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Sustainable Dyeing of Cotton Fabrics with Papaver Rhoeas-Derived Anthocyanins: Impact of Mordant and Acid Types

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ABSTRACT

This study explored the eco-friendly application of natural dyes extracted from Papaver rhoeas petals for cotton fabric coloration. Due to growing environmental concerns, natural dyes are being considered as alternatives to synthetic dyes; however, they often suffer from low color strength and poor fastness. To overcome these challenges, this study examined how different mordanting methods, including pre-, meta-, and post-mordanting, a range of metallic and plant-based mordants, and various acid types influence dyeing performance. The petals of Papaver rhoeas contain anthocyanins, especially cyanidin-3-O-glucoside, which provide bright red to purple shades. The results showed that the mordanting method, acid type, and mordant type significantly affected color strength, shade, and fastness properties. Among the tested acids, citric and oxalic acids provided the most favorable dyeing performance, while meta-mordanting was the most effective method overall. Furthermore, natural mordants such as pomegranate rind, oak bark, and Juglans regia performed as well as or better than traditional metal mordants such as tin and iron. Pomegranate rind produced the highest color strength, while these bio-mordants improved color depth and durability. Overall, the study demonstrates that when appropriate mordanting methods, mordant types, and acid types are selected, Papaver rhoeas can be used as an effective and sustainable natural dye for cotton fabrics. Prog Color Colorants Coat. 20 (2027), 203-220© Institute for Color Science and Technology.

1. Introduction

Natural dyes obtained from plants have been used since ancient times, long before the development of synthetic dyes. However, their use in textile applications has been limited due to technological challenges, higher production costs, a limited range of colors, low dye uptake, and poor colorfastness. Despite these limitations, natural dyes are generally considered to be more environmentally friendly than their synthetic counterparts [1]. Numerous efforts have been undertaken to address the inherent limitations associated with natural dyes. Recent research has focused on enhancing their dyeing performance through the development of advanced application methods, including the use of various mordanting agents [2, 3]. Moreover, the application of certain metal-based mordants, such as potassium dichromate and stannic chloride, while effective in improving dye fixation, introduces significant environmental and health hazards, comparable to those associated with synthetic dyes [4]. In this context, the environmental impact of the dyeing industry can be significantly reduced through the adoption of eco-friendly mordants. These sustainable alternatives, often sourced from agricultural by-products, present a safer and more environmentally responsible option. Recent studies

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have demonstrated that natural mordants are capable of delivering color strength and fastness properties comparable to, or even exceeding, those achieved with traditional metal-based mordants [2, 3, 5]. Furthermore, natural dyes, particularly those rich in anthocyanin compounds, exhibit the potential to generate a broad spectrum of colors. This versatility is influenced by variations in mordanting techniques, the specific mordant employed, the choice of acid, and the pH of the dyeing environment [6-8].

Anthocyanins are a class of water-soluble pigments belonging to the flavonoid family, widely recognized for their vibrant colors in fruits and vegetables [9]. With over 635 identified types, they possess diverse chemical properties and health benefits [10]. These compounds exhibit several beneficial properties, making them relevant to textile coloration, nutrition, and health [9, 11, 12].

Papaver rhoeas, commonly known as the corn poppy or red poppy, is an annual herbaceous plant belonging to the *Papaveraceae* family. It is widely distributed across temperate regions of Europe, Western Asia, and North Africa, typically thriving in disturbed soils such as agricultural fields and grasslands [7, 13]. A *Papaver rhoeas* flower is shown in Figure 1. *Papaver rhoeas* is renowned for its striking red flowers and has long been valued not only for ornamental purposes but also for its use in traditional medicine [11]. The petals of *Papaver rhoeas* contain a variety of bioactive compounds, including alkaloids, flavonoids, and anthocyanins, which have demonstrated antioxidant, anti-inflammatory, and mild sedative properties [14-16]. The predominant anthocyanin in *Papaver rhoeas* petals is cyanidin-3-O-glucoside, whose general chemical structure is illustrated in Figure 1. The concentration of cyanidin-3-O-glucoside in fresh petals ranges from 4.72 to 5.19 mg/g [14, 17].

Recent studies have also explored the potential of *Papaver rhoeas* as a natural dye source for applications in the food, cosmetic, and textile industries [7, 8, 11, 15, 17]. In a comprehensive study, Gedik et al. [11] investigated the effects of different pre-treatment methods, including cationization, mordanting, and the sequence in which these processes were applied, on the dyeing performance of cotton fabrics dyed with *Papaver rhoeas* petal extracts. The study focused on evaluating color strength (K/S values), fastness properties (washing and light fastness), and antibacterial performance. Their results demonstrated that cationization prior to mordanting significantly enhanced color uptake and improved both fastness and antibacterial characteristics of the dyed cotton fabrics. Boussoum et al. [8] examined the dyeing behavior of *Papaver rhoeas* extracts, emphasizing their effectiveness as natural dyes for textile fibers. This study explored the role of various metal mordants, such as alum, iron sulfate, and copper sulfate, in improving dye fixation and producing a broader range of color shades. The findings indicated that both mordant type and dyeing conditions had a substantial influence on the final hue and uniformity of coloration. Merdan et al. [17] applied *Papaver rhoeas* flower extracts to wool fabrics and evaluated the impact of ultrasonic energy on the dyeing process. The results showed a marked improvement in color yield and dye penetration when ultrasonic-assisted dyeing was employed, compared to conventional dyeing techniques. This finding suggests that ultrasound facilitates better dye-fiber interactions and promotes deeper coloration. In a subsequent study, Merdan et al. [7] extended the investigation to silk fabrics, assessing the dyeing outcomes under both traditional and ultrasonic methods. The results confirmed that the use of ultrasonic energy, especially in conjunction with appropriate mordants, significantly improved the overall quality and durability of the coloration on silk substrates.

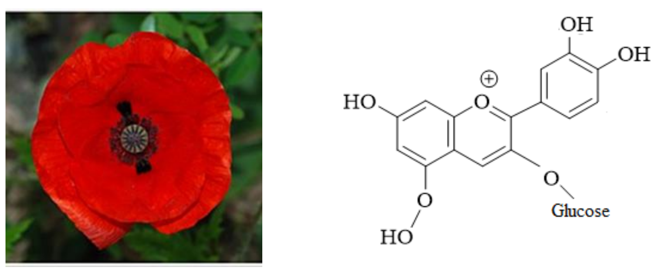


Figure 1: *Papaver rhoeas* plant and structure of cyanidin-3-O-glucoside.

Natural dyes are particularly relevant for dyeing cotton fabrics intended for sensitive user groups, such as infants and young children. In these cases, the use of synthetic dyes may pose risks due to possible allergenic or toxic residues, whereas natural dyes offer additional functional properties beyond coloration. These include anti-allergic, antibacterial, and ultraviolet (UV) protective effects, which contribute to both wearer safety and comfort [15, 16, 18]. Despite these advantages, the successful application of natural dyes in the textile industry depends on meeting essential performance criteria. Among the most important factors are the range and depth of achievable colors, as well as the color fastness to washing, light, and sublimation [19, 20]. Meeting these technical requirements is essential to ensure the practical viability and commercial scalability of natural dye applications in modern textile manufacturing.

In response to the growing demand for environmentally friendly and sustainable dyeing practices, the present study focused on the extraction of natural dye from *Papaver rhoeas* petals and its application on cotton fabrics. The research investigated the effects of different mordanting techniques, including pre-mordanting, meta-mordanting, and post-mordanting, as well as the influence of various mordant types, both metallic and plant-based, on the dyeing performance. In addition, the role of acid type in modifying dye uptake and color development was assessed. The colorimetric characteristics of the dyed fabrics were analyzed in detail, along with the evaluation of key fastness properties, including resistance to washing, light, and sublimation.

2. Experimental

2.1. Materials and dyeing process

Papaver rhoeas flowers, collected from agricultural regions of Iran, were used as a natural dye source. To extract the dye, the flowers were heated in distilled water at 80 °C for 60 minutes, and the resulting extract was filtered thoroughly using Whatman filter paper No. 42 and allowed to cool to room temperature.

Plain-woven cotton fabric (140 g/m²) with a warp density of 48 and a weft density of 42, obtained from Horang Co., Iran, was used as the dyeing substrate. Prior to dyeing or mordanting, the cotton fabric was scoured by immersing it in a 2 mL/L aqueous solution of a non-ionic detergent (Lissapol NC) at 60 °C for 30 minutes, followed by thorough rinsing with tap water.

To evaluate the influence of the mordanting method and acid type on colorimetric properties, three different mordanting techniques were applied: pre-mordanting, meta-mordanting, and post-mordanting.

- **Pre-mordanting:** The cotton fabric was treated with the mordant solution prior to dyeing. After mordanting, the fabric was rinsed, squeezed, and then dyed using the prepared flower extract.
- **Meta-mordanting:** The mordant and dye extract were added simultaneously to the dye bath, allowing the fabric to be treated in a single step.
- **Post-mordanting:** The fabric was first dyed with the *Papaver rhoeas* extract. After dyeing, it was rinsed, squeezed, and then subjected to the mordanting process.

The temperature and holding times during the dyeing and mordanting processes were strictly controlled. The cotton fabric was initially equilibrated at 40 °C for 10 minutes. The bath temperature was then increased at a rate of 2 °C per minute to 80 °C and maintained at this temperature for 60 minutes. Subsequently, the temperature was decreased to 50 °C and held for a defined period before rinsing. This controlled heating, holding, and cooling sequence is illustrated in Figure 2.

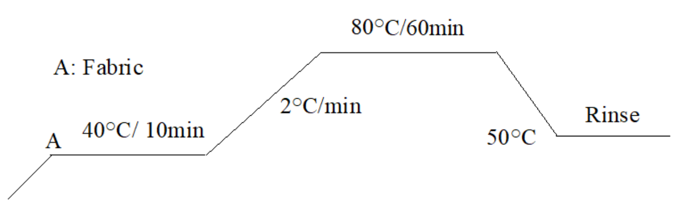


Figure 2: Details of dyeing and mordanting procedures.

To investigate the influence of acid type on the mordanting and dyeing processes, potassium aluminum sulfate (Merck, Germany) was used as a mordant at a concentration of 10 % on-weight-of-fabric (o.w.f.). Potassium aluminum sulfate was selected as a representative metal mordant with a defined chemical composition, allowing the effect of acid type to be assessed under controlled conditions. The effect of acid type was not investigated in combination with plant-based mordants, since these natural mordants contain complex mixtures of tannins, flavonoids, phenolic compounds, and inherent colorants that could confound the results. Additionally, several organic and inorganic acids, including acetic, sulfuric, citric, oxalic, formic, tartaric, and gallic acids (Merck, Germany), were each applied at 4 % o.w.f. during both the mordanting and dyeing stages. For comparison, a cotton fabric sample was dyed without any acid (Control 1). The dyeing process was carried out using an exhaust method, with 60 % o.w.f of the dye.

To assess the impact of mordant type, cotton fabrics were mordanted with seven different metal mordants and ten plant-based mordants. Metal salts, including potassium aluminum sulfate (Al), ferrous sulfate (Fe), copper (II) sulfate (Cu), tin chloride (Sn), potassium dichromate (Cr), nickel chloride (Ni), and zinc chloride (Zn), were purchased from Merck, Germany. The plant-based mordants were obtained from agricultural waste materials or local markets in Iran and included corn silk, white onion peel, Pistacia vera (pistachio skin), Citrus limon peel (lemon peel), Punica granatum L. (pomegranate rind), Juglans regia, pinecone, oak bark, Quercus infectoria, and date kernel. For comparison purposes, a cotton fabric sample was also dyed without the application of any mordant (Control 2). The mordanting and dyeing processes in this step were carried out following the same temperature and time profile as illustrated in Figure 2. During the mordanting procedure, cotton fabrics were treated with Al at a concentration of 10 % o.w.f., while other metal mordants were applied at 5 % o.w.f. Plant-based bio-mordants were used at a concentration of 15 % o.w.f. The dyeing process was carried out using the exhaust method, with 60 % o.w.f. of the dye. Both the mordanting and dyeing processes were conducted at a controlled pH of 4, with a liquor-to-fabric ratio of 50:1. The pH of the dyeing bath was adjusted using acetic acid.

2.2. Colorimetric and fastness characterization

The color coordinates of the dyed samples were measured using the CIELAB (1976) color space, which includes parameters L*, a*, b*, C*, and h°, using a YS6010 benchtop reflectance spectrophotometer under D65 illuminant and a 10° standard observer. In this system, L* represents lightness (with 0 indicating the darkest and 100 indicating the lightest), a* corresponds to the red-green axis, b* corresponds to the yellow-blue axis, C* reflects color purity, and h° indicates the hue angle. For each measurement, three replicate readings were taken, and the average value was automatically calculated.

To evaluate the color differences between fabrics dyed with different acids and those dyed without acid (Control 1), or between fabrics dyed with different mordants and those dyed without mordant (Control 2), the total color difference (ΔE) was calculated. The equation used to calculate ΔE is as follows (Eq. 1):

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (1)$$

Where ΔL, Δa, and, Δb represent the differences in lightness, redness-greenness, and yellowness-blueness, respectively, between the dyed samples treated with acids and Control 1, or between the dyed samples treated with mordants and Control 2.

To assess color strength (K/S), the Kubelka-Munk equation was applied, which is based on the sample's reflectance (R) at the wavelength of maximum absorption (Eq. 2):

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

Color-fastness-to-washing test was conducted according to ISO 105-C06 (2010), with color change measured using the ISO 105-A02 gray scale, ranging from 1 to 5. Light fastness was determined following the ISO 105-B02 (2014) method using a Xenon Test Chamber (Reessanj Co., Model XTC97) equipped with a 1000 W xenon lamp. The color fastness to dry heat (sublimation) was assessed based on ISO 105-PO1 (1993), where the dyed fabric samples were exposed to a temperature of 150°C ± 2°C for 30 seconds. The resulting color change was evaluated using the gray scale, with ratings ranging from 1 to 5.

3. Results and Discussion

3.1. Effect of acid type on colorimetric and fastness parameters

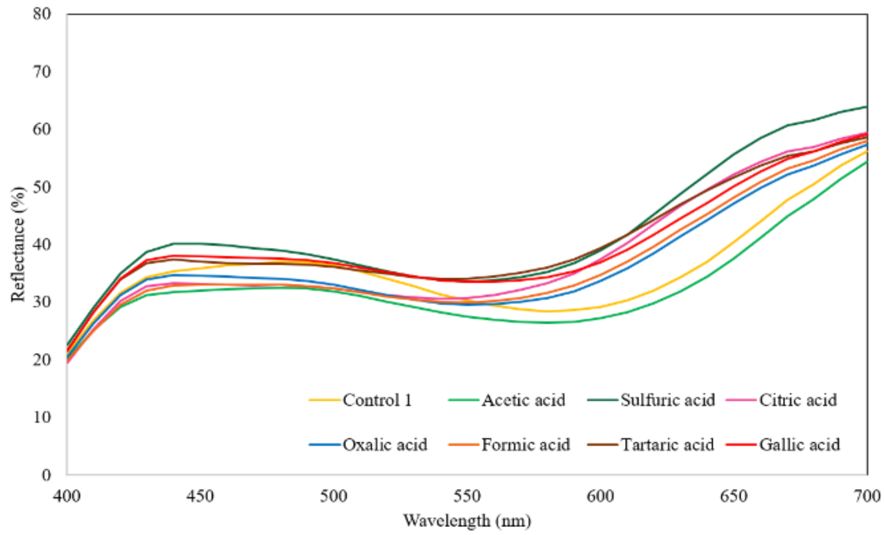
The results, as shown in Tables 1-3 and Figures 3-5, indicate significant variations in color strength, colorimetric values, and fastness properties depending on the various acids applied and mordanting procedures.

The acids influence the dyeing process in two key ways: (1) by modifying the pH of the dye bath, and (2) through chemical interaction with both fiber and dye molecules, especially via hydroxyl and carboxyl groups [6, 7, 17]. The pH of the dye bath has a direct impact on the stability and ionization state of anthocyanin compounds, which are the main chromophores in *Papaver rhoeas* petals. Under mildly acidic conditions (pH ~3–5), anthocyanins exist predominantly in the flavylium cation form, which is responsible for producing intense red to purple colors [21-23]. Organic acids such as citric, oxalic, and formic acids help maintain this optimal pH range, supporting the stability of the dye and promoting deeper color development. This is evident in Tables 1-3, where the highest K/S was observed in samples treated with citric acid (K/S = 2.18) and oxalic acid (K/S = 2.10) in the meta-mordanting method. Additionally, the total color difference values (ΔE*) support these results. Citric acid also exhibited high ΔE* values in pre-mordanting (11.54) and meta-mordanting (15.39), corresponding to significant but desirable color enhancement compared to the control 1 sample. In contrast, strong mineral acids such as sulfuric acid can lower the pH excessively, leading to partial hydrolysis or degradation of anthocyanin molecules [21]. This could explain the relatively lower K/S values (e.g., 1.33 in pre- and meta-mordanting) and the faded appearance of fabrics treated with sulfuric acid, as shown in Figures 3 and 4. Sulfuric acid in meta-mordanting caused the highest ΔE* value (16.45), which may reflect degradation or unintended color shifts. These findings align with previous literature indicating that excessively acidic environments can destabilize natural pigments and compromise dye uptake [7].

Beyond their pH-modifying role, several acids, particularly citric, tartaric, and oxalic acids, contain multiple hydroxyl and carboxyl functional groups (Figure 6). These groups enable the acids to participate directly in the dye-fiber binding process by acting as chelating agents or secondary mordants. Through this mechanism (Figure 6), they may form coordination complexes that bridge between the hydroxyl groups of cellulose fibers and reactive moieties on anthocyanin molecules, such as phenolic –OH groups [8, 24, 25]. This hypothesis is supported by the chromatic and fastness data in Tables 1-3.

Table 1: Colorimetric and fastness properties of dyed fabrics with various acids using the pre-mordanting method.

pre	L*	a*	b*	ΔE*ab	C*	h°	K/S	W. F	L.F	S. F
Control 1	63.38	-0.54	-4.47	--	4.50	263.18	1.46	3-4	3	3-4
Acetic acid	60.82	0.97	-3.71	3.06	3.83	284.71	1.58	4	3-4	4-5
Sulfuric acid	67.29	7.88	-2.26	9.54	8.19	343.99	1.33	3-4	3	4
Citric acid	64.79	9.08	1.75	11.54	9.24	10.89	1.67	4	6	4
Oxalic acid	63.62	6.52	-2.03	7.47	6.83	342.69	1.53	3-4	3-4	4
Formic acid	63.84	6.89	0.42	8.91	6.91	3.51	1.62	3-4	3	4
Tartaric acid	67.09	6.85	0.51	9.65	6.87	4.22	1.41	3-4	3-4	4
Gallic acid	66.53	5.31	-1.41	7.31	5.49	345.16	1.42	3-4	4	4



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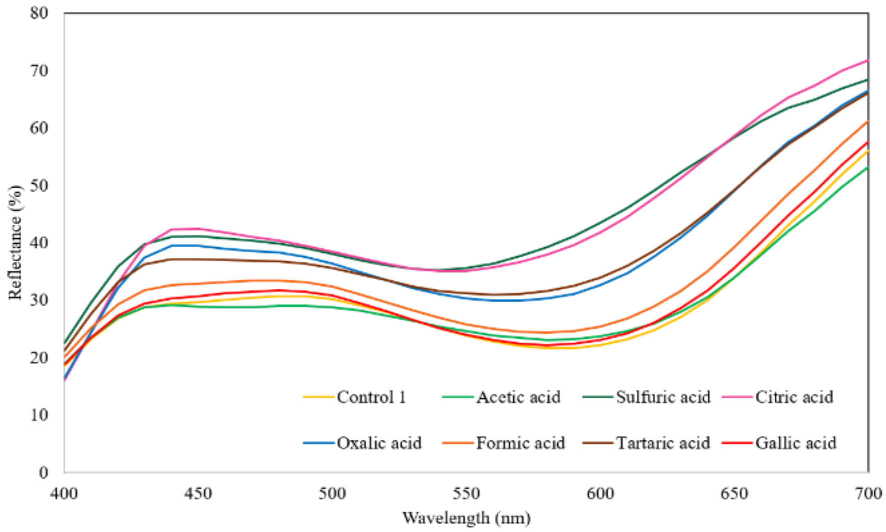

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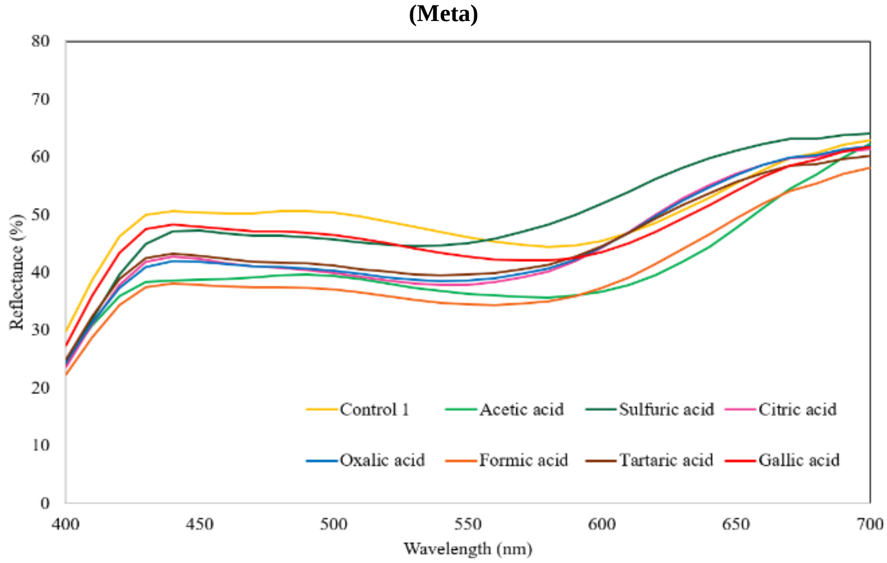

(Post)

Figure 3: Reflectance spectra of fabrics dyed using different mordanting methods and acids.

Table 2: Colorimetric and fastness properties of dyed fabrics with various acids using the meta-mordanting method.

meta	L*	a*	b*	ΔE*ab	C*	h°	K/S	W. F	L.F	S. F
Control 1	57.62	-1.02	-5.99	--	6.07	260.29	1.78	3-4	3	4
Acetic acid	57.95	0.53	-4.26	2.34	4.29	277.08	1.72	4	3	4
Sulfuric acid	68.99	9.52	-0.47	16.45	9.54	357.17	1.33	3	2-3	3-4
Citric acid	68.66	8.73	-1.52	15.39	8.86	350.15	2.18	3	3	4-5
Oxalic acid	64.52	4.98	-5.63	9.15	7.52	311.49	2.10	3-4	2-3	4
Formic acid	59.95	1.39	-6.27	3.36	6.43	282.50	1.59	4	3	3-4
Tartaric acid	64.88	5.25	-3.16	10.00	6.13	328.90	1.46	3	3	4-5
Gallic acid	58.11	0.17	-6.51	1.38	6.51	271.51	1.74	3-4	3	4

Table 3: Colorimetric and fastness properties of dyed fabrics with various acids using the post-mordanting method.

post	L*	a*	b*	ΔE*ab	C*	h°	K/S	W. F	L.F	S. F
Control 1	74.47	0.27	-2.32	--	2.34	276.54	0.83	4	4	4-5
Acetic acid	67.77	1.50	-0.86	6.97	1.73	330.20	1.16	4	4	4-5
Sulfuric acid	74.61	6.23	2.41	7.61	6.68	21.16	1.21	3-4	4	4
Citric acid	70.10	7.81	-0.18	8.97	7.81	358.70	1.24	3	4	4-5
Oxalic acid	70.40	6.92	0.74	8.38	6.95	6.09	1.17	3-4	4-5	4-5
Formic acid	66.90	4.48	-0.71	8.81	4.54	351.02	1.35	4	4	4-5
Tartaric acid	70.85	6.13	0.22	7.34	6.14	2.09	1.13	3-4	4-5	4-5
Gallic acid	72.54	2.07	-2.64	2.66	3.35	308.11	0.96	4	5	4-5

Figure 4: Digital images of cotton fabrics dyed using different mordanting methods and acids.

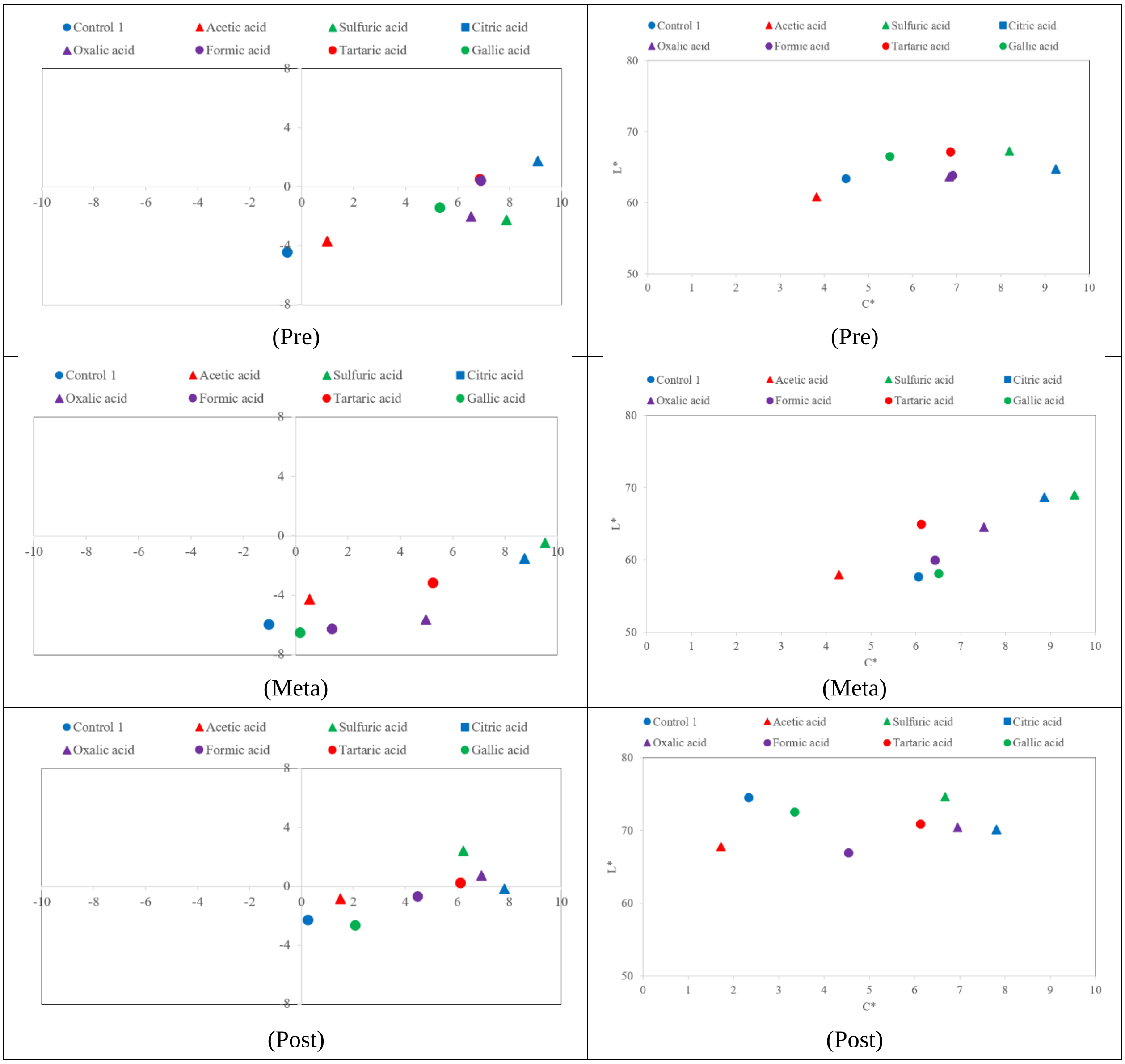

Figure 5: a*b* and C*L* plots of cotton fabrics dyed using different mordanting methods and acids.

For instance, citric acid in pre-mordanting produced intense reddish hues (a*=9.08) and high chroma (C*=9.24) along with good light fastness (rating of 6) and very good washing and sublimation fastness (grade 4), indicating both strong coloration and durable dye fixation. In meta-mordanting, similar values were recorded (a* = 8.73 and C* = 8.86), reinforcing the effectiveness of citric acid across different mordanting sequences. Oxalic acid also demonstrated effective performance, likely due to similar bridging interactions. In contrast, acetic acid, which has fewer coordination sites (single carboxyl group and single hydroxyl functionality as illustrated in Figure 6, showed moderate performance. Although it can help maintain a favorable pH, its limited complexation ability may explain the lower K/S values and reduced chroma observed, particularly in post-mordanting (e.g., acetic acid: C* = 1.73, K/S = 1.16). Gallic acid, though rich in hydroxyl groups (Figure 6), showed inconsistent behavior. While it might participate in complexation, its potential for oxidative reactions may interfere with dye stability or hinder effective adsorption on cotton fibers, resulting in lower K/S values and subdued hues (Figure 5). Sulfuric acid, especially in meta-mordanting, resulted in weaker light fastness ratings (2-3), indicating poor dye fixation or pigment breakdown [7].

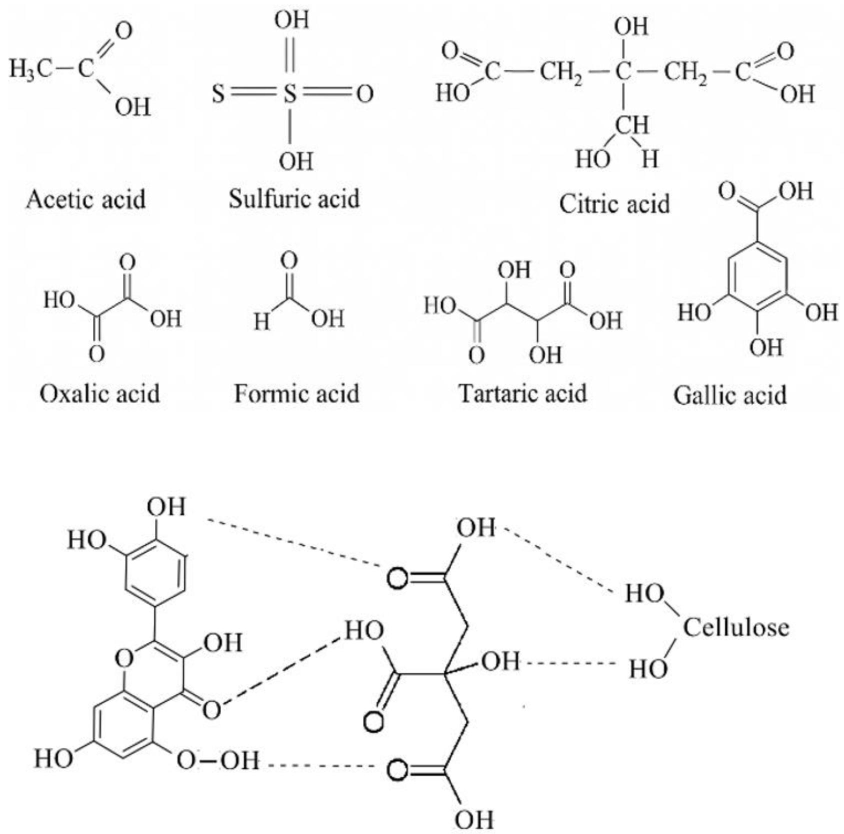

Figure 6: Chemical structures of the acids used and proposed interactions among anthocyanin, acids, and cotton fiber.

As illustrated in Figure 5, the a*b* and C*L* plots show that samples treated with polyfunctional organic acids such as citric and oxalic acids occupy regions associated with high saturation, red-shifted, and yellow-shifted hues. These acids contribute to more uniform and vibrant colors due to their dual role in pH stabilization and intermolecular bonding. Similar effects were observed with tartaric acid, although its impact on K/S was slightly less pronounced. Among the acid-treated samples, acetic and gallic acids lie closer to the center of the chromatic space, indicating duller and less saturated coloration.

A Comparison of the results for three mordanting methods indicated that meta-mordanting emerged as the most effective in terms of color strength and vividness, particularly when combined with citric acid (K/S = 2.18) and oxalic acid (K/S = 2.10). Pre-mordanting also provided strong coloration with good fastness, making it a suitable alternative when intense hues and performance are both priorities. Post-mordanting, while yielding lower color intensity, offered consistent fastness, indicating its potential for applications where durability is more critical than color depth. These observations are supported by the reflectance spectra in Figure 3, where pre- and meta-mordanted samples exhibited lower reflectance (higher absorption) compared to post-mordanted samples. The colorimetric data in Tables 1-3 and visual comparisons in Figure 4 further confirm this trend.

In conclusion, for optimal dyeing results with Papaver rhoeas extract, both the acid type, particularly its chemical structure, and the mordanting sequence must be carefully selected. Acids with multiple functional groups capable of chelation, combined with meta- or pre-mordanting techniques, offer a promising and eco-friendly route to achieve high-quality, durable coloration in cotton fabrics using Papaver rhoeas extract.

3.2. Effect of metal and plant-based mordants on colorimetric and fastness parameters

The results, presented in Figures 7-9 and Tables 4-6, show that both the type of mordant and the dyeing method influenced the reflectance, color strength, color coordinates (a*, b*, C*, h°), and fastness properties.

One of the main findings was that mordanted samples dyed much better than the sample without any mordant (Control 2). In all dyeing methods, the Control 2 sample showed lower K/S values compared with almost all other treated samples. For example, in the pre-mordanting method (Table 4), control 2 had a K/S of only 1.27 and showed a light reddish-beige color (L* = 67.48, a* = 5.82, b* = 2.00, C* = 6.16), as seen in Figure 8. In comparison, samples treated with pomegranate rind (K/S = 4.29) or Sn (K/S = 3.65) showed much deeper and more intense colors. This improvement is due to the fact that anthocyanins in the dye extract do not bond well to cotton without mordants [11, 25, 26]. Cotton fibers lack reactive sites for strong bonding, so the dye is readily removed during washing. Mordants help by forming stable bonds between the dye and the fiber. Specifically, metal mordants act as bridging agents, coordinating with hydroxyl or carbonyl groups of anthocyanins and hydroxyl groups on cellulose chains in cotton (Figure 10) [26, 27]. As a result, color differences (ΔE) between control 2 and mordanted samples were usually greater than 10, indicating clearly visible differences in shade and intensity. Moreover, for natural mordants, the binding mechanisms rely primarily on polyphenols such as tannins, flavonoids, and phenolic acids. These compounds can bind with anthocyanins via hydrogen bonding, π–π stacking, and hydrophobic interactions (Figure 10) [25, 26, 28].

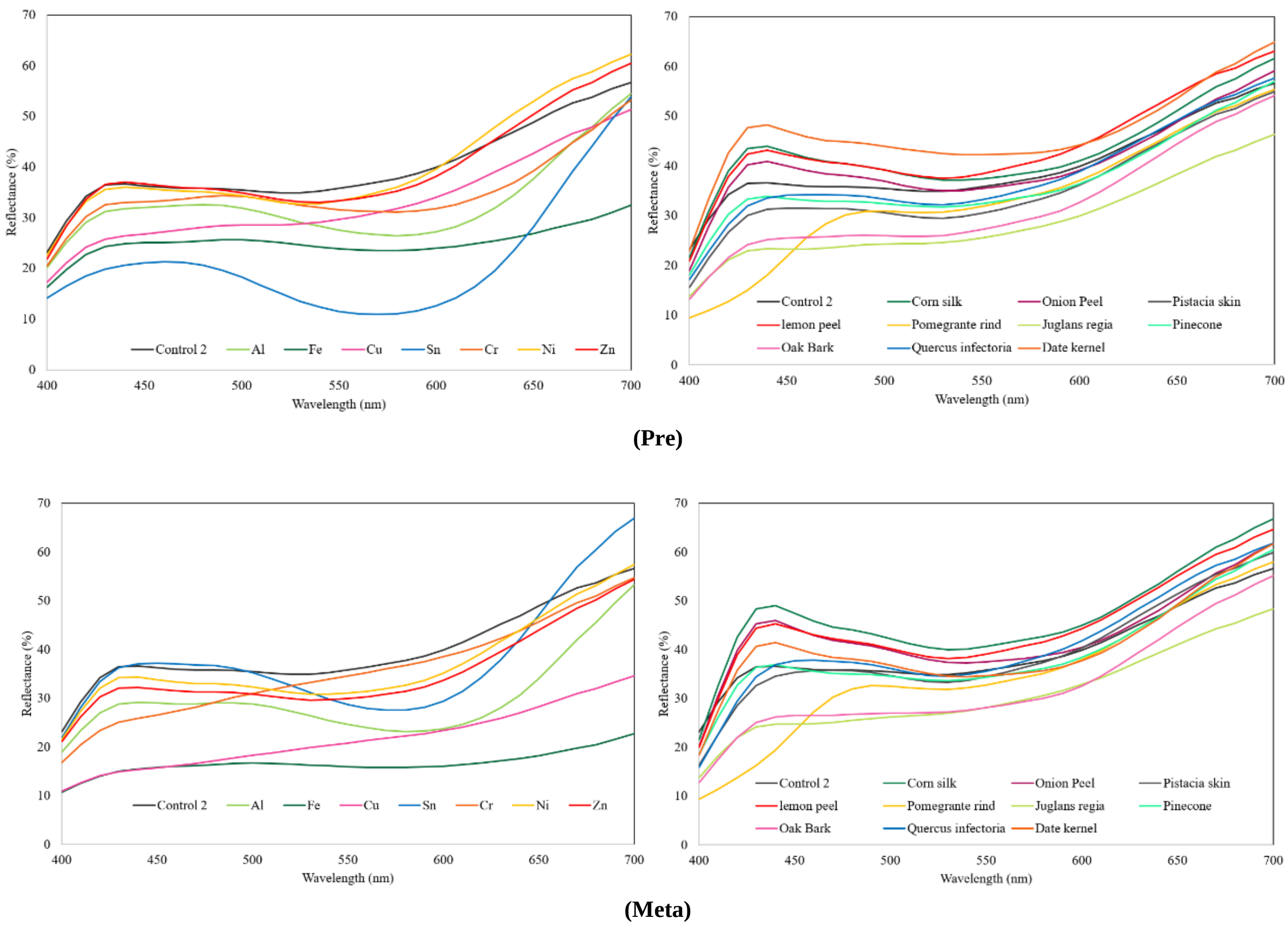

Figure 7: Reflectance spectra of fabrics dyed using different mordanting methods and mordants.

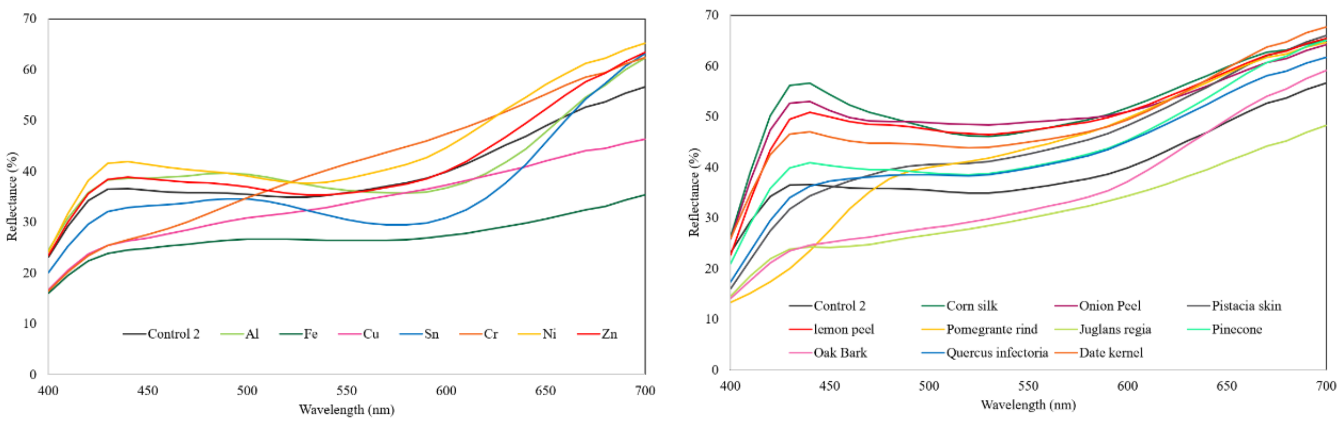

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Figure 7: Continue.

Table 4: Colorimetric and fastness properties of dyed fabrics with various mordants using the pre-mordanting method.

Sample	L*	a*	b*	ΔE*ab	C*	h°	K/S	W. F	L.F	S. F
Control 2	67.48	5.82	2.00	--	6.16	18.98	1.27	3-4	3	4
Al	60.82	0.97	-3.71	10.02	3.83	284.71	1.58	4	3-4	4-5
Fe	56.54	-0.28	-0.40	12.75	0.48	234.91	2.16	4-5	3	4-5
Cu	62.41	5.52	6.58	6.83	8.59	50.04	1.97	4	5	4-5
Sn	44.82	7.03	-12.72	27.04	14.53	298.93	3.65	4	4	4-5
Cr	63.83	0.60	-0.30	6.77	0.68	333.23	1.54	4	4	4
Ni	66.53	8.70	1.27	3.12	8.79	8.30	1.33	4	3-4	4-5
Zn	66.30	7.19	-0.16	2.82	7.19	358.75	1.40	3-4	3-4	4-5
Corn silk	69.08	5.90	-2.49	4.77	6.40	337.15	1.42	3-4	3-4	4
Onion Peel	67.54	5.89	-1.70	3.70	6.13	343.93	1.73	3-4	3-4	4
Pistacia skin	63.83	7.62	3.00	4.19	8.19	21.46	2.27	4	4	4
lemon peel	70.01	7.29	-0.23	3.68	7.29	358.19	1.50	3-4	3-4	4
Pomegranate rind	64.27	2.22	17.51	16.24	17.65	82.76	4.29	4	4-5	5
Juglans regia	58.79	6.50	6.34	9.74	9.08	44.33	2.69	4-5	4-5	4-5
Pinecone	64.99	6.04	1.85	2.50	6.32	17.04	1.86	4	4-5	4-5
Oak Bark	60.71	8.13	6.47	8.43	10.39	38.53	2.83	4-5	5	4-5
Quercus infectoria	65.99	7.05	3.21	2.28	7.75	24.49	2.00	3-4	4-5	4
Date kernel	72.07	3.76	-2.14	6.51	4.32	330.37	1.29	4	4	4

Table 5: Colorimetric and fastness properties of dyed fabrics with various mordants using the meta-mordanting method.

Sample	L*	a*	b*	ΔE*ab	C*	h°	K/S	W. F	L.F	S. F
Control 2	67.48	5.82	2.00	--	6.16	18.98	1.27	3-4	3	4
Al	57.95	0.53	-4.26	12.57	4.29	277.08	1.72	4	3	4
Fe	47.30	-0.32	1.44	21.10	1.48	102.70	3.69	4-5	3-4	4-5

Table 5: Continue.

Sample	L*	a*	b*	ΔE*ab	C*	h°	K/S	W. F	L.F	S. F
Cu	52.93	3.63	10.75	17.12	11.35	71.32	3.62	5	5	4-5
Sn	62.92	3.75	-6.47	9.84	7.48	300.13	1.39	3-4	2-3	4
Cr	65.66	3.53	12.03	10.44	12.54	73.67	2.05	4-5	4	4-5
Ni	64.24	6.80	-0.18	4.03	6.80	358.44	1.42	4	3-4	4-5
Zn	63.10	6.26	0.51	4.65	6.28	4.67	1.47	4	3	4
Corn silk	71.53	6.94	-3.11	6.61	7.60	335.82	1.42	3	3	4-5
Onion Peel	69.15	5.64	-3.94	6.17	6.88	325.02	1.57	3-4	3-4	4-5
Pistacia skin	67.04	7.10	3.48	2.00	7.91	26.08	2.14	3-4	4	4-5
lemon peel	70.50	7.28	-1.35	4.74	7.40	349.47	1.60	3-4	4	4
Pomegranate rind	65.18	2.14	16.35	14.99	16.49	82.55	4.35	4	5	4-5
Juglans regia	61.01	6.26	7.68	8.62	9.90	50.81	2.71	4	5	4
Pinecone	66.58	6.36	1.07	1.40	6.45	9.54	1.79	3-4	4-5	4
Oak Bark	61.28	7.03	6.04	7.49	9.27	40.66	2.99	4-5	5	4
Quercus infectoria	68.05	7.28	2.66	1.70	7.75	20.07	2.22	3-4	3	4
Date kernel	67.04	5.87	-2.86	4.88	6.53	334.02	1.81	3-4	4	4-5

Table 6: Colorimetric and fastness properties of dyed fabrics with various mordants using the post-mordanting method.

Sample	L*	a*	b*	ΔE*ab	C*	h°	K/S	W. F	L.F	S. F
Control 2	67.48	5.82	2.00	--	6.16	18.98	1.27	3-4	3	4
Al	67.77	1.50	-0.86	5.19	1.73	330.2	1.16	4	4	4-5
Fe	58.77	0.48	3.43	10.32	3.47	82.04	2.19	4-5	5	5
Cu	64.96	2.94	10.39	9.22	10.8	74.19	2.08	4	5-6	4-5
Sn	63.55	1.71	-0.7	6.29	1.85	337.74	1.58	4	4	4-5
Cr	70.44	4.27	18.32	16.66	18.81	76.89	2.11	3-4	4	4-5
Ni	70.20	8.06	0.76	3.73	8.09	5.41	1.19	4	3-4	4-5
Zn	67.91	6.49	0.15	2.01	6.49	1.3	1.25	4	4	5
Corn silk	75.55	6.69	-3.48	9.79	7.55	332.5	1.03	3-4	3	4-5
Onion Peel	75.95	3.25	-0.26	9.13	3.27	355.41	1.06	4	3	4-5
Pistacia skin	72.12	4.06	10.72	10.03	11.46	69.27	2.19	4	4	4
lemon peel	75.3	4.41	0.46	8.09	4.44	5.90	1.31	4	4	4-5
Pomegranate rind	72.4	1.29	21.36	20.48	21.4	86.53	2.82	5	5-6	5
Juglans regia	62.08	5.31	10.06	9.71	11.38	62.17	2.49	5	5-6	5
Pinecone	70.68	6.78	2.94	3.47	7.39	23.46	1.48	4	4-5	4-5
Oak Bark	63.81	7.32	11.79	10.56	13.88	58.15	2.62	4-5	5	4-5
Quercus infectoria	70.34	5.04	6.56	5.43	8.28	52.47	1.97	4	4-5	4-5
Date kernel	73.88	5.68	1.64	6.41	5.91	16.08	1.05	3-4	4	4-5

Figure 8: Digital images of cotton fabrics dyed using different mordanting methods and mordants.

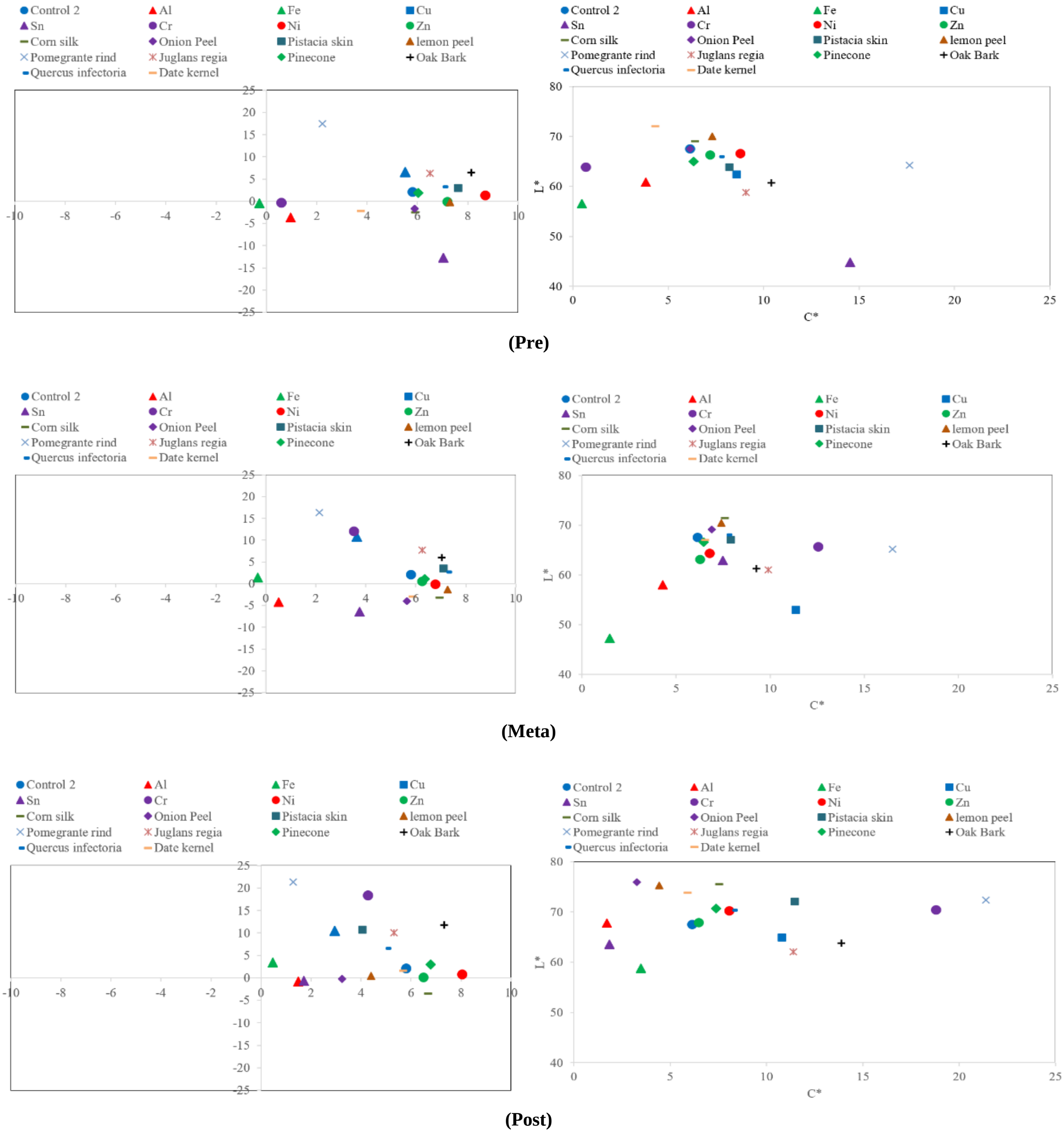

Figure 9: The a*b* and C*L* plots of cotton fabrics dyed using different mordanting methods and mordants.

Among the metal mordants, Sn exhibited the lowest reflectance (Figure 7), indicating the strongest color (K/S = 3.65) in the pre-mordanting method (Table 4). The sample appeared purplish (L* = 44.82, a* = 7.03 and b* = –12.72). This is because Sn can form stable complexes with anthocyanins, especially in slightly acidic conditions, resulting in deeper colors [26, 29]. In the meta-mordanting method, Fe yielded the highest K/S (3.69) and produced a dark reddish-brown tone (C* = 1.48, h° = 102.70), with high wash and sublimation fastness (grade 4-5, Table 5). The effectiveness of Fe can be attributed to it bonds strongly with the dye structure to form stable pigments that resist fading [30]. However, in this sample, light fastness was relatively poor, with a rating of 3-4 (Table 5). Cu also produced moderately bright colors (C = 11.35, h° = 71.32, K/S = 3.62), possibly due to bonding behavior similar to that of Fe [30]. Ni and Zn were less effective, giving higher reflectance (Figure 7), lower K/S values (< 1.5), and paler shades (Figure 8), possibly due to weaker interaction with the dye [30].

Natural mordants produced a wider range of colors and interacted in more complex ways with the dye. Among them, pomegranate rind, oak bark, and Juglans regia performed best. Pomegranate rind showed the highest K/S values across all methods, 4.29 (pre), 4.35 (meta), and 2.82 (post), and produced bright yellowish-brown colors (e.g., b* = 17.51, C* = 17.65, h° ≈ 82.76 in pre-mordanting, Table 4). Its corresponding low-reflectance curve is visible in Figure 7, confirming intense coloration. This is because it is rich in tannins, especially ellagitannins and punicalagin, which help fix the dye [3, 31]. It also contains natural pigments like anthocyanins and flavonoids (quercetin), which may act as secondary dyes, further enhancing the color [31, 32]. The high b* and ΔE values (>16) confirm this effect (Figure 8). Oak bark showed similar dual action. Its tannins, gallic acid, and ellagic acid helped fix the dye and added a reddish-brown tone (Figure 8) [3]. In pre-, meta-, and post-mordanting, oak bark gave K/S values of 2.83, 2.99, and 2.62 and warm tones (a* > 7, b* > 6, C* > 9), with clear color changes (ΔE > 7.5). Juglans regia, which contains the pigment juglone, produced deep brownish-red tones (Figure 8) [33]. In pre-mordanting (Table 4), juglans regia-mordanted samples showed L* = 58.79, a* = 6.50, b* = 6.34, and C* = 9.08. These muted yet rich shades, and ΔE = 9.74 from control 2, confirm its strong natural dyeing ability. Other natural mordants such as onion peel and corn silk, although they contain flavonoids such as quercetin, were less effective due to lower tannin levels [2]. For instance, onion peel gave a weak purplish color (a* = 5.89, b* = –1.70, K/S = 1.73) in pre-mordanting (Table 4 and Figure 8). Date kernel, which lacks active tannins, produced minimal dyeing (C* = 4.32, K/S = 1.29) [2, 3]. Some natural mordants gave intermediate results. Quercus infectoria, which is rich in gallic acid [34], showed better dye binding (K/S ≈ 2, C* ≈ 8). Pinecone and lemon peel had moderate effects due to limited tannin content [2, 3]. These results suggest that the success of bio-mordants depends mainly on their chemical composition, especially tannins, flavonoids, and natural pigments. Some of these natural mordants also contribute their intrinsic color to the fabric, thereby functioning as both mordants and dyes.

In comparing metal and natural mordants, several natural mordants performed even better. For example, pomegranate rind gave higher K/S (4.35, Table 5) and brighter colors (C* = 16.49, h° = 82.55) than Sn, Fe, or Cu in meta-mordanting. While metal mordants like Fe and Cu exhibited moderate to excellent fastness (grade 4-5 for wash, grade 5-6 for light, and grade 5 for sublimation fastness, Table 6), natural mordants like oak bark, pomegranate rind, and juglans regia showed comparable durability (grade 5 for wash, grade 5-6 for light, and grade 5 for sublimation fastness, Table 6). Natural mordants also tend to produce warmer, more colorful hues because of their own pigment content (Figures 8 and 9). In contrast, metal mordants often result in darker or duller tones due to chemical shifts in the dye. Natural mordants also have important environmental advantages: they are biodegradable, safe, and compatible with eco-friendly dyeing [1, 24].

The method of mordanting had a major impact. Meta-mordanting gave the highest K/S values and most vivid shades. Pomegranate rind, oak bark, Fe, and Cu all gave their best results in this method. Meta-mordanted samples had lower L* and higher K/S values, meaning deeper and more vivid colors. This deeper color expression is also visible in the reflectance drop in Figure 7 for meta-mordanted samples. Post-mordanting produced lighter colors with lower saturation, though fastness was still good. These trends are visible in Figure 9; meta-mordanted fabrics are located further from the center in a*b* and C*L* plots, while post-mordanted samples are nearer the center, indicating weaker color development.

Overall, the results demonstrate that both mordant type and its method of application play a critical role in determining the final dyeing performance of cotton dyed with *Papaver rhoeas*. The effectiveness of these mordants depends on their ability to form strong chemical bonds with anthocyanins.

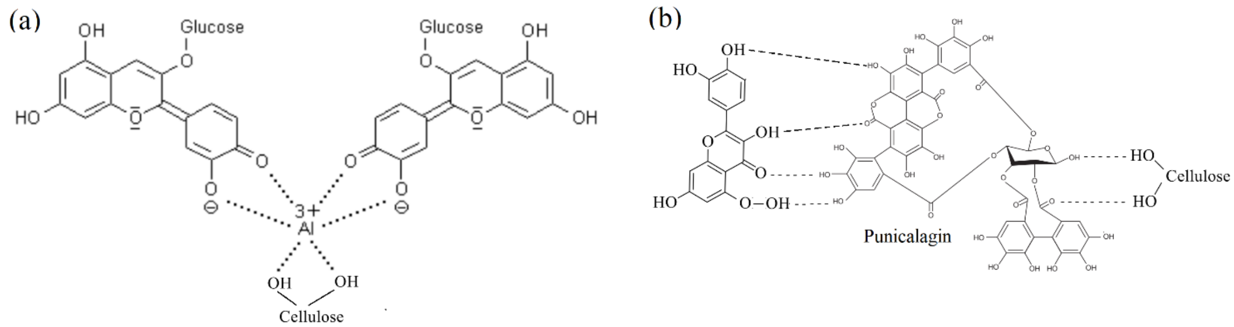

Figure 10: Proposed mechanism of colorant–fiber bonding mediated by (a) metallic and (b) bio-mordants.

4. Conclusions

This study demonstrated the potential of *Papaver rhoeas* petal extract as a natural and sustainable dye source for cotton fabrics. The anthocyanins present in the petals, especially cyanidin-3-O-glucoside, exhibited promising color strength and produced a wide range of hues when used under suitable dyeing conditions. The performance of the dye was significantly influenced by both the mordanting method and the type of mordant or acid applied. Among the mordanting techniques, meta-mordanting proved to be the most effective, resulting in higher color strength (K/S values) and more vivid coloration. Citric and oxalic acids were the most successful acid additives, helping to stabilize the dye molecules and improve bonding with cotton fibers. These organic acids not only enhanced the chromatic properties but also contributed to better fastness characteristics. The results also showed that the performance of plant-based mordants was highly dependent on their source. Among the tested bio-mordants, pomegranate rind, oak bark, and *Juglans regia* showed the most promising results, providing higher color strength and good to excellent fastness properties compared with several conventional metallic mordants. In contrast, some other plant-based mordants produced lower color strength and less pronounced shade development.

This study highlights the potential integrating of Papaver rhoeas as a natural dye source within modern textile processing and emphasizes the role of green chemistry in improving sustainable textile coloration while maintaining acceptable colorimetric properties and fastness performance under the tested conditions. By carefully selecting suitable acid types, mordanting methods, and mordant types, Papaver rhoeas can be effectively utilized to achieve both aesthetic appeal and essential technical performance in cotton fabric coloration. However, this study was limited to cotton fabric and laboratory-scale dyeing conditions, and only selected colorimetric and fastness properties were evaluated. Therefore, further studies should investigate the performance of *Papaver rhoeas* dye under pilot- and industrial-scale conditions, its applicability to other textile fibers, its durability after repeated laundering and long-term use, and the environmental and economic aspects of the proposed dyeing process.

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5. References

1. Nambela L, Haule LV, Mgani Q. A review on source, chemistry, green synthesis and application of textile colorants. J Clean Prod. 2020; 246:119036. https://doi.org/10.1016/j.jclepro.2019.119036.
2. Tehrani M, Ahmadi S. Ecological dyeing of cotton fabrics with cochineal: influence of bio-mordants on colorimetric and aging parameters. Fiber Polym. 2025;26:3047-3060. https://doi.org/10.1007/s12221-025-01006-y .
3. Tehrani M, Asadi Farsani T. Sustainable wool dyeing: utilizing Syzygium aromaticum (clove bud) extract and plant-derived mordants. Prog Color Colorants Coat. 2025; 18(3):363-373. https://doi.org/10.30509/pccc.2025.167426.1343.
4. Saha A, Roy S. Harmful effects of different classes of heavy metals in our beautiful environment. Asian J Res Chem. 2023;16(1):13-17. https://doi.org/10.527 11/ 0974-4150.2023.00003 .

5. Hosseinnezhad M, Gharanjig K, Imani H, Razani N. Green dyeing of wool yarns with yellow and black myrobalan extract as bio-mordant with natural dyes. J Nat Fibers. 2022;19(10):3893-3915. https://doi.org/10.1080/15440478.2020.1848735.
6. Kamali-Moghaddam M, Ghanbari-Adivi M, Tehrani M. Effect of acids and different mordanting procedures on color characteristics of dyed wool fibers using eggplant peel (Solanum melongena L.). Prog Color Colorant Coat. 2019; 12(4):219-230. https://doi.org/10.30509/pccc.2019.81557.
7. Merdan N, Yilmaz B, Kocak E, Ari G. Colour and fastness properties of silk fabrics dyed with colours obtained from the flowers of Papaver rhoeas (common poppy). Asian J Chem. 2012; 24(10):4295-4299.
8. Boussoum MO, Ouldmokhtar R, Nehari AA, George B. Characterization of extracts from Papaver rhoeas and potential valorization of these extracts in dyeing applications. Turk J Chem. 2021;45(5):1576-1584. https://doi.org/10.3906/kim-2105-44
9. Sangeeta S, Rai S, Bisht S, Nazim M. Chemical properties of anthocyanins sourced from different subtropical fruits. In: Anthocyanins in Subtropical Fruits. CRC Press; 2023. p.33-58. https://doi.org/10.1201/9781003242598.
10. Mohammad SS, Santos RO, Barbosa MI, Barbosa Junior JL. Anthocyanins: chemical properties and health benefits: a review. Curr Nutr Food Sci. 2021; 17(7). https://doi.org/10.2174/1573401317999210101150652.
11. Gedik G, Yavas A, Avinc O, Simsek Ö. Cationized natural dyeing of cotton fabrics with corn poppy (Papaver rhoeas) and investigation of antibacterial activity. Asian J Chem. 2013; 25(15):8475–8483. https://doi.org/10.14233/ajchem.2013.14793.
12. Alam MS, Maity MK, Nazmi AS, Ali MY. Anthocyanins: pharmacology and nutraceutical importance. In: Anthocyanins: Antioxidant Properties, Sources and Health Benefits. Bentham Sci Publishers; 2024; 93-116. https://doi.org/10.2174/9789815223880124010009.
13. Dudek B, Schneider B, Hilger HH, Stavenga DG, Martínez-Harms J. Highly different flavonol content explains geographic variations in UV reflecting properties of Papaver rhoeas flowers. Phytochem. 2020; 178:112457. https://doi.org/10.1016/j.phytochem.2020.112457
14. Velickovic JM, Mitic MN, Arsic BB, Paunovic DĐ, Stojanovic T, Veljkovic JN, et al. HPLC analysis of extracts of fresh petals of Papaver rhoeas L. Stud U Babes-Bol Chem. 2019;64(3):239-247. https://doi.org/10.24193/subbchem.2019.3.20.
15. Bujak T, Zagórska-Dziok M, Ziemlewska A, Nizioł-Łukaszewska Z, Lal K, Wasilewski T, et al. Flower extracts as multifunctional dyes in the cosmetics industry. Molecules. 2022; 27(3):922. https://doi.org/10.3390/molecules27030922.
16. Marsoul A, Ijjaali M, Oumous I, Bennani B, Boukir A. Determination of polyphenol contents in Papaver rhoeas L. flowers extracts and antioxidant activity. Mater Today Proc. 2022;31:183-189. https://doi.org/10.1016/j.matpr.2020.08.082.
17. Merdan N, Saçlıoğlu MZ, Koçak D, Şahinbakan Yılmaz B. Investigation on colour and fastness properties of wool fabrics dyed with Papaver rhoeas flowers. Adv Environ Biol. 2012; 6(2):750-755.
18. Martínez-Harms J, Hadar R, Márquez N, Menzel R, Shmida A, Stavenga DG, et al. Enhanced UV-reflection facilitated a shift in pollination system of Papaver rhoeas. Plants. 2020;9(8):927. https://doi.org/10.3390/plants9080927.
19. Pizzicato B, Pacifico S, Cayuela D, Mijas G, Riba-Moliner M. Advancements in sustainable natural dyes for textile applications: a review. Molecules. 2023;28(16):5954. https://doi.org/10.3390/molecules28165954
20. Saxena S, Raja ASM. Natural dyes: sources, chemistry, application and sustainability issues. In: Roadmap to Sustainable Textiles and Clothing. Springer; 2014. https://doi.org/10.1007/978-981-287-065-0_2.
21. Enaru B, Drețcanu G, Pop TD, Stănilă A, Diaconeasa Z. Anthocyanins: factors affecting stability and degradation. Antioxidants. 2021;10(12):1967. https://doi.org/10.3390/antiox10121967.
22. Giusti MM, Wrolstad RE. Acylated anthocyanins from edible sources and their applications in food systems. Biochem Eng J. 2003;14(3):217-225. https://doi.org/10.1016/S1369-703X(02)00221-8
23. Stavenga DG, Leertouwer HL, Dudek B. Coloration of flowers by flavonoids and pH-dependent absorption. Front Plant Sci. 2021; 11:600124. https://doi.org/10.3389/fpls.2020.600124.
24. Tehrani M, Ghaheh FS, Beni ZT, Rahimi M. Stability of dyes from spent coffee grounds on silk fabrics using eco-friendly mordants. Environ Sci Pollut Res. 2023;30(26):68625-68635. https://doi.org/10.1007/s11356-023-27157-0.
25. Wang H, Tang Z, Zhou W. Dyeing cotton fabric with anthocyanin dyes extracted from mulberry fruits. Color Technol. 2016;132(3):222-231. https://doi.org/10. 1111/COTE.12212
26. Phan K, Van Den Broeck E, Van Speybroeck V, De Clerck K, Raes K, De Meester S. Anthocyanins from blueberries as natural dye for cotton. Dyes Pigm. 2020; 176:108180. https://doi.org/10.1016/j.dyepig.2019.108180.
27. Yasukawa A, Chida A, Kato Y, Kasai M. Dyeing silk and cotton fabrics using natural blackcurrants. Text Res J. 2017;87(19):2379-2387. https://doi.org/10.1177/ 0040517516671125
28. Shahmoradi Ghaheh F, Kamali Moghaddam M, Tehrani M. Eco-friendly dyeing of viscose rayon fabrics using anthocyanin from Hibiscus sabdariffa. J Nat Fibers. 2022; 19(16):13052-13062. https://doi.org/10.1080/15440478.2022.2084659
29. Vankar PS, Shukla D. Natural dyeing with anthocyanins from Hibiscus rosa-sinensis flowers. J Appl

Polym Sci. 2011;122(5):3361-3368. https://doi.org/10.1002/APP.34415.
30. Zarkogianni M, Mikropoulou E, Varella E, Tsatsaroni E. Colour and fastness of natural dyes: revival of traditional dyeing techniques. Color Technol. 2011;127 (1):18-27. https://doi.org/10.1111/J.1478-4408.2010.00273.X.
31. Yang R, Li J, Cheng G, Inta A, Yang L. Dyeing of textiles with pomegranate peel extract using natural mordant. J Nat Fibers. 2023;20(2):2282056. https://doi.org/10.1080/15440478.2023.2282056
32. Shams Nateri A, Dehnavi E. Effect of mordanting method on absorption behavior of natural dyes. Pigm Resin Technol. 2022; 51(5):489-498. https://doi.org/10.1108/PRT-05-2021-0050
33. Thakur A. Juglone: a therapeutic phytochemical from Juglans regia L. J Med Plants Res. 2011; 5:5324-5330.
34. Dhanania Y, Singhee D, Samanta AK. Optimization of dyeing process variables for eco-friendly cotton dyeing with babul bark extract. J Nat Fibers. 2022; 19(13): 5478-5495. https://doi.org/10.1080/15440478.2021.1875955

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