

Ecoprint on Cabretta Leather Using Natural Dyes from Selected Leaves and Flowers: Visual Characteristics and Color Fastness under Different Mordants

Ismadi, I Wayan Suardana, I Ketut Sunarya, Aida Roihana Zuhro, Dedy Sartono

How to cite: Ismadi, Suardana IW, Sunarya IK, Zuhro AR, Sartono D. Ecoprint on Cabretta Leather Using Natural Dyes from Selected Leaves and Flowers: Visual Characteristics and Color Fastness under Different Mordants. Textile & Leather Review. 2026; 9:961-992. <https://doi.org/10.31881/TLR.2026.961>

How to link: <https://doi.org/10.31881/TLR.2026.961>

Published: 17 April 2026



Ecoprint on Cabretta Leather Using Natural Dyes from Selected Leaves and Flowers: Visual Characteristics and Color Fastness under Different Mordants

Ismadi*, I Wayan Suardana, I Ketut Sunarya, Aida Roihana Zuhro, Dedy Sartono

Department of Fine Arts Education, Faculty of Languages, Arts and Culture, Universitas Negeri Yogyakarta, Jl. Colombo No.1 Karang Malang, Caturtunggal, Depok, Sleman, Yogyakarta 55281, Special Region of Yogyakarta, Indonesia

*ismadi@uny.ac.id

Article

<https://doi.org/10.31881/TLR.2026.961>

Received 4 October 2025; Accepted 3 March 2026; Published 17 April 2026

ABSTRACT

*Ecoprint, a natural dyeing technique that transfers plant pigments and shapes directly onto substrates, has gained increasing attention as an eco-friendly alternative for leather decoration. This study examines the effects of three mordants—calcium carbonate (CaCO_3), ferrous sulfate (FeSO_4), and aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$)—on the visual characteristics and color fastness of Cabretta leather ecoprinted using selected plant materials (*Hibiscus rosa-sinensis*, *Cosmos caudatus*, *Cosmos sulphureus*, *Tagetes erecta*, and *Rumohra adiantiformis*). Both visual assessment and quantitative scoring (1–5), supported by defined criteria, were applied to evaluate color intensity, motif clarity, and overall aesthetic appearance. Calcium carbonate produced soft, pastel-like hues; ferrous sulfate yielded dark, high-contrast patterns; and aluminium sulfate generated balanced and well-defined motifs.*

Color fastness tests revealed that aluminium sulfate exhibited the highest light fastness, while all mordants produced acceptable washing and rubbing fastness for Cabretta leather. One-way ANOVA showed significant differences in washing and light fastness among mordant treatments, while rubbing fastness presented no statistically significant difference. These results demonstrate that the choice of mordant plays a critical role in determining both aesthetic outcomes and durability in leather ecoprinting, providing practical insights for sustainable leather craft and eco-friendly material development.

KEYWORDS

ecoprint, natural dyes, cabretta leather, mordants, color fastness

INTRODUCTION

Natural dyeing techniques have long been valued for their aesthetic, cultural, and environmental significance. Among these, ecoprint, which transfers pigments and plant patterns directly onto a substrate, has emerged as a sustainable and innovative approach. Unlike synthetic dyes that generate hazardous effluents, ecoprint offers an environmentally friendly alternative while enhancing the visual and symbolic qualities of the dyed material [1-5]. Initially developed for textiles, the technique has expanded into leather processing and attracted growing interest in craft, design, and sustainable fashion. Ecoprint typically uses leaves and flowers, such as *Hibiscus rosa-sinensis*, *Cosmos caudatus*, and other pigment-rich plant species, which release natural tannins, flavonoids, and anthocyanins under heat and pressure. While ecoprint has been widely explored on cellulose-based fabrics such as cotton and silk, its application to protein-based substrates like goat leather presents unique challenges. Leather's collagen matrix, variable porosity, and sensitivity to chemical treatments influence pigment penetration, diffusion, and motif definition differently from plant-based textiles [6-11]. These substrate-specific conditions underscore the need for dedicated studies on ecoprint applied to leather. A central factor in natural dyeing is the use of mordants, including calcium carbonate (CaCO_3), ferrous sulfate (FeSO_4), and aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$). Mordants enhance pigment fixation, modify hue, and improve fastness against light, washing, and abrasion [12-17]. While their effects are well documented in textile studies, their interactions with collagen fibers are more complex. Metallic ions may influence fiber swelling, crosslinking, and chromophore bonding, producing distinct visual outcomes. For example, FeSO_4 tends to yield darker and more contrasted motifs, CaCO_3 produces softer, pastel-like patterns, whereas alum enhances brightness and motif clarity [15,18-22]. These differences highlight how mordant selection directly affects both the aesthetic and functional properties of ecoprint leather. Despite expanding interest, comparative research specifically focused on ecoprint for Cabretta leather remains limited [23-28]. Existing literature rarely integrates qualitative visual evaluations with instrumental colorimetry such as CIELAB parameters (L^* , a^* , b^* , ΔE) and reflectance (R%). Moreover, most studies overlook the importance of testing inter-rater reliability in visual scoring, potentially reducing the objectivity of evaluation methods. Additionally, many dyeing studies do not incorporate a non-mordanted control group, limiting the interpretation of mordant effects on color formation and fastness. Cabretta leather is widely used in premium products such as gloves, wallets, and small accessories due to its fine grain and durability. Applying

ecoprint to this material offers both aesthetic innovation and practical relevance, supporting sustainable craft practices and reducing reliance on synthetic chemical dyes. However, collagen-based substrates are also more prone to chemical degradation and environmental sensitivity, making it essential to examine how different mordants influence durability in terms of washing, light exposure, and rubbing. Instrumental testing, including ΔE values and reflectance measurements, provides a crucial complement to visual observations, enabling nuanced assessment of pigment stability. Recent literature highlights the nuanced role of mordants in shaping both the visual and functional properties of ecoprint leather. Calcium carbonate (CaCO_3) generally produces brighter, pastel-like motifs; ferrous sulfate (FeSO_4) yields dark, high-contrast patterns; and aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$) provides balanced coloration and motif clarity [15,18-21]. These variations underscore the need to evaluate the combined effects of mordants on motif definition, pigment stability, and overall aesthetic quality, particularly given the structural characteristics of collagen fibers. Cabretta leather introduces additional considerations in terms of color fastness, as collagen-based substrates are more susceptible to environmental and chemical factors than cellulose fibers. While earlier research has focused mainly on synthetic dyes, studies exploring natural pigments and mordanting combinations remain limited [13,29]. Accordingly, assessing washing, light, and rubbing resistance is essential to validate the practical use of ecoprint leather. Instrumental measurements—such as reflectance (R%) and CIELAB color differences (ΔE)—provide objective support to visual observations and help quantify changes that may not be perceptible to the human eye. This study addresses these gaps by systematically evaluating the effect of three mordants—calcium carbonate, ferrous sulfate, and alum—on ecoprint outcomes using selected leaves and flowers. It integrates qualitative visual scoring with quantitative colorimetry and inter-rater reliability analysis to provide a comprehensive assessment of both aesthetic and functional aspects of leather ecoprinting. Specifically, the study investigates: Visual characteristics of ecoprint motifs under different mordants, including color intensity, motif clarity, and aesthetic impression.

Quantitative color retention (R%) to evaluate pigment stability on collagen fibers.

CIELAB parameters and ΔE to characterize color differences among treatments.

By combining visual and instrumental methods, this research contributes to sustainable natural dyeing scholarship and offers practical guidance for ecoprint artisans, leatherworkers, and eco-friendly material designers seeking enhanced durability and aesthetic quality.

EXPERIMENTAL

Materials and Methods

Materials

The present study employed three main categories of materials: Cabretta leather, plant-based dye sources, and mordants. The materials used in this study are summarized in Table 1.

Cabretta leather. Cabretta leather was used as the primary substrate in this study. It is a fine-grained, soft sheep leather known for its high absorptive capacity, making it suitable for natural dye penetration in ecoprint processing. The Cabretta leather used in this experiment had a thickness of 0.6–0.8 mm and was obtained from a local tannery in Yogyakarta. Its collagen-based structure and vegetable-tanned surface supported optimal interaction between plant pigments and mordants.

Plant-based dyes. Nine plant materials were used as natural dye sources for ecoprinting. *Cosmos caudatus* (pink kenikir flowers) produced greenish-yellow tones; *Cosmos sulphureus* (sulfur cosmos flowers) generated orange–yellow hues; *Hibiscus rosa-sinensis* (hibiscus flowers) yielded red to pink shades; *Tagetes erecta* (marigold flowers) produced yellow–orange tones; *Jatropha integerrima* (peregrina flowers) contributed reddish pigments; *Antigonon leptopus* (coral vine) generated pinkish tones; *Manihot esculenta* var. *japonica* (Japanese cassava leaves) produced light-green hues; *Tagetes erecta* leaves contributed light-brown tones; and *Rumohra adiantiformis* (leatherleaf fern leaves) provided brown shades. These plant materials have been widely recognized as effective eco-friendly natural colorants for textile and leather applications [22,29].

Mordants. Three mordants were used to enhance pigment fixation and modify the visual characteristics of the ecoprint patterns: calcium carbonate (CaCO_3), ferrous sulfate (FeSO_4), and aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$). These compounds were selected based on their established interactions with natural pigments and collagen fibers. Calcium carbonate, a mild alkaline agent, is known to brighten hues and produce softer, pastel-like tones. Ferrous sulfate typically darkens colors and increases contrast through strong coordination with tannins and flavonoids. Aluminium sulfate acts as a widely used mordant that improves color clarity and stability without excessive darkening. The three mordants were included to represent different ionic strengths and pH effects, enabling a systematic comparison of their influence on pigment uptake, hue

modification, and color fastness on protein-based substrates such as leather. The Cabretta leather substrate, plant materials, and mordants used in the experiment are shown in Figure 1.

Table 1. Materials used in the study

Category	Local name	Scientific name	Function
Media	Cabretta leather	–	Substrate for dye absorption
Plant sources	Pink kenikir flowers	<i>Cosmos caudatus</i> Kunth	Greenish-yellow pigment source
	Sulfur kenikir flowers	<i>Cosmos sulphureus</i> Cav.	Orange-yellow pigment source
	Hibiscus flowers	<i>Hibiscus rosa-sinensis</i> L.	Red to pink pigment source; bluish tint in alkaline conditions
	African marigold (flower)	<i>Tagetes erecta</i> L.	Yellow–orange pigment source
	Peregrina / spicy jatropa flowers	<i>Jatropha integerrima</i> Jacq.	Red to reddish-purple pigment source
	coral vine / Mexican creeper	<i>Antigonon leptopus</i> Hook. & Arn.	Pink to magenta pigment source
	Japanese cassava leaves	<i>Manihot esculenta</i> var. <i>japonica</i>	Light green pigment source
	Marigold leaves (African marigold)	<i>Tagetes erecta</i> L.	Light brown pigment source
Mordants	Leatherleaf fern leaves	<i>Rumohra adiantiformis</i> (G. Forst.) Ching	Brown pigment source
	Lime	Calcium carbonate (CaCO ₃)	pH modifier; brightening agent
	Iron sulfate / tunjung	Ferrous sulfate (FeSO ₄)	Darkening agent, color modifier
	Alum	Aluminium sulfate (Al ₂ (SO ₄) ₃)	Color fixer, brightener



(a) Cabretta leather



(b) *Cosmos caudatus* Kunth



(c) *Cosmos sulphureus* Cav. (sulfur kenikir flowers)



(d) *Hibiscus rosa-sinensis* L. (hibiscus flowers)



(e) *Tagetes erecta* L. (marigold flower)



(f) *Jatropha integerrima* Jacq. (Jatropha Integerrima flowers)

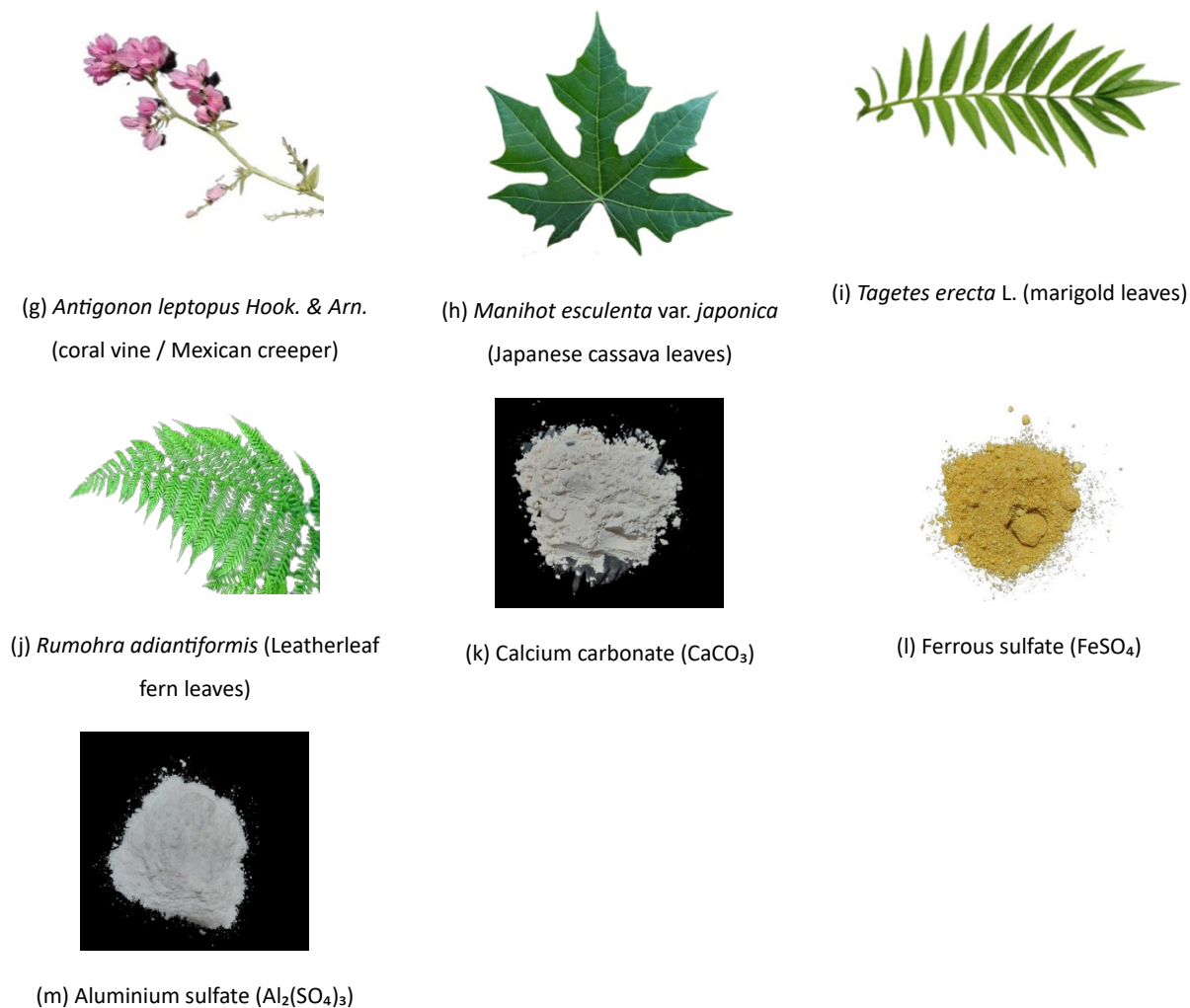


Figure 1. Materials used in the study: (a) Cabretta leather; (b) *Cosmos caudatus* Kunth (pink kenikir flowers); (c) *Cosmos sulphureus* Cav. (sulfur kenikir flowers); (d) *Hibiscus rosa-sinensis* L. (hibiscus flowers); (e) *Tagetes erecta* L. (marigold flower); (f) *Jatropha integerrima* Jacq. (peregrina / spicy jatropha flowers); (g) *Antigonon leptopus* Hook. & Arn. (coral vine / Mexican creeper, air mata pengantin flowers); (h) *Manihot esculenta* var. *japonica* (Japanese cassava leaves); (i) *Tagetes erecta* L. (marigold leaves); (j) *Rumohra adiantiformis* (G. Forst.) Ching (leatherleaf fern leaves); (k) Calcium carbonate (CaCO_3); (l) Ferrous sulfate (FeSO_4); (m) Aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$)

Ecoprint Process

1. Leather Preparation

The Cabretta leather was first cleaned to remove residual oils, surface dirt, and processing chemicals that could inhibit pigment penetration. After cleaning, the leather was immersed in a mordant solution—calcium

carbonate (CaCO_3), ferrous sulfate (FeSO_4), or aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$)—for 6–12 hours. The mordanting step facilitates ionic interaction between metal ions and collagen functional groups ($-\text{COOH}$ and $-\text{NH}_2$), increasing the affinity of the leather fibers for natural pigments.

Calcium carbonate, a mild alkaline mordant, increases fiber openness by slightly raising the pH, whereas Fe^{2+} and Al^{3+} form coordination complexes with tannins, flavonoids, and other plant chromophores. These interactions improve pigment fixation, enhance color intensity, and contribute to higher washing and light fastness, as reported in earlier studies on protein-based substrates [22,27-30]. The pre-mordanted leather was then dried until it reached a semi-damp condition suitable for the ecoprinting process.

2. Ecoprint Technique with Steam

(1) Arrangement of Motifs

The prepared leaves and flowers (*Cosmos caudatus* Kunth, *Cosmos sulphureus* Cav., *Hibiscus rosa-sinensis* L., *Tagetes erecta* L., *Jatropha integerrima* Jacq., *Antigonon leptopus* Hook. & Arn., *Manihot esculenta* var. *japonica*, and *Rumohra adiantiformis*) were placed directly onto the surface of the pre-mordanted Cabretta leather. Plant materials were arranged in a controlled pattern, ensuring consistent pressure and orientation to minimize variability in pigment transfer. The arrangement step is critical because differences in contact pressure, moisture content, and vein structure affect motif clarity.

(2) Rolling

After arrangement, the leather was tightly rolled using a heat-resistant cotton cloth. The roll was secured with natural fiber string to ensure uniform compression. Tight rolling prevents displacement of plant materials and creates the necessary contact between pigments and collagen fibers during steaming. Uniform pressure is essential to maintain consistent motif sharpness across samples, as documented in previous ecoprint studies on protein-based substrates.

(3) Steaming Process

The rolled samples were placed in a steam chamber and processed for 90–120 minutes at a controlled temperature of 90–100 °C. Steam acts as a heat-moisture catalyst that accelerates the release and migration of natural pigments such as anthocyanins, carotenoids, chlorophylls, and tannins from the plant tissues.

3. Variation of Fixation

After the steaming stage, the leather rolls were carefully unwrapped and air-dried at room temperature. To stabilize the transferred pigments and enhance color intensity, a post-steaming fixation process was applied using three different mordant solutions. This step strengthens the coordination bonding between metal ions and plant-derived chromophores, thereby improving color durability and motif clarity. The fixation procedure followed established natural dyeing protocols for protein-based materials [29].

The three mordants produced distinct visual and chemical effects:

- Calcium carbonate (CaCO_3)

Functioning primarily as an alkaline pH regulator, CaCO_3 promotes the brightening of colors and yields soft, pastel-like yellowish tones. The alkaline environment causes partial swelling of collagen fibers, facilitating pigment penetration and resulting in subtle motif appearance [31,32].

- Ferrous sulfate (FeSO_4)

Fe^{2+} ions act as strong darkening agents due to their ability to form stable iron–tannin complexes. This produces darker, muted, and high-contrast hues, especially enhancing the definition of leaf veins and midrib structures. Iron mordants often reduce luminosity (L^*) and shift colors toward gray-brown tones, as reported in prior ecoprint literature [33,34].

- Aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$)

Al^{3+} ions form coordination complexes with flavonoids and phenolic pigments, intensifying color brightness while maintaining motif clarity. Aluminium sulfate tends to preserve chromatic purity (a^* and b^* values) and produces vivid, balanced colors with sharp edges [35,36].

The use of these mordants produced a wide spectrum of visual outcomes, ranging from soft pastels tones to dark, dramatic contrasts, while maintaining the principles of sustainable leather processing. The main stages of the ecoprint process applied to Cabretta leather are summarized in Table 2. These variations demonstrate how metal-ion chemistry influences pigment fixation, color stability, and visual aesthetics on collagen-based substrates [27,28,37].

Table 2. Summary of the Ecoprint Process on Leather Using Steam

Stage	Procedure	Technical Purpose / Scientific Effect
1. Leather Preparation	Leather cleaned, degreased, and soaked in mordant solution (CaCO_3 , FeSO_4 , or $\text{Al}_2(\text{SO}_4)_3$) for 6–12 hours.	Swelling of collagen fibers; increased porosity; improved diffusion of plant chromophores; initial ion-exchange interactions between mordant ions (Ca^{2+} , Fe^{2+} , Al^{3+}) and collagen functional groups.
2. Motif Arrangement	Leaves/flowers placed directly on leather surface with controlled pressure and moisture.	Ensures consistent pigment–fiber contact; allows controlled transfer of anthocyanins, flavonoids, tannins; determines motif definition.
3. Bundling (Tight Wrapping)	Leather tightly rolled using heat-resistant material and bound firmly.	Prevents motif displacement; promotes even steam penetration; stabilizes plant pressure points for consistent pigment diffusion.
4. Steaming	Steamed for 1–2 hours at controlled temperature (90–100 °C).	Heat induces pigment release; promotes metal–chromophore complex formation; initiates binding of pigments to collagen via hydrogen bonding and coordination reactions.
5. Drying & Fixation	Leather unrolled, air-dried, and fixation reinforced by mordant residues.	CaCO_3 brightens and shifts hue via alkaline pH; FeSO_4 forms dark iron–tannin complexes; $\text{Al}_2(\text{SO}_4)_3$ enhances chromatic clarity through stable Al–flavonoid coordination and improves final color stability.

The ecoprint procedure used in this study is illustrated in Figure 2.

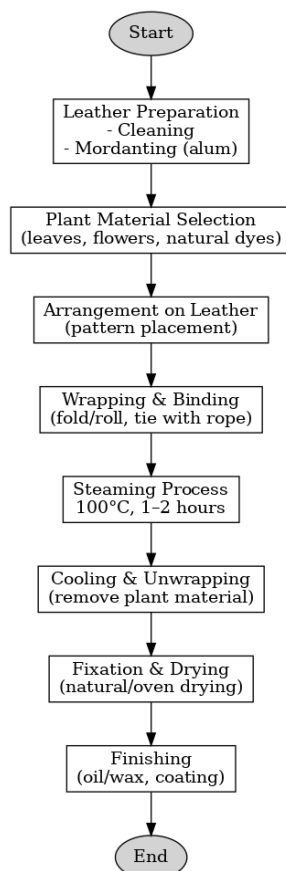


Figure 2. Flowchart of Ecoprint Process on Leather Using Steam

Color Evaluation

Color evaluation was conducted using a combination of qualitative and quantitative methods to ensure objective, replicable, and scientifically valid assessment of the ecoprinted leather samples.

1. Visual Observation

Visual examination was conducted under standardized lighting conditions (D65 daylight simulator).

To minimize subjectivity, a structured 5-point scoring rubric was used to evaluate:

- Color intensity
- Motif clarity
- Edge definition (sharpness)
- Overall visual uniformity

The scoring criteria were defined as follows.

The scoring criteria used for the visual evaluation of ecoprint motifs are presented in Table 3.

Table 3. Scoring Criteria for Visual Evaluation of Ecoprint Motifs

Score	Criterion Description
5	Very clear motif transfer, sharp edges, high color intensity, no blotching.
4	Clear motif with minor diffusion; good color intensity.
3	Moderate clarity; slight blurring; acceptable color intensity.
2	Weak motif visibility; blurred edges; uneven color distribution.
1	Very poor clarity; indistinct motif; weak pigmentation.

2. Reflectance Value (R%)

Reflectance values (R%) were measured using a calibrated spectrophotometer.

R% represents the percentage of incident light reflected at specific wavelengths:

- Low R% → darker color / stronger pigment absorption
- High R% → lighter color / weaker pigment absorption

This parameter provides an objective measure of color depth and optical behavior of the ecoprinted leather surface [38-40].

3. CIELAB Color Space (L^* , a^* , b^* , ΔE)

Quantitative color analysis was conducted using the CIELAB color system, which is widely accepted for evaluating natural dyeing results [36,41]:

- L^* = lightness (0 = black, 100 = white)
- a^* = green (–) to red (+) axis
- b^* = blue (–) to yellow (+) axis

The overall color difference (ΔE) between samples was calculated using:

$$\Delta E = \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}$$

ΔE values were interpreted using standard thresholds [46,47]:

- $\Delta E < 1$: Not perceptible
- 1–2: Slight, perceptible only to trained observers
- 2–5: Perceptible to most people
- > 5 : Large color difference

4. Overall Evaluation Workflow

The color evaluation proceeded in three integrated stages:

- (1) Standardized visual scoring (with rubric + inter-rater reliability)
- (2) Reflectance measurement (R%)
- (3) CIELAB analysis (L^* , a^* , b^* , ΔE)

This workflow is summarized in Figure 3, and the measurement results are presented in Tables 4 and 5.

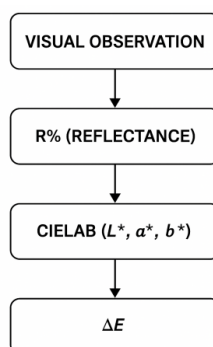


Figure 3. Color Evaluation Flowchart

Table 4. Results of Measurement of Reflectance Value (R%) on Cabretta Ecoprint Leather

Sample	R (%)	Visual Description
Untreated leather (before ecoprint)	43.99	Natural cream tone, baseline state
No mordant (control)	59.73	Noticeably darker than untreated leather; low motif clarity
Calcium Carbonate (CaCO ₃) fixation	32.45	Brighter appearance with soft, pastel-like tones
Ferrous Sulfate (FeSO ₄) fixation	12.00	A very dark tone with strong contrast and strong motif definition
Aluminium Sulfate (Al ₂ (SO ₄) ₃) Fixation	25.60	Moderate brightness; balanced color and motif clarity

Table 5. CIELAB Color Analysis Results on Ecoprint Cabretta Leather

Sample	L*	a*	b*	ΔE (compared to reference)	Notes
Untreated leather (reference)	82.40	2.10	18.30	0.00	Baseline natural cream color
No mordant (control)	58.20	4.85	22.60	25.42	Darker tone, reduced clarity
Calcium Carbonate (CaCO ₃) fixation	72.10	1.95	24.40	14.55	Brighter, pastel-like tone
Ferrous Sulfate (FeSO ₄) fixation	41.50	-2.60	20.10	45.70	Very dark, high contrast
Aluminium Sulfate (Al ₂ (SO ₄) ₃) Fixation	65.80	3.25	28.50	20.12	Balanced color intensity

CIELAB values (L*, a*, b*) were used to objectively quantify color differences among the different mordant treatments. As expected, FeSO₄-treated samples exhibited the lowest L* values, indicating the darkest visual appearance due to strong iron–tannin interactions. In contrast, CaCO₃ produced higher L* values, resulting in brighter and pastel-like tones. The ΔE values further confirmed that FeSO₄ generated the largest perceptual color shift relative to the untreated leather, demonstrating its strong influence on both chromaticity and visual contrast.

Note: Although CIELAB values (L*, a*, b*) were successfully obtained, several data points fell outside the typical measurement range (- 100 to + 100). This deviation is likely caused by the optical properties of Cabretta leather, including surface gloss, collagen fiber irregularities, and non-uniform reflectance, which may lead to instrumental anomalies during spectrophotometric measurement [42,43]. To maintain analytical reliability, ΔE was therefore prioritized as the primary parameter for comparing color differences across treatments, as it provides a more stable and perceptually meaningful indicator.

Color fastness was subsequently evaluated following ISO/SNI standards for washing [44], light [45], and rubbing [46]. The results are summarized in Table 6.

Table 6. Ecoprint Color Fastness Test Results on Cabretta Leather

Sample	Washing Fastness (Grey Scale, 1–5)	Light Fastness (Blue Wool, 1–8)	Rubbing Fastness, Dry (Grey Scale, 1–5)	Evaluation
Without Mordant	4-5	5-6	4-5	Good overall fastness; acceptable stability despite absence of mordant.
Calcium Carbonate (CaCO ₃) fixation	4	5-6	4-5	Good fastness; slightly reduced washing resistance due to lighter pastel tones.
Ferrous Sulfate (FeSO ₄) fixation	4	5-6	4-5	Good durability; dark shades remain stable under rubbing and washing.
Aluminium Sulfate (Al ₂ (SO ₄) ₃) Fixation	4-5	8	4-5	Best performance overall; excellent light fastness indicating strong pigment–fiber bonding.

Aluminium sulfate (Al₂(SO₄)₃) produced the highest light fastness (Blue Wool = 8), indicating superior photostability of plant pigments on collagen fibers. In contrast, calcium carbonate showed slightly decreased washing resistance, consistent with its tendency to produce softer, pastel-like motifs. Overall, all treatments demonstrated acceptable to very good fastness, confirming the applicability of natural dyes for ecoprinting on leather.

Data Analysis

Qualitative Descriptive Analysis

The results of the color fastness tests—including washing, light, and dry rubbing—indicate that all ecoprinted Cabretta leather samples exhibit good to very good performance across treatments.

1. Without Mordant

Samples without fixation showed washing fastness of 4–5, indicating good stability with only minor perceptible changes after laundering [44,47-49]. Light fastness reached 5–6, and dry rubbing also scored 4–5, reflecting stable coloration.

Overall, untreated samples maintained acceptable fastness despite the absence of mordanting.

2. Calcium Carbonate (CaCO₃) Fixation

CaCO₃-treated samples demonstrated washing fastness of 4, slightly lower than unmordanted and alum-treated samples. Light fastness remained in the 5–6 range, while dry rubbing was stable at 4–5. These

results indicate that CaCO_3 produces soft, lighter tones with adequate, though slightly reduced, washing resistance compared to alum-based fixation [32,44-46,50].

3. Ferrous Sulfate (FeSO_4) Fixation

FeSO_4 -fixed samples recorded washing fastness of 4, light fastness of 5–6, and rubbing fastness of 4–5, comparable to CaCO_3 . Although FeSO_4 darkens the coloration due to iron–tannin interactions, its fastness performance remains consistently in the good category [17,33,34,44-46,51]. This mordant provides strong visual contrast without compromising durability.

4. Aluminium Sulfate ($\text{Al}_2(\text{SO}_4)_3$) Fixation

$\text{Al}_2(\text{SO}_4)_3$ showed the best performance, especially in light fastness, achieving a Blue Wool rating of 8, indicating excellent photostability. Washing and rubbing scores remained at 4–5, similar to other treatments. Strong pigment–fiber bonding with alum contributes to improved color retention and higher visual stability compared to CaCO_3 and FeSO_4 [35,36,44-46].

Overall Comparison

Aluminium sulfate produced the most durable color, particularly in light exposure, while calcium carbonate and ferrous sulfate provided good but lower stability. Samples without mordant still performed adequately but may be more prone to long-term degradation during use or exposure [52,53].

This analysis confirms that mordant type meaningfully influences color fastness, with $\text{Al}_2(\text{SO}_4)_3$ emerging as the most effective option for ecoprinting on Cabretta leather.

Quantitative Analysis

A one-way ANOVA was used to examine whether different mordant treatments (no mordant, CaCO_3 , FeSO_4 , $\text{Al}_2(\text{SO}_4)_3$) produced statistically significant differences in the color fastness of ecoprinted Cabretta leather [1,7,54,55]. The results are summarized in Table 7.

Table 7. One-Way ANOVA Test Results for Color Fastness

Test Parameters	<i>F</i> (df = 3, 8)	p-value	Interpretation
Washing fastness	256.00	<0.001	Significant differences between treatments
Light fastness	473.00	<0.001	Significant differences between treatments
Rubbing fastness	0.00	1.000	No significant difference

The ANOVA results indicate that mordant type had a statistically significant effect on both washing fastness ($F(3, 8) = 256.00, p < 0.001$) and light fastness ($F(3, 8) = 473.00, p < 0.001$). These findings confirm that fixation using CaCO_3 , FeSO_4 , or $\text{Al}_2(\text{SO}_4)_3$ contributes differently to the stability of natural pigments on collagen fibers. In contrast, rubbing fastness showed no significant differences across treatments ($F(3, 8) = 0.00, p = 1.000$), suggesting that resistance to mechanical abrasion remains relatively constant regardless of mordant type. Overall, the statistical results demonstrate that mordant selection plays a critical role in enhancing washing and light fastness, whereas rubbing fastness is inherently stable across treatments. This reinforces the importance of optimizing mordanting strategies to improve ecoprint performance and achieve more durable and competitive leather products [56-58].

RESULTS AND DISCUSSION

Result

Visual Observation of Ecoprint on Cabretta Leather

The ecoprint process using nine plant materials produced clear variations in motif definition, hue, and tonal depth across the Cabretta leather samples. Overall, the resulting patterns differed not only by plant species but also by the mordant applied during pre-treatment.








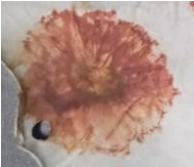






Flowers such as *Cosmos caudatus*, *Cosmos sulphureus*, *Hibiscus rosa-sinensis*, and *Tagetes erecta* produced vivid yellow, orange, and red pigments, whereas foliage materials such as *Manihot esculenta*, *Tagetes erecta* leaves, and *Rumohra adiantiformis* generated greenish to brown tones. These results confirm the role of anthocyanins, carotenoids, tannins, and flavonoids as the dominant colorants transferred during steaming. More importantly, the visual outcomes were strongly influenced by mordant type, consistent with reviewer recommendations to emphasize objective interpretation:

- Calcium carbonate (CaCO_3): produced brighter, pastel-like motifs with softer edges.
- Ferrous sulfate (FeSO_4): generated darker, high-contrast patterns with increased definition.
- Aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$): resulted in balanced colors with clear motif outlines and good contrast.

These differences correspond to the well-documented interaction between metallic ions and plant chromophores, which modifies hue and pattern clarity through pigment–collagen binding mechanisms.

A summary of plant materials and representative ecoprint outcomes is shown in Table 8.

Table 8. Plant materials and Representative Ecoprint Outcomes on Cabretta leather

No.	Plant material (<i>Scientific name</i>)	Local name	Plant image	Ecoprint result (image)
1	<i>Cosmos caudatus</i> Kunth	Pink kenikir flower		
2	<i>Cosmos sulphureus</i> Cav.	Sulfur kenikir flower		
3	<i>Hibiscus rosa-sinensis</i> L.	Hibiscus flower		
4	<i>Tagetes erecta</i> L. (flower)	Marigold flower		
5	<i>Jatropha integerrima</i> Jacq.	Peregrina / Jatropha flower		
6	<i>Antigonon leptopus</i> Hook. & Arn.	Coral vine / Mexican creeper		
7	<i>Manihot esculenta</i> var. <i>japonica</i>	Japanese cassava leaves		

8	<i>Tagetes erecta</i> L. (leaves)	Marigold leaves		
9	<i>Rumohra adiantiformis</i> (G. Forst.) Ching	Leatherleaf fern leaves		

As summarized in Table 8, the plant species produced varied pigmentations and motif clarity on Cabretta leather. These baseline differences were further influenced by the mordanting process, which significantly altered background color, motif sharpness, and overall aesthetic perception.

The visual observation revealed distinct differences in ecoprint outcomes on Cabretta leather depending on the type of mordant applied. The use of calcium carbonate (CaCO₃) produced a relatively bright and soft appearance, with a cream to yellowish background [32,50]. However, the motifs appeared less sharp, with blurred edges that created a more natural but subtle impression. In contrast, ferrous sulfate (FeSO₄) resulted in the darkest tones, ranging from grayish-brown to blackish [7,33,34,51]. This mordant enhanced motif clarity, producing highly contrasted and well-defined patterns, which gave the leather a bold and dramatic overall aesthetic perception. Meanwhile, aluminium sulfate (Al₂(SO₄)₃) generated intermediate brightness, typically reddish-brown to orange, with moderately clear motifs. The overall effect was visually balanced, combining brightness and motif clarity to create a warm and aesthetically vivid result [35,59].

These qualitative findings are summarized in Table 9, while a quantitative scoring system (1–5) is presented in Table 10 to provide an objective comparison of color intensity, motif clarity, and overall aesthetic perception.

Table 9. Visual Observation Summary

Mordant	Background Color	Motif Clarity	Aesthetic perception
Calcium carbonate (CaCO ₃)	Cream–yellowish (bright)	Low (slightly blurred)	Soft, subtle, natural
Ferrous sulfate (FeSO ₄)	Grayish–blackish (dark)	High (sharp and well-defined)	Strong, bold, high contrast
Aluminium sulfate (Al ₂ (SO ₄) ₃)	Reddish–orange (medium)	Moderate (clear)	Warm, balanced, aesthetically vivid

Table 10. Summary Table–Quantitative Scoring (1–5)

Mordant	Color Intensity	Motif Clarity	Aesthetic perception
Calcium carbonate (CaCO_3)	3	2	3
Ferrous sulfate (FeSO_4)	5	5	5
Aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$)	4	3	4

Note: Scoring key: 1 = very low/poor, 5 = very high/excellent.

Figure 4 presents a side-by-side visual comparison of the ecoprint results on Cabretta leather treated with three different mordants: calcium carbonate (CaCO_3), ferrous sulfate (FeSO_4), and aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$). Clear variations can be observed in background color, motif definition, and overall aesthetic impression.



Figure 4. Visualization of Color Difference and Ecoprint Motif on Cabretta Leather Using Three Mordants (CaCO_3 , FeSO_4 , $\text{Al}_2(\text{SO}_4)_3$)

Calcium carbonate (CaCO_3) produces bright cream–yellowish tones with soft, slightly blurred motifs, consistent with its mild pH-modifying and brightening properties [44,60]. Ferrous sulfate (FeSO_4) yields dark grayish–blackish tones with sharp, high-contrast motifs, reflecting strong Fe^{2+} interactions that intensify pigments and enhance edge definition [61,62]. Aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$) generates reddish–orange tones with moderate clarity and a balanced, aesthetically vivid appearance, attributed to effective Al^{3+} coordination with plant tannins and flavonoids [63-65].

These qualitative visual outcomes correspond strongly with the quantitative scoring results presented in Table 9, confirming that FeSO_4 consistently produces the highest color intensity and motif clarity, CaCO_3 results in the softest and least intense patterns, and $\text{Al}_2(\text{SO}_4)_3$ provides an intermediate and visually balanced effect.

DISCUSSION

The present study demonstrates how three mordants—calcium carbonate (CaCO_3), ferrous sulfate (FeSO_4), and aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$)—influence the visual quality, color stability, and fastness performance of ecoprinted Cabretta leather. Through the integration of qualitative assessment, quantitative scoring, reflectance measurement, CIELAB analysis, and fastness testing, this research expands current knowledge on natural dye–mordant interactions in protein-based substrates. While most earlier studies focus on cellulose-based fabrics, the present findings highlight the unique behavior of natural pigments on collagen fibers and clarify the mechanistic roles of different metal ions in shaping ecoprint outcomes.

1. Visual Characteristics of Mordant Treatments

Visual observation revealed distinct color tones and motif clarity across mordant treatments, which were further supported by quantitative scoring (Tables 9–10, Figure 4). These differences reflect specific chemical interactions between metal ions, plant pigments, and collagen fiber structure.

Calcium Carbonate (CaCO_3)

Cabretta leather treated with CaCO_3 exhibited bright cream–yellowish backgrounds with soft, blurred motifs, corresponding to moderate color intensity (3/5) and low motif clarity (2/5). The mild alkalinity of CaCO_3 slightly increases the surface pH of collagen, enhancing pigment diffusion but not strongly binding natural chromophores. Consequently, pigment particles remain more superficially distributed, leading to reduced edge definition and a pastel-like aesthetic.

Such visual effects are consistent with studies reporting that CaCO_3 acts primarily as a pH regulator rather than a strong coordination agent [32,66]. In eco-print scenarios requiring gentle tonal transitions or soft motifs, CaCO_3 may therefore be preferred.

Ferrous Sulfate (FeSO_4)

In contrast, FeSO_4 produced dark grayish–blackish backgrounds with very sharp, high-contrast motifs, reflected in the maximum scores (5/5) for color intensity, motif clarity, and overall aesthetic impact. Fe^{2+} ions strongly react with phenolic compounds (tannins, flavonoids, and anthocyanins), forming stable metal–phenolic complexes that darken hue and enhance motif definition [7,33,34,51]. The high affinity of iron for hydroxyl groups in plant chromophores facilitates deeper penetration into collagen fibers, explaining the

uniform darkness and crisp outlines observed. These findings reinforce the well-established role of FeSO_4 as a powerful color modifier, making it suitable for ecoprint designs emphasizing dramatic contrast or fine detail.

Aluminium Sulfate ($\text{Al}_2(\text{SO}_4)_3$)

Treatment with $\text{Al}_2(\text{SO}_4)_3$ produced moderate brightness with reddish–orange tones and moderately sharp motifs, aligning with intermediate scoring values (intensity 4/5; clarity 3/5; aesthetic perception 4/5). As a trivalent metal ion, Al^{3+} forms coordination complexes with phenolic compounds that enhance pigment fixation while preserving brightness. Unlike Fe^{2+} , aluminium does not significantly darken the chromophore structure, resulting in a visually balanced and vibrant appearance.

Literature suggests that $\text{Al}_2(\text{SO}_4)_3$ often yields bright, warm shades with good motif clarity in natural dyeing of both textiles and leather [35,59,67]. These properties make it desirable for artisan applications requiring strong but not overly dark coloration.

The differences in visual characteristics among mordants highlight the role of chemical interactions between mordant ions and collagen fibers. Collagen, being a protein with carboxyl and amino functional groups, can interact with metal ions to form complexes that influence pigment fixation, penetration, and distribution. Calcium carbonate provides a mild ionic environment, ferrous sulfate creates stronger metal-phenolic complexes, and aluminium sulfate forms a network of coordination bonds that balance pigment retention and visual brightness. These mechanistic insights align with the observations in the present study and previous literature [7,21,67,68].

2. Correlation Between Visual Observation and Quantitative Scoring

The integration of quantitative scoring (1–5) with visual observation enhances the objectivity of evaluating mordant effects on Cabretta leather. Calcium carbonate produced soft motifs with moderate brightness, consistent with its lower numerical scores; ferrous sulfate generated bold, high-contrast patterns that received the highest scores; while aluminium sulfate produced intermediate values that reflect its balanced aesthetic characteristics. This alignment between visual inspection and numerical scoring strengthens the reliability of the assessment framework and ensures reproducibility in evaluating ecoprint quality on protein-based substrates.

The combination of qualitative and quantitative approaches also supports more informed decision-making for artisans and designers. Ferrous sulfate is suitable for high-contrast, statement motifs; aluminium sulfate

offers clarity with improved long-term stability; and calcium carbonate is preferred for subtle, soft-toned impressions. Establishing clear connections between visual outcomes and scoring thus provides a systematic foundation for evaluating natural dyeing performance [52,53,69].

Previous studies on natural dyeing of textiles and leather similarly emphasize the importance of mordant type in determining color intensity, motif definition, and fastness properties. Research has shown that different metal ions influence dye–fiber interactions and affect both aesthetic and durability outcomes [1,59,70,71]. The present results on Cabretta leather are consistent with these findings and extend them to a specific protein-based substrate, demonstrating that a combined qualitative–quantitative method offers a reliable approach for assessing eco-friendly dyeing processes [1,68,69].

3. Color Fastness and Mordant Effects

Color fastness testing revealed significant differences among mordants in response to washing, light, and rubbing (Tables 4–6). Aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$)-treated leather exhibited the highest light fastness (Blue Wool scale rating of 8), consistent with its strong pigment-binding properties that protect against photodegradation [8,72]. Calcium carbonate (CaCO_3) and ferrous sulfate (FeSO_4) samples showed good but slightly lower light fastness (ratings 5–6), while washing and rubbing resistance were generally stable across all treatments. ANOVA results indicated significant effects for washing and light fastness ($F = 256$, $p < 0.001$; $F = 473$, $p < 0.001$, respectively), but not for rubbing ($F = 0$, $p = 1.000$), suggesting that mordant fixation primarily influences pigment retention rather than mechanical resistance [63,65,73-76].

These findings demonstrate the importance of mordant selection not only for visual aesthetics but also for functional durability. Aluminium sulfate offers superior performance for products exposed to light and environmental conditions; ferrous sulfate provides dark, high-contrast tones suitable where visual impact is prioritized; and calcium carbonate yields softer motifs with adequate fastness for casual or decorative applications.

4. Mechanistic Insights

The observed effects of mordants on Cabretta leather can be explained through the interplay of chemical and physical interactions. Iron (II) ions from ferrous sulfate (FeSO_4) form strong complexes with polyphenols present in plant pigments, producing dark, high-contrast colors that enhance motif definition [34,59,66]. Aluminium ions from aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$) simultaneously bind to pigment molecules and collagen

fibers, improving fixation while maintaining brightness [59,77,78]. In contrast, calcium ions from calcium carbonate (CaCO_3) interact more mildly with pigment molecules, resulting in softer, more subtle color tones [32,66,79].

In addition to chemical binding, the penetration of pigments into collagen fibers is influenced by the porosity and protein structure of Cabretta leather. Mordants such as CaCO_3 and $\text{Al}_2(\text{SO}_4)_3$ can enhance fiber swelling, allowing deeper pigment uptake, which affects both color intensity and motif sharpness [80,81]. Mordant-induced pH changes also play a role: alkaline conditions created by CaCO_3 yield muted tones, whereas neutral to slightly acidic conditions from $\text{Al}_2(\text{SO}_4)_3$ optimize pigment binding and visual brightness [82-84].

These mechanisms demonstrate that successful ecoprint outcomes depend on the combined effects of mordant chemistry, substrate properties, and pigment characteristics, aligning well with previous reports on natural dyeing of protein-based materials [26,85-87]. Understanding these interactions provides a scientific basis for selecting appropriate mordants to achieve desired color and motif quality on Cabretta leather.

5. Integration with Literature

The present findings align well with earlier studies on mordant effects in natural dyeing. Previous work reported that mordants modulate both color intensity and motif sharpness, a pattern that is clearly reflected in the current ecoprint results on Cabretta leather [88]. Other studies noted that protein-based substrates respond differently to mordants compared to cellulose fibers, explaining the distinctive color and motif effects observed on leather [85]. The stabilizing role of alum in protecting pigments against light and enhancing durability is also evident in the superior light fastness of aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$)-treated samples [36,78,89]. Furthermore, other research emphasizes that integrating aesthetic evaluation with functional testing strengthens eco-friendly dyeing practices, a principle reflected in the combined visual and quantitative assessments used in this study [10,30,90,91].

Beyond confirming previous findings, this research extends knowledge of eco printing on leather—a less explored substrate compared to textiles. It demonstrates that careful selection of mordants enables tailored outcomes in both aesthetic quality and durability, effectively bridging traditional craftsmanship with sustainable material innovation.

6. Practical Implications for Leather Craft

For artisans, designers, and researchers, these results offer actionable insights into mordant selection for ecoprint on leather. Calcium carbonate (lime) produces soft, pastel motifs, making it suitable for delicate, decorative designs, whereas ferrous sulfate (tunjung) is ideal for bold, high-contrast patterns that emphasize motif definition [21,32-34,51,59,66,79,92]. Aluminium sulfate provides a balanced outcome, combining aesthetic appeal with functional stability, particularly for products requiring long-term light resistance [36,59]. By integrating qualitative observation, quantitative scoring, and fastness testing, this study provides a practical framework for selecting mordants based on design intent and product application. Moreover, this approach supports sustainable practices by optimizing the use of natural dyes, reducing reliance on synthetic chemicals, and enhancing both the environmental and cultural value of leather products.

7. Limitations and Future Research

While the study provides comprehensive insights into the effects of mordants on ecoprint Cabretta leather, certain limitations should be acknowledged. The research focused exclusively on Cabretta leather, and other leather types may exhibit different responses to mordant treatments. Similarly, only four plant sources were employed, and expanding botanical diversity could reveal additional color–mordant interactions. Fixed mordant concentrations were used throughout the experiments; exploring a range of concentrations may further optimize color intensity and fastness outcomes. Additionally, the study primarily assessed short-term fastness, leaving long-term durability and environmental aging effects for future investigation.

Future research could build on these findings by conducting comparative studies on different leather types, such as sheep leather, goat leather, and cowhide. The inclusion of additional mordants, particularly environmentally benign metal salts, may enhance sustainable practices. Advanced imaging and spectrophotometric analyses could be employed to quantitatively assess motif sharpness and pigment distribution, while integration with design workflows would facilitate translation of ecoprint techniques into commercial and artisanal leather applications.

CONCLUSION

This study demonstrates that the choice of mordant critically shapes both the visual aesthetics and functional durability of ecoprint Cabretta leather. Calcium carbonate produced soft, pastel-like motifs with moderate fastness, ferrous sulfate resulted in bold and highly contrasted patterns with strong motif clarity, and

aluminium sulfate provided a balanced outcome, combining moderate brightness, motif sharpness, and superior light fastness. These findings confirm that mordant chemistry strongly determines the interaction between plant pigments and collagen fibers, thereby influencing both artistic expression and material performance.

Beyond its scientific relevance, the research provides practical guidance for artisans, designers, and sustainable fashion practitioners. By integrating qualitative observation, quantitative scoring, and fastness evaluation, this study offers a systematic framework for selecting mordants based on design intent and product application. The results highlight that calcium carbonate is suitable for subtle and decorative designs, ferrous sulfate for bold statement pieces, and aluminium sulfate for products requiring long-term stability. In this way, the study bridges traditional craftsmanship with modern material innovation, strengthening eco-friendly practices in contemporary leather craft.

At the same time, certain limitations indicate promising directions for future inquiry. This research was limited to Cabretta leather, three mordants, and specific botanical sources; expanding to different leather types, alternative mordant systems, and broader plant diversity could further refine ecoprint outcomes. Advanced analytical techniques such as spectrophotometry and microscopic imaging may provide deeper mechanistic understanding, while long-term durability studies under real usage conditions would strengthen practical applicability. Taken together, these contributions position eco printing on leather not only as a sustainable material innovation but also as a culturally relevant practice with potential impact across artisanal and industrial domains.

Author Contributions

Conceptualization – Ismadi I.; methodology – Ismadi I. and Zuhro A.R.; formal analysis – Ismadi I. and Zuhro A.R.; investigation – Ismadi I.; resources – Ismadi I.; writing—original draft preparation – Ismadi I., Zuhro A.R., and Sartono D.; writing—review and editing – Ismadi I., Sunarya I.K., and Suardana I.W.; visualization – Ismadi I.; supervision – Sunarya I.K. and Suardana I.W. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by Universitas Negeri Yogyakarta (UNY), Grant Number T/578/UN34.9/PT.01.03/2025.

Conflicts of Interest

The authors declare no conflict of interest. No financial, personal, or professional relationships have influenced the research process, analysis, or interpretation of the results presented in this manuscript.

Acknowledgements

The authors would like to express their sincere gratitude to Universitas Negeri Yogyakarta for the institutional support provided during the research process. The authors also thank the Editorial Office and reviewers of *Textile & Leather Review* for their constructive comments and guidance, which helped improve the quality of this manuscript.

REFERENCES

- [1] Putri EP. Ecoprint: Contemporary batik materials with plant waste. *Physics and Mechanics of New Materials and Their Applications*. 2024; 313–324. Available from: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85199440025&partnerID=40&md5=4ceeb97b12709b4001d7cc281045aa9d>
- [2] Rehman A. Eco-friendly textile desizing with indigenously produced amylase from *Bacillus cereus* AS2. *Scientific Reports*. 2023; 13(1):11991. doi: 10.1038/s41598-023-38956-3
- [3] Lestari P. Application of alum fixator for eco print batik making using a pounding technique in fine arts learning in junior high school. *ASEAN Journal of Science and Engineering*. 2022; 2(2):167–172. doi: 10.17509/ajse.v2i2.38676
- [4] Habib N, Adeel S, Ibrahim M, Rehman F. Eco-friendly ultrasonic-assisted appraisal of herbal-based yellow natural colorant for silk dyeing. *Energy Science & Engineering*. 2024; 12(11):5061–5077. doi: 10.1002/ese3.1928
- [5] Fiona PT, Banupriya J. Vegan leather *Solanum lycopersicum* pigment dyeing with *Ceratonia siliqua* over blended fabric with presence of vanillin. *International Journal of Advancement in Life Sciences Research*. 2025; 8(4):207–220. doi: 10.31632/ijalsr.2025.v08i04.015
- [6] Sk S, Mia R, Haque MA, Shamim AM. Review on extraction and application of natural dyes. *Textile & Leather Review*. 2021; 4(4):218–233. doi: 10.31881/TLR.2021.09

- [7] Ismadi S, Rohidi TR, Syakir BS, Fathurrahman M, Sartono D. Evaluation of the strength of natural dyeing from teak wood extract on traditional weaving yarn. *Textile & Leather Review*. 2025; 8:326–348. doi: 10.31881/TLR.2025.003
- [8] Onem E, Cin G, Alankus A, Pehlivan H, Mutlu MM. Utilization of chestnut shell wastes as a dyeing agent for leather industry. *Leather and Footwear Journal*. 2016; 16(4):257–264. doi: 10.24264/lfj.16.4.1
- [9] Palomino E, Rahme L, Káradóttir KM, Kokita M, Freysteinnsson SP. Traditional fish leather dyeing methods with indigenous Arctic plants. *Heritage*. 2024; 7(7):3643–3663. doi: 10.3390/heritage7070173
- [10] Mandal S, Venkatramani J. A review of plant-based natural dyes in leather application with a special focus on color fastness characteristics. *Environmental Science and Pollution Research*. 2023; 30(17):48769–48777. doi: 10.1007/s11356-023-26281-1
- [11] Zhou Y, Yuan C, Zhang Q, Zhang X, Li Y, Wen H. Preparation of quaternary ammonium lignosulfonate modified UV resistant polyurethane and its application in leather dyeing. *International Journal of Biological Macromolecules*. 2025; 292:139259. doi: 10.1016/j.ijbiomac.2024.139259
- [12] Repon MR, Dev B, Rahman MA, Jurkonienė S. Textile dyeing using natural mordants and dyes: A review. *Environmental Chemistry Letters*. 2024; 22(3):1473–1520. doi: 10.1007/s10311-024-01716-4
- [13] Grande R, Raisanen R, Dou J, Rajala S, Malinen K. In situ adsorption of red onion (*Allium cepa*) natural dye on cellulose model films and fabrics exploiting chitosan as a natural mordant. *ACS Omega*. 2023; 8(6):5451–5463. doi: 10.1021/acsomega.2c06650
- [14] Raza Naqvi SA, Adeel S, Mia R, Hosseinezhad M. Modern ecofriendly approach for extraction of luteolin natural dye from weld for silk fabric and wool yarn dyeing. *Sustainable Chemistry and Pharmacy*. 2024; 39:101554. doi: 10.1016/j.scp.2024.101554
- [15] Jabar JM, Ogunsade AF, Odusote YA, Yılmaz M. Utilization of Nigerian mango (*Mangifera indica* L.) leaves dye extract for silk fabric coloration: Influence of extraction technique, mordant and mordanting type on the fabric color attributes. *Industrial Crops and Products*. 2023; 193:116235. doi: 10.1016/j.indcrop.2022.116235
- [16] Tehrani M, Navayee T. Suitability of dyes from cinnamon bark on wool fibers using metal and bio-mordants. *Environmental Science and Pollution Research*. 2024; 31(21):31414–31423. doi: 10.1007/s11356-024-33381-z
- [17] Zahid AASM, Islam MR, Maitra B, Al-Amin M, Azad AK, Khatun MH. Dyeing of silk and cotton using facile and green extracted natural dye from *Bombax ceiba*. *Journal of the Indian Chemical Society*. 2025; 102(2):101572. doi: 10.1016/j.jics.2025.101572
- [18] Quispe-Quispe A, Lozano F, Machaca-Machaca V, Quispe-Marcátoma J. Textile characteristics, medullation, and colorimetry of wool fiber dyed with *Dactylopius coccus* using atmospheric pressure plasma jet (APPJ). *Applied Sciences*. 2025; 15(1):421. doi: 10.3390/app15010421
- [19] Datta MK, Talukder ME, Faisal MA, Sarker A, Jiang H. The sustainable coloration of wool fabric using

- naturally extracted dyes from sappan heartwood. *Journal of Natural Fibers*. 2022; 19(14):9348–9362. doi: 10.1080/15440478.2021.1982825
- [20] Sumang R, Panpho P. Investigating the potential of waste oyster shell as a sustainable bio-mordant in natural dyeing. *Scientific Reports*. 2024; 14(1):25509. doi: 10.1038/s41598-024-74944-x
- [21] Hassan MM. Valorisation of sulphonated lignin as a dye for the sustainable colouration of wool fabric using sustainable mordanting agents: enhanced colour yield, colourfastness, and functional properties. *RSC Sustainability*. 2024; 2(3):676–685. doi: 10.1039/d3su00402c
- [22] Ozdemir MB, Karadag R. Anatolian acorn oak's economic potential in the application to the textile and leather industries. *Textile & Leather Review*. 2023; 6:320–332. doi: 10.31881/TLR.2023.044
- [23] Peinado LR. Materiality of medieval fabrics from San Isidoro de Leon: Dye and colour. *Archivo Español de Arte*. 2022; 95(380):359–378. doi: 10.3989/aearte.2022.19
- [24] Islam T, Khan AM, Karim MR, Hossain S, Jalil MA. Assessing the dyeing efficacy and environmental impact of cotton fabric dyed with sawmill bio-waste extracts and metal salts. *SPE Polymers*. 2024; 5(3):444–456. doi: 10.1002/pls2.10136
- [25] Sha D. Preparation of polyphenol-structural colored silk fabrics with bright colors. *International Journal of Biological Macromolecules*. 2024; 266:131140. doi: 10.1016/j.ijbiomac.2024.131140
- [26] Hwang Y, Kim H, Kim HR. Dyeing properties of bacterial cellulose fabric using *Gardenia jasminoides*, green tea, and pomegranate peel, and the effects of protein pretreatment. *Journal of the Korean Society of Clothing and Textiles*. 2024; 48(3):511–527. doi: 10.5850/JKSCT.2024.48.3.511
- [27] Naam MF, Prasetyaningtyas W, Achmadi TA, Mustikaningtyas D, Fitriyah ND, Azzahra F. Development of eco print on leather craft products to increase production of Faro leathercraft artisans. *Jurnal Abdimas*. 2024; 28(1):136–141. doi: 10.15294/p8hfx22
- [28] Meganathan MK, Ramakrishnan S, Ganesan G, Ramalingam S, Alagumuthu TS. Natural dyed watch strap: Chemical mordant free dyeing with mordanted homoisoflavonoids and anthocyanins for biocompatible and wound-healing wearables. *ACS Sustainable Resource Management*. 2025; 2(3):481–491. doi: 10.1021/acssusresmgt.4c00468
- [29] Minn J, Kim H, Kim HR. Assessing the dyeing properties of bacterial cellulose using plant-based natural dyes. *Journal of the Korean Society of Clothing and Textiles*. 2024; 48(4):707–728. doi: 10.5850/JKSCT.2024.48.4.707
- [30] Andalo LA, Sang PKM, Tanui R. Physical and fastness properties of leather dyed with a natural dye extracted from beetroot peels using a biomordant. *Journal of the Society of Leather Technologists and Chemists*. 2023; 107(6):226–231.
- [31] Todorova DA, Miladinova PM. Investigation on the influence of reactive dyes over the colour stability of offset printing paper during ageing. *Bulgarian Chemical Communications*. 2017; 49:181–186. Available from: bcc.bas.bg/BCC_Volumes/Volume_49_Special_L_2017/181-186-Todorova-21.pdf

- [32] Atika, Kusumastuti A, Mukti L, Kamis A. Quality results of cotton fabric coloring with mangsi (*Phyllanthus reticulatus*) fruit extract. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*. 2024; 122(2):94–101. doi: 10.37934/arfmts.122.2.94101
- [33] Roengthanapiboon N, Sindhuphak A, Egwutvongsa S. Dyeing of silk yarn with natural dye from teak leaves. *Revista Gestão Social e Ambiental*. 2024; 18(2):e06761. doi: 10.24857/rgsa.v18n2-154
- [34] Jain N, Nigam M. Exploring sustainable approaches to coloration: A review. *Journal of the Textile Association*. 2024; 85(3):274–281. doi: 10.5281/zenodo.14273608
- [35] Bakici GG. Investigation of atmospheric plasma in textile finishing. *Industria Textila*. 2025; 76(1):119–130. doi: 10.35530/IT.076.01.202413
- [36] Elsis H, Elmaaty TA, Negm E, Abouelenin S. Dyeing wool fabrics with specialized dyes and their mixtures using supercritical CO₂. *Scientific Reports*. 2025; 15(1):40377. doi: 10.1038/s41598-025-25134-w
- [37] Kusumaningtyas RD, Widjanarko D, Prasetiawan H, Prajanti SDW, Retnoningsih A, Margunani M. Valorization of bio-based waste through research and community service in university towards circular economy transition and future sustainability: Case study in Indonesia. In: *Valorization of Bio-based Waste through Research and Community Service in University towards Circular Economy Transition and Future Sustainability*. 2024. doi: 10.1201/9781003441144-29
- [38] Kanamori KS, Tarragó MG, Jones A, Cheek EH. Surface color spectrophotometry in a murine model of steatosis: an accurate technique with potential applicability in liver procurement. *Laboratory Investigation*. 2021; 101(8):1098–1109. doi: 10.1038/s41374-021-00600-x
- [39] Zhou H, Ye Z, Feng Z, Su M, Du J, Zhang X, Li X. Comparison of storability and flavor among peach fruits with different soluble solids contents based on clustering and principal component analysis. *Journal of Fruit Science*. 2022; 39(11):2149–2162. doi: 10.13925/j.cnki.gsx.20220248
- [40] De Donno A, Calvano M, Lauretti C, Angrisani C, Santoiemma I, Introna F. Spectrophotometric analysis of post-mortem lividity: A new objective measure to define time of death. *Forensic Science International*. 2022; 340:111422. doi: 10.1016/j.forsciint.2022.111422
- [41] Shams-Nateri AS, Nateri FS. Eco-friendly and sustainable antibacterial functionalization of medical textiles using natural dyes: A review. *Results in Chemistry*. 2025; 17:102589. doi: 10.1016/j.rechem.2025.102589
- [42] Akyol Yılmaz G, Becerir B. Investigation of mordant application in reactive dyeing of nylon fabrics. *AATCC Journal of Research*. 2023; 10(2):110–129. doi: 10.1177/24723444221132309
- [43] Vedhanayagam M. Fabrication of mesoporous PdO–TiO₂ nanocomposite coated flexible leather for colorimetric hydrogen gas detection at room temperature. *Applied Nanoscience*. 2025; 15(2):12. doi: 10.1007/s13204-025-03090-1
- [44] International Organization for Standardization. ISO 105-C06:2010 Textiles — Tests for colour fastness — Part C06: Colour fastness to domestic and commercial laundering. Geneva: ISO; 2010. Available from:

<https://cdn.standards.iteh.ai/samples/51276/bb37ae4124174869ac303511b7cc742f/ISO-105-C06-2010.pdf>

- [45] International Organization for Standardization. ISO 105-B02:2014 Textiles — Tests for colour fastness — Part B02: Colour fastness to artificial light: Xenon arc fading lamp test. Geneva: ISO; 2014. Available from: <https://www.iso.org/standard/65209.html>
- [46] International Organization for Standardization. ISO 105-X12:2016 Textiles — Tests for colour fastness — Part X12: Colour fastness to rubbing. Geneva: ISO; 2016. Available from: <https://cdn.standards.iteh.ai/samples/65207/24ffe38b766c4035a11b0316b3b07e7b/ISO-105-X12-2016.pdf>
- [47] Kayir Ö, Özkınalı S. Synthesis, spectroscopic characterization and dyeing properties of new metal complexed azo dyes derived from gallic acid. *Journal of Molecular Structure*. 2025; 1327:141144. doi: 10.1016/j.molstruc.2024.141144
- [48] Izzah SN, Marwoto P, Iswari RS. Markisa fruit (*Passiflora edulis* var. *flavicarpa*) as a fixation material of natural colour of mangrove waste on batik. *Journal of Physics: Conference Series*. 2018; 983(1):012009. doi: 10.1088/1742-6596/983/1/012009
- [49] Mamun AA, Bashar MM, Khan S, Roy MN, Hossain MM, Khan MA. Mordant-free dyeing of nylon fabric with mahogany (*Swietenia mahagoni*) seed pods: A cleaner approach of synthetic fabric coloration. *Textile Research Journal*. 2022; 92(17–18):3111–3119. doi: 10.1177/00405175211050526
- [50] Miladinova PM, Todorova DA. Synthesis, characterization, and application of new reactive triazine dye on cotton and paper. *Fibers and Polymers*. 2022; 23(6):1614–1620. doi: 10.1007/s12221-022-4020-8
- [51] Safapour S, Shabbir M, Rather LJ, Assiri MA, Mir SS. A study of the effect of organic acids (gallic acid and ascorbic acid) on the coloration and functionalization of wool yarns with *Milletia laurentii* sawdust natural dye. *Journal of the Textile Institute*. 2024; 116(5):772-783. doi: 10.1080/00405000.2024.2354144
- [52] Chakraborty R, Samanta AK, Vankar PS, Chakraborty S. Effect of dual mordanting, selective dye concentrations and dye compatibility for minimizing variation in natural dyeing of jute fabrics for compound shade matching. *Journal of the Institution of Engineers (India): Series E*. 2024; 106:1–27. doi: 10.1007/s40034-024-00292-0
- [53] Mirki LK, Barani H, Khaleghi S. Enhancing sustainability and hygiene in dyeing of wool yarn with *Daphne mucronata*. *Sustainable Chemistry and Pharmacy*. 2024; 37:101382. doi: 10.1016/j.scp.2023.101382
- [54] Thakker AM, Sun D. Engineering sustainable inks from natural biomaterials for digital printing. *Sustainability and Climate Change*. 2022; 15(4):272–278. doi: 10.1089/scc.2022.0010
- [55] Lin L. Sustainable traditional grass cloth fiber dyeing using the Taguchi L16 (4⁴) orthogonal design. *Scientific Reports*. 2022; 12(1):13833. doi: 10.1038/s41598-022-18213-9
- [56] Field A. *Discovering Statistics Using IBM SPSS Statistics*; 4th ed. London, UK: Sage Publications; 2013.

- [57] Maxwell SE, Delaney HD, Kelley K. *Designing Experiments and Analyzing Data: A Model Comparison Perspective*. New York, NY, USA: Routledge; 2017.
- [58] Montgomery DC. *Design and Analysis of Experiments*; 9th ed. Hoboken, NJ, USA: Wiley; 2017.
- [59] Vuthiganond N, Chitichotpanya P, Nakpathom M, Mongkholrattanasit R. Ecological dyeing of acrylic yarn with colorant derived from natural lac dye. *Journal of Metals, Materials and Minerals*. 2022. 32(4):71–78. doi: 10.55713/JMMM.V32I4.1529
- [60] Lamichhane S, Chaudhary P, Rijal R, Maharjan R, Kandel K. Outcome of posterior short segment fixation with implanting pedicle screw at the fractured level for treatment of thoracolumbar fracture. *Journal of Orthopaedics*. 2025; 62:106–111. doi: 10.1016/j.jor.2024.10.026
- [61] Suksikarn R, Suksikarn J. Craft-design collaboration: Designing and developing products from banana fibers through community participation. *Archives of Design Research*. 2024; 37(5):197–218. doi: 10.15187/adr.2024.11.37.5.197
- [62] Risnasari I, Solihat NN, Rambey R, Purnawati R. Characterization and application of sikkam (*Bischofia javanica* Blume) as a natural dye and antibacterial agent for eco-printing textiles. *Waste and Biomass Valorization*. 2025; 16:4863–4878. doi: 10.1007/s12649-025-02958-1
- [63] Imani H, Gharanjig K, Ahmadi Z. Eco-friendly single bath dyeing of wool yarns with extracted cochineal dye: optimization and additives effect. *Pigment & Resin Technology*. 2023; 52(3):321–330. doi: 10.1108/PRT-04-2022-0048
- [64] Khazaei F, Barani H. Sustainable enhancement of wool fibers using *Hymenocrater platystegius* flower and natural dyes for improved insect-repellent and color properties. *Results in Chemistry*. 2024; 12:101885. doi: 10.1016/j.rechem.2024.101885
- [65] Narayanaswamy V, Gowda KNN, Sudhakar R. Natural dye from the bark of *Casuarina equisetifolia* for silk. *International Journal of Pharma and Bio Sciences*. 2013; 4(3):B94–B104
- [66] Nurfitri MA, Widiastuti W. The development of the effect of fixation using Jamaican cherry leaves on the direction of hue. *Journal of Physics: Conference Series*. 2020; 1700(1):012091. doi: 10.1088/1742-6596/1700/1/012091
- [67] Śliwka-Kaszyńska M, Ślebioda M. Multi-technique investigation of grave robes from 17th and 18th century crypts using combined spectroscopic, spectrometric techniques, and new-generation sequencing. *Materials*. 2021; 14(13):3535. doi: 10.3390/ma14133535
- [68] Ismadi I, Dedy S. From forest to fabric: Natural dyeing with teak wood extract (*Tectona grandis*) on traditional yarns. *Vlakna a Textil*. 2025; 32(3):3–12. doi: 10.15240/tul/008/2025-3-001
- [69] Hunt RWG, Pointer MR. *Measuring Colour*; 4th ed. Chichester, UK: Wiley; 2011.
- [70] Mendili M, Aschi-Smiti S, Khadhri A. Phytochemical screening of natural textile dyes extracted from Tunisian lichens. *Biomass Conversion and Biorefinery*. 2025; 15(1):1443–1460. doi: 10.1007/s13399-023-05135-3

- [71] Shokrzadeh S, Razbin M, Ghaheh FS, Tehrani M, Sadrjahani M. Optimizing the eco-friendly dyeing of wool and nylon fabrics with *Prangos ferulacea* (L.) Lindl using artificial intelligence. *Scientific Reports*. 2025; 15(1):13267. doi: 10.1038/s41598-025-97551-w
- [72] Räsänen R, Primetta A, Toukola P, Fager S, Ylänen J. Biocolourants from onion crop side streams and forest mushroom for regenerated cellulose fibres. *Industrial Crops and Products*. 2023; 198:116748. doi: 10.1016/j.indcrop.2023.116748
- [73] Raji Y, Nadi A, Chemchame Y, Mechnou I. Eco-friendly extraction of flavonoids dyes from Moroccan (*Reseda luteola* L.), wool dyeing, and antibacterial effectiveness. *Fibers and Polymers*. 2023; 24(3):1051–1065. doi: 10.1007/s12221-023-00019-9
- [74] Swetha K, Chinnammal SK. A sustainable technique to enhance the color intensity of natural dyes on cotton fabric. *Journal of Environmental Nanotechnology*. 2024; 13(2):477–483. doi: 10.13074/jent.2024.06.242656
- [75] Akduman C, Kahvecioglu Sari H. The Turkish art of marbling (ebru) on textile fabrics: Investigation of thickening agent, mordant and fixation temperature. *Sakarya University Journal of Science*. 2023; 27(5):930–942. doi: 10.16984/saufenbilder.1283596
- [76] Imtiaz F, Shallan RS, Ihsan S, Sajid A. Investigation of dyeing properties of olive fruit waste extract on cotton fabric using metallic mordant. *Journal of the Textile Institute*. 2025; 116(1):112–118. doi: 10.1080/00405000.2024.2319003
- [77] Shahid-ul-Islam, Wani SA, Mohammad F. Imparting functionality viz color, antioxidant and antibacterial properties to develop multifunctional wool with *Tectona grandis* leaves extract using reflectance spectroscopy. *International Journal of Biological Macromolecules*. 2018; 109:907–913. doi: 10.1016/j.ijbiomac.2017.11.068
- [78] Islam SU, Mohammad F. Reflectance spectroscopic optimization of dyeing process and color characterization of ammonia post-treated wool dyed with *Tectona grandis* L. leaves extract. *Environmental Progress & Sustainable Energy*. 2018; 37(6):1993–1999. doi: 10.1002/ep.12883
- [79] Failisnur S. Reuse of liquid waste from textile dyeing with natural dyes gambier (*Uncaria gambir* Roxb.) for cotton yarn dyeing. *ARPN Journal of Engineering and Applied Sciences*. 2017; 12(18):5313–5318
- [80] Shi L, Fang K, Song Y, Xie R, Xue Z, Li X. Interaction enhancement of Lyocell cellulose chains for controlled fibrillation behavior with greener application in eco-textiles. *Industrial Crops and Products*. 2023; 198:116652. doi: 10.1016/j.indcrop.2023.116652
- [81] Zhu H, Pei L, Yi J, Sun S, Hu Q, Wang J. Efficient zero wastewater and salt-free cotton fiber dyeing via hydrophobic organic chemical/water two-phase dyeing system. *Journal of Cleaner Production*. 2024; 451:141886. doi: 10.1016/j.jclepro.2024.141886
- [82] Belowar S. Design, synthesis, and characterization of a novel pH-responsive azo dye incorporating a 1,3,4-thiadiazole ring for advanced textile applications. *Dyes and Pigments*. 2024; 231:112410. doi:

10.1016/j.dyepig.2024.112410

- [83] Yameen M. Enhancing wool dyeing with clove bud (*Syzygium aromaticum*) based natural dye via microwave treatment using a central composite design. *Science Progress*. 2023; 106(4):1-22. doi: 10.1177/00368504231215593
- [84] Al-Qahtani SD. Development of cellulose aerogel as a colorimetric swab imprinted with betalain-extracted beetroot (*Beta vulgaris* L.) for sweat monitoring. *International Journal of Biological Macromolecules*. 2025; 309:143001. doi: 10.1016/j.ijbiomac.2025.143001
- [85] Periyasamy AP. Natural dyeing of cellulose fibers using *Syzygium cumini* fruit extracts and a bio-mordant: A step toward sustainable dyeing. *Sustainable Materials and Technologies*. 2022; 33:e00472. doi: 10.1016/j.susmat.2022.e00472
- [86] Chen J, Zou S, Wu W, Zheng J, Lü J. Research progress on the UV resistance of fabrics made of gambiered Guangdong gauze. *Journal of Silk*. 2024; 61(7):64–73. doi: 10.3969/j.issn.1001-7003.2024.07.007
- [87] Hu Q, Jiang W, Yang Ta, Zhang M, Zhu F, Wu M, et al. Influencing factors of silk printing and dyeing wastewater treatment by mixed-valence MIL-53(Fe) activated peracetic acid process. *Journal of Silk*. 2022; 59(6):27–33. doi: 10.3969/j.issn.1001-7003.2022.06.004
- [88] Sholikhah R, Widowati, Nurmasitah S. The impact of the use of different mordant types on ecoprint dyeing using secang wood (*Caesalpinia sappan* Linn) dye on primisima fabric. *AIP Conference Proceedings*. 2023; 2677(1):100003. doi: 10.1063/5.0113010
- [89] Klaykruayat B, Vuthiganond N, Chitichotpanya P. Optimization of ultrasound-assisted anthocyanin extraction from agricultural waste purple corn silk for multifunctional hemp finishes. *Journal of Metals, Materials and Minerals*. 2024; 34(4):2027. doi: 10.55713/JMMM.V34I4.2027
- [90] Abubakar MY, Garba F, Muhamad MA, Bioltif YE, Adam AB, Lawal U. Optimization of dyeing conditions of natural dye obtained from *Vaccinium corymbosum* (blueberry) on cotton fabric. *Orbital: The Electronic Journal of Chemistry*. 2024; 16(4):253–257. doi: 10.17807/orbital.v16i4.20223
- [91] Agrawal HS, Praneetha M, Singh A, Rajpoot AK. A comprehensive survey on production of fabric from the organic extract. *Proceedings of the IEEE International Conference on Computing, Communication, and Intelligent Systems (ICCCIS)*. 2023; 6–12. doi: 10.1109/ICCCIS60361.2023.10425232
- [92] Wang XU, Zheng G, Ma X, Fortin D. Iron speciation of mud breccia from the Dushanzi mud volcano in the Xinjiang Uygur Autonomous Region, NW China. *Acta Geologica Sinica (English Edition)*. 2018; 92(6):2201–2213. doi: 10.1111/1755-6724.13723