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Sustainable Dyeing of Silk Fabric with Mango Leaf Extract: Comparative Assessment of Natural and Metallic Mordants on Colorimetric and Fastness Properties

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ABSTRACT

This study investigates the sustainable dyeing of silk fabric with mango leaf extract and compares the effects of natural and metallic mordants on colorimetric and fastness properties. Silk fabric was degummed, bleached, and dyed using mango leaf extract under pre-, simultaneous, and post-mordanting techniques with bio-mordants (Aloe vera, lemon, myrobalan, mango bark, eucalyptus) and metallic salts (alum, copper sulfate, ferrous sulfate). Color analysis showed that simultaneous mordanting with mango bark achieved the highest color strength among natural mordants (K/S = 16.25, 127 %), while ferrous sulfate produced the deepest shade under post-mordanting (K/S = 14.93, 117 %). Aloe vera and lemon generated lighter shades, whereas tannin-rich mordants significantly reduced reflectance and improved absorption at λ_{max}, confirming their strong affinity for dyes. Fastness performance was satisfactory across all samples, with washing and rubbing ratings ranging from 4 to 5 on the ISO grey scale. Results demonstrate that natural mordants can provide color performance comparable to that of metallic salts while reducing environmental hazards. The findings highlight the potential of natural mordants and mango leaf extract as eco-friendly alternatives for protein-based textile dyeing; however, further research is necessary to enhance shade reproducibility, extraction efficiency, and scalability for industrial applications. Prog Color Colorants Coat. 19 (2026), 231-245© Institute for Color Science and Technology.

1. Introduction

From the creation of fabrics to their dyeing and finishing, the textile sector is responsible for over 20 % of the world's polluted water and around 3.3 billion metric tonnes of greenhouse gas emissions per year [1]. This environmental footprint is not just a statistic-it represents rivers turned toxic, ecosystems disrupted, and communities affected by polluted water supplies. Traditional dyeing methods heavily depend on synthetic dyes, levelling agents, chemical mordants, surfactants, and metallic salts to attain stable shades [2, 3]. Synthetic dyes, primarily obtained from coal-tar and petroleum sources, pose severe ecological and human health hazards because of their carcinogenic, non-

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biodegradable, and hazardous nature [4, 5]. Discharge of dyeing effluents leads to severe ecological consequences, including imbalance of pH, increased COD and BOD levels, and long-term contamination of water bodies and agricultural land [6]. Against this backdrop of urgent environmental concern, the global textile industry is searching for safer, more sustainable coloration methods.

Natural dyes, obtained from renewable resources such as animals and plants, are recognized for their low toxicity, biodegradability, and compatibility with eco-friendly practices [7]. They also offer added functionalities such as UV protection properties, antibacterial, and antioxidant, which make them increasingly relevant in modern textile applications [8]. However, despite their promise, natural dyes are still underused in mainstream silk production—partly because of challenges like low color yield, inconsistent fastness, and resource-intensive extraction processes [9, 10]. Overcoming these barriers could transform silk dyeing into a greener, locally sourced, and culturally resonant craft with global relevance. Conventional extraction techniques often require excessive energy, solvents, and time, while advanced methods such as microwave-assisted extraction and response surface methodology (RSM) optimization have been explored to enhance dye uptake, reduce process time, and minimize effluent loads [11-13]. These innovative approaches significantly improve extraction efficiency and fabric-dye interaction without altering the fiber or dye chemistry [14, 15].

Silk, commonly known as the "queen of fibres," is renowned for its distinctive blend of luster, strength, lightweight properties, and comfort [16]. Its luxurious feel, excellent moisture absorption, and drape make it widely used in apparel, home textiles, and high-end fashion. However, silk coloration traditionally relies on chemically synthesized dyes, which compromise its sustainability and introduce harmful chemicals into the ecosystem [17]. Moreover, to enhance functionalities such as UV resistance or antibacterial properties, additional synthetic additives are often applied, further reducing environmental compatibility [18]. Replacing synthetic dyes with natural dyes is therefore not only an environmental imperative but also an opportunity to add unique aesthetics and functionalities to silk fabrics. Therefore, replacing synthetic dyes with natural dyes for silk coloration offers both ecological and functional benefits. For silk fabric to have a higher market value and more end-use applications, its colouration is crucial. Many researchers have investigated natural dyes for silk. For instance, Balakrishnan et al. [19] demonstrated that vibrant pastel shades with fair to exceptional washing and light fastness are produced when Basella alba fruit extract is combined with soymilk solution in a 4:1 ratio at 30 °C. Through a three-step chemical modification at room temperature, Guo et al. [20] developed an energy-efficient, fast-reactive dyeing technique that produces azo dyes directly on silk fibroin with impressive color fastness. According to Naheed et al. [21], using sustainable mordants makes the procedure more eco-friendly. They also demonstrated that using a microwave to extract and dye silk fabric using hematein obtained from logwood produces great color fastness and strength. Roychowdhury et al. [22] used optimised ammonia fermentation to study a purple natural dye from the lichen Parmotrema perlatum. The dye showed strong color strength, fastness, and dye fixing, suggesting worthwhile sustainable silk dyeing alternatives.

Among natural sources, mango trees provide leaves and bark that contain coloring compounds suitable for textile dyeing. Mango bark has been reported as a traditional dye source for cotton and silk, producing varied hues with mordanting [23], while mango leaves have been investigated mainly for non-textile purposes, such as adsorbents for dye removal [24]. Limited studies have utilized mango leaf extracts for silk coloration, although some work reports their application in batik and comparative studies with other natural dyes [25, 26]. This gap suggests an opportunity to transform an abundant natural product into a valuable, eco-friendly resource for premium silk coloration.

The use of metallic mordants such as $KAl(SO_4)_2\,12H_2O$, $CuSO_4{\cdot}5H_2O$, and $FeSO_4{\cdot}7H_2O$ in natural dyeing has traditionally improved shade depth and fastness, but their toxicity raises concerns about sustainability. In contrast, natural mordants derived from plants (such as aloe vera, lemon, myrobalan, mango bark, and eucalyptus bark) are gaining attention as safer alternatives, contributing to both color variation and environmental safety. However, comparative studies analyzing the performance of natural and metallic mordants in combination with mango leaf dye on silk fabrics remain scarce, and mango leaf extract itself is an underutilized, renewable dye source for protein-based textiles. This lack of comparative data creates uncertainty about the eco-friendliness and color performance of bio-mordants versus traditional metallic salts. Addressing this knowledge gap is essential for designing sustainable dyeing practices that both preserve color performance and significantly reduce environmental impact.

This study focuses on the sustainable dyeing of silk fabric using natural dye extracted from mango leaves through an alkaline aqueous method. It evaluates the effect of natural mordants (aloe vera, lemon, myrobalan, mango bark, eucalyptus bark) and metallic mordants (alum, copper, ferrous sulfate) applied through pre-, simultaneous-, and post-mordanting techniques. The research aims to analyze colorimetric properties, color strength, and fastness characteristics (washing and rubbing) of dyed fabrics according to international standards to identify sustainable alternatives to metallic mordants for eco-friendly silk coloration. By situating mango leaf dyeing within the urgent global push for sustainable textiles, this work not only compares mordant performance but also demonstrates how locally available plant materials can serve as credible, lower-impact substitutes for toxic metallic salts-helping to align silk dyeing practices with circular economy principles. In contrast to previous studies on mango leaf dyes or silk coloration, which typically examined fewer mordants or a single mordanting route, this work provides a systematic comparison of multiple bio-mordants and metallic mordants across all three mordanting techniques. By linking quantitative colorimetric analysis and fastness performance, the study highlights a potential pathway for reducing dependence on metallic mordants while maintaining high color quality in sustainable silk dyeing.

The specific objectives are:

1. to optimize dye extraction and application using eco-friendly methods;
2. to investigate shade variations and colorimetric properties under different mordanting conditions;
3. to compare unmordanted and mordanted samples in terms of color fastness and strength; and
4. to identify sustainable alternatives to metallic mordants for eco-safe silk dyeing.

2. Experimental

The experimental methodology comprised the collection of raw materials, preparation of natural dye extract, pretreatment of silk fabric, dyeing with mango leaf extract using different mordants, and evaluation of colorimetric properties and fastness characteristics.

2.1. Collection of material

Raw silk fabric (1/1 plain weave, 22 g/m²) was obtained from Sopura Silk Mills Ltd., Dhaka, Bangladesh, with permission for research use. Fresh mango (Mangifera indica) leaves were collected with authorization from Barishal Textile Engineering College (BTEC), Barishal, Bangladesh, where the trees are maintained on campus grounds. Additional natural mordants, including aloe vera (Aloe barbadensis), lemon (Citrus limon), myrobalan (Terminalia chebula), mango bark, and eucalyptus leaves, were collected locally from home gardens and public trees with verbal consent from property owners. Metallic mordants (alum [$KAl(SO_4)_2\cdot12H_2O$], ferrous sulfate [$FeSO_4$], and copper sulfate [$CuSO_4$]) were purchased from Wata Chemicals Ltd., Bangladesh, and applied at 5 % on the weight of fabric (owf). All analytical-grade auxiliary chemicals (soap, wetting agent, sequestering agent, hydrogen peroxide, and sodium carbonate) were kindly provided by Wata Chemicals Ltd., Bangladesh, for research use through institutional connections. The raw materials used in this study are shown in Figure 1.

2.2. Extraction

The mango leaves were washed thoroughly with water to remove dirt and impurities. They were dried under direct sunlight until completely moisture-free and ground into fine particles using a mechanical grinder. Coarse residues and waste materials were separated using a fine strainer, and the final weight of the powdered leaves was recorded.

Figure 1: a) mango leaves, b) aloe vera, c) mango bark, d) lemo, e) Myrobalan fruit, and f) ecalyptus.

The dye extraction was carried out by boiling 10 g of the ground mango leaves in distilled water at a material-to-liquor ratio of 1:10, maintaining the pH at 10, and heating at 100 °C for 60 minutes in a Sample Lab Dyeing Machine. After extraction, the dye solution was cooled to room temperature and filtered multiple times through fine filter paper to ensure clarity. Preliminary optimization trials were performed by varying extraction temperature (80-100 °C) and extraction duration (45-75 min) at constant pH and material-to-liquor ratio. These tests showed that 100 °C for 60 min produced the highest color strength without noticeable degradation of the extract; therefore, these parameters were selected for subsequent dyeing experiments. All process temperatures and times reported in this study were optimized by the authors through preliminary trials to achieve the best dyeing performance and fiber integrity.

Natural mordants such as Aloe vera, lemon juice, Myrobalan, and mango bark were also extracted prior to use. Fresh Aloe vera gel was collected, crushed, and filtered; lemon juice was freshly squeezed and diluted with distilled water. Myrobalan fruit and mango bark were washed, dried under sunlight, ground into fine powder, and extracted by boiling with distilled water under controlled temperature and time according to literature procedures. The mordant extracts were filtered thoroughly before application.

Metallic mordants including $FeSO_4$, $[KAl(SO_4)_2\ 12\ H_2O]$, and $CuSO_4$ were used at a fixed concentration of 5 % on the weight of fabric (owf). These mordants were prepared as aqueous solutions and applied directly without further extraction.

2.3. Degumming

The raw silk fabric was first degummed to remove sericin. Degumming was performed in an aqueous solution containing 15 g/L soap at pH 9, maintaining a material-to-liquor ratio (M:L) of 1:40, at a temperature of 80 °C for 50 minutes in a laboratory dyeing machine. After degumming, the fabric was washed with 5 g/L detergent at 65 °C for 5 minutes to ensure the removal of residual impurities.

2.4. Bleaching

The degummed silk fabric was bleached using a low concentration of hydrogen peroxide (32 % H_2O_2 at 2.74 mL/L) at pH 9, maintaining a material-to-liquor ratio of 1:40, at 60 °C for 50 minutes under controlled conditions to prevent fiber damage. These parameters fall within reported safe bleaching ranges for silk; for example, optimized peroxide bleaching of Tasar silk has been successfully performed at 6-18 g/L H_2O_2 without compromising fiber integrity [27]. After bleaching, the fabric was washed again with 5 g/L detergent at 65 °C for 5 minutes to neutralize any residual chemicals and stabilize the fabric.

2.5. Mordanting for shades development

To develop stable and durable shades, three metallic mordants, such as $FeSO_4$, $[KAl(SO_4)_2{\cdot}12H_2O]$, and $CuSO_4$, were applied at a concentration of 5% (o.w.f). Each solution was prepared by dissolving the required amount of salt in distilled water. Mordanting was carried out at 60 °C for 60 minutes with a material-to-liquor ratio of 1:30. Three techniques, including pre-, post-, and simultaneous mordanting (sm), were employed to examine the effect of mordanting sequence on shade and fastness properties.

For natural mordants, Aloe vera and lemon were freshly collected, their juice extracted and filtered before use. Mango bark, myrobalan bark, and eucalyptus leaves were dried, ground into small pieces, and boiled in distilled water at 90-100 °C for 45 minutes to obtain tannin-rich extracts. These extracts were filtered thoroughly and used directly for mordanting. Natural mordanting was also performed at 80 °C for 45 minutes with a material-to-liquor ratio of 1:30. The preparation of metallic and natural mordants is shown in Figure 2.

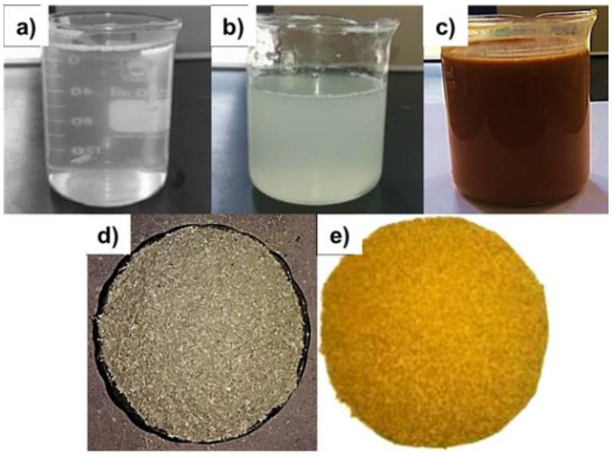

Figure 2: a) aloe vera juice, b) lemon juice, c) eucalyptus leaf extract, d) grinded mango bark, e) grinded myrobalan bark.

2.6. Dyeing procedure

The silk fabric was dyed with the extracted mango leaf dye under optimized conditions. The dyeing was performed at 80°C for 60 minutes using a material-to-liquor ratio of 1:25 at a slightly acidic pH (~5.5). The dyed fabric samples were then removed, rinsed thoroughly in cold water, and air-dried at room temperature. Small-scale dyeing trials at pH 5.0 and pH 5.5 were conducted to assess shade depth and uniformity. The pH 5.5 condition yielded slightly deeper and more uniform shades and was therefore adopted for the final dyeing runs.

2.7. Color yield of dyed fabrics

The color yield of dyed samples was assessed by measuring the reflectance curve in the wavelength range of 350-750 nm using a reflectance spectro-photometer (illuminant D65, F11-10 (TL84), A-10, 10° observer). The minimum reflectance (Rmin) was used to calculate the color strength (K/S value) using the Kubelka-Munk equation (Eq. 1):

$$K/S = \frac{(1-R_{min})^2}{2R_{min}} \qquad (1)$$

where R is the reflectance at λ_{max}.

This study was an initial exploratory investigation; therefore, formal statistical analyses, such as ANOVA or hypothesis testing, were not performed. Comparative evaluations were used to identify trends, and future work will include replicate trials with statistical validation to enhance reliability.

2.8. Color coordinates of dyed fabrics

The color coordinates of the dyed fabrics were determined using a dual-beam reflectance spectro-photometer and analyzed in the CIELab color space. The three coordinates L* (lightness), a* (red-green axis), and b* (yellow-blue axis) were recorded. Additionally, chroma (C*), hue (H*), and ΔE values were computed to compare color differences among pre-mordanted, simultaneous mordant, and post-mordanted samples.

2.9. Color fastness

The dyed samples were subjected to standard color fastness evaluations:

- Washing fastness: ISO 105 C02
- Rubbing fastness: ISO 105 X12

The ratings were assessed using standard gray scales for color change and staining.

3. Results and Discussion

3.1. Color characteristics and shade variation

The effect of various mordants and mordanting techniques on the colorimetric properties of silk fabrics dyed with mango leaf extract is summarized in Table 1. The unmordanted fabric recorded a K/S value of 12.75 and CIELab coordinates of L* = 67.36, a* = 7.73, b* = 32.90. This served as the baseline for evaluating shade modification due to mordants. Additionally, these numerical results are further explained by the reflectance spectra in Figure 3, which illustrate the absorption characteristics of each sample. In this study, the unmordanted silk exhibited moderate reflectance across the visible region, while samples treated with tannin-rich natural mordants (e.g., mango bark, eucalyptus) or metallic mordants (e.g., ferrous sulfate) showed lower reflectance at shorter wavelengths, suggesting stronger absorption and deeper shades. Among the mordanting techniques, simultaneous mordanting appeared to produce more pronounced absorption minima than pre- or post-mordanting, which is consistent with the slightly higher K/S values observed under these conditions. These spectral patterns support the colorimetric results and indicate enhanced dye-fiber interactions under certain mordanting approaches.

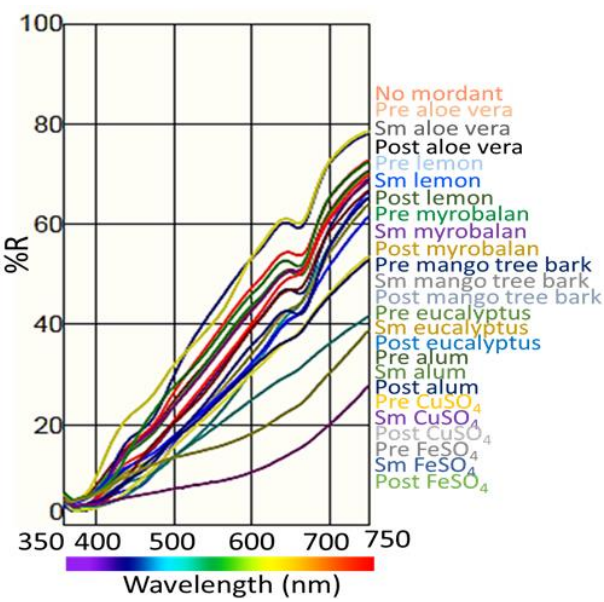

Figure 3: Reflectance spectra of silk fabrics dyde with mango leaf extract using various mordants and techniques.

3.2. Natural mordants

Natural mordants produced significant variation in both color strength and hue. Aloe vera, as a bio-mordant, achieved its maximum colour strength in the pre-mordanting condition, with a K/S value of 16.31 (128 %), whereas simultaneous mordanting yielded a slightly lower value of 15.68 (123 %). Post-mordanting, however, resulted in a drastic reduction to 7.83 (61 %), accompanied by an increase in L* and a shift toward duller tones (ΔEcmc = 4.51). These findings suggest that Aloe vera interacts more effectively with silk when applied before or during dyeing, consistent with Teklemedhin and Gopalakrishnan [28], who reported acceptable fastness and moderate depth for Aloe vera-mordanted silk using Cassia singueana dye. However, contrary to reports by Berhanu and Ratnapandian [29], which indicated uniformly good fastness and tone with Aloe vera on tanned leather, our results show that Aloe vera provides weaker fixation when applied post-dyeing, likely due to the limited migration of its active compounds into already dyed fibres. This behavior highlights the importance of mordant timing when using bio-mordants with low molecular weight polyphenolics like Aloe vera gel-pre- or simultaneous application allows these molecules to penetrate the fiber and form hydrogen or ionic bonds before the dye–fiber complex stabilizes.

Lemon juice displayed a similar trend: the highest K/S value was recorded in simultaneous mordanting (16.07, 126 %), followed by pre-mordanting (15.68, 123 %), while post-mordanting yielded 9.22 (72 %). These results partially align with those of Manicketh et al. [30], who observed wide variations in colour tone, ranging from pale yellow to green, when lemon was used as a mordant. However, unlike our data, previous research did not consistently report signi-ficant differences between techniques, possibly due to variations in fibre type or dye chemistry. The presence of citric acid in lemon juice likely chelates dye molecules or modifies the silk fibroin surface charge, enhancing dye uptake during simultaneous mordan-ting. Lower performance in post-mordanting suggests that once dye-fiber bonds form, the acidic environ-ment is less effective at altering fibre–dye interactions (Table 1).

Table 1: CIELab color coordinates, K/S values, and ΔEcmc of silk fabrics dyed with mango leaf extract using different mordants and mordanting methods.

Mordant	K/S at λ_{max}*	Color strength (%)**	Condition	Color coordinates					ΔE_{CMC}***
				L*	a*	b*	C*	H*	
No mordant	12.75	100	D65-10	67.36	7.73	32.90	33.80	76.79	-
			F11-10 (TL84)	67.36	7.92	36.39	37.24	77.72	
			A-10	70.05	12.94	35.33	37.63	69.88	
Pre aloe vera	16.31	128	D65-10	-3.46	2.93	3.33	3.97	-1.98	2.94
			F11-10 (TL84)	-3.24	2.59	3.74	4.24	-1.64	2.69
			A-10	-3.03	2.76	3.99	4.71	-1.15	2.65
Sm aloe vera	15.68	123	D65-10	-9.28	2.73	1.80	2.45	-2.17	4.34
			F11-10 (TL84)	-9.11	1.75	1.87	2.22	-1.28	3.87
			A-10	-8.95	2.54	2.67	3.41	-1.41	4.04
Post aloe vera	7.83	61	D65-10	4.12	0.77	-7.59	-7.10	-2.79	4.51
			F11-10 (TL84)	3.83	1.79	-8.10	-7.33	-3.88	4.94
			A-10	3.88	0.41	-7.65	-6.89	-3.34	4.69
Pre lemon	15.68	123	D65-10	-4.19	2.24	-0.47	0.13	-2.28	2.68
			F11-10 (TL84)	-4.16	2.08	-0.34	0.17	-2.10	2.45
			A-10	-3.98	2.05	-0.11	0.65	-1.94	2.44

Table 1: Continue.

Mordant	K/S at λ_{max}*	Color strength (%)**	Condition	Color coordinates					ΔE_{CMC}***
				L*	a*	b*	C*	H*	
Sm lemon	16.07	126	D65-10	-11.08	0.43	4.56	4.54	0.59	4.91
			F11-10 (TL84)	-11.08	0.14	4.86	4.79	0.85	4.90
			A-10	-10.94	1.11	4.53	4.64	0.49	4.76
Post lemon	9.22	72	D65-10	-2.31	0.11	-3.16	-3.04	-0.87	1.87
			F11-10 (TL84)	-2.45	-0.06	-3.29	-3.22	-0.67	1.83
			A-10	-2.43	-0.16	-3.08	-2.93	-0.94	1.85
Pre myrobalan	9.89	78	D65-10	-2.41	0.72	-1.19	-0.97	-0.99	1.40
			F11-10 (TL84)	-2.42	0.41	-1.05	-0.94	-0.63	1.17
			A-10	-2.39	0.33	-0.92	-0.75	-0.63	1.16
Sm myrobalan	13.30	104	D65-10	3.61	-1.04	3.88	3.59	1.80	2.77
			F11-10 (TL84)	3.74	-0.99	4.05	3.79	1.75	2.71
			A-10	3.67	-0.54	3.68	3.31	1.70	2.62
Post myrobalan	12.53	98	D65-10	3.25	1.29	-5.64	-5.08	-2.76	3.72
			F11-10 (TL84)	3.10	1.91	-5.96	-5.26	-3.38	3.96
			A-10	3.17	1.06	-5.41	-4.59	-3.05	3.78
Pre mango tree bark	12.60	99	D65-10	-5.87	1.94	-0.06	0.44	-1.89	2.91
			F11-10 (TL84)	-5.83	1.66	0.22	0.60	-1.57	2.68
			A-10	-5.68	1.65	0.38	0.95	-1.40	2.63
Sm mango tree bark	16.25	127	D65-10	-13.24	6.72	-2.02	0.30	-7.01	8.32
			F11-10 (TL84)	-13.10	5.74	-2.11	-0.34	-6.11	7.39
			A-10	-12.61	5.95	-0.31	2.16	-5.55	7.32
Post mango tree bark	12.72	100	D65-10	-2.98	0.95	-2.91	-2.57	-1.65	2.27
			F11-10 (TL84)	-3.05	0.74	-2.97	-2.72	-1.40	2.10
			A-10	-3.00	0.64	-2.76	-2.34	-1.60	2.20
Pre eucalyptus	15.68	123	D65-10	-9.58	2.81	-3.03	-2.12	-3.55	5.11
			F11-10 (TL84)	-9.61	2.24	-3.18	-2.52	-2.97	4.70
			A-10	-9.43	2.29	-2.36	-1.31	-3.02	4.72
Sm eucalyptus	14.16	111	D65-10	-5.21	2.29	-0.91	-0.28	-2.45	3.06
			F11-10 (TL84)	-5.15	1.82	-0.93	-0.47	-1.99	2.67
			A-10	-5.01	2.05	-0.30	0.47	-2.01	2.76
Post eucalyptus	10.41	82	D65-10	-10.16	1.70	-6.90	-6.14	-3.58	5.95
			F11-10 (TL84)	-10.37	1.15	-7.29	-6.76	-2.96	5.69
			A-10	-10.30	0.94	-6.42	-5.56	-3.35	5.71

Table 1: Continue.

Mordant	K/S at λ_{max}*	Color strength (%)**	Condition	Color coordinates					ΔE$_{CMC}$***
				L*	a*	b*	C*	H*	
Pre alum	13.18	103	D65-10	-6.30	1.69	1.52	1.88	-1.26	2.89
			F11-10 (TL84)	-6.34	1.91	2.81	3.17	-1.22	3.05
			A-10	-6.09	2.07	1.31	1.97	-1.46	2.89
Sm alum	8.81	69	D65-10	-0.41	-1.36	-0.97	-1.24	1.12	1.19
			F11-10 (TL84)	-0.64	-0.80	-0.05	-0.21	0.77	0.72
			A-10	-0.61	-0.79	-1.86	-2.02	0.10	0.94
Post alum	15.68	123	D65-10	-8.83	2.39	2.03	2.57	-1.80	4.06
			F11-10 (TL84)	-8.73	2.08	2.51	2.92	-1.44	3.87
			A-10	-8.54	2.10	2.53	3.11	-1.06	3.75
Pre $CuSO_4$	15.68	123	D65-10	-12.35	0.27	1.45	1.48	0.06	4.95
			F11-10 (TL84)	-12.41	0.17	2.31	2.29	0.32	4.98
			A-10	-12.34	0.45	1.11	1.20	-0.04	4.84
Sm $CuSO_4$	12.04	94	D65-10	-11.21	-0.01	-2.71	-2.63	-0.63	4.65
			F11-10 (TL84)	-11.40	0.01	-2.16	-2.11	-0.48	4.59
			A-10	-11.38	-0.25	-3.07	-2.96	-0.86	4.70
Post $CuSO_4$	12.75	100	D65-10	-16.32	-1.29	-2.33	-2.56	0.75	6.62
			F11-10 (TL84)	-16.59	-1.17	-1.80	-2.00	0.79	6.60
			A-10	-16.66	-1.44	-3.09	-3.39	0.31	6.67
Pre $FeSO_4$	11.71	92	D65-10	-31.66	-2.44	-21.30	-21.05	-4.07	16.40
			F11-10 (TL84)	-32.71	-2.79	-23.34	-23.22	-3.66	16.81
			A-10	-33.00	-4.68	-22.15	-22.07	-5.04	16.89
Sm $FeSO_4$	9.61	76	D65-10	-20.73	-3.52	-19.38	-19.64	-1.55	12.43
			F11-10 (TL84)	-21.75	-3.48	-21.17	-21.39	-1.68	12.90
			A-10	-22.08	-5.20	-20.62	-21.00	-3.34	13.11
Post $FeSO_4$	14.93	117	D65-10	-8.66	2.07	0.86	1.36	-1.78	3.86
			F11-10 (TL84)	-8.60	1.75	1.25	1.62	-1.42	3.66
			A-10	-8.45	1.68	1.32	1.84	-1.10	3.55

* K/S at λ_{max} is the Kubelka-Munk function value measured at the wavelength of maximum absorption. Color Strength (%) is K/S at λ_{max} expressed relative to the unmordanted control (100 %).

** Color strength (%) was calculated by normalizing K/S at λ_{max} values to the unmordanted fabric, which was set as 100 %.

*** ΔEcmc represents the colour difference calculated using the Colour Measurement Committee (CMC) formula, which accounts for human perceptibility of colour variations.

Among tannin-rich natural mordants, mango bark and myrobalan provided noticeable improvements in color strength. Mango bark in simultaneous mordanting achieved 16.25 (127 %), the highest among all natural mordants, while pre- and post-mordanting recorded 12.60 (99 %) and 12.72 (100 %), respectively. This confirms the literature findings by Wangatia et al. [31], which indicate that tannin-rich mango bark enhances dye uptake, particularly when mordanting occurs during the dyeing process. Similarly, myrobalan exhibited a maximum K/S of 13.30 (104 %) under simultaneous mordanting, with weaker tones in the pre-mordanting (9.89, 78 %) and post-mordanting (12.53, 98 %) stages. Previous studies consistently report myrobalan's ability to boost colour strength through tannin-based complexation. However, differences in fibre morphology and tannin concentration explain variations between our data and those reported for cotton or jute [32, 33]. These results emphasize the strong role of hydrolysable tannins in forming covalent or hydrogen bonds with silk fibroin, which stabilizes dye molecules and deepens shade intensity. The superior performance of mango bark and myrobalan compared with Aloe vera or lemon underlines the advantage of high-tannin mordants in achieving metallic-like colour strength without introducing heavy metals.

Eucalyptus extract also produced intense shades, comparable to mango bark. Pre-mordanting delivered 15.68 (123 %), simultaneous mordanting 14.16 (111 %), and post-mordanting 10.41 (82 %). These results confirm the observations of Anandhan et al. [34] and Dutta et al. [35], who highlighted eucalyptus as a potential substitute for metal mordants, with performance approaching that of alum or copper sulfate under optimised conditions. The darker hues recorded in pre- and simultaneous mordanting likely result from the higher availability of tannin during the dye-fibre bonding process. The darker hues observed for eucalyptus in pre- and simultaneous mordanting likely arise from condensed tannins forming strong dye–fiber complexes, while lower K/S in post-mordanting reflects limited complex formation once dye molecules are already fixed. Importantly, the comparable performance of eucalyptus to metallic mordants demonstrates its potential as an eco-friendly alternative for silk dyeing, reducing reliance on environmentally hazardous salts while maintaining acceptable colour depth and fastness.

3.3. Metallic mordants

Metallic mordants demonstrated even greater colour variation and depth, particularly ferrous sulfate, which produced the most intense and darkest shades. Pre-mordanting with $FeSO_4$ recorded a K/S value of 11.71 (92 %), which seems lower than the control in terms of percentage strength but represents a profound hue shift-L* decreased by more than 31 units (ΔEcmc = 16.40), creating deep olive-brown tones (negative a* and b* values). Simultaneous mordanting with $FeSO_4$ yielded 9.61 (76 %), still much darker in perception due to strong absorption in the visible region, while post-mordanting increased colour strength to 14.93 (117 %), indicating different complexation behaviour when applied after dyeing. Such tone darkening by iron salts is consistent with prior findings by Tehrani et al. [36], which report that Fe^{2+} forms stable coordination complexes that shift colours toward grey or black. This strong tone modification can be attributed to Fe^{2+} interacting with phenolic groups in the mango leaf dye to form iron–tannin complexes, which absorb strongly in the blue–red region, thereby producing deep olive or blackish hues. The higher effectiveness of post-mordanting for $FeSO_4$ suggests that applying iron after dye–fiber bonding enables additional complexation directly on the fiber surface, deepening shade intensity.

Copper sulfate and alum induced less drastic but still significant shade modifications. For $CuSO_4$, post-mordanting produced the highest K/S of 12.75 (100 %), with ΔEcmc exceeding 6, indicating a substantial colour difference compared to the control. Pre-mordanting and simultaneous treatments yielded 15.68 (123 %) and 12.04 (94 %), respectively, demonstrating that copper enhances brightness under some conditions but not as dramatically as iron. The observed differences may reflect copper's lower tendency to form extensive crosslinking with phenolic groups, resulting in brighter but less saturated tones. The higher K/S in pre-mordanting may also arise from Cu^{2+} altering silk fibroin's amino groups prior to dye fixation, increasing dye affinity. The alum showed contrasting behaviour: post-mordanting yielded the deepest tone (15.68, 123 %), while simultaneous mordanting resulted in the weakest (8.81, 69 %). These variations support previous studies conducted by Manicketh et al. [37], which documented alum's role in achieving brighter yellow or orange tones, depending on pH and method. Alum's trivalent Al^{3+} ions likely form weaker coordination complexes compared to iron or copper, and the effect of pH on alum hydrolysis may reduce its interaction when added simultaneously with dye, explaining the weaker shades observed.

Finally, simultaneous mordanting generally produced the highest colour strength for natural mordants. In contrast, metallic mordants behaved differently, with post-mordanting favouring alum and copper, and pre-mordanting intensifying iron-based shades. All mordant-treated fabrics exhibited ΔEcmc values well above 1.0, confirming perceptible and significant shade differences compared to the unmordanted control. These numerical results correspond closely with the visual differences seen in Table 2, where ferrous sulfate mordanted samples appear the darkest, followed by tannin-rich natural mordants (mango bark, eucalyptus), while Aloe vera and lemon impart lighter, yellow-green hues. This distinction underscores that metallic mordants follow different binding dynamics compared to bio-mordants: metals may compete with dye molecules during simultaneous application, reducing efficiency, while post- or pre-mordanting allows more controlled complex formation. These results not only validate traditional practices of using iron for dark tones and alum for bright shades but also highlight that careful selection of mordanting sequence can fine-tune colour outcomes without increasing chemical load. From a sustainability perspective, recognizing these behaviours allows dyers to minimize metallic salt use while achieving targeted shades, or to substitute natural tannin-rich mordants where metallic depth is not critical, thereby reducing environmental hazards.

Table 2: Color shades of silk fabrics dyed with mango leaf extract using different mordants.

No mordant			
Mordant	**Resulting Shade**	**Mordant**	**Resulting Shade**
Pre aloe vera		Sm aloe vera	
Post aloe vera		Pre lemon	
Sm lemon		Post lemon	
Pre myrobalan		Sm myrobalan	
Post myrobalan		Pre mango tree bark	

Table 2: Continue.

Mordant	Resulting Shade	Mordant	Resulting Shade
No mordant			
Sm mango tree bark		Post mango tree brak	
Pre Eucalyptus		Sm eucalyptus	
Post eucalyptus		Pre alum	
Sm alum		Post alum	
Pre $CuSO_4$		Sm $CuSO_4$	
Post $CuSO_4$		Pre $FeSO_4$	
Sm $FeSO_4$		Post $FeSO_4$	

3.4. Washing and rubbing fastness

The washing and rubbing fastness properties of silk fabrics dyed with mango leaf extract under different mordanting conditions are presented in Table 3. In general, all dyed samples exhibited good to excellent fastness ratings, ranging from 4 to 5 on the ISO grey scale, indicating that natural dye-mordant systems can provide satisfactory performance for practical use. These values approach those typically expected from commercial synthetic dyes on silk, suggesting that mango leaf extract, when properly mordanted, can deliver industrially acceptable durability.

Washing fastness results showed minimal color change across all mordanting conditions, with ratings between 4 and 5, which is consistent with previous studies on natural dyes applied to protein fibers [28, 38].

Table 3: Washing and rubbing fastness (ISO grey scale) of silk fabrics dyed with mango leaf extract using different mordants.

Mordant	Washing Fastness							Rubbing Fastness	
	Color change	Color Staining							
		Di-acetate	Bleached cotton	Polyamide	Polyester	Acrylic	Wool	Dry	Wet
No mordants	4	5	4	5	4	5	5	4	4
Pre Alovera	5	5	5	5	5	5	5	4	4
Sm Alovera	4	5	4	5	5	5	5	5	4
Post Alovera	4	5	4	5	5	4	5	4	4
Pre Lemon	5	5	5	5	4	5	5	5	4
Sm Lemon	4	5	4	5	5	5	5	5	4
Post Lemon	4	5	5	4	5	5	5	4	4
Pre Myrobalan	4	5	5	5	4	5	5	5	4
Sm Myrobalan	4	5	4	4	5	4	5	4	4
Post Myrobalan	4	5	4	5	5	5	5	4	4
Pre Mango bark	5	5	3	5	5	5	5	4	4
Sm Mango bark	5	5	4	5	5	5	5	4	4
Post Mango bark	4	5	4	5	4	4	5	4	4
Pre Eucalyptus	5	5	4	5	5	5	5	4	4
Sm Eucalyptus	5	5	5	5	5	5	5	4	4
Post Eucalyptus	4	5	4	5	5	4	5	4	4
Pre Alum	5	5	4	5	4	5	5	5	4
Sm Alum	5	4	4	4	5	4	4	5	4
Post Alum	4	4	3	5	5	4	5	4	4
Pre $FeSO_4$	4	5	4	5	5	5	5	4	4
Sm $FeSO_4$	4	4	4	4	4	5	4	5	4
Post $FeSO_4$	4	5	4	5	5	5	5	4	4
Pre $CuSO_4$	4	5	4	5	5	5	5	4	4
Sm $CuSO_4$	5	5	5	5	5	4	5	4	4
Post $CuSO_4$	4	5	4	5	5	5	5	4	4

The control (unmordanted) sample recorded 4 for color change and 4-5 for staining, which improved further with natural and metallic mordants. Aloe vera and lemon displayed the best performance under pre-mordanting (both achieving 5 for color change and 5 for staining). At the same time, simultaneous and post-mordanting showed slightly lower but still excellent ratings of 4 out of 5. These results align with reports that bio-mordants, such as Aloe vera and citrus-based agents, improve wash durability by forming hydrogen and ionic bonds between the dye and fiber [29]. This suggests that small-molecule bio-mordants can penetrate the fiber before or during dyeing, enhancing dye–fiber interactions and reducing dye leaching during laundering. The slightly lower ratings in simultaneous and post-mordanting could result from fewer active binding sites being available once initial dye–fiber complexes have formed.

Among tannin-based mordants, mango bark and eucalyptus recorded superior results, often matching or exceeding the performance of metallic mordants, with most values at 5 for both color change and staining. Myrobalan provided similarly strong ratings, supporting earlier findings by Kumaresan et al. [39] that tannin-rich mordants significantly enhance dye fixation through covalent linkages, reducing dye migration during laundering. These findings are significant because they show that locally sourced, tannin-rich plant materials can achieve durability comparable to environmentally problematic metallic salts, making them strong candidates for sustainable dyeing systems.

Metallic mordants also exhibited good washing fastness, with alum and copper sulfate showing the highest stability. In contrast, ferrous sulfate maintained strong ratings but slightly lower consistency in simultaneous mordanting (4 for color change). These observations are consistent with studies by Tehrani et al. [39] that note ferrous salts tend to promote darker shades but may introduce minor wash-off due to incomplete penetration of metal complexes. This minor reduction in wash stability for $FeSO_4$-treated fabrics may also reflect the formation of larger surface-bound complexes that are more easily removed under agitation, highlighting the need for optimized iron concentrations or post-treatments if maximum durability is desired.

Rubbing fastness (both dry and wet) values were equally promising, with most results falling within the 4–5 range, confirming good surface adherence of the dye. All natural mordants provided excellent dry rubbing ratings (5) across techniques, while wet rubbing values were slightly lower, 4 in some cases, particularly post-mordanting. Mango bark, myrobalan, and eucalyptus consistently achieved 4 or 5, reinforcing their role in improving surface fixation. Metallic mordants showed comparable performance; however, simultaneous mordanting with alum and copper displayed marginally reduced wet rubbing resistance 4, likely due to increased surface deposition of loosely bound dye-metal complexes. These fastness values correspond with similar studies on silk dyeing using natural colorants [30, 32], where the presence of tannins or metallic ions improves the bonding between dye molecules and fibroin amino groups, thereby enhancing mechanical and washing durability. The similar rubbing fastness of bio-mordants and metals underscores that effective dye–fiber bonding can be achieved without relying solely on heavy metals. From an industrial perspective, these results demonstrate that substituting tannin-based mordants could maintain fabric handling and wear properties while reducing toxic effluent.

4. Conclusion

This study demonstrated that mango leaf extract is a promising natural dye for silk fabrics, offering an eco-friendly alternative to synthetic dyes. The application of bio-mordants, such as mango bark, myrobalan, euca-lyptus, Aloe vera, and lemon, significantly improved colour strength and fastness properties. Tannin-rich sources, like mango bark and eucalyptus, showed performance comparable to that of metallic salts. Among metallic mordants, ferrous sulfate produced the deepest shades, while alum and copper sulfate offered bright tones but pose environmental concerns. Fastness tests confirmed good durability, with washing and rubbing ratings mostly between 4 and 5, making the process suitable for practical use. However, issues such as non-reproducibility of shades, lengthy extraction processes, and occasional fastness limitations highlight the need for further optimization. Initial adjustments to extraction temperature, extraction duration, and dye bath pH were incorporated in this study to improve color performance; nevertheless, comprehensive optimi-zation of additional parameters, including material-to-liquor ratio, mordant concentration, and mordanting technique, will be addressed in future research to enhance reproducibility and industrial scalability. Although reflectance spectra were used to evaluate absorption characteristics in this study, future work should incorporate UV–Visible and FTIR spectros-copic analyses of both the mango leaf dye extract and dyed silk fabric to provide deeper chemical insight into dye–fiber interactions and chromophoric compo-sition. Sustainable development in this area requires reducing the reliance on harmful metallic mordants and enhancing the commercial viability of bio-mordants to ensure a balance between ecological safety and industrial applicability.

Here are the following recommendations:

1. Develop faster, energy-efficient extraction and dyeing processes to reduce time and cost.
2. Standardize bio-mordant concentrations and application conditions to improve reproducibility.
3. Conduct detailed toxicity, safety, and biodegradability studies for natural dyes and mordants.
4. Explore new bio-mordant sources from underutilized plants and agricultural waste.
5. Introduce hybrid systems that combine biomordants with eco-friendly additives to enhance fastness.
6. Reduce or eliminate the use of metallic mordants to minimize environmental hazards.
7. Implement pilot-scale trials to evaluate scalability, economic feasibility, and process sustainability.
8. Integrate natural dyeing processes into sustainable textile frameworks aligned with circular economy principles.

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