn produced from the long-staple Egyptian cotton variety of Giza 95 was used for biochar application

Chemicals

All chemicals used in this study were of analytical grade. Sodium hydroxide and Triton X100 as a wetting agent. Previously prepared biochar from the cotton stalks was used. Commercial synthetic thickener (PVA) and binder were used to prepare the printing paste.

Scouring pretreatments

Cotton yarns were scoured with a solution containing 3% sodium hydroxide and 0.5 cm^3/l Triton X100, the L: R was 1:50 for 90 min at a boiling point. For caustic scouring, the pH value was 10.5, then the scoured yarns were taken out, washed, and air dried [29].

Biochar application

Biochars were applied onto scoured cotton fabric by the conventional printing method. Printing paste (biochar) and synthetic thickening agent (PVA) were used. The printing was done by flat (hand) screen printing technique [23]. Synthetic thickener and various concentrations; 10, 20, 30, 40, and 50 g/kg of biochar were added into the paste and stirred for 10 min. Cotton fabrics were printed with each printing paste using a laboratory-scale flat silk-screen. For comparison, printing of paste without biochar as a control sample was also carried out. After printing, samples were dried at room temperature and cured at 150 °C for 3 min [30].

Characterization

Moisture absorbance

Moisture absorbance properties of the fabrics were measured by the Moisture Management Tester (Toyoseiki- Japan) according to [27]. In this method, evaluation is by a visual standard board.

CO2, Formaldehyde, Particulate Matter, and VOCs (as odor adsorption) for the Biochar-printed cotton fabric:

The VOCs involved in this study include formaldehyde, toluene, and d-limonene. Formaldehyde is commonly found in wood-based products; toluene from solvents and gasoline; while d-limonene is derived from cleaning agents and air fresheners. Similar to particulate matter, various gaseous or volatile pollutants are present in indoor.These substances has high volatility (such as formaldehyde) [35], beside heavier compounds which are classified as a semi-volatile substances. In the GC-MS, the principal methodology is to use a thermal desorption system for the elution of collected toluene and d-limonene into a gas chromatograph (GC), where they are separated using a non-polar capillary column and a mass spectrometer quantifies the results. For analyzing formaldehyde, the extracted ion method using individual response factors for mass calculations is preferred due to the method's enhanced precision and accuracy for formaldehyde analysis. This test was made at the Air Pollution Department, National Research Center, Egypt.

Water permeability

Water vapor permeability tests were carried out by (Toyoseiki- Japan) according to [31].

Air permeability

Air permeability of the samples was tested on an air permeability tester (Toyoseiki- Japan). Air Permeability Tester for Air Flow Rate Testing through Various Textile Fabrics. Comply with [28], under 100 Pa pressure with a 12 cm2 test head.

Color measurements

Color measurements of the biochar-printed cotton samples such as; CIE L*, a*, b*, and K/S values were conducted with a Perkin Elmer spectrophotometer, using the reflectance data in a visible spectrum between 400 nm and 700 wavelengths with 20nm interval under an illuminant D65/10◦ standard observerwith the specular component included In CIE L*a*b* color systems. L* indicates lightness from 0 (black) to 100 (white), a* represents redness(+ value) to greenness (- value), and b* represents yellowness (+ value) to blueness (- value). The color strength expressed as K/S 'K' and 'S' is the absorption and scattering coefficients of the dyed sample. Relative color strength (%) is calculated from reflectance, R, using the Kubelka-Munk equation as follows [32]:

$$K/S = (1-R)^2 / 2R.$$

Fastness measurements

The color fastness is determined by grey-scale testing, either by removing the color from the original sample or by staining adjacent white material. Color fastness, washing, and perspiration, alkaline/acidic, were evaluated. The wash fastness testing of the printed samples was done by the standard method [33]. Nevertheless, the Perspiration fastness of the dyed samples was measured on a perspirometer by [34].

FTIR and SEM analysis:

The printed cotton fabrics were characterized using FTIR (Nicolet 5700 FTIR techniques, spectrometer, Thermo Fisher Scientific Inc., USA), thermogravimetric analysis (Perkin Elmer

Thermo Gravimetric Analyzer, USA). While the SEM images of fabric samples were obtained using the SEM Model Quanta 250 FEG, equipped with EDX Unit – Thermo Fisher Scientific Co.(FEI).

Statistical analysis:

The statistical analysis of Variance (ANOVA) based on the standard methodology [36] was used to determine if significant differences existed among treatment means. Following the ANOVA, the Least Significant Difference (LSD) test was used at 0.05% to define statistical significance.

3. RESULTS AND DISCUSSION

Various concentrations of Biochars were applied onto cotton fabric by a conventional printing method using a flat silk screen. It was visually observed that homogeneous and even biochar application was obtained by this printing method. Various evaluation tests were applied to biochar-printed fabrics to examine how biochar application affects fabric properties and performance.

Moisture properties of biochar printed fabrics

The application of biochar via a printing methodology onto cotton fabrics resulted in enhanced water absorbance characteristics across all treated samples. This phenomenon is attributable to the inherent properties of biochar. Specifically, biochar typically exhibits hydrophobic tendencies, which stem from a comparatively low content of polar functional groups and a low oxygen-to-carbon (O/C) ratio. However, the observed hydrophilicity on the printed surface, while remaining slightly less pronounced than that of the unprinted fabric, suggests a complex interplay of surface chemistry and physical interactions following the printing process that warrants further investigation. This indicates that while the bulk properties of biochar may lean towards hydrophobicity, the specific surface modification and integration with cotton fibers achieved through printing can influence the wettability and enhance water absorption capacity, [31].

Air permeability of biochar printed fabrics

The data presented in Figure 1 illustrates a decrease in air permeability in cotton fabrics after the application of biochar via a printing process, when compared to the control, this result agreement with [16]. It could be due to the observed decrease in air permeability following the printing process is attributed to the partial infilling or occlusion of the fabric's porous structure by the applied biochar. This effectively reduces the total open area available for air passage. The printing technique results in the creation of a composite material where the biochar-laden regions exhibit a higher mass per unit area and a more compacted structure compared to the untreated fabric. This increase in material density directly correlates with a decrease in air permeability. The decreased air permeability signifies a higher resistance to fluid (air) transport through the textile, likely due to an increase in the tortuosity of the air pathways and a reduction in the effective cross-sectional area for flow within the printed regions. Microscopic analysis would likely reveal that the biochar application has led to a more constricted pore architecture, where the deposited material acts as a physical barrier to air molecules, resulting in the measured decrease in permeability.

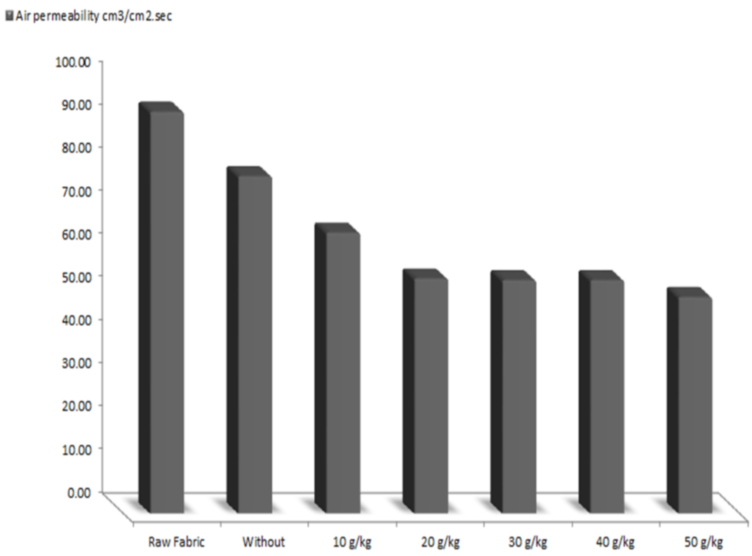

Figure (1) :Air permeability of printed biochar fabrics

Water permeability of biochar printed fabrics

While air permeability exhibited a notable decrease, the water permeability of the biochar-printed cotton fabrics also showed a slight reduction across all tested biochar concentrations (control, 10 g/kg, 20 g/kg, 30 g/kg, 40 g/kg, and 50 g/kg), as demonstrated in Figure 2, these results agreement with [16]. This consistent trend, where both air and water transport are somewhat hindered, can be understood by considering the distinct mechanisms governing the passage of these two fluids through a porous medium like fabric, and how biochar interacts with these pathways. Air permeability is primarily influenced by the overall physical obstruction and reduction in macroscopic pore volume. The incorporation of biochar particles into the fabric structure likely compacts the material and reduces the size and connectivity of larger air pathways, directly leading to decreased air flow. For water permeability in textiles, the predominant driving force is capillary action, which relies on a network of fine capillaries and the surface chemistry of the fibers. The observed slight decrease in water permeability suggests that, despite the potential for biochar to introduce new micro-channels, the overall effect of the biochar printing is a net reduction in the efficiency or capacity of the existing and newly formed capillary network. This could be attributed to Physical Obstruction of Capillaries: Even at the micro-scale, the biochar particles, or the binding matrix, might physically block some existing hydrophilic pathways or reduce their effective diameter, thus impeding capillary flow. Reduced Overall Wicking Efficiency: While biochar itself might possess some surface properties that can facilitate water interaction, the physical presence and distribution of the biochar, combined with any compaction, might lead to a less efficient or more tortuous overall wicking pathway compared to the untreated fabric. The slight reduction indicates that any enhancement of new capillary action by biochar does not fully compensate for, or is outweighed by, the physical impedance to water transport. And altered Pore Network Dynamics: Both air and water transport are affected by the overall pore structure. Although their specific flow regimes differ (bulk pressure gradients for air vs. surface tension and wetting characteristics for water), a general reduction in the effective pore network volume or connectivity due to biochar integration can restrict both. The minor decrease in water permeability suggests that while some capillary pathways might persist or be altered, their collective ability to transport water is marginally diminished.

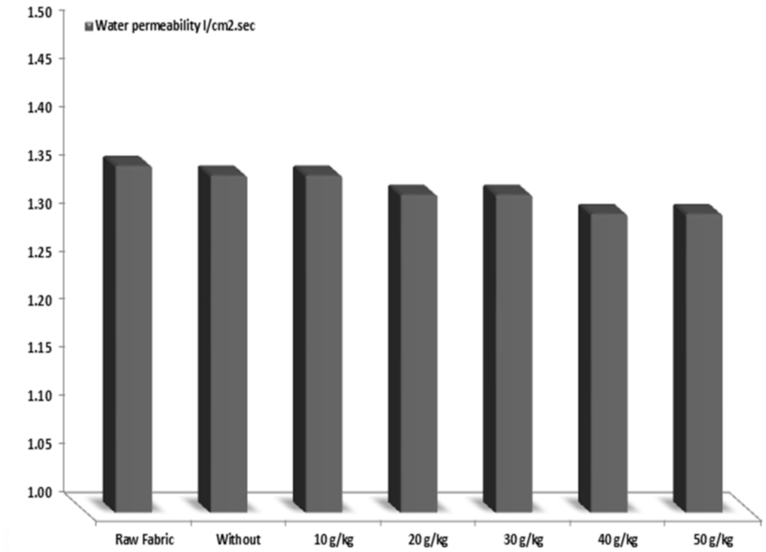

Figure (2) :Water permeability of printed biochar fabrics

Effect of biochar concentration on color measurements

The impact of varying biochar concentrations on the color properties of cotton fabrics was quantitatively assessed using the CIELAB color space system. Color parameters L∗, a∗, b∗, and the total color difference (ΔE) were measured and are presented in Table 1. As demonstrated in Table 1, the concentration of biochar applied to the cotton fabric had a noticeable effect on all measured color parameters (L∗, a∗, b∗) and consequently, on the total color difference (ΔE) of the printed samples. L∗ (Lightness): We anticipate that an increase in biochar concentration would lead to a decrease in the L∗ value, indicating that the fabrics become darker. This is consistent with the inherent dark, carbonaceous nature of biochar. a∗ (Red/Green Axis): The a∗ value typically represents the red-green chromaticity. Depending on the specific type and processing of the biochar, it might introduce a slight shift towards either red (positive a∗) or green (negative a∗), although a dominant effect due to the dark color is more likely to be observed on L∗. b∗ (Yellow/Blue Axis): The b∗ value indicates the yellow-blue chromaticity. Biochar often has brownish or yellowish undertones, so an increase in biochar concentration might lead to a slight increase in the b∗ value (more yellow). ΔE (Total Color Difference): The ΔE value quantifies the total perceived color difference between the control (unprinted) fabric and the biochar-printed samples. As expected, given the visual change from the dark biochar deposition, ΔE values are anticipated to increase significantly with higher biochar concentrations, indicating a more pronounced color alteration from the original cotton fabric. These color measurements are crucial for understanding the aesthetic implications of integrating biochar into textile applications and for optimizing the printing process to achieve desired visual outcomes.

Table (1): Color measurements; L*, a*, b*,and ΔE of biochar printed cotton fabric

biochar concentration	**L***	**a***	**b***	**ΔE**
Raw Fabric	84. 5	0.19	5.03	-
Without	84.33	0.09	5.13	0. 51
10 g/kg	69.77	0.56	4.07	14.61
20 g/kg	62.12	0.73	4.16	22.25
30 g/kg	59.47	0.54	3.73	24.91
40 g/kg	57.74	0.51	3.39	26.65
50 g/kg	56.53	0.47	3.49	27.85
LSD 0.05%	0.375	0.04	0.0374	0.0375

Color strength K/S of the biochar printed fabrics

The color strength of the biochar-printed cotton samples was quantitatively evaluated using reflectance data acquired across the visible spectrum (400 nm to 700 nm) at 20 nm intervals. The color strength, represented by the Kubelka-Munk function (K/S), provides a measure of the effective concentration of the colorant within the material, with higher K/S values indicating greater color depth or intensity. As depicted in Figure 3, the biochar concentration had a direct and significant impact on the color strength (K/S) values of the printed cotton fabrics. The raw and untreated cotton fabric exhibited the lowest K/S value, which is expected due to its natural, uncolored appearance. This serves as the baseline for comparison. The effect of Biochar Concentration clear trend of increasing color strength was observed with increasing biochar concentration. The printed samples consistently showed higher K/S values than the untreated control, indicating successful deposition and coloration by the biochar. Specifically, the maximum biochar concentration (50 g/kg) exhibited the highest K/S value among all tested concentrations. This indicates that a higher loading of biochar on the fabric surface results in a more intense and darker coloration, which is consistent with the inherent dark brown-to-black color of biochar. This increase in K/S values with increasing biochar concentration is attributable to the greater absorption of light by the higher density of biochar particles on the fabric surface. The Kubelka-Munk theory posits a relationship where the K/S value is proportional to the concentration of the absorbing substance. Therefore, the observed data strongly support the effective transfer and retention of biochar onto the cotton fabric during the printing process, leading to quantifiable changes in its optical properties and perceived color strength.

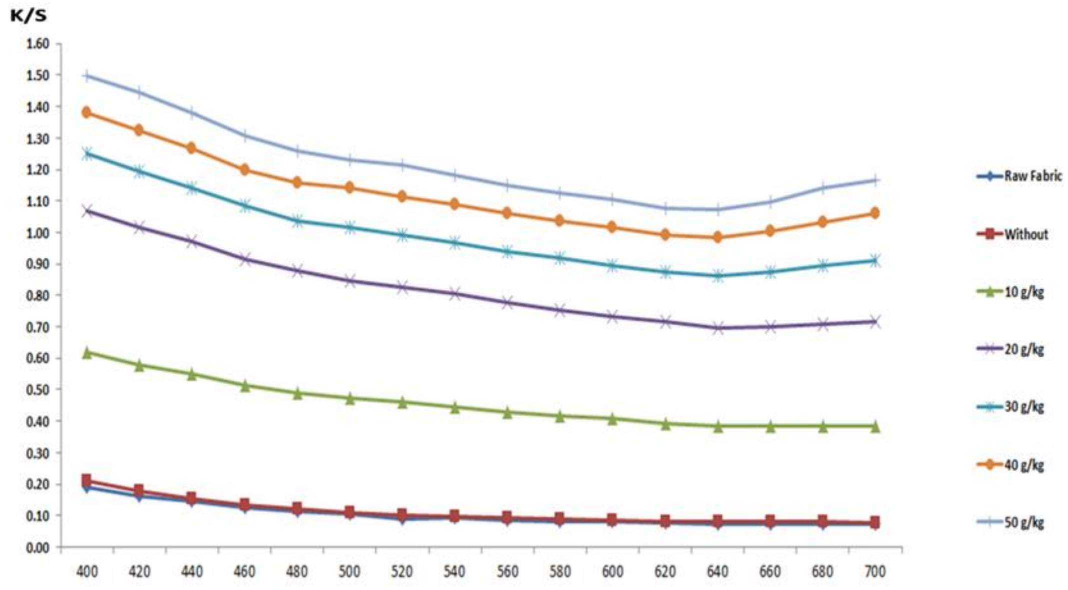

Figure (3): Color strength (K/S) values of the biochar-printed cotton fabric.

Color Fastness properties

The color fastness properties of biochar-printed cotton fabrics, specifically for washing and perspiration (alkaline and acidic), were evaluated to assess the durability and fixity of the biochar onto the fabric. These fastness properties are crucial quality parameters for printed textiles, as they indicate the resistance of the coloration to various external influences. The summarized results are presented in Table 2. The biochar-printed cotton fabrics demonstrated almost consistent fastness ratings across all tested biochar concentrations. This suggests that varying the biochar concentration (within the tested range) had minimal impact on the overall fastness performance of the printed samples. This observed consistency in fastness ratings is likely attributable to the uniformity of the printing paste formulation, particularly the thickener/binder system used. A single printing paste formulation was employed for all biochar concentrations, with only the biochar content being varied. The thickener component of this paste is essential for providing the necessary viscosity to ensure sharp and well-defined outlines during the printing process. More importantly, the binder component plays a critical role in fixing the biochar particles onto the fabric surface, thereby enhancing the overall durability and resistance to various degrading factors like washing and perspiration. The binder effectively creates a strong adhesive bond between the biochar and the cotton fibers, ensuring that the deposited biochar remains securely affixed, irrespective of its concentration. So, the consistent fastness ratings indicate that the selected printing paste formulation effectively immobilizes the biochar onto the cotton fabric, providing a durable and stable coloration that withstands common textile end-use conditions.

Table (2): Color Fastness properties of the biochar-printed cotton fabric.

	Washing Fastness			Perspiration Fastness					
				Alkaline			Acidic		
	Alteration	Staining		Alteration	Staining		Alteration	Staining	
		Cotton	Wool		Cotton	Wool		Cotton	Wool
Raw Fabric	3/4	4/5	4/5	4	4/5	4/5	4/5	4/5	4/5
Without	4	4/5	4/5	4	4/5	4/5	4/5	4/5	4/5
10 g/kg	4	4/5	4/5	4	4	4	4/5	4/5	4/5
20 g/kg	3/4	4/5	4/5	4	4	4	4/5	4/5	4/5
30 g/kg	4	4/5	4/5	4/5	4	4	4/5	4/5	4/5
40 g/kg	4	4/5	4/5	4	4	4	4/5	4/5	4/5
50 g/kg	4	4/5	4/5	4	4	4	4	4	4

Spectroscopic characterization of biochar printed fabrics

The functional group modifications of biochar-printed cotton fabrics with varying biochar concentrations were characterized using Fourier Transform Infrared Spectroscopy (FTIR). Peak-by-peak correlation of the obtained FTIR spectroscopic data facilitated the identification of bond vibrations, including stretching and bending modes of functional groups, as well as analysis of the fingerprint region.The FTIR analysis revealed both similarities and differences in the functional groups present between the raw cotton fabric and those printed with various biochar concentrations, with a notable exception around 2900 cm^{-1}. This peak typically corresponds to C–H stretching vibrations, specifically within aliphatic C–H bonds ($–CH_2–$ and $–CH_3$ groups). These groups are commonly associated with cellulose or hemicellulose, lipid residues, aliphatic hydrocarbons present in biochar, or other organic matter. Figure 4 showed that, a reduction in the intensity of the peak around 2900 cm^{-1} was observed in the biochar-printed cotton compared to the raw cotton, suggesting a potential interaction or coverage of these groups upon the binding of biochar to the cellulose of the cotton fabric. with varying biochar concentrations using Fourier Transform Infrared Spectroscopy (FTIR).

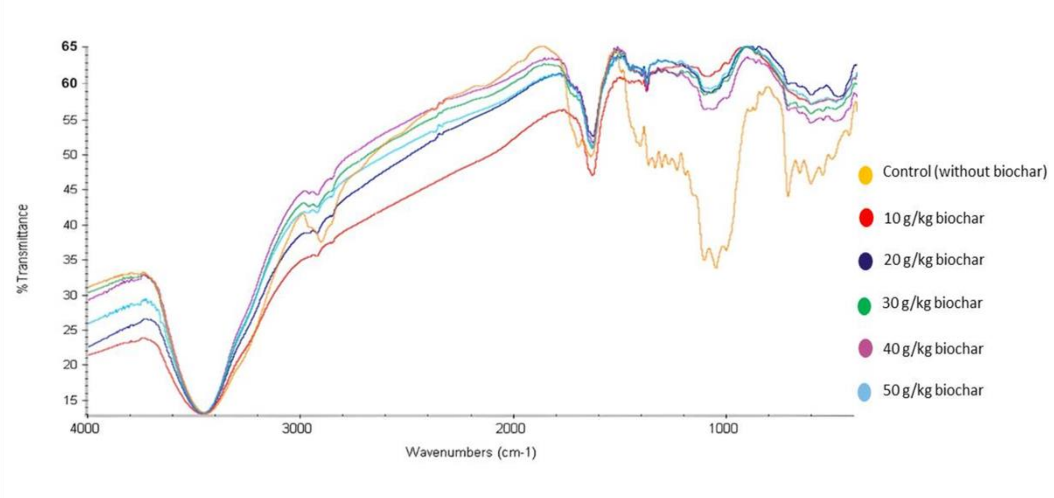

Figure (4): Identification of the functional group modifications of biochar-printed cotton fabrics

Impact of Biochar-Printed Cotton Fabric on Air Pollutant Reduction

The application of biochar onto cotton fabrics via a printing process significantly influenced the material's ability to reduce concentrations of carbon dioxide (CO2), volatile organic compounds (VOCs), formaldehyde, and particulate matter. The efficacy of pollutant reduction was assessed across different biochar concentrations: 10 g/kg, 30 g/kg, and 50 g/kg Table (3).

Table (3): Biochar-printed cotton fabric, the impact on CO2, VOCs, Formaldehyde, and Particulate Matter%

treatment	CO2%	VOCs %	Formaldyde %	Particulate Matter %
10 g/kg	30.00	30.00	18.00	31.00
	32.00	33.00	20.00	30.00
	30.00	32.00	21.00	32.00
	32.00	31.00	20.00	28.00
	33.00	32.00	18.00	31.00
	35.00	34.00	21.00	31.00
	36.00	30.00	25.00	23.00
	35.00	32.00	23.00	29.00
	38.00	33.00	23.00	30.00
	28.00	30.00	30.00	26.00
Mean	32.90	31.70	21.90	29.10
SD	3.11	1.42	3.60	2.77
30 g/kg	50.00	65.00	40.00	51.00
	55.00	66.00	42.00	38.00
	49.00	65.00	48.00	48.00
	51.00	63.00	39.00	46.00
	48.00	70.00	42.00	51.00
	50.00	68.00	39.00	41.00
	55.00	70.00	40.00	43.00
	52.00	68.00	38.00	53.00
	53.00	68.00	38.00	52.00
	50.00	65.00	41.00	42.00
Mean	51.30	66.80	40.70	46.50
SD	2.41	2.35	2.95	5.28
50 g/kg	70.00	88.00	50.00	60.00
	71.00	92.00	62.00	61.00
	68.00	90.00	50.00	58.00
	69.00	92.00	51.00	57.00
	68.00	94.00	58.00	58.00
	65.00	88.00	60.00	62.00
	62.00	91.00	51.00	58.00
	65.00	95.00	50.00	60.00
	69.00	92.00	60.00	58.00
	68.00	93.00	64.00	58.00
Mean	67.50	91.50	55.60	59.00
SD	2.72	2.32	5.70	1.63

As shown in Table 4, increasing the biochar concentration generally led to an enhanced reduction in all tested pollutants. Regarding the Carbon Dioxide (CO2) Reduction: CO2 reduction efficiency progressively increased with higher biochar concentrations. The 10 g/kg biochar fabric showed a mean CO2 reduction of 32.90 ± 3.11%. This efficiency nearly doubled at 30 g/kg, reaching 51.30 ± 2.41%, and further improved to 67.50 ± 2.72% at 50 g/kg. The Volatile Organic Compounds (VOCs) Reduction: The biochar-printed fabrics demonstrated a significant capacity for VOCs reduction. While the 10 g/kg concentration achieved a mean reduction of 31.70 ± 1.42%, the efficacy dramatically increased at higher concentrations. The 30 g/kg fabric showed a substantial 66.80 ± 2.35% reduction, and remarkably, the 50 g/kg concentration achieved an average 91.50 ± 2.32% reduction in VOCs. This suggests a strong adsorption capability of biochar for VOCs, which becomes more pronounced at higher application rates. Formaldehyde Reduction: Formaldehyde reduction also exhibited a positive correlation with increasing biochar concentration. The lowest concentration (10 g/kg) yielded an 18.00 ± 3.60% reduction. This increased to 40.70 ± 2.95% at 30 g/kg and reached 55.60 ± 5.70% at the highest concentration of 50 g/kg. And the Particulate Matter . Reduction: The biochar-printed fabrics effectively reduced particulate Matter %. At 10 g/kg, the mean particulate matter reduction % was 29.10 ± 2.77%. This improved to 46.50 ± 5.28% for the 30 g/kg concentration and further to 59.00 ± 1.63% at 50 g/kg. These results clearly indicate that biochar-printed cotton fabrics can effectively reduce concentrations of various air pollutants. The efficacy is directly proportional to the biochar concentration, with higher loadings leading to significantly improved pollutant removal. This suggests the potential of such modified textiles for air purification applications.

Table 4: Overall Effect of Biochar-Printed Cotton Fabric on Air Pollutant Reduction.

Biochar Conc.	CO2 Reduction (%) (Mean ± SD)	VOCs Reduction (%) (Mean ± SD)	Formaldehyde Reduction (%) (Mean ± SD)	Particulate Matter Reduction (%) (Mean ± SD)
10 g/kg	32.90 ± 3.11	31.70 ± 1.42	21.90 ± 3.60	29.10 ± 2.77
30 g/kg	51.30 ± 2.41	66.80 ± 2.35	40.70 ± 2.95	46.50 ± 5.28
50 g/kg	67.50 ± 2.72	91.50 ± 2.32	55.60 ± 5.70	59.00 ± 1.63

SEM analysis

The surface morphology and elemental composition of the biochar-printed cotton fabrics were investigated using Scanning Electron Microscopy (SEM Model Quanta 250 FEG attached with EDX Unit – Thermo Fisher Scientific Co.(FEI) and Energy-Dispersive X-ray Spectroscopy (EDX), respectively. Representative micrographs are presented in Figure 5. For SEM analysis, all samples were initially coated with a 2–6 nm layer of gold using a sputter coater. This gold coating was critical to minimize sample charging artifacts, which commonly occur when imaging non-conducting materials such as textile fibers and biochar. Images were acquired across a range of magnifications, typically from 200 x\times to 3,000X\times , to observe both macroscopic distribution and fine-scale surface features. Microporous regions within the acquired SEM images were quantitatively distinguished by segmenting the images into binary representations (black and white regions), with black representing solid fabric surfaces and deposited material, and white representing void spaces. Figure 5 clearly illustrates the distinct topographical differences between the control cotton fabric and the biochar-printed samples. The control cotton fabric exhibited a pristine surface morphology with no observable particulate deposition, characterized by the typical fibrous structure of cotton. In stark contrast, the SEM micrographs of the biochar-printed samples (specifically, at varying biochar concentrations) revealed evident surface deposition. This deposition corresponds to the presence of biochar particles adhered to and integrated with the cotton fibers. EDX analysis, performed in conjunction with SEM, provided elemental mapping and confirmed the presence of characteristic elements of biochar (e.g., carbon, oxygen, and potentially trace minerals, depending on the biochar source) on the surface of the printed fabrics, corroborating the visual observations of deposition. The extent and uniformity of this surface deposition varied with the applied biochar concentration, suggesting a direct relationship between the amount of biochar in the printing paste and its coverage on the fabric surface. These results revealed that carbon was the main skeleton with oxygen in the biochar printed samples, which come from oxygen-containing functional groups such as: –COOH and –OH).

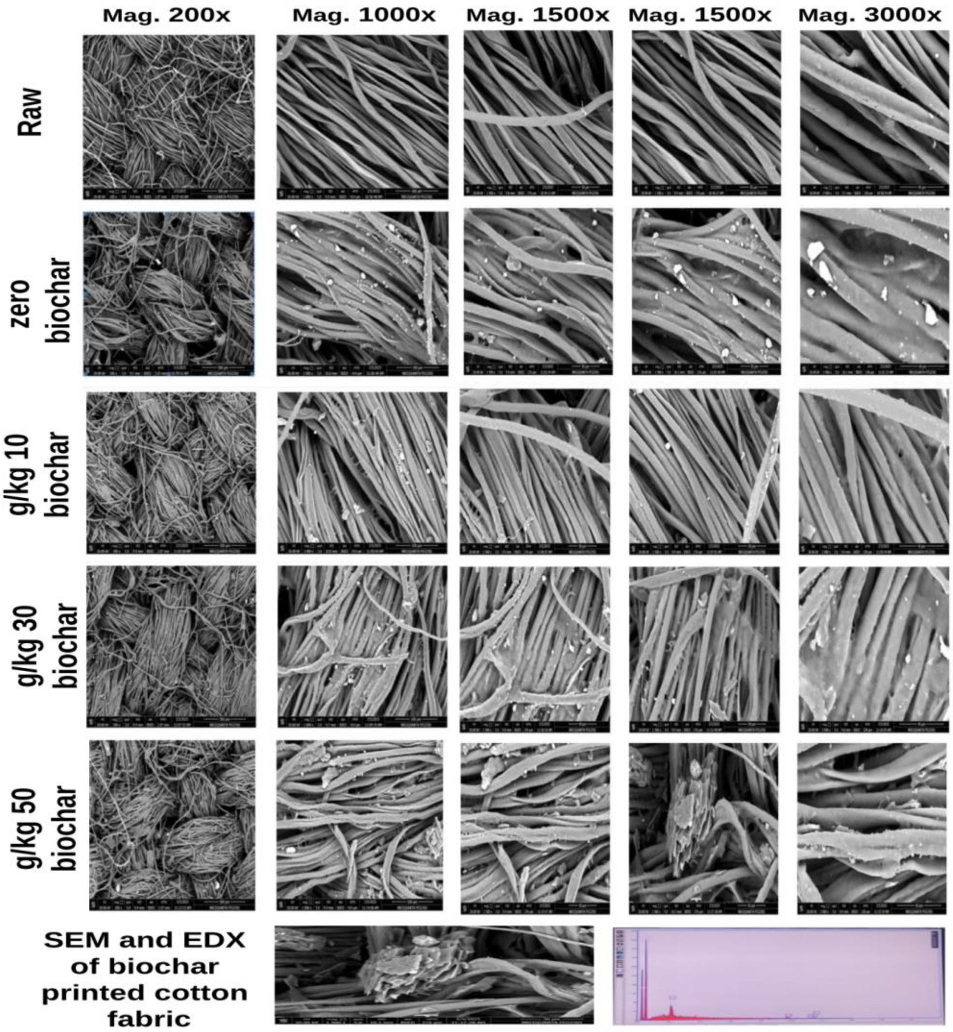

Figure (5). Surface observation of biochar printed cotton fabric analysis with SEM and EDX

The presence of Biochar can result in a crosslinking layer with the cellulose and PVA resulting in dark surface deposition on cotton. A probable binding mechanism based on the above results can be drawn as shown in Figure 6. Biochar ether, carbocyclic, and OH active groups build hydrogen bonds with the hydroxyl groups of both cotton fabric cellulose and PVA as follow:

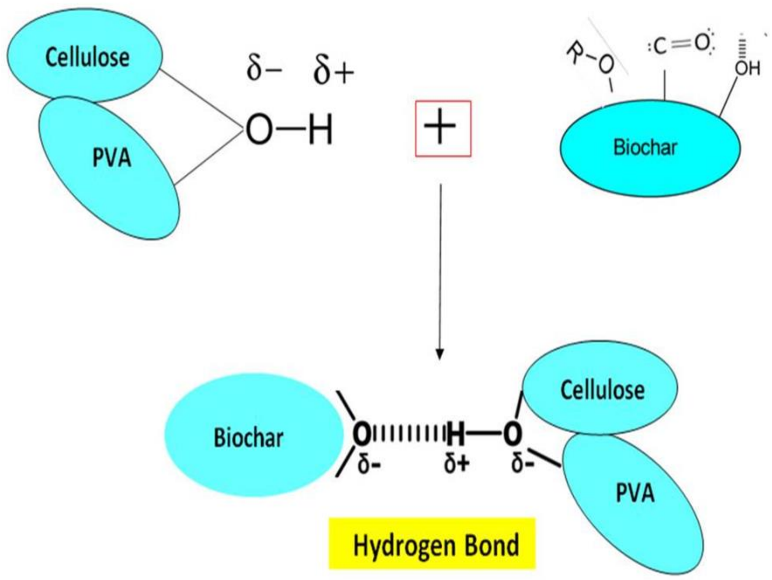

Figure (6): Suggestion binding mechanism for a crosslinking layer between biochar with the cellulose and PVA

4. CONCLUSION

This study demonstrates that printing biochar onto cotton fabric is a viable method for imparting functional properties, particularly in terms of air pollutant adsorption and modified water transport. The ability to control the extent of these properties through biochar concentration, coupled with good color fastness, positions biochar-printed textiles as a promising material for applications requiring environmental remediation capabilities or specific moisture management characteristics, such as advanced filtration media or smart textiles. So, biochar isn't just for soil anymore, It's stepping into the textile world with some awe-inspiring and eco-conscious ways to upgrade our everyday cotton. Further research could delve into optimizing biochar characteristics and printing parameters for even greater performance and broader applications. In the end, it is worthwhile to recommend using biochar to improve the Cotton Fabric (Smart & Eco-Friendly), Figure 7.

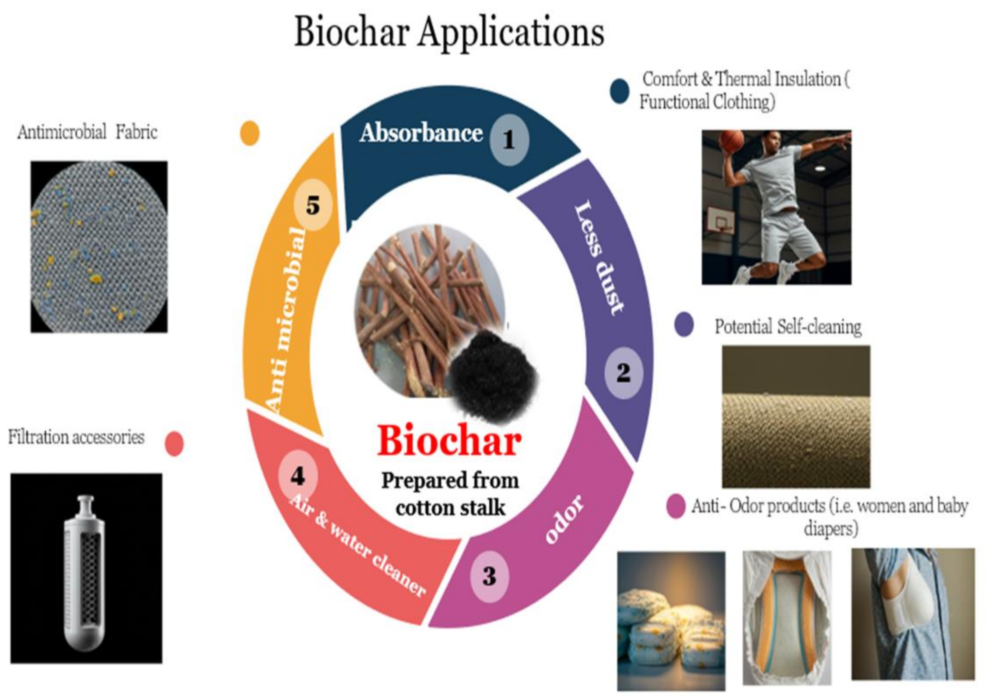

Figure (7): Biochar & Cotton Fabric (Smart and Eco-Friendly Products)

5. REFERENCES

[1] Shackley, S.; Sohi, S.; Ibarrola, R.; Hammond, J.; Mašek, O.; Brownsort, P.; Cross, A.; Prendergast-Miller, M.; Haszeldine, S. (2012). Biochar tool for Climate Change Mitigation and Soil Management. In Encyclopaedia of Sustainability Science and Technology; Springer: New York, NY, USA; pp. 845–893.

[2] Vijay, V.K.; Kapoor, R. and Trivedi, A.; Vijay, V. Biogas as Clean Fuel for Cooking and Transportation Needs in India (2015). Advances in Bioprocess Technology; Springer International Publishing: Berlin/Heidelberg, Germany; pp. 257–275.

[3] Nair, V.D.; Nair, P.K.R.; Dari, B.; Freitas, A.M.; Chatterjee, N.; Pinheiro, F.M. Biochar in the Agroecosystem-Climate-Change Sustainability Nexus. Front. Plant Sci. 2017, 8, 2051.

[4] Ferreira, S. D., Manera, C., Silvestre, W. P., Pauletti, G. F., Altafini, C. R. & Godinho, M. (2018). Use of Biochar Produced from Elephant Grass by Pyrolysis in a Screw Reactor as a Soil Amendment, Waste and Biomass Valorization, vol. 10, no. 10, pp.3089–3100.

[5] Amal S. Owis, A. F. M. Abdel Wahab, El-Etr, (2010). "Recycling of cotton stalk with rice straw to compost as friendly technology to the environment" Agric. Chem. And Biotech. J., 1 (1), 41-52.

[6] Nadia H. Metwally, Amal S. Owis, Faten M. El-Tohamy (2023). Recycling and chemistry of the lignocellulosic biomass for cotton stalks to primer value-added products. Egypt. J. Chem. Vol. 66, No. 11 pp. 53-61.

[7] Batista, E. M., Shultz, J., Matos, T. T., Fornari, M. R., Ferreira, T. M., Szpoganicz, B., de Freitas, R. A. & Mangrich, A. S. (2018). Effect of Surface and Porosity of Biochar on Water Holding Capacity Aiming Indirectly at Preservation of the Amazon Biome, Scientific Reports, vol. 8, no. 1.

[8] Liu W-J, Jiang H, Yu H-Q (2015). Development of biochar-based functional materials: toward a sustainable platform carbon material. Chem Rev 115:12251–12285. https://doi.org/10.1021/84. acs. chemrev.5b00195 84.

[9] Li S, Lyons-Hart J, Banyasz J, Shafer K (2001). Real-time evolved gas analysis by FTIR method: an experimental study of cellulose pyrolysis. Fuel 80:1809–1817. https://doi.org/10.1016/S0016- 2361(01)00064-3

[10] Yang, K., Torah, R. Wei, Y., Beeby, S., and Tudor, J., (2014). Water based PVA sacrificial material for low temperature MEMS fabrication and applications on e-textiles. Procedia Engineering 87.pp. 1565 – 1568

[11] Rocío López (2023). Enhancing textiles with biochar: Discover how biochar enhances fabric performance while contributing to sustainability. https://www.jord.one/blogs/enhancing-textiles-with-biochar.

[12] Marco Barbalini, Mattia Bartoli, Alberto Tagliaferro and Giulio Malucelli (2020). Phytic Acid and Biochar: An Effective All Bio-Sourced Flame Retardant Formulation for Cotton Fabrics. Polymers, 12(4), 811; https://doi.org/10.3390/polym12040811.

[13] Zhaoxia Liu, Wenjuan Niu, Wenjuan Niu, Heying Chu and Zhiyou Niu (2018). Effect of the Carbonization Temperature on the Properties of Biochar Produced from the Pyrolysis of Crop Residues. BioResources 13(2). DOI: 10.15376/biores.13.2.3429-3446**.**

[14] Ahmet Cay, Jale Yanik, Cigdem Akduman and Gozde Duman (2019). Application of textile waste derived biochar onto cotton fabric for improved performance and functional properties. Journal of Cleaner.

[15] Gokulan Ravindiran, Sivarethinamohan Rajamanickam, Gorti Janardhan , Gasim Hayder, Avinash Alagumalai, Omid Mahian, Su Shiung Lam and Christian Sonne (2024). Production and modifications of biochar to engineered materials and its application for environmental sustainability: a review. Biochar 6:62 https://doi.org/10.1007/s42773-024-00350-1.

[16] Ahmet Çay, Jale Yanık ,Çigdem Akduman ,Gozde Duman and Hasan Ertas, (2020). Application of textile waste derived biochars onto cotton fabric for improved performance and functional properties, Journal of Cleaner Production, 251, https://doi.org/10.1016/j.jclepro.2019.119664

[17] De Jesus, J. H., da S. Matos, T. T., da C. Cunha, G., Mangrich, A. S. & Romão, L. P. (2019). Adsorption of Aromatic Compounds by Biochar: Influence of the Type of Tropical Biomass Precursor, Cellulose, vol. 26, no. 7, pp.4291–4299.

[18] Lin, C. M. & Chang, C. W. (2008). Production of Thermal Insulation Composites Containing Bamboo Charcoal, Textile Research Journal, vol. 78, no. 7, pp.555–560.

[19] Uzma Younis, Tasveer Zahra Bokhari, Muhammad Farooq Qayyum, Saeed Ahmad Malik, Humaira Majeed, M. Hasnain Raza Shah and Athar Tariq, (2015). "Biochemical characterization of cotton stalks biochar suggests its role in soil as amendment and decontamination", American-Eurasian J. Agric. & Environ. Sci., 15 (11): 2304-2311.

[20] Ahmed Y. Elnour , Abdulaziz A. Alghyamah , Hamid M. Shaikh, Anesh M. Poulose , Saeed M. Al-Zahrani , Arfat Anis and Mohammad I. Al-Wabel, (2019). Effect of Pyrolysis Temperature on Biochar Microstructural Evolution, Physicochemical Characteristics, and Its Influence on Biochar/Polypropylene Composites, Appl. Sci., 9, 1149; doi:10.3390/app906114

[21] Schmidt, H.P., (2012). "uses of biochar". Ithaka J. ,1/2012, 286 - 289. http://refhub.elsevier.com/S0959-6526(19)34534-2/sref25

[22] Jost, K., Perez, C.R., McDonough, J.K., Presser, V., Heon, M., Dion, G., Gogotsi, Y., (2011). Carbon coated textiles for flexible energy storage. Energy Environ. Sci. 4, 5060e5067.

[23] Broadbent AD (2001). Basic Principles of Textile Coloration. Bradford: Society of Dyers and Colourists. p. 436-438, 496-499, 520-525, 528-541

[24] Kandhavadivu, P., Vigneswaran, C., Ramachandran, T., Geethamanohari, B., (2011). Development of polyester-based bamboo charcoal and lyocell-blended union fabrics for healthcare and hygienic textiles. J. Ind. Text. 41 (2), 142e159.

[25] Gunasekaran, G., Prakash, C., Periyasamy, S., (2019). Effect of charcoal particles on thermophysiological comfort properties of woven fabrics. J. Nat. Fibers. https://doi.org/10.1080/15440478.2019.1623745.

[26] Lin, C.M. and Chang, C.W., (2008). Production of thermal insulation composites containing bamboo charcoal. Text. Res. J. 78 (7), 555e560.

[27] BS 3702(1982): AMD 7004, method of test for determination of resistance of textile fabrics to surface wetting (spray test).

[28] ASTM D737-18(2023). Standard Test Method for Air Permeability of Textile Fabrics.

[29] Menezes E. and Choudhari, M. (2011). Pre-treatment of Textiles Prior to Dyeing, Rossari Biotech Ltd., Mumbai, India, chapter 11, 222-240 .

[30] Bipul RANA, Zahid HASAN, Azharul ISLAM, ROKONUZZAMAN, Shahjalal KHANDAKER, Mahbubul BASHAR (2022). Printing Effects of Different Natural Colourants on Cotton Fabric , TEXTILE & LEATHER REVIEW, 5 , 280-295.

[31] ASTM D4491/D4491M-22. Standard Test Methods for Water Permeability of Geotextiles by Permittivity.

[32] Kubelka, P., & Munk, F. (1931). Ein Beitrag zur Optik der Farbanstriche. Zeitung von Technologie und Physik, 12, 593.

[33] ISO 105-C10 (2006). Textile Tests for colour fastness Part C10: Colour fastness to washing with soap or soap and soda.

[34] ISO 105-E04 (2013). Textiles Tests for colour fastness, Part E04: Colour fastness to perspiration.

[35] ASTM D 5197-03 Test Method for “Determination of Formaldehyde and Other Carbonyl Compounds in Air (Active Sampler) .

[36] Snedecor, G. W. & Cochran, W. G. (1980). Statistical Methods. 7th Edition, Iowa State University Press, Ames.

[37] Inyang M., and Dickenson E. (2015). "The potential role of biochar in the removal of organic and microbial contaminants from potable and reuse water: A review," Chemosphere, vol. 134, pp. 232-240, 2015. DOI: http://doi.org/10.1016/j.chemosphere.2015.03.072.