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RESEARCH ARTICLE

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Eco-sustainable printing of cellulosic polymeric material using bio-colorants and bio-crosslinkers

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Abstract

A sustainable solution to lessen environmental damage, improve health and fulfill the increasing need for environmentally conscious goods might be for the textile industry to use eco-friendly printing techniques and natural colors. Without the use of toxic metal-based mordants, this research work set out to examine how natural thickeners, biomordants, and dyes interacted when printed on cotton knit fabric. Two natural dyes from natural resources leaves Jujube leaves (JL) and Eucalyptus bark (EB) were extracted in an aqueous medium. A printing paste was produced using different proportions of two bio-mordants. For an eco-friendly printing process, tamarind seeds, and Indian gooseberries were used that have been extracted using a Soxhlet apparatus at 80°C for 8 h. All but a handful of samples using natural binders showed outstanding fastness in the printed sample which was graded 4 or 5. The development of the dye-fiber bond was indicated by the presence of an intense covalent bond between the dye and fiber molecules as indicated by FTIR. The CMC lab data and K/S value of the printed samples were also obtained satisfactorily with maximum RFL value 77.319 and K/s value 1.659. This method not only lessens the environmental impact of the sector but also supports a better and more ecologically sensitive manufacturing technique. Moreover, sustainable apparel, household textiles, technical fabrics, and environmentally friendly packaging can all benefit from eco-friendly printing using bio-colorants and bio-crosslinkers.

Highlights

- Eco-friendly printing on cotton using jujube and eucalyptus dyes reduces environmental harm.
- Bio-mordants from tamarind seeds and gooseberry effectively replace harmful metal-based mordants.
- Printed samples show excellent fastness ratings of 4–5, proving the quality of eco-friendly printing.

- FTIR analysis confirms strong covalent bonds between dye and fiber molecules.
- This method supports sustainability by using renewable, biodegradable resources in textile production.

KEYWORDS

bio crosslinkers, bio dye, bio mordant, color fastness, textile printing

1 | INTRODUCTION

Among synthetic printing's many negative aspects are its expensive price tag, possible health risks, and negative effects on the environment. Pollution and the release of greenhouse gases are two ecological disasters that can result from synthetic printing processes that use chemical substitutes. The term "natural printing" describes a printing method that focuses on lessening its negative effects on the environment by using sustainable materials and processes. It employs recyclable components, reduces chemical exposure, prioritizes hygiene and security, and practices environmental responsibility.[1,2] Environmental friendliness, lack of toxicity, lack of allergenicity, and lack of carcinogenic components have contributed to natural dyes meteoric rise in popularity compared to synthetic dyes.[3,4] In comparison to synthetic dyes, natural dyes are better for the environment because they break down more slowly and are more environmentally friendly in general.[5–7]

Natural dyes, with a few notable exceptions, require mordants because they do not adhere to fibers solely. Mordants are chemicals that have a dual purpose: they attach to fabric and interact with dye. The problem is that metallic mordants are widely used, but they can be harmful and contribute to pollution. Developing efficient mordants that firmly attach dye to fibers while reducing negative environmental impacts is the main objective. Sustainable and ecologically friendly natural dyeing procedures support that objective.[8–10]

A natural printing process should be developed in order to lessen negative effects on health and the environment. A wide variety of plant, floral, and fruit-based materials can be used to create biodegradable and ecologically friendly dyes.[11]

Jujube leaves (JL) and Eucalyptus bark (EB) were chosen as dyes 1 and 2, respectively, for this study. The leaves of the jujube tree can be used to make paper. Natural dyes derived from these leaves can help make printing more sustainable and environmentally friendly. To name a few chromophore groups found in jujube leaves: carotenoids, flavonoids, and chlorophylls. Coloration and pigmentation in leaves are attributed to these chromophore groups.[12] Among the most important sources is the yellowish-brown colorant found in EB. Elements such as tannins, eriodictyol, naringenin, quercetin, rhamnazin, rhamnetin, and toxifolin are all present in EB. One of the main ingredients in EB that gives it its color is quercetin, which also has antioxidant properties.[13] For printing with natural materials, two mordants are used. The tannin in amla is responsible for its valuable anti-scorbutic characteristics, which are present in both the fresh and dried forms of the fruit. Amla is also used to prevent the oxidation of vitamins. Vitamin oxidation in amla is effectively retarded or prevented by the presence of gallic acid, a naturally occurring molecule that contains tannin. Amla is also used to treat jaundice and anemia.[14] Finally, polyphenols, phenolic compounds, sugar, tannins, and saponins are the most common components found in tamarind seed testa. Tamarind seeds can form complexes with metal ions due to the presence of functional groups like hydroxyl groups and carboxylic acids. The colorfastness of the fabric is enhanced because these complexes strengthen the bond between the dye and the fabric.[15]

Sodium aliginate and gelatin were chosen for this investigation as thickener. Sodium alginate is a naturally occurring polysaccharide that comes from algae. When it is mixed with water, it forms a gel-like substance.[16,17] As a binder, gelatin makes the ink stick better to the printing surface, which means the print will last longer and look better for longer. Our printing paste also contains chemicals such as caustic (NaOH) and urea. Natural dyes are fixed onto the fabric with the help of the caustic (NaOH), which also improves the fabric's colorfastness. Sodium hydroxide also helps eliminate natural waxes and contaminants from the fabric, which improves dye penetration and adherence. Urea, on the other hand, keeps the printing solution or paste moist by acting as a humectant.[18] In addition, urea helps with dye leveling, which means that the fabric will have uniform color distribution without blotching or uneven absorption. Natural printing processes often include urea as an additive.

Although there are significant amount of research on the use of synthetic mordants with dyes in textile printing, studies using natural dye and biomordant especially for 100% cotton knit fabrics have not been well studied.[19–25] Although there is growing concern about sustainable and eco-friendly textile processing, no comprehensive studies have been conducted to investigate the possibilities of biomordants along with natural dyes for cotton fabrics. Previous works usually cover single aspects of natural dyeing or the application of biomordants and scanty on their synthesis into an integrated unit. Sustainable printing techniques for cellulosic polymeric materials utilizing bio-colorants and bio-crosslinkers are the focus of this research work. Using environmentally friendly binders derived from Indian gooseberries and tamarind seeds, this study explores the interactions of natural dyes, biomordants, and thickeners on cotton knit fabric. This research aims to promote eco-friendly printing processes that reduce the textile industry's environmental footprint and support sustainable manufacturing practices (Figure 1).

There is minimal data available on the performance, wash fastness and light fastness of fabrics that are dyed with natural dyes in combination extractions over those treated synthetically. The current research focusing on the new biomordants along with natural dye that can be used commercially as an alternative to synthetic ones for more sustainable textile printing practices.[26–28] The results will offer essential information on the resource efficiency, training requirements, and economic opportunities of natural dyes and biomordants for application on a large scale. Biodegradable packaging, sustainable fashion, home textiles, and technical textiles are just a few examples of the many industries that can benefit from eco-sustainable printing of cellulosic polymeric materials with bio-colorants and bio-crosslinkers.

2 | EXPERIMENTAL

2.1 | Materials and methods

2.1.1 | Materials

The bark of the eucalyptus tree was gathered in the Sirajganj district in northern Bangladesh. In the same region, we also gathered Jujube (*Ziziphus zizyphus*) and Amla (*Phyllanthus emblica*) leaves. The seeds of the tamarind tree (*Tamarindus indica*) were gathered in Gazipur (Figure 2). The printing paste was made with sodium alginate and gelatin. The Chemical Market in Tongi, Bangladesh was the source for both items. We gathered the caustic (NaOH) and urea chemicals from the dyeing lab of Mawlana Bhashani Science and Technology University (MBSTU). To ensure that the powder for extraction had uniform particle size, the ground material was sieved. The fabric used was Single Jersey, a plain knit pretreated 100% cotton (60 GSM, 30Ne) material sourced from DEPZ, Grameen Knitwear Ltd. It was ready to print on since the fabric had been pretreated. This printing was done using the screen-printing technique. We ran 20-mesh fabric through the printing frame.

2.2 | Dye extraction from natural sources

2.2.1 | Dye extraction from EB

EB was initially rinsed with running water and then left to dry in the sun for 7 or 8 days. The bark was subsequently ground into the required powder. The aqueous

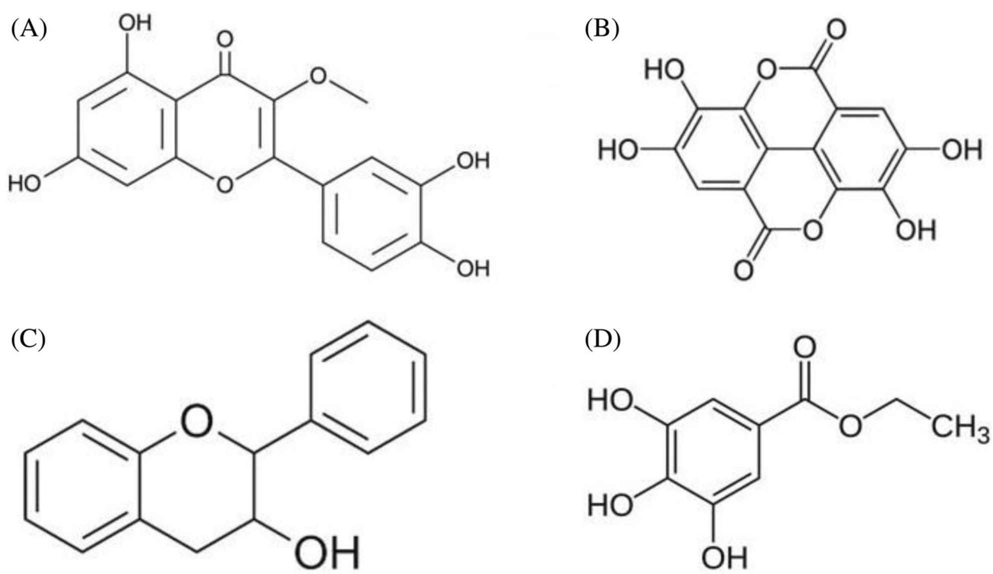

FIGURE 1 Chemical structure of (A) 3,7-Di-O-methylquercetin (Jujube leaves),[29] (B) Ellagic acid (Eucalyptus bark),[30] (C) flavan-3-ols (tamarind seeds),[31] and (D) phyllemblin (Indian gooseberry).[32]

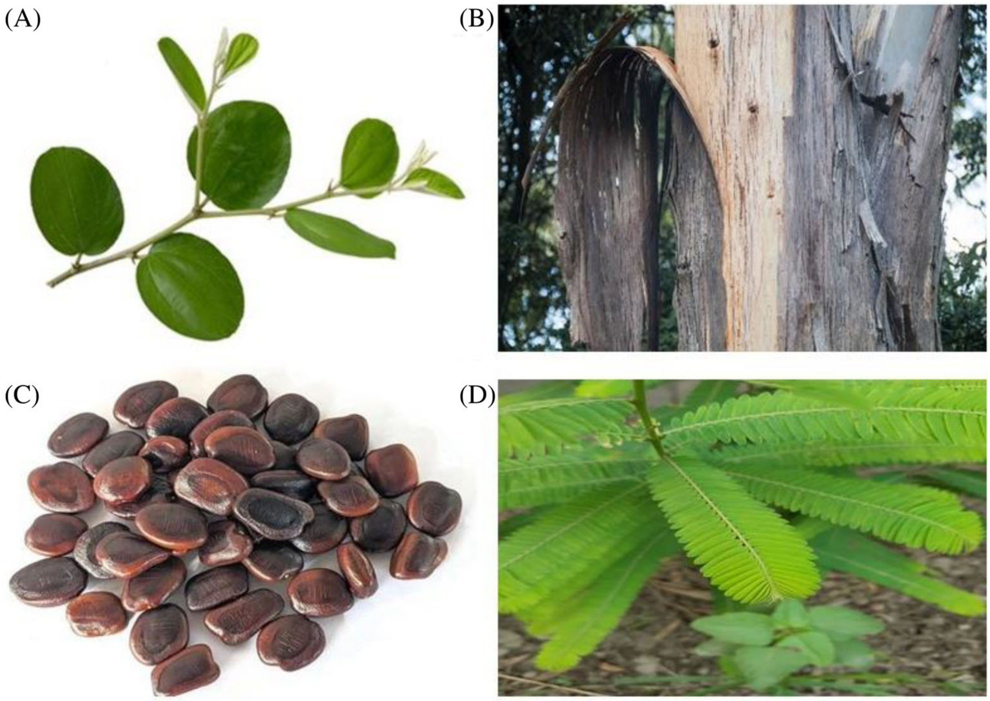

FIGURE 2 Photographs of jujube leaves (A), eucalyptus bark (B), tamarind seeds (C), and Indian gooseberry leaves (D).

solution was then obtained by filtering the powder form multiple times. During the extraction period, 2.5 L of water were mixed with 50 g of liquor according to a 1:50 ratio. After soaking for 6–8 h, the 50 g of powder began to release its color. The 250 mL purest solution was obtained by heating it below boiling point and filtering it multiple times.

2.2.2 | Dye extraction from Jujube leaves

After washing in sunlight at room temperature, the leaves dried in 7 or 8 days. The leaves have been crushed into powder. The powder was then used to generate a 1:50 liquor solution. Add 50 g of colored powder to 2.5 L of water and heat until half is boiling. Filtering, boiling, and filtering again brought the solution to 250 mL purity.

2.3 | Bio-crosslinker/mordant extraction

2.3.1 | Indian gooseberry

The leaves were gently rinsed and allowed to air dry for 7 or 8 days. We got the powder form of the leaves by grinding them with a blender. To get better separation efficiency and to prevent solvent and residue filtration, we used this extraction method. The thimble of the soxhlet extractor contained 40 gm of amla leaves powder, while the RB flask contained 300 mL of solvent. A condenser with a high-water flow rate was placed over the mixture. Eight hours were spent heating the soxhlet apparatus to 80°C. The extraction was followed by filtering and printing of the extract.

2.3.2 | Tamarind seeds

These seeds underwent rinsing and subsequent drying at room temp for at least 7 days. The seeds were blended into powder. Our extraction method improved separation efficiency while eliminating solvent and residue filtration. A 300 mL solvent-filled RB flask, 40 g of tamarind seed powder, and a high-flow condenser should be placed in the soxhlet extractor thimble. Heating the soxhlet to 80°C took 8 h. Printers used filtrate shortly after extraction. The extraction of the bio-crosslinker/mordant is shown in Figure 3.

2.4 | Printing paste preparation and application

2.4.1 | Preparation

The paste was made in 12 separate batches using a variety of ingredients, including natural colors, biomordants, thickener, and binder. To make the printing paste, boil two solutions in water at 80°C for 10 min. Then, caustic and urea to each were added until the mixture reached

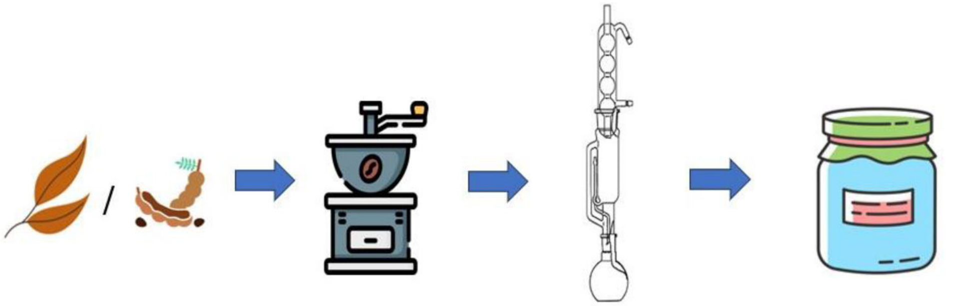

FIGURE 3 Extraction of bio-crosslinker/mordant.

the required viscosity. The recipe for the printing paste called for 25 mL. The formulation of recipe for printing on cotton fabric is shown in Table 1.

The samples are identified and described in Table 2.

2.4.2 | Application of printing paste on substrate

The mixing of natural colors obtained from tamarind seeds and Indian gooseberries, mordants derived from sodium alginate, a binder made of gelatin and a thickener made of EB resulted in the development of a printing paste that was used for 12 batches overall. In order to produce the printing paste, two solutions were brought to a boil at 80°C for 10 min. For printing on samples, a mesh size of 110 threads per inch was used. This range allows for detailed, precise printing while ensuring adequate ink flow and coverage. Table 3 displays samples images and identification of printed fabrics.

2.5 | Properties analysis

Fourier transform infrared spectroscopy (FTIR) (7800A, UK) to determine functional groups. reflectance-to-transmittance ratio, and K/S, is determined by plugging the sample's reflectance (R) into the equation $K/S = (1-R)^2/2R$, where R is the sample's reflectance and S is its transmittance or absorption.[33,34] An important metric for determining the intensity of colors is RFL (Reflectance) which is the ratio of incident light to reflected light. The difference between two colors is quantified by DE (Delta E) which measures perceptual changes. a* (green to red), b* (blue to yellow), and L* (lightness) make up the Lab* color space which allows for accurate color evaluation. Chroma abbreviated as C*, is a measure of color saturation or intensity. The color's position on the color wheel is indicated by H*, the hue angle. When taken as a whole, these

TABLE 1 Recipe formulation for printing on cotton fabric.

S/L no	Sample code	Dyes/chemicals/ reagents	Amount/ concentration
1	D1	Formulation	100% Dye
		Dye-JL	25 mL
		Sodium alginate	1.25 gm
		Caustic (NaOH)	0.3 gm
		Urea	0.5 gm
2	D1B	Formulation	100% dye
		Dye-JL	25 mL
		Sodium alginate	1.5 gm
		Gelatin	0.5 gm
		NaOH	0.3 gm
		Urea	0.5 gm
3	D1M1	Formulation	50% dye: 50% mordant
		Dye-JL	12.5 mL
		Mordant-Indian gooseberry	12.5 mL
		Sodium alginate	1.75 gm
		NaOH	0.3 gm
		Urea	0.5 gm
4	D1M1B	Formulation	50% dye: 50% mordant
		Dye-JL	12.5 mL
		Mordant-Indian gooseberry	12.5 mL
		Sodium alginate	1.75 gm
		Gelatin	0.5 gm
		NaOH	0.3 gm
		Urea	0.5 gm
5	D1M2	Formulation	50% dye: 50% mordant
		Dye-JL	12.5 mL
		Mordant-Tamarind seeds	12.5 mL

(Continues)

TABLE 1 (Continued)

S/L no	Sample code	Dyes/chemicals/ reagents	Amount/ concentration
		Sodium alginate	1.50 gm
		NaOH	0.3 gm
		Urea	0.5 gm
6	D1M2B	Formulation	50% dye: 50% mordant
		Dye-JL	12.5 mL
		Mordant-Tamarind seeds	12.5 mL
		Sodium alginate	1.50 gm
		Gelatin	0.5 gm
		NaOH	0.3 gm
		Urea	0.5 gm
7	D2	Formulation	100% dye
		Dye-EB	25 mL
		Sodium alginate	1.5 gm
		NaOH	0.3 gm
8	D2B	Formulation	100% dye
		Dye-EB	25 mL
		Sodium alginate	1 gm
		Gelatin	0.5 gm
		Urea	0.3 gm
9	D2M1	Formulation	50% dye: 50% mordant
		Dye-EB	12.5 mL
		Mordant-Indian gooseberry	12.5 mL
		Sodium alginate	1.50 gm
		NaOH	0.3 gm
		Urea	0.5 gm
10	D2M1B	Formulation	50% dye: 50% mordant
		Dye-EB	12.5 mL
		Mordant-Indian gooseberry	12.5 mL
		Sodium alginate	1.25 gm
		Gelatin	0.5 gm
		NaOH	0.3 gm
		Urea	0.5 gm
11	D2M2	Formulation	50% dye: 50% mordant
		Dye-EB	12.5 ml
		Mordant-Tamarind seeds	12.5 mL
		Sodium alginate	1.25 gm

(Continues)

TABLE 1 (Continued)

S/L no	Sample code	Dyes/chemicals/ reagents	Amount/ concentration
		NaOH	0.3 gm
		Urea	0.5 gm
12	D2M2B	Formulation	50% dye: 50% mordant
		Dye-EB	12.5 mL
		Mordant-Indian gooseberry	12.5 mL
		Sodium alginate	1 gm
		Gelatin	0.5 gm
		NaOH	0.3 gm
		Urea	0.5 gm

TABLE 2 Sample identification and description.

Abbreviation	Description
D1	Dye—Jujube leaves
D1B	Dye—Jujube leaves + Binder—Gelatin
D1M1	Dye—Jujube leaves + Mordant—Indian gooseberry
D1M1B	Dye—Jujube leaves + Mordant—Indian gooseberry + Binder—Gelatin
D1M2	Dye—Jujube leaves + Mordant—Tamarind seeds
D1M2B	Dye—Jujube leaves + Mordant—Tamarind seeds + Binder—Gelatin
D2	Dye—Eucalyptus Bark
D2B	Dye—Eucalyptus Bark + Binder—Gelatin
D2M1	Dye—Eucalyptus Bark + Mordant—Indian gooseberry
D2M1B	Dye—Eucalyptus Bark + Mordant—Indian gooseberry + Binder—Gelatin
D2M2	Dye—Eucalyptus Bark + Mordant—Tamarind seeds
D2M2B	Dye—Eucalyptus Bark + Mordant—Tamarind seeds + Binder—Gelatin

parameters allow for an in-depth examination of color, which is vital for textile and other industry quality control. The reflectance, transmission, and absorption of samples are all measured by spectrophotometers, which are instruments. For the purpose of determining how well the colors would hold up to washing and perspiration, the multi-fiber and colored sample was cut and stitched during the process. Gray scale was used to measure color change and staining of the prepared samples for the standard following procedures: Color fastness to wash: ISO 105-C06:2010 and color fastness to perspiration: ISO 105-E04:2013. All specimens were subjected to a conditioning period of 24 h in an environment with a relative humidity of 65 ± 5% and a temperature of 20 ± 2°C.

3 | RESULTS AND DISCUSSION

3.1 | FTIR analysis

Dye fixation onto fiber can be better understood by first gaining an appreciation for how dye and fiber interact

TABLE 3 Sample identification of printed fabric and their photographs.

Sample code	Sample photograph	Sample code	Sample photograph
D1		D2	
D1B		D2B	
D1M1		D2M1	

(Continues)

TABLE 3 (Continued)

Sample code	Sample photograph	Sample code	Sample photograph
D1M1B		D2M1B	
D1M2		D2M2	
D1M2B		D2M2B	

with one another. To achieve strong fixation, the fiber and dye and tannic acid form covalent bonds. Cellulose, dye, and tannic acid all contain functional groups that can interact with one another, such as —COOH, —COO—, and —OH, respectively. Different peaks were identified as belonging to bio-mordants and dyes when we examined the FTIR plot. The glucose units' carbon atoms include hydroxyl (—OH) functional groups in cellulose as cotton is used for this study.[35,36]

The large signal at 3748 cm^{-1} in the FTIR plot indicates cotton cellulose hydroxyl groups (O—H stretch, non-bonded). The anthocyanins found in tamarind seeds and EB dye act as chromophores and may have interactions with cellulose and tannic acid due to their hydroxyl (—OH) groups. Tannic acid forms ester bonds with cellulose.

Ester linkages when (—OH) groups combine in this reaction. Tannic acid's hydroxyl and anthocyanin's carbonyl functional bonds form H_2 bonds that allow them to interact with one another. As a consequence of this interaction, tannic acid, and anthocyanin produce a stable combination that stabilizes and intensifies the final mixture's color. Cellulose and the dyes chromophore groups may be able to form stronger bonds at 2976 cm^{-1}, which is also a peak for vibrations in alkanes and C—H stretching.[37–39] Dye made from jujube leaves contains aldehyde groups that can link to polysaccharides. The cellulose in cotton fabric forms a complex with the tartaric acid in tamarind ($C_4H_6O_6$). This is where tartaric acid, which is derived from tamarind, forms a complex with hydroxyl groups in cellulose. When the O═C═O functional group (CO_2) is stretched, a peak at 2358 cm^{-1} is observed. Nitrogen-oxygen bond in nitro compounds is correlated with a transmission mode peak at 1534 cm^{-1}.[40] Tannins, alcohols, esters, and carboxylic acids all contain phenolic groups, which are characterized by C—O and C—C bonds, as shown by the peak at 1020 cm^{-1}.[41] This observable peak is very important because all of our dyes contain tannins and tannic acid connects the dye to the fiber. Lastly, the aromatic compounds present in Indian Gooseberry melanins may be responsible for the alkyl C—H bending peak at 559 cm^{-1}. A complex is formed when the tannins found in gooseberries ($C_{76}H_{52}O_{46}$) reacts.[42] A tannin-cellulose complex is formed when the hydroxyl groups in cellulose react with the tannins in Indian gooseberries.[43] Printing samples FT-IR data is displayed in Figure 4.

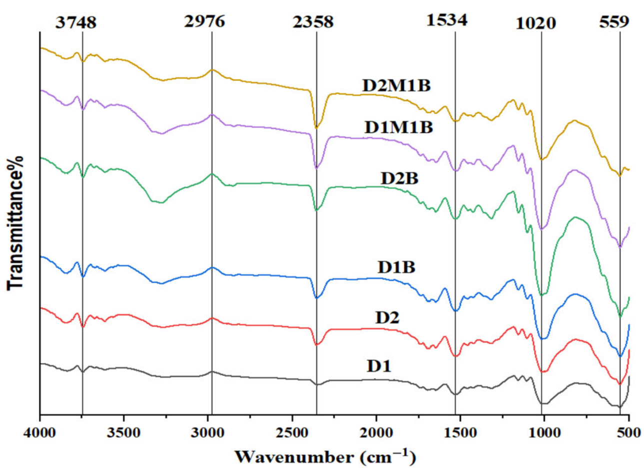

FIGURE 4 FT-IR data of printed samples.

3.2 | Color measurement evaluation

3.2.1 | RFL values analysis

The reflectance data at 700 nm is often used in remote sensing due to its effectiveness in capturing information about chromophores. The coloring components that reflect light most efficiently in infrared regions (~700–900 nm). Therefore, this research work was conducted at 700 nm to leverage this optimal reflectance range. The results demonstrated that the printed surfaces exhibited a satisfactory level of reflectance. Figure 2 shows that out of all the printed samples, the one with the highest reflectance value was the D1M1 at 77.319, and the one with the lowest was the D2M1B at 53.711. When reflectance was considered, the D2M1's 77.029 RFL value placed it second. The fact that the Indian Gooseberry bio-mordant produced the highest RFL values when applied to JL is intriguing. Conversely, the sample with the lowest reflectance was the D2M1B one. The effect of bio-mordants and bio-colorants on RFL values is illustrated in Figure 5.

3.2.2 | Colorimetric data analysis

Table 4 compares 12 samples (D1, D1B, D2, D2B, D1M1, D1M1B, D1M2, D1M2B, D2M1, D2M2B, D2M2, and D2M1B) based on their colorimetric properties (L*, a*, b*, C*, H*, and DE). D1 shows moderate lightness (L* = 82.71), low a* (2.60), and moderate b* (10.7), indicating a light color with a slight red and yellow tint. D1B has slightly reduced lightness but increased a* and b*, suggesting a shift towards redder and yellower tones. D2 and D2B display a similar trend, with D2B having significantly lower lightness and higher a* and b* values, indicating a more pronounced color shift. The modified samples (D1M1, D1M1B, D1M2, and D1M2B) show a wider range of lightness and color changes. D1M1 has the highest lightness but low a* and b*, indicating a very light color. In contrast, D1M1B and D1M2 show increased redness and yellowness with reduced lightness. D2M1 stands out with the highest a* value, suggesting a strong red tint, while D2M2B and D2M2 show significant variations in lightness and chroma (C*), indicating diverse color characteristics. The DE values suggest notable color differences across all samples, with D2M1 having the highest DE, indicating the greatest color deviation. Colorimetric values were examined in Table 4 to determine the effect of various bio-colorant and bio-mordant formulations used in printing recipes.

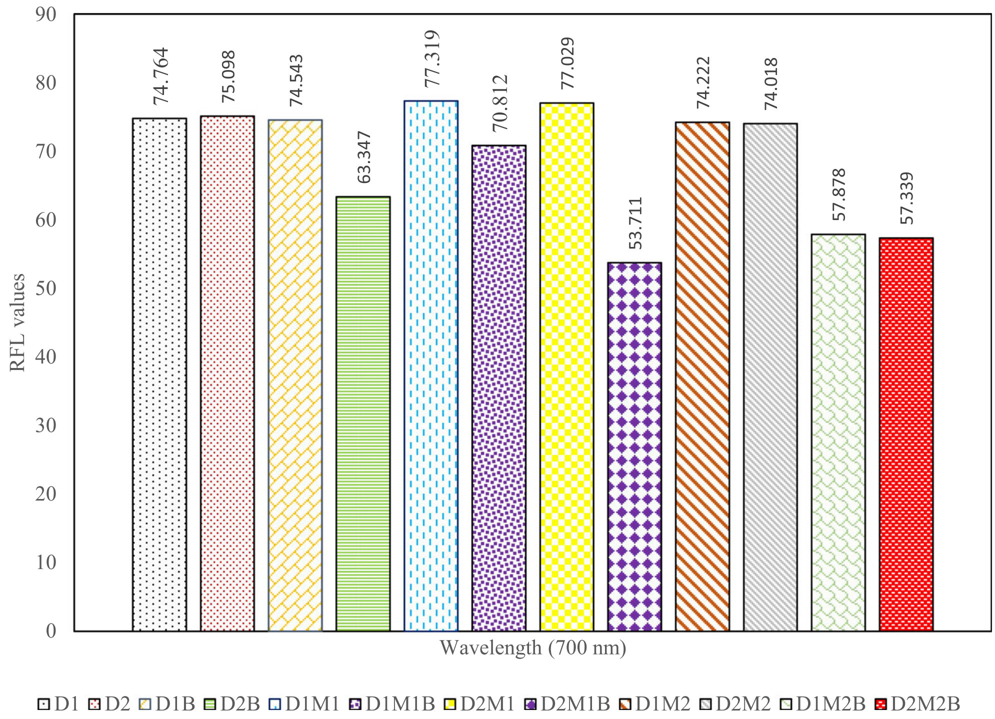

FIGURE 5 Impact of bio-colorants and bio-mordants on RFL values.

TABLE 4 Impact of different printing recipe formulation of bio-colorants and bio-mordants on colorimetric values.

S/L	Sample ID	L*	a*	b*	C*	H*	DE
1	D1	82.71	2.60	10.7	11.01	76.27	4.96
2	D1B	80.61	3.63	13.14	13.63	74.49	4.14
3	D2	82.99	3.231	10.56	11.04	72.95	4.39
4	D2B	73.34	4.961	11.46	12.49	66.57	5.05
5	D1M1	86.62	1.02	8.05	8.11	82.72	7.62
6	D1M1B	79.14	3.34	13.11	13.53	75.67	4.11
7	D1M2	83.26	1.52	12.2	12.29	82.84	6.88
8	D1M2B	72.45	3.22	9.7	10.22	71.58	2.38
9	D2M1	83.08	9.948	4.58	10.96	24.75	14.23
10	D2M2B	68.89	4.97	16.47	17.21	73.15	4.82
11	D2M2	65.55	6.09	11.58	13.08	62.23	3.40
12	D2M1B	81.63	2.81	13.32	13.61	78.05	5.39

3.2.3 | Analysis of bio-colorants and bio-mordants on color strength

According to the measured K/S values and shade percentages, the printed surfaces had sufficient color strength. According to Figure 3, the D1M2B printed sample had the strongest color with the value of 1.659, whereas the lowest K/S value found for D1B which is 0.144. In terms of color strength, the D2M1B sample ranked second-highest with1.473. The bio-mordant made of tamarind seeds and JL, with gelatin added for binding, had the highest K/S value at 360 nm. The K/S value was lowest in the D1B sample, on the other hand. How bio-colorants and bio-mordants affect color strength (K/S) is illustrated in Figure 6.

3.3 | Analysis of color fastness (CF) performance

3.3.1 | CF to dry rubbing

Dyeing cotton with EB and JL produces the best color shift on a greyscale scale.[44] Not only did the mordants prepared from tamarind seeds and Indian gooseberry seeds perform exceptionally well in terms of color fastness and staining, but they also rated extremely high overall. The color depth is slightly reduced when a natural binder, such as gelatin, is coupled with a bio-mordant made from tamarind seeds and a dye made from EB. A very small amount of staining is visible in the D2M2B sample. The color fastness to dry rubbing is displayed in Table 5.

3.3.2 | Color fastness to wet rubbing

Wet rubbing, which is affected by moisture, was used to evaluate the screen printed samples. When wet, some fabrics absorb more color than dry. There was a small improvement in dry rubbing fastness compared to wet rubbing fastness.[45] Excellent to very good grades were shown by the dry rubbing, which means that most of the dye was absorbed by the fibers and very little dye was left on the surface. A very good wet rubbing fastness rating, however, indicates that some color transfer occurred—albeit within a tolerable range—during the evaluation. Samples D1, D2M1, D1M1B, and D2B showed very little staining and a little loss of color intensity. In contrast, sample D2M2B exhibited moderate staining and a discernible decrease in shade intensity. Color fastness to wet rubbing is displayed in Table 6.

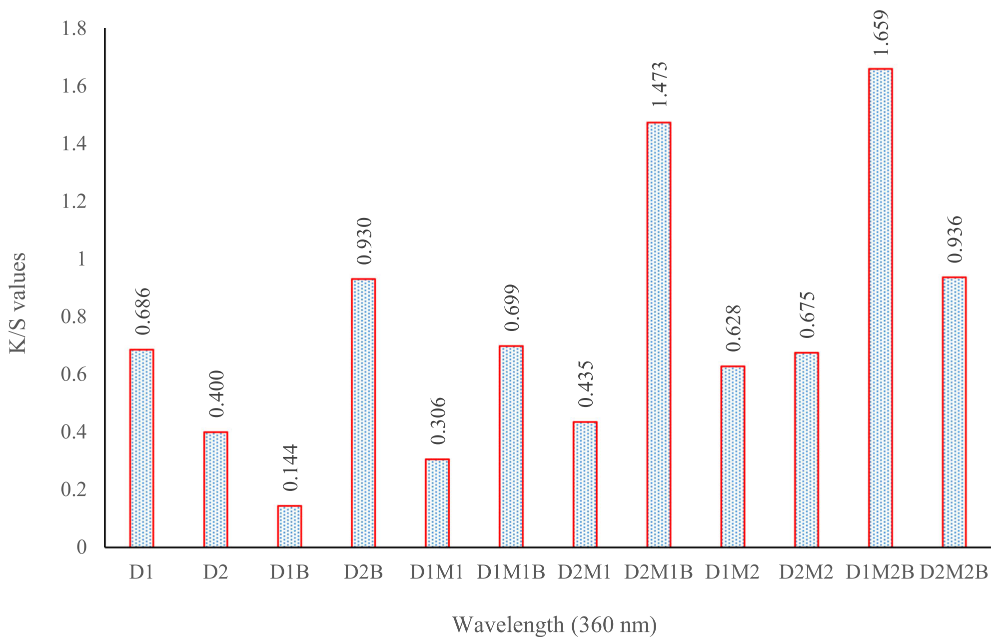

FIGURE 6 Impact bio-colorants and bio-mordants on color strength (K/S).

TABLE 5 CF to dry rubbing.

Fastness	Sample code	Rating
CF to rubbing (dry)	D1	5
	D2	5
	D1B	5
	D2B	5
	D1M1	5
	D1M1B	5
	D2M1	5
	D2M1B	5
	D1M2	5
	D2M2	5
	D1M2B	5
	D2M2B	4–5

Abbreviation: CF, color fastness.

TABLE 6 CF to wet rubbing.

Fastness	Sample name	Grade
CF to rubbing (wet)	D1	4–5
	D2	5
	D1B	5
	D2B	4
	D1M1	5
	D1M1B	4–5
	D2M1	4–5
	D2M1B	3
	D1M2	5
	D2M2	5
	D1M2B	4
	D2M2B	3–4

Abbreviation: CF, color fastness.

TABLE 7 Impact of bio-colorants and bio-mordants on color fastness to wash.

			SC					
Fastness	**Sample types**	**CC**	**W**	**PAC**	**P**	**PA**	**C**	**A**
CF to wash	D1	4–5	5	5	5	5	5	5
	D2	3–5	5	5	5	5	5	5
	D1B	4–5	5	5	5	5	5	5
	D2B	4	5	5	5	5	5	5
	D1M1	4	5	5	5	5	5	5
	D1M1B	5	5	5	5	5	5	5
	D2M1	3	5	5	5	5	5	5
	D2M1B	4–5	5	5	5	5	5	5
	D1M2	3–5	5	5	5	5	5	5
	D2M2	4	4–5	4–5	4–5	4–5	4–5	4–5
	D1M2B	4–5	5	5	5	5	5	5
	D2M2B	4	4–5	4–5	4–5	4–5	4–5	4–5

Note: Change in Color = CC; Staining in color = SC; Acetate = A; Cotton = C; Polyester = P; Poly acrylic = PAC; Poly amide = PA; Wool = W.
Abbreviation: CF, color fastness.

TABLE 8 CF to perspiration (Acid).

			SC					
Fastness	**Sample types**	**CC**	**W**	**PAC**	**P**	**PA**	**C**	**A**
Color fastness to perspiration	D1	3	4–5	4–5	4–5	4–5	4–5	4–5
	D2	4	5	5	5	5	5	5
	D1B	2–3	4	4–5	4	4	4	4
	D2B	4	4–5	4–5	4–5	4–5	4–5	4
	D1M1	4	4–5	4–5	4–5	4–5	4–5	4–5
	D1M1B	2	4–5	4–5	4–5	5	4–5	5
	D2M1	4	5	5	5	5	5	5
	D2M1B	2	3–4	3–4	4	3–4	3–4	4
	D1M2	4	5	5	5	5	5	5
	D2M2	4	5	5	5	5	5	5
	D1M2B	2–3	3–4	3–4	4	4	3–4	3–4
	D2M2B	2	3–4	3–4	3–4	3–4	3–4	2–3

Note: Change in Color = CC; Staining in color = SC; Acetate = A; Cotton = C; Polyester = P; Poly acrylic = PAC; Poly amide = PA; Wool = W.
Abbreviation: CF, color fastness.

3.3.3 | Color fastness to wash

Both the mordants and the dyes had washing fastness grades of 5, which means that there was barely any change in color after washing.[46] There was very little to no staining on the cotton fabric, as evidenced by the fact that each of the samples revealed color staining that varied from four out of five to five. Among the samples D2, D2M1, and D1M2, the ones that had the most significant differences in shade were the ones that received ratings of ¾ and 3, respectively. While this was the case, their color staining scores were consistently good to extraordinary, regardless of the kind of fabric that they were applied on. Kinetic and thermodynamic processes mediated by metal complex growth may explain the colorant's excellent washing properties. When the samples are rubbed, the following is a list of the parameters that have an effect on the length of time that the color remains stable. The effect of bio-mordants and bio-colorants on washability is shown in Table 7.

TABLE 9 CF to Perspiration (Alkali).

Fastness	Sample types	CC	SC					
			W	PAC	P	PA	C	A
CF to perspiration	D1	2–3	4	4	4	4	4	4
	D2	4	4	4	4	4	4	4
	D1B	3	4	4	4	4	4	4
	D2B	3	4	4	4	4	4	4
	D1M1	3–4	4–5	4	4	4–5	4	4
	D1M1B	2–3	4	4	4	4	4	4
	D2M1	4	4	5	5	5	5	5
	D2M1B	2–3	3–4	4–5	4–5	4	4–5	4–5
	D1M2	4	4	5	5	5	5	5
	D2M2	4–5	4–5	5	5	5	5	5
	D1M2B	2–3	4	5	4	5	5	5
	D2M2B	2	3	3–4	3–4	3–4	3–4	2–3

Note: Change in Color = CC; Staining in color = SC; Acetate = A; Cotton = C; Polyester = P; Poly acrylic = PAC; Poly amide = PA; Wool = W.
Abbreviation: CF, color fastness.

3.3.4 | CF to acid perspiration

However, the findings of the acidic and alkaline sweat tests performed on silk samples that had been screen-printed were not very outstanding. After being subjected to the acid solution, the samples D1B, D1M1B, D2M1B, D1M2B, and D2M2B all exhibited discernible color changes. These changes were seen in all of the samples. In addition to this, the D1M2B and D2M2B samples that were treated had a distinct staining of hues. Both animals were found to exhibit this behavior. Because the conjugated systems and benzene rings of the dye create strong connections and the samples display amazing color fastness. This is the reason why the samples continue to demonstrate their extraordinary color fastness. Exactly because of this, the samples have been able to keep their color for such a considerable amount of time.[47] The color fastness to perspiration (Acid) is displayed in Table 8.

3.3.5 | CF to alkaline perspiration

The silk samples that were screen printed showed no difference in the acid and alkaline perspiration tests. Samples D1, D1M1B, D2M1B, D1M2B, and D2M2B showed color changes in response to the acid and alkaline solutions, respectively. In the alkaline solution test, the treated D2M2B sample also showed noticeable color staining. Table 9 displays the color fastness to alkaline perspiration.

4 | CONCLUSION

Sustainable printing of cellulosic polymeric materials with bio-colorants and bio-crosslinkers advances eco-friendly textile processing. This method uses renewable dyes and crosslinking agents to reduce the environmental impact of traditional printing. Bio-based components reinforce sustainability and improve printed material's functionality and durability. This novel approach reduces synthetic chemical use and promotes eco-friendly alternatives in the textile industry. The findings of this study indicate that natural dyes derived from JL and EB can be utilized to print on cotton fabric in a manner that is not harmful to the nature of the environment. In the case of dyes, we utilized the aqueous extraction technique, whereas the soxhlet technique was utilized for the extraction of bio-mordants, such as tamarind seeds and Indian gooseberry. One of the most promising opportunities for environmentally responsible textile production is the use of biomordants and eco-friendly inks to print on cotton fabric. A smaller environmental footprint can be achieved through the utilization of natural dyes that are derived from renewable resources, such as JL and EB, as well as mordants that are biodegradable. In spite of the fact that there are still challenges, particularly with regard to achieving color fastness that is satisfactory to sweat, additional research and experimentation might result in the development of inventive solutions. The investigation of various extraction methods and the identification of the optimal concentration of dyes and bio-mordants could potentially contribute to the improvement of eco-friendly printed cotton fabric in all aspects, including quality, colorfastness, and performance. The production of environmentally friendly printing is supported by sustainability initiatives all over the world because it contributes to the reduction of pollution levels and makes products safer for both workers and consumers. Businesses have a fantastic opportunity to demonstrate their concern for social and environmental justice by giving biomordants and natural dyes a higher priority in their procurement processes.

AUTHOR CONTRIBUTIONS

Faisal Ahmed: Conceptualization, methodology, resources, supervision, visualization, writing–original draft preparation. **Md. Reazuddin Repon:** Conceptualization, formal analysis, methodology, resources, writing–original draft preparation. **Arnob Dhar Pranta**: Resources, formal analysis, and writing–original draft preparation. **Md. Sayed Ragib Yasar:** Data curation and writing–original draft preparation. **Md. Faisal Rakib:** Methodology, resources, data curation, and writing–editing & reviewing. **Ishtiak Ahmed:** Conceptualization, methodology, formal analysis, and writing–editing & reviewing. **Toufiq Ahmed Emon:** Conceptualization, resources and writing–editing & reviewing. **Tarakul Alam Nishat:** Methodology, resources, data curation, and writing–original draft.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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