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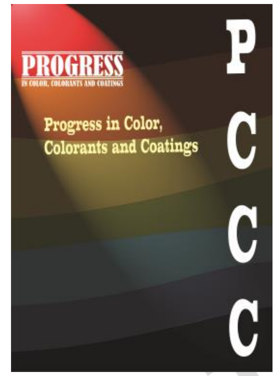

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Eco-Friendly Dyeing of Cotton Fabrics Using *Dalbergia sissoo* Wood Waste Extract and Bio-Mordants for Multifunctional Performance

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Abstract

Considering increasing environmental awareness, research has shifted towards the development of eco-friendly alternatives to synthetic dyes. This study analyzes the potential of *Dalbergia sissoo* wood waste, a natural dye source containing neoflavonoids, for use in 100% cotton fabric. The dye was applied using bio-mordants at 90 °C for 60 minutes without using other auxiliaries. The color strength (K/S) results showed that the dyed cotton fabric without any mordant provided a moderate K/S value of 1.5. However, the involvement of amla as a bio-mordant considerably increased the color intensity, resulting in a higher K/S value of 3.2. FTIR analysis confirms the intermolecular interactions between cotton fibers and dye molecules. The colored fabrics provided satisfactory fastness properties. The undyed fabric and dyed fabric without mordant displayed high moisture management ability (OMMC 0.8563 and 0.8657, respectively), while dyed fabrics mordanted with aloe vera, tamarind, myrobalan, and amla showed lower performance due to pore blockage by bio-mordant residues. The dyed fabric exhibited functional properties, including improved ultraviolet protection, and achieved a reduction of 52.4% in bacterial count compared to the undyed samples. Overall, the outcomes recommend that *Dalbergia sissoo* wood waste extract can be an effective natural dye for cotton fabric. Moreover, this approach offers an auxiliary-free dyeing process that aligns with eco-friendly textile practices and reduces the environmental footprint of conventional textile dyeing.

Keywords: Bio-waste, Auxiliary-free, Functionality, Antibacterial, Natural dye.

1. Introduction

In recent years, the textile industry has faced growing pressure to move towards environmentally friendly practices in the area of fabric dyeing. Conventional dyeing processes depend on synthetic dyes, which have caused considerable environmental and health issues. Their widespread use poses potential risks to both human health and the environment [1]. It is estimated that about 200,000 tons of synthetic dyes are discharged into wastewater each year, which is responsible for environmental pollution and risks to ecosystems with water quality [2, 3]. In response to this issue, there has been a growing global interest in natural dyes, which are obtained from renewable, biodegradable, and non-toxic materials such as agricultural residues, plant biomass, and wood waste for fabric dyeing [3].

Among other sources, colorants obtained from wood waste have attracted significant interest due to their renewable and non-toxic properties. Sawdust, a common byproduct produced during timber making, is disposed of through open burning. Such disposal practices are responsible for the greenhouse effect and environmental pollution. Converting sawdust into a value-added dye source promotes a practical approach to waste utilization. This approach also helps the principles of a circular economy by converting industrial byproducts into eco-friendly colorants for fabric dyeing. Previous studies on wood waste have reported promising shade depth and acceptable fastness ratings on both cotton and wool fabrics. However, most of these studies depended on metallic mordants, which generate toxic effluents and undermine the environmental advantages of natural dyeing. Mahogany wood has been investigated as a sustainable alternative for synthetic naphthol dyes, where alum was used as a fixing agent to achieve satisfactory color strength and fastness properties [4]. In a previous study by Mia et al., nonwoven cotton fabric was dyed with mahogany wood waste extract using metal salts, and the dyed fabrics showed good to excellent fastness properties [5]. Kandasamy et al used an ultrasound-assisted approach to extract dyes from Pterocarpus indicus sawdust for cotton dyeing, which is a complex extraction method [6]. Islam et al also used mahogany sawdust dye extract for cotton fabric, showing improvements in color fastness and color strength when metallic mordants were applied [7]. Rossi et al., in their work, dyed 100% cotton fabric using eucalyptus wood waste extract and achieved poor light fastness [8]. Sultana et al. dyed 100% cotton fabric using metal mordants and dye extract of Albizia procera sawdust, and found lower color fastness results [9]. Safapour et al. effectively utilized *Millettia Laurentii* carpentry sawdust waste as a sustainable natural dye source for wool coloration and UPF functionalization, with improved color strength, fastness, and functional properties through the use of metal salts [10].

Within this context, *Dalbergia sissoo* (commonly known as shishu or Indian rosewood) emerges as a particularly promising natural dye source. The wood waste from *D. sissoo* contains neoflavonoids, tannins and other phenolic compounds, which are responsible for fabric dyeing [11]. Neoflavonoids and other polyphenolic compounds contribute to producing deep brown to reddish hues on cotton fiber, due to their aromatic structures and the ability to form stable compounds [12, 13]. Cotton is composed of cellulose containing hydroxy groups that can possibly form hydrogen bonds with the neoflavonoid and phenolic compounds [14]. *D. sissoo* contains bioactive constituents that exhibit antibacterial and ultraviolet (UV) protective properties, indicating that fabrics dyed with this extract also provide enhanced antibacterial activity and improved ultraviolet protection factor (UPF) [15, 16].

Natural dyes derived from wood waste are gaining increasing importance in textile coloration due to their renewable origin, rich color potential, and eco-friendly characteristics. Nawaz et al used *D. sissoo* leaves to dye wool fabrics, where the metal mordant had a considerable impact on the dyed wool [17]. The study utilized different mordants, such as ferrous sulfate, alum, and stannous chloride, to enhance the dyeing process. The results indicated that the choice of mordant significantly influenced the color yield and fastness properties of the dyed wool [17]. Iqbal et al further investigated the dyeing of wool using bark extract from *D. sissoo* using bio-mordants, which were effective in enhancing both the color strength and fastness of the dyed wool [18]. However, its application to cotton, a cellulose-based fiber, remains largely unexplored. This research gap highlights an important opportunity for developing auxiliary-free dyeing approaches that eliminate the dependence on harmful synthetic dyes while promoting eco-friendly alternatives.

Therefore, this study focuses on extracting natural dye from *Dalbergia sissoo* wood waste and applying it to 100% cotton fabric using an auxiliary-free dyeing process. To increase dye affinity and fixation, bio-mordants like amla, myrobalan, aloe vera, and tamarind seed powder were used. These bio-mordants, rich in tannins with polyphenols and other bioactive compounds, not only promote improved color fastness but also contribute to the antibacterial activity, improved ultraviolet protection factor (UPF), and better moisture management (MMT) behavior of the dyed fabrics. The primary goal of this research is to establish an auxiliary free dyeing approach that utilizes wood waste, supports environmental conservation, and advances the development of eco-friendly multifunctional textile production.

2. Experimental

2.1. Materials

For this study, commercially available scoured and bleached 100% cotton single jersey knitted fabric with an areal density of 150 g/m² was sourced from Gildan Active Wear Ltd., Dhaka, Bangladesh. The *Dalbergia sissoo* wood waste (Figure 1), used as the natural dye source, was collected from a local sawmill. Natural mordants, including aloe vera (*Aloe barbadensis*) extract, tamarind (*Tamarindus indica*) seed powder, myrobalan (*Terminalia chebula*) seed powder, and amla (*Phyllanthus emblica*) seed powder, were procured from the local market and utilized during the dyeing experiments. Distilled water served both as the extraction medium for preparing the dye solution and as the dyeing medium. A commercial soaping agent (INDOCLEAN MFD), obtained from Hue and Chem Global Ltd., Bangladesh, was employed during the soaping process to ensure proper removal of unfixed dye.

Figure 1. Process sequence for dyeing cotton fabrics using Dalbergia sissoo wood waste.

2.2. Methods

2.2.1. Dye extraction

The wood waste was first sun-dried for 8 hours and then further dried under controlled room conditions to retain its natural color. Dye extraction was carried out by boiling 515 g of the dried wood waste in 5.15 L of distilled water at 90 °C for 1 hour, maintaining a material-to-liquor ratio of 1:10. The resulting solution was then filtered through filter paper to obtain the dye extract, which was subsequently used for the dyeing process [5].

2.2.2. Dyeing procedure

Dyeing was carried out on scoured and bleached 100% cotton samples (10 g each) using a laboratory dyeing machine (Xiamen Rapid Precision Machinery Co., Ltd., Taiwan). The fabrics were treated simultaneously [19] with the extracted dye solutions and bio-mordants at 90 °C for 60 minutes to ensure uniform dye uptake and mordant dye fiber interaction [20, 21]. The details of the dyeing conditions and corresponding sample codes for cotton fabrics treated with *Dalbergia sissoo* wood-waste extract are summarized in Table 1. Figure 1 illustrates the dyeing procedure for dyeing cotton fabrics with *Dalbergia sissoo* wood waste extract. Following dyeing, the bath was allowed to cool, and the liquor was drained. A soaping bath containing 2% soaping agent was then prepared, and the temperature was gradually raised to 70 °C. The fabrics were treated under the specified conditions for 15 minutes, after which the dye bath was allowed to cool naturally, and the liquor was subsequently discharged [22]. Finally, the dyed fabrics were dried at 80 °C for 5 minutes using a laboratory mini dryer (Xiamen Rapid Precision Machinery Co. Ltd., Taiwan) [23].

Table 1 provides the sample codes for the various dyeing conditions applied to cotton fabrics using *Dalbergia sissoo* wood waste.

Sample code	Fabric type	Mordant	Concentration of mordant (%)
S0	Undyed	N/A	N/A
S1	Dyed	Without mordant	N/A
S2	Dyed	Aloe vera	4%
S3	Dyed	Tamarind	4%
S4	Dyed	Myrobalan	4%
S5	Dyed	Amla	4%

2.3. Characterizations

2.3.1. Fourier transform infrared (FTIR) spectroscopy analysis

Fourier-transform infrared (FT-IR) spectroscopy (JASCO 4700, Japan) was used to analyze the chemical characteristics of dyed and undyed cotton fabrics. Spectra were recorded in transmission mode within the range of 4000-500 cm^{-1} [21, 24].

2.3.2. Assessment of colorimetric properties

The color strength and color difference of the dyed fabrics were evaluated using a Datacolor 650 spectrophotometer. Shade depth, expressed as the K/S value, was calculated according to the Kubelka–Munk equation 1, where K represents the absorption coefficient, S the scattering coefficient, and R the reflectance of the dyed fabric [25, 26] .

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

The color properties and depth of shade of the dyed fabric specimens were evaluated using a Datacolor 650 spectrophotometer. To assess the color characteristics, both CIE Lab and CIE LCh color coordinates were employed. The lightness of the fabric, ranging from black to white, is represented by the L* value on a scale from 0 to 100. In addition, the a* value indicates the redness–greenness axis, while the b* value corresponds to the yellowness–blueness axis, with no specific numeric limits. Furthermore, the color's brightness or dullness is quantified by the C* value, while the hue angle is represented by h* [27]. The color difference, or relative color strength, of the dyed fabric samples compared with the undyed control was determined using the CIE L*a*b* color coordinates, as described in equation 2.

$$(\Delta E^*)2= (\Delta L^*)2+(\Delta a^*)2+(\Delta b^*)2 \quad (2)$$

In the CIE L*a*b* color space, L* represents the lightness of the color, a* corresponds to the red-green axis, and b* reflects the yellow-blue axis [28].

2.3.3. Colorfastness properties

Wash fastness testing assesses the ability of dyed textiles to resist color during repeated washing. This evaluation is crucial for ensuring the durability and visual stability of the product. The wash fastness of the samples was examined according to the ISO 105-C10:2006 standard method [28, 29]. The perspiration fastness test evaluates the ability of dyed textiles to resist color change or staining when exposed to sweat. In this study, the test was performed according to the ISO 105-E04:2013 standard [30]. This test examines the influence of both acidic and alkaline perspiration on the color stability of dyed fabrics. Rubbing fastness evaluates the ability of dyed textiles to resist color that transfers from the dyed fabrics onto a standard test cloth under both dry and wet conditions. The assessment was performed using a crock meter in accordance with the ISO 105-X12:2016 standard [31]. Light fastness testing is essential for evaluating the durability of color in cotton fabrics dyed with natural dyes, as such dyes generally exhibit lower resistance to fading under sunlight or artificial light. In this study, the evaluation of light fastness was conducted according to the ISO 105-B02:2013 standard [32].

2.3.4. Moisture management performance

The moisture management properties of the fabrics were characterized using a Moisture Management Tester (Model M290, SDL Atlas Ltd.) according to the AATCC 195–2017 standard. This evaluation focused on several key parameters, including wetting time, absorption rate, maximum wetted radius, spreading speed, accumulative one-way transport index (AOTI), and overall moisture management capability (OMMC) [27].

2.3.5. Ultraviolet protection factor

Ultraviolet (UV) protection is an important functional property in textiles, as it helps to protect the wearer from the harmful effects of UV radiation. In this study, the UPF was analyzed over the 280–400 nm wavelength according to the BS EN 13758-1:2002 standard [33, 34].

2.3.6. Antibacterial activity

The antibacterial activity of both undyed and dyed cotton fabric against Staphylococcus aureus was assessed using the ASTM E2149-20 standard method [35, 21]. The evaluation was based on comparing the number of bacterial colonies formed on undyed and dyed fabric samples after incubation. Antibacterial property was represented as the percentage reduction in bacterial growth, calculated from the difference in colony counts between the two sets of samples [20]. The results were presented as inhibition percentages, calculated according to equation 3.

Reduction (%) = A – B / A * 100 …………. (3)

In this equation, A refers to the absorbance of the control sample without the inhibitor, while B represents the absorbance of the sample treated with the inhibitor.

3. Results and Discussions

3.1 FTIR analysis

As shown in Figure 2, the FTIR spectra of cotton fabrics dyed with *Dalbergia sissoo* wood-waste extract, both with and without bio-mordants, suggest chemical interactions between the dye molecules and the cellulose matrix. In RFD fabric, the peak at 3305 cm^{-1} shifts to 3301 cm^{-1} after dyeing, suggesting the possible formation of hydrogen bonds between the neoflavonoid chromophore and the hydroxyl group of cellulose [36]. The absorption peaks recorded at 2870 cm^{-1} in undyed cotton shifted to 2894 cm^{-1} in the dyed sample correspond to C–H stretching vibrations of aliphatic groups present in cellulose. The slight change in peak intensity after dyeing suggests the deposition of dye molecules. The peak at 1647 cm^{-1} in undyed cotton shifted to 1670 cm^{-1} in dyed fabric, which can be attributed to the presence of aromatic C=C stretching from neoflavonoid compounds in the dye extract [37]. Strong absorption peaks found around 1018 cm^{-1} for undyed cotton, which shifted to 1024 cm^{-1} after dyeing, represent the C-O-C and C-O stretching vibrations of cellulose and phenolic compounds. The increased intensity of these peaks in dyed fabric shows the presence of ether and phenolic groups from the wood waste extract, confirming the successful deposition of dye molecules onto the cotton fabric [38].

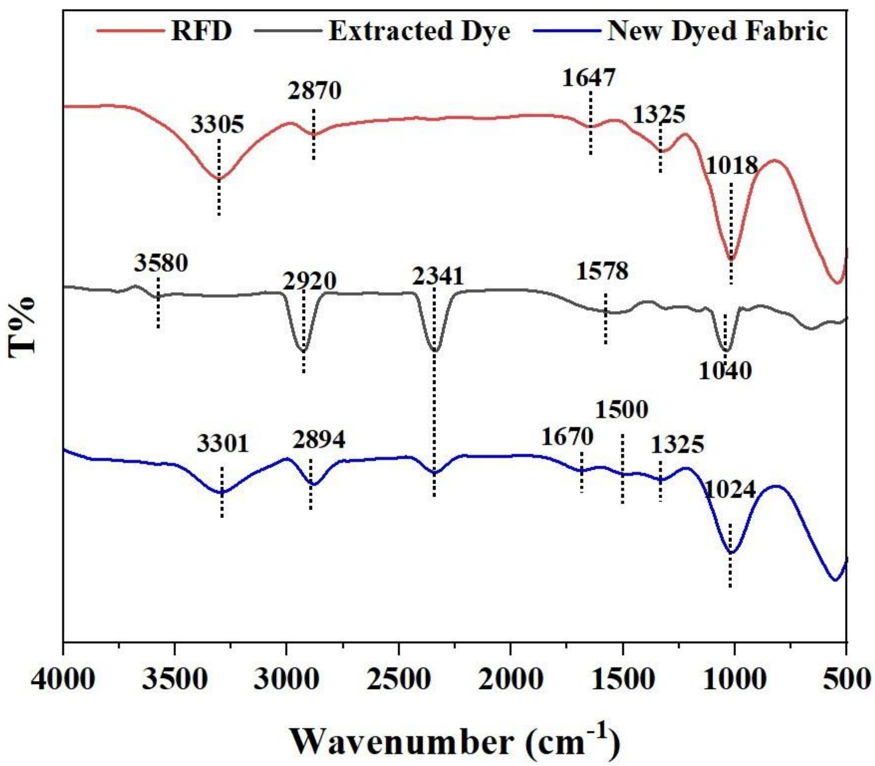

Figure 2. FTIR spectra of RFD (Ready for Dye), extracted dye, and dyed cotton.

As illustrated in Figure 3, neoflavonoids present in the *D. sissoo* extract are capable of forming possible hydrogen bonds and coordination-type linkages with the hydroxyl groups of cellulose, resulting in stable dye–fiber complexes. FTIR findings indicate that *D. sissoo* wood-waste extract possibly forms hydrogen-bond and coordinate interactions with cotton cellulose. These interactions are further strengthened by natural bio-mordants such as Aloe vera, Tamarind, Myrobalan, and Amla, contributing to improved color fixation and enhanced durability of the dyed fabrics [39-41]. The bio-mordants in the mordant-assisted dyeing process serve as a natural bridge between cotton cellulose and neoflavonoid dye molecules extracted from the *Dalbergia sissoo* wood waste.

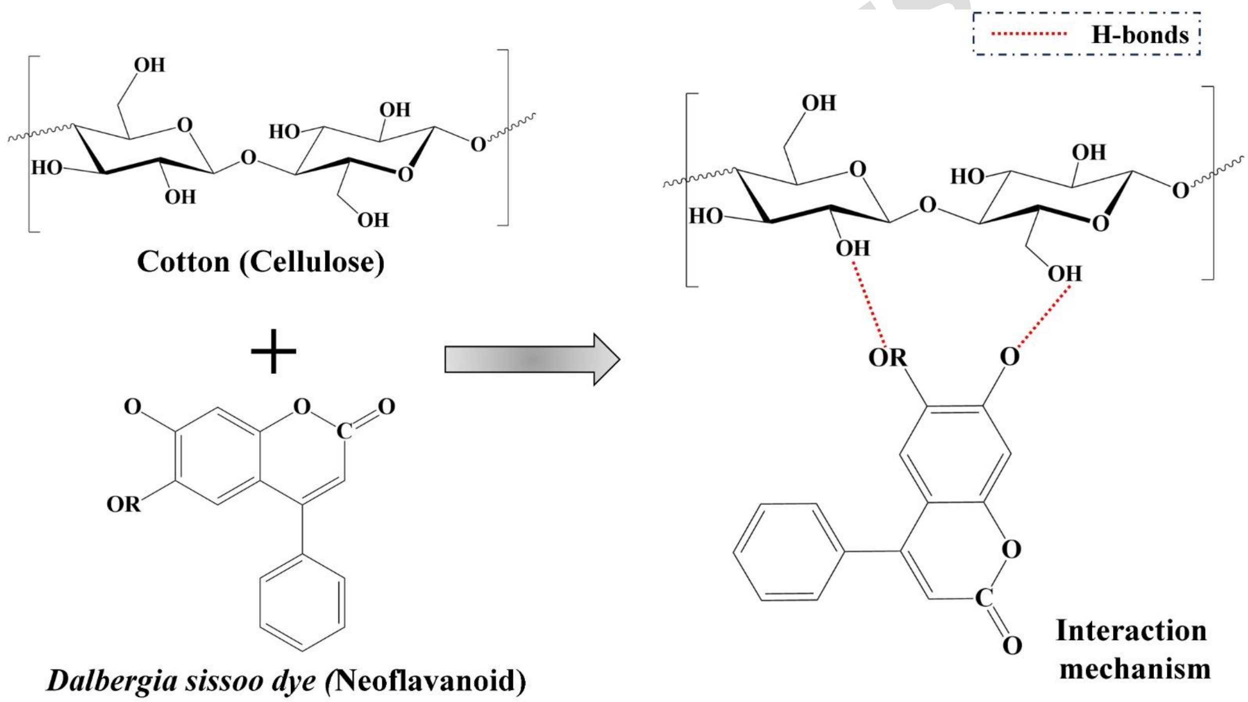

Figure 3. Possible bonding mechanics between the neoflavonoid of *Dalbergia sissoo* wood waste extract and cotton.

3.2. Color strength analysis

The color intensity of dyed fabrics was presented as K/S values, which are shown in Figure 4. Higher K/S values indicate darker shades; lower values are considered lighter shades. Dyed fabric without using any mordant received a K/S value of 1.5, showing a moderate shade depth due to direct dye-fiber interactions. When bio-mordants such as aloe vera, myrobalan, and tamarind were applied, the K/S values were slightly lower than those without mordanted fabric (1.2, 1.1, and 0.7, respectively), recommending that these mordants provided limited enhancement of dye affinity towards cellulose fiber, where amla provided a considerable improvement, as the highest K/S value was achieved at 3.2. This enhancement is attributed to the high tannin and polyphenolic content of amla, which facilitates the possible formation of hydrogen bonds between the dye molecules and the hydroxy groups of cellulose [11]. Similar results have been reported in previous research, where bio-mordants with high polyphenol content, like amla and myrobalan, were found to improve both the shade depth and the fastness properties of dyed fabrics [38, 39]. The superior performance of amla in this case demonstrates its ability to strengthen the interaction between *Dalbergia sissoo* extract and cotton fibers, while the weaker results for other mordants may be due to less effective binding or surface deposition rather than deeper penetration into the fiber structure.

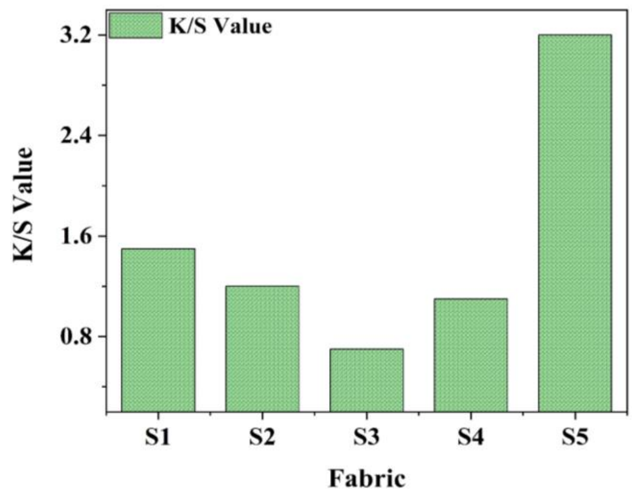

Figure 4. Assessment of the color strength of cotton fabrics dyed using *Dalbergia sissoo* wood waste extract

3.3. CMC (Color Measurement Committee) value analysis

Table 2 shows the color difference results for cotton fabrics dyed with *D. sissoo* wood waste, demonstrating considerable changes in color characteristics among the samples. The undyed sample (S1) provided the maximum color difference (ΔE^* = 23.38) with a drop in lightness (ΔL^* = –27.86), indicating adsorption and dye fiber interactions. In comparison, the bio-mordanted fabrics provided much lower ΔE^* values, recommending that the mordants helped to offer more even shade formation by increasing dye fiber bonding. Among the treated samples, myrobalan mordanted fabric (S4) showed the lowest ΔE^* (13.43), pointing towards improved color consistency and reduced shade variation. Tamarind-mordanted sample (S3) also produced a stable chromatic profile by achieving a deeper shade. Amla mordanted fabric (S5) showed the deepest shade (ΔL^* = –41.82) but moderate chromaticity, indicating high dye uptake with reduced brightness. The reduced hue variations (Δh^*) among bio-mordanted samples indicate improved hue constancy, confirming the role of phenolic and tannin-rich compounds, which stabilize dye fiber complexes and improve color uniformity [38, 40, 41]. Figure 5 presents the shade card of both undyed and dyed fabric samples with *D. sissoo* wood-waste extract.

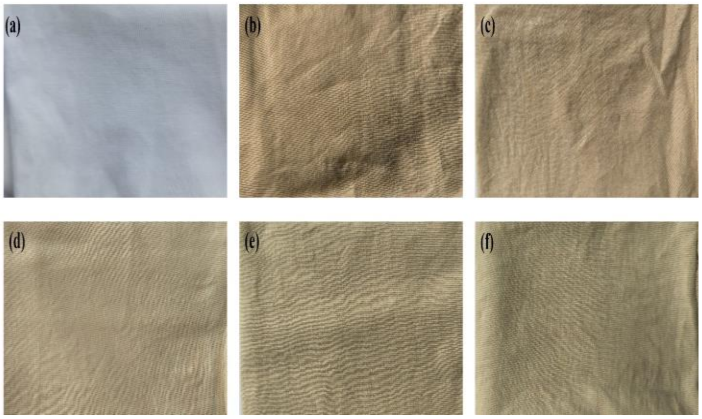

Figure 5. Shade card of undyed and dyed fabric samples with *Dalbergia sissoo* wood waste, where (a) to (f) sections represent the sample codes from S0 to S5, respectively.

Table 2. Color measurement committee (CMC) report of cotton fabric dyed with *Dalbergia sissoo* wood waste.

Sample code	ΔE*	ΔL*	Δa*	Δb*	ΔC*	Δh*
S1	23.38	-27.86	6.08	9.26	10.58	-3.29
S2	14.05	-22.90	5.14	8.93	9.89	-2.90
S3	13.88	-16.06	5.42	9.93	10.92	-2.95
S4	13.43	-20.85	2.95	9.73	10.04	-1.64
S5	16.03	-41.82	2.28	5.81	6.06	-1.49

3.4. Color fastness properties

3.4.1. Color fastness to wash

Table 3 shows the wash fastness of dyed fabric, achieving a grade from 3 to 3/4 on the grey scale, indicating moderate to good resistance to washing. Sample S1 received a grade of 3 due to the limited affinity between the dye molecules and the cotton cellulose. In this case, the dye fixation depends on weaker interactions such as hydrogen bonding and Van der Waals forces [42]. Sample S2 also received a wash fastness grade of 3, indicating that its polysaccharides and organic acids provided a lower improvement in dye-fiber interactions. Aloe vera can act as a mild natural mordant. Its lower content of tannins and phenolic compounds causes moderate dye fixation [43]. In contrast, samples S3 and S4 showed improved wash fastness grades of 3-4. This improvement has occurred due to the higher tannin content present in tamarind seed coat and myrobalan, which enables the formation of possible hydrogen bonding interactions between the dye molecules and the hydroxy groups of cellulose. These interactions help to enhance color retention [38]. Sample S5 provided a wash fastness grade of 3, similar to Sample S1. However, it showed excellent grading for color staining (grades 4-5) on multifiber fabrics, indicating that the dye was well-fixed on the cotton [44]. The results highlight that tannin-rich bio-mordants, myrobalan and tamarind, received wash fastness grades of 3-4. This improvement can occur due to the crosslinking between tannins and cellulose, which enhances dye fixation on the cotton fibers and improves color retention [45, 46]. This interaction provides the attachment of the dye molecules, which strengthens the fabric's ability to retain color, as evidenced by the improved color strength and wash fastness of dyed fabrics, whereas aloe vera and amla provide only marginal benefits compared with the untreated fabric. Overall, *D. sissoo* wood-waste extract showed consistent and stable coloration when bio mordants used during dyeing. Similar results were received by Iqbal et al, who found that *D. sissoo* extract with tannin-rich natural mordants significantly improved the wash fastness of the dyed fabrics [18].

Table 3. Evaluation results of wash fastness for the dyed cotton fabrics.

Sample code	Grading for color change	Grading for color staining					
		Acetate	Cotton	Nylon	Polyester	Acrylic	Wool
S1	3	4-5	4-5	4-5	4-5	4-5	4-5
S2	3	4-5	4-5	4-5	4-5	4-5	4-5
S3	3-4	4-5	4-5	4-5	4-5	4-5	4-5
S4	3-4	4-5	4-5	4-5	4-5	4-5	4-5
S5	3	4-5	4-5	4-5	4-5	4-5	4-5

3.4.2. Color fastness to perspiration

Table 4 presents the perspiration fastness of dyed cotton fabrics, with ratings ranging from 4 to 4/5 on the grey scale under both acidic and alkaline conditions. Sample S1 ensured a stable rating of 4 in both acidic and alkaline conditions, indicating a moderate level of resistance to color changes by perspiration [40]. Sample S1 provided moderate color stability, which can be attributed to weak hydrogen-bonding interactions between the dye molecules and the hydroxy groups of cellulose [40]. The aloe vera mordanted sample (S2) received ratings of 4 under both acidic and alkaline conditions, indicating lower improvement compared to the undyed sample. This observation matches with previous studies, which have shown that aloe vera provides only moderate enhancements in fastness, largely due to its polysaccharide composition [47]. Sample S3 showed a moderate improvement, maintaining a grade of 4 under alkaline conditions and increasing to 4/5 in acidic perspiration, which suggests that the tannin content in this sample enhanced the stability of the dye fiber interactions [36]. Sample S4 provided consistent ratings of 4 in both acidic and alkaline conditions, indicating satisfactory performance. The highest ratings were found for sample S5, which received 4/5 under both acidic and alkaline conditions. The performance occurred due to the high tannin content of amla, which enables the formation of stable complexes with the dye molecules and the hydroxy groups of cellulose. These interactions help to enhance color retention when the fabric is exposed to perspiration [36, 38]. Overall, these results recommend that tannin-rich mordants such as amla (S5) promote the most reliable improvement in perspiration fastness, while tamarind (S3) shows enhancement in acidic conditions, and aloe vera (S2) and myrobalan (S4) provide stability without significant improvement [36, 48].

Table 4. Test results for the Color fastness of dyed cotton samples against perspiration in both acidic and alkaline conditions

Sample code	Color fastness to perspiration (acidic)							Color fastness to perspiration (alkaline)						
	Color change	Grading for color staining						Color change	Grading for color staining					
		Acetate	Cotton	Nylon	Polyester	Acrylic	Wool		Acetate	Cotton	Nylon	Polyester	Acrylic	Wool
S1	4	4	3-4	3-4	4	4	4	4	4	3-4	3-4	4-5	4-5	4-5
S2	4	4	4	4	4-5	4-5	4	4	4-5	4	4	4-5	4-5	4
S3	4-5	4-5	4-5	4	4-5	4-5	4	4	4-5	4	4	4-5	4-5	4
S4	4	4-5	3-4	4	4-5	4-5	3-4	4	4-5	4-5	4-5	4-5	4-5	4
S5	4-5	4-5	4	4-5	4-5	4-5	4	4-5	4-5	4	4	4-5	4-5	3-4

3.4.3 Color fastness to rubbing and light

As presented in Table 5, the rubbing fastness of cotton fabrics dyed with *Dalbergia sissoo* wood-waste extract ranged from grade 3 to 4/5 on the grey scale, both under dry and wet conditions. In dry rubbing, all the fabrics, including sample S1 as well as the mordanted fabrics (S2-S5), achieved consistent ratings of 4/5, reflecting good resistance to surface dye transfer [37]. Under wet rubbing, however, a noticeable reduction was observed for the fabric without mordant (S1), which dropped to grade 3, indicating weaker dye–fiber adhesion in the absence of mordants. Conversely, the mordanted samples (S2–S5) exhibited enhanced color stability, with all samples achieving a rating of 4 under wet conditions, indicating strong resistance to color fading and staining during washing. This improvement can be attributed to the presence of polyphenolic compounds in tamarind, myrobalan, and especially amla, which facilitate the possible formation of hydrogen bonds and coordination complexes with dye molecules and cellulose, thereby enhancing dye fixation and minimizing color loss during mechanical abrasion [36, 38],

[39]. In comparison, the performance of aloe vera (S2) was slightly more modest, as its polysaccharide-rich composition provides hydroxyl and carboxyl groups for hydrogen bonding but lacks the high density of tannins present in amla and myrobalan, resulting in relatively weaker improvement [49, 50]. The results clearly indicate that tannin-rich bio-mordants, particularly amla (S5) and myrobalan (S4), exhibited superior performance in enhancing the wet rubbing fastness of the dyed cotton fabric, while aloe vera (S2) provides only partial enhancement compared with these stronger bio-mordants [36-38].

As shown in Table 5, the light fastness of cotton fabrics dyed with *Dalbergia sissoo* wood-waste extract ranged between grades 2/3 and 4 on the grey scale. Samples S1 and S2 both recorded lower ratings of 2/3, indicating weaker stability of the dye when exposed to light. This reduced resistance can be attributed to the absence of strong mordant–dye–fiber linkages in S1 and the limited number of phenolic groups in aloe vera, which fail to provide effective light fastness [45, 49]. In contrast, Sample S3 received the highest light-fastness rating of 4, which indicates improved stabilization of the dye molecules against photodegradation. This improvement has occurred due to the higher tannin content present in tamarind, which creates crosslinking between tannins and cellulose, which enhances dye fixation on the cotton fibers and improves color retention [36, 50]. Samples S4 and S5 both received light-fastness ratings of 3/4, indicating better resistance than S1 and S2, though slightly lower than S3. The improved performance of these samples can be attributed to the high content of hydrolysable tannins in amla and myrobalan, which facilitates the formation of bonds between the dye molecules and the hydroxy groups of cellulose, thereby enhancing color stability under light exposure [37], [39]. Overall, the findings indicate that tannin-rich mordants, including tamarind, myrobalan, and amla, are more effective in enhancing light fastness, whereas aloe vera provides only minimal improvement, compared to the fabric without mordant [36, 38].

Table 5. Evaluation outcomes of color fastness to rubbing and light of dyed cotton fabrics.

Sample code	Grading for color fastness to rubbing		Grading for color fastness to light
	Dry	Wet	
S1	4-5	3	2-3
S2	4-5	4	2-3
S3	4-5	4	4
S4	4-5	4	3-4
S5	4-5	4	3-4

3.5. Moisture management performance

3.5.1. Impact of wetting time

Figure 6 illustrates the wetting time (seconds) for both the top and bottom surfaces of cotton fabrics dyed with *Dalbergia sissoo* wood-waste extract (samples S0–S5). Wetting time refers to the duration required for the fabric surface to begin absorbing moisture. Shorter times indicate faster liquid uptake and better initial wettability. As shown, all fabrics exhibited faster wetting on the bottom surface compared to the top, confirming directional moisture transfer within the fabric structure. Sample S1 and S2 fabrics demonstrated relatively shorter wetting times on both surfaces, suggesting enhanced hydrophilicity and effective capillary absorption due to minimal surface obstruction. In contrast, sample S5 displayed the longest wetting time on the top surface, indicating reduced surface energy and delayed moisture absorption, likely resulting from the presence of bio-mordant residues that partially blocked fiber pores. These findings align with the results of Matusiak et al., who observed that surface modification and finishing agents can significantly influence fabric wettability and moisture transport behavior [51]. Furthermore, Fan et al. reported that natural bio-finishes can alter surface polarity and capillary flow, thereby affecting wetting kinetics in cotton-based textiles [52].

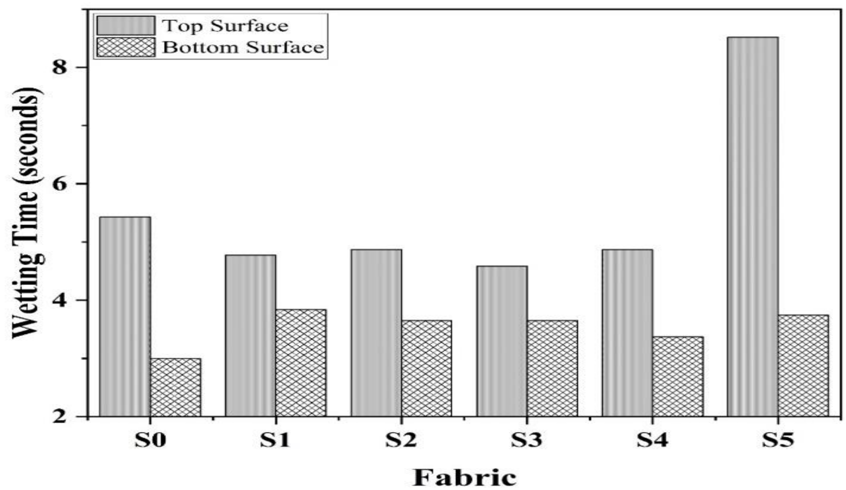

Figure 6. Wetting time (seconds) of cotton fabrics dyed with *Dalbergia sissoo* wood-waste extract.

3.5.2. Influence on the rate of absorption

Figure 7 presents the absorbency rates (%) of the top and bottom surfaces of cotton fabrics treated with *Dalbergia sissoo* wood-waste extract for samples S0–S5. Consistently, the bottom surface showed higher absorbency compared to the top surface across all samples, reflecting effective wicking and one-way liquid transport through the fabric structure. Samples S1 and S2 exhibited slightly higher absorbency rates, which may be attributed to their less obstructed pore pathways and more open surface morphology, facilitating faster moisture migration. By contrast, sample S5 recorded noticeably lower absorbency on both surfaces, likely due to partial blockage of capillary channels by deposited bio-mordant residues, mirroring the reduced moisture management capability observed in the MMT test for this sample. These observations align with recent findings that surface chemistry and pore architecture significantly influence moisture transport behavior in textiles [53, 54].

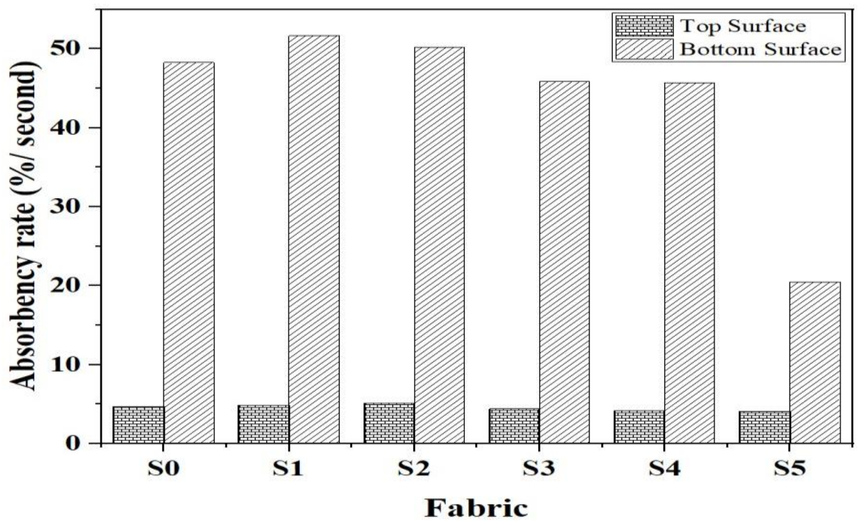

Figure 7. Absorbency rate (%/ second) of cotton fabrics dyed with *Dalbergia sissoo* wood-waste extract.

3.5.3. Impact on maximum wetted radius

Figure 8 illustrates the maximum wetted radius (mm) for both the top and bottom surfaces of cotton fabrics dyed with *Dalbergia sissoo* wood-waste extract (samples S0–S5). The wetted radius represents the spreading ability of moisture across the fabric surface. A higher value indicates greater moisture distribution and enhanced comfort performance. As observed, the bottom surfaces of all samples generally exhibited a slightly higher wetted radius compared to the top surfaces, confirming the presence of one-way liquid transport from the inner to the outer fabric layer. Sample S1, S2, and S4 fabrics maintained nearly equal and higher moisture spread across both surfaces, signifying efficient capillary action and uniform wetting. In contrast, sample S5 displayed the lowest wetted radius on both surfaces, suggesting that the deposition of bio-mordant residues partially blocked the pores and capillary channels, thereby restricting lateral moisture diffusion. This reduction in wetted radius after bio-mordanting aligns with prior findings that natural bio-extracts containing polyphenols and tannins can modify fiber surface energy and reduce hydrophilicity, leading to slower moisture spreading [55]. Similarly, Amir et al. emphasized that moisture management behavior strongly depends on fabric porosity, surface chemistry, and the presence of finishing agents, which collectively influence wetting and spreading characteristics [56].

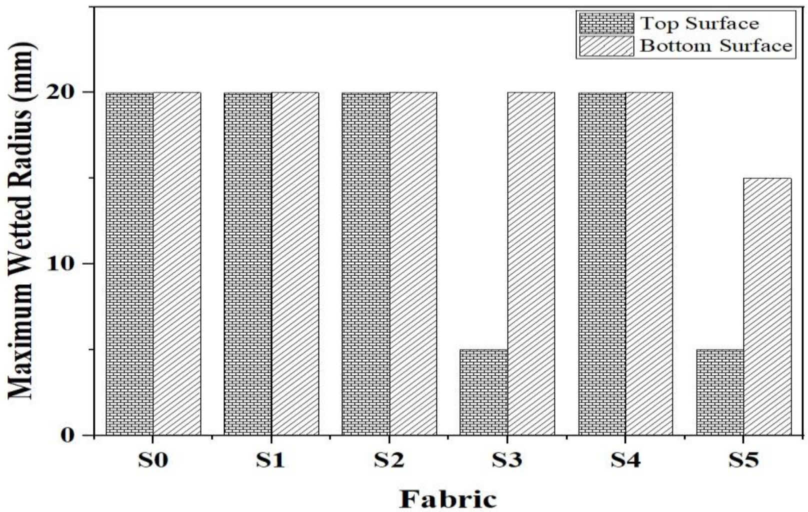

Figure 8. Maximum wetted radius (mm) of cotton fabrics dyed with *Dalbergia sissoo* wood-waste extract.

3.5.4. Influence on spreading speed

Figure 9 illustrates the moisture spreading speed (mm/sec) for the top and bottom surfaces of cotton fabrics dyed with *Dalbergia sissoo* wood-waste extract (samples S0–S5). Spreading speed represents the rate at which moisture disperses across the fabric surface. A higher value reflects faster liquid transport and improved comfort performance. As shown, the bottom surfaces consistently exhibited slightly higher spreading speeds than the top surfaces, indicating effective one-way liquid transport within the fabric structure. Samples S0 and S1 achieved the highest spreading speeds (4.2-4.4 mm/sec), demonstrating optimal moisture mobility due to an open porous structure and the absence of surface residues. Conversely, Sample S5 and S3 fabrics showed the lowest spreading speeds, suggesting that the deposition of natural polyphenolic compounds from the bio-mordants partially obstructed surface capillaries, impeding moisture diffusion. These findings align with prior research indicating that hydrophilic surfaces and adequate pore connectivity enhance wicking and moisture transport, whereas bio-based finishes may reduce spreading efficiency by altering surface energy [57]. Similarly, Shahzad and Fan highlighted that the spreading speed in cotton fabrics depends strongly on fiber porosity, surface chemistry, and finishing effects that modify wetting behavior [58].

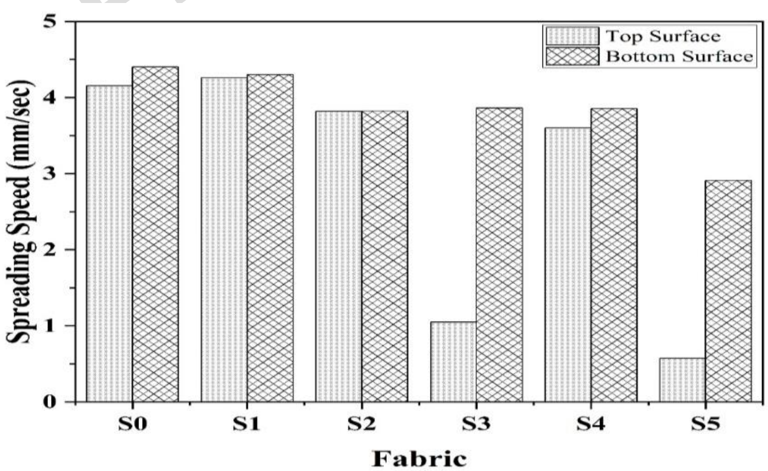

Figure 9. Spreading speed (mm/sec) of cotton fabrics dyed with *Dalbergia sissoo* wood-waste extract.

3.5.5. Impact on Accumulative One-Way Transport Index (AOTI)

Figure 10 presents the AOTI value for cotton fabrics dyed with *Dalbergia sissoo* wood-waste extract. This parameter indicates the fabric's ability to transport moisture from the inner (skin-facing) surface to the outer (environment-facing) surface. A higher AOTI value reflects more efficient liquid transfer and better moisture management performance. As observed, Sample S1 and S2 fabrics exhibited the highest AOTI values, suggesting superior one-way liquid transport. This behavior can be attributed to their relatively open pore structure and enhanced hydrophilicity, which facilitate capillary-driven moisture movement. In contrast, sample S5 displayed a substantially lower AOTI value, indicating restricted moisture transmission through the fabric. This reduction is likely due to the deposition of tannin-rich bio-mordant residues on the fiber surface, which can reduce pore size and hinder moisture diffusion. These results are consistent with the findings of Matusiak et al., who reported that fiber surface chemistry and fabric microstructure significantly influence one-way liquid transport efficiency in cotton fabrics [59]. Furthermore, Shahzad and Fan et al. demonstrated that natural finishes and surface coatings can modify wicking behavior and diminish accumulative one-way transport capacity by altering inter-fiber capillarity [60].

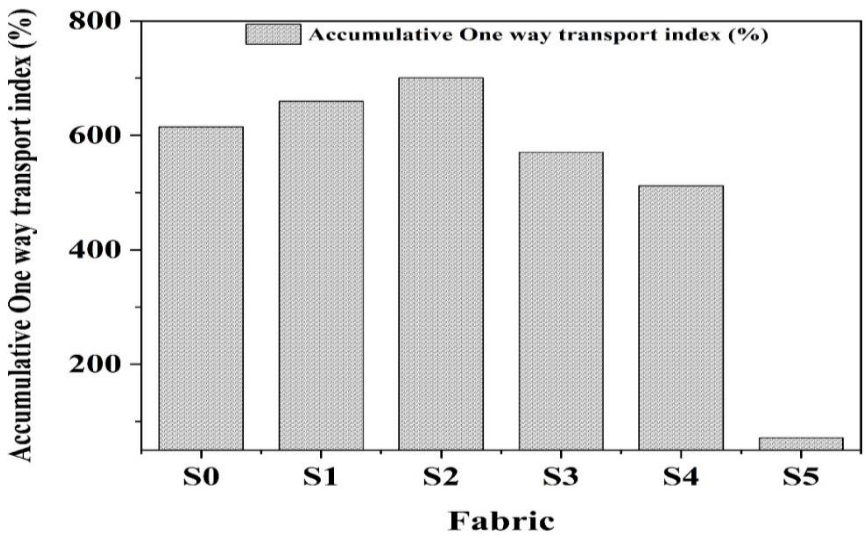

Figure 10. Accumulative one-way transport index (%) of cotton fabrics dyed with *Dalbergia sissoo* wood-waste extract.

3.5.6. Influence on Overall Moisture Management Capability (OMMC)

The OMMC of cotton fabrics dyed with *D. sissoo* wood-waste extract is presented in Figure 6. The undyed fabric (S0) provided an OMMC value of 0.8563, which decreased slightly during dyeing and mordanting treatments. Sample S1 recorded a slightly higher value of 0.8657, indicating that the dye molecules alone did not considerably restrict the capillary moisture transport of cotton. On the other hand, the mordanted fabrics showed lower OMMC values: aloe vera (S2) showed 0.8468, tamarind (S3) showed 0.8380, myrobalan (S4) showed 0.8370, and amla (S5) showed the lowest performance at 0.8231. This decline in moisture transport is likely due to the deposition of polyphenolic compounds and other bio-mordant deposits on the fiber surface, which partially block the capillary pores, reduce surface wettability, and slow liquid transfer. The effect was pronounced in the amla-treated fabric (S5), where the high content of hydrolysable tannins possibly forms a thin coating on the fiber surface, limiting moisture transfer efficiency [36, 38]. Similar results were observed in previous studies, where natural dyeing combined with bio-mordanting enhanced color strength and fastness, simultaneously reducing the moisture transport capacity of cotton fabrics due to partial pore blockage and alterations in fiber surface characteristics [37, 39]. Overall, these results indicate that although bio-mordants improve color fastness, they may reduce the moisture management capability of the fabric, with the degree of this balance mainly depending on the mordant type and its concentration [45].

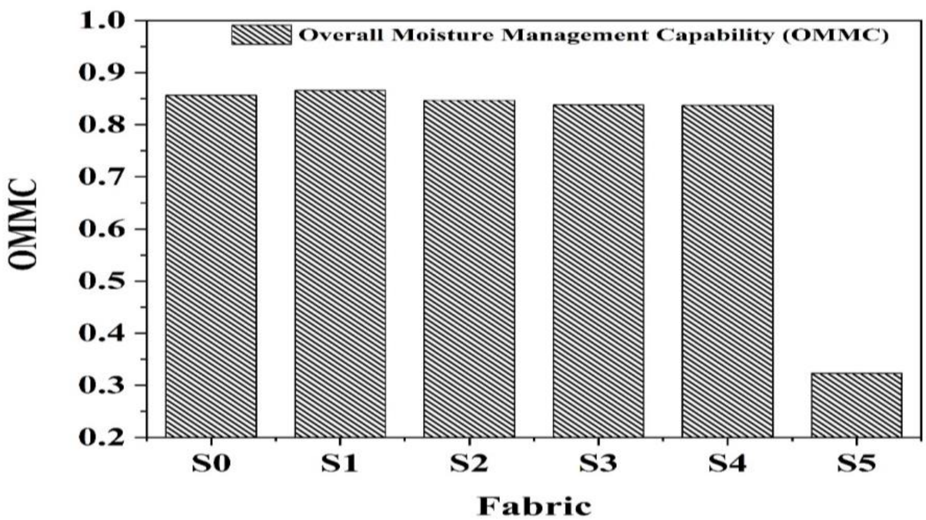

Figure 11. OMMC value of cotton fabric samples treated with *Dalbergia sissoo* wood-waste extract.

3.6. Ultraviolet protection factor analysis

Ultraviolet radiation can significantly degrade natural dyes, and factors such as fiber type, fabric structure, thickness, dyeing and finishing processes, shade depth, and added auxiliaries all play an important role in determining the UV-absorbing ability of textiles [16]. The undyed cotton fabric provided a UPF value of 10, classifying it as poor UV protection (UPF < 15), with only limited protection due to its low UV absorption. After dyeing with *D. sissoo* wood-waste extract, the UPF increased to 42, representing a considerable improvement in UV-blocking performance. This enhancement evaluates the dyed fabric as an excellent UP protection category (UPF 40–50), indicating much more effective sun protection. The phenolic and neoflavonoid compounds present in the *D. sissoo* extract work as natural UV absorbers within the cotton fiber, functioning as UV filters. The dyeing offered uniform deposition of the extract, increasing the effective path length of UV photons and enhancing light screening. The darker shade of the dyed fabric is responsible for UV absorption, while the strong interactions between the dye molecules and cellulose fiber form a continuous protective layer, boosting the fabric's UV-blocking efficiency. Previous studies have also reported that the use of bio-mordants can provide additional protection against ultraviolet radiation [16, 61, 62, 53].

3.7. Antibacterial properties analysis

Given the increasing demand for multifunctional textiles in clinical and protective applications, exploring the antibacterial properties of plant-based natural colorants is both relevant and timely, considering their well-established therapeutic benefits. Many plants contain phenolic compounds and neoflavonoids in their microstructures, which play a key role in their natural defense against pathogens. The concentration of these compounds significantly affects the plant species' intrinsic resistance to microbial attack [63]. These compounds can penetrate the fabric surface, forming a protective barrier that inhibits the growth and spread of germs, even after multiple washes. Additionally, the interaction between these compounds and the cellulose fibers may further enhance the fabric's resistance to bacterial colonization [64]. The sample dyed with *Dalbergia sissoo* wood waste extract without mordant was assessed for its ability to inhibit the growth of the

Gram-positive bacterium *Staphylococcus aureus*. This bacterium is commonly found in the skin, nose, and respiratory tract of both humans and animals and is known for its potential to cause infections [56]. Cotton fabric dyed with *Dalbergia sissoo* wood-waste extract, even in the absence of any mordant, achieved a bacterial reduction of 52.4%, highlighting the intrinsic bioactivity of the phytochemicals present in the extract, as seen in Figure 12. This improvement can be attributed to the presence of neoflavonoids, which are known to disrupt bacterial cell-wall integrity, interfere with enzymatic pathways, and impair vital metabolic processes, ultimately leading to cell death [65, 66]. Neoflavonoids, as natural polyphenols, exhibit broad-spectrum antibacterial action by forming stable complexes with microbial proteins and polysaccharides, thereby restricting microbial growth and colonization [65]. The affinity of these polyphenolic compounds toward cellulose fibres further contributes to their durability. By penetrating the fabric matrix, these compounds form strong interactions that remain effective over laundering, thereby enhancing the long-term antibacterial performance of the dyed cotton [60]. In contrast, undyed cotton fabric exhibited 0% bacterial reduction, reflecting the natural vulnerability of cellulose fibres to microbial colonization. This susceptibility is primarily due to their hydrophilic character and high surface area, which create favorable conditions for bacterial adhesion and growth [66]. The natural mordants used in this study can further improve the antibacterial property of dyed cotton fabric, as mentioned in the earlier works [62-65].

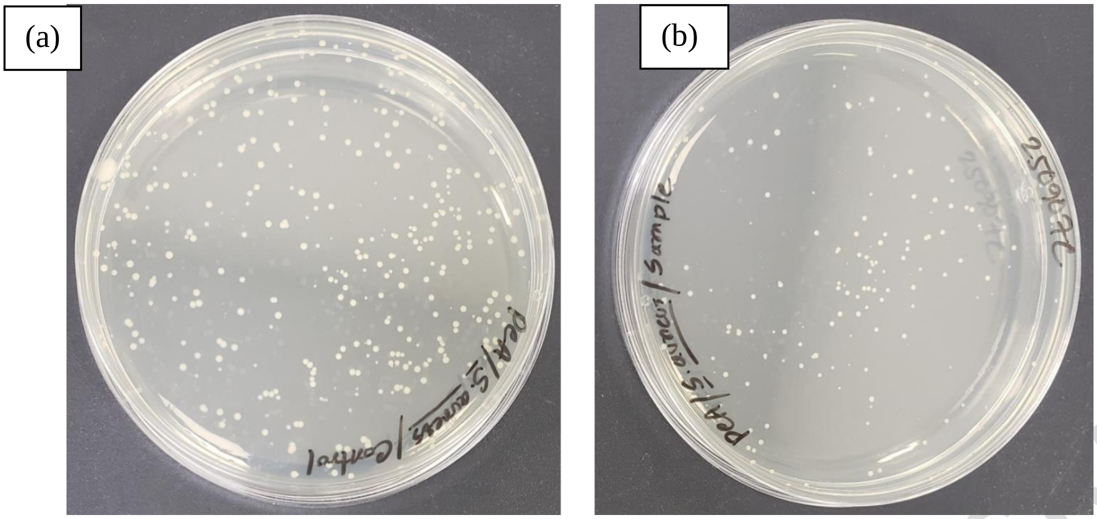

Figure 12. Assessment of antibacterial activity of the dyed fabric samples against *S. aureus*: (a) Undyed cotton sample, (b) Sample dyed with wood waste

4. Conclusion

This study demonstrated a chemical-free and eco-friendly approach to dyeing 100% cotton fabric using *Dalbergia sissoo* wood-waste extract. The dyeing process was carried out without synthetic auxiliaries, relying only on natural bio-mordants such as aloe vera, tamarind, myrobalan, and amla. Colorimetric evaluation revealed that mordanting had a notable effect on shade depth, with amla-treated samples showing the highest K/S value of 3.2, followed by aloe vera, myrobalan, and tamarind. FTIR analysis confirmed the interaction between the neoflavonoid in the dye extract and the hydroxyl groups of cotton, indicating the possible formation of new bonds, as seen in the FTIR analysis. Overall, the dyed fabrics exhibited satisfactory fastness properties. Wash fastness ranged from 3 to 3/4, perspiration fastness remained consistent at around good to excellent under both acidic and alkaline conditions, and rubbing fastness was good, with dry rubbing at 4/5 and wet rubbing of 3 to 4. Light fastness was moderate, with tamarind and amla mordanted fabrics providing relatively better resistance against light exposure. Moisture management results showed that mordanting slightly reduced the moisture management property compared to the undyed and the sample without mordant, which may be attributed to partial pore blockage by bio-mordant residues. Importantly, antibacterial testing confirmed that fabrics dyed with *Dalbergia sissoo* extract achieved a 52.4% reduction in *Staphylococcus aureus*, whereas untreated cotton showed no activity. Moreover, the without mordant dyed sample have demonstrated outstanding improvement in the ultraviolet protection compared to undyed samples. This indicates that *Dalbergia sissoo* wood waste extract not only can be an eco-friendly source of natural dye but also can impart functionality to the dyed cotton fabric, which broadens the application area of the dyed cotton fabric. However, this study focuses on extracting natural dye from sawdust. As the properties of wood can vary over time, it is difficult to maintain uniformity in the extracted dye from the sawdust, which may vary with time. Hence, proper attention should be given to collecting the sawdust and the dye extraction process to maintain the consistency of the process. Additionally, future studies should be focused on standardizing the dyeing process.

Looking forward, future research should aim to improve the light fastness and wet rubbing performance of *Dalbergia sissoo* dyed fabrics, possibly through optimized mordanting strategies or eco-friendly post-treatments. Techniques such as enzymatic or plasma surface modification could further strengthen dye–fiber interactions, enhancing durability. Combining *Dalbergia sissoo* extract with other agro-waste-based natural dyes may also broaden the shade range while introducing additional functionalities. Future studies should also investigate the tannin composition, concentration, and chemical characteristics to better understand their specific influence on mordanting performance, dye fixation, antibacterial behavior, and UV-protective properties. On a larger scale, industrial adoption of this process has the potential to transform wood waste into a sustainable dye source, reducing the environmental footprint of textile dyeing while producing multifunctional fabrics with antibacterial and UV protection properties suitable for protective and healthcare applications. This study, focusing on extracting natural dye from *Dalbergia sissoo* wood waste and applying it to 100% cotton fabric through an auxiliary-free dyeing process, highlights the dual benefits of valorization of waste material alongside enhancement of the functionality of textile fabrics.

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