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Effect of Multicomponent Mordant Ratios ($MgSO_4$–Na_2CO_3–$Al_2(SO_4)_3$) on the Color and Physical Properties of Ecoprinted Leather

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ABSTRACT

This study examined the influence of varying ratios of $MgSO_4$, Na_2CO_3, and $Al_2(SO_4)_3$ on the chromatic and mechanical properties of ecoprinted sheep leather. A completely randomized design with five treatments (0–60% $MgSO_4$) was applied under constant total mordant mass. Evaluated parameters included color intensity (K/S), color difference (ΔE), fastness to washing, rubbing, perspiration, and light, as well as tensile strength, tear strength, stitch strength, elongation, and softness. Statistical analysis (ANOVA followed by DMRT) confirmed that the mordant ratio significantly influenced all measured properties ($p < 0.05$). The 30–45% $MgSO_4$ proportion yielded optimal overall performance, particularly via increased color intensity (K/S 13.9–14.6), improved stability (ΔE 6.5–7.2), and satisfactory fastness ratings. Mechanical properties such as tensile and tear strength were maintained or improved, while stitch strength remained comparable across treatments, with P3 showing the highest numerical value. Although $Al_2(SO_4)_3$ remained present, its reduced proportion relative to conventional single-metal systems suggests a potentially lower environmental burden. Further investigation of effluent characteristics (COD, BOD, and biodegradability) is necessary to substantiate its sustainability profile.

KEYWORDS
ecoprint leather, environmentally promising alternative, multicomponent mordant system, sheep leather, color properties

INTRODUCTION

The leather tanning and processing industry is one of the key sectors that provides raw materials for fashion, handicrafts, and interior products. Conventional dyeing processes in leather production have traditionally relied on synthetic dyes and heavy metal-based mordants such as chromium, copper, and iron. These substances can contribute to the generation of toxic, non-biodegradable waste and pose significant environmental risks when discharged into water bodies, due to their persistence and potential bioaccumulation in ecosystems [1]. These environmental concerns have encouraged the development of eco-friendly dyeing technologies based on natural dyes.

One such method is ecoprinting, a natural dyeing technique that utilizes the shapes and pigments of leaves or flowers directly transferred onto the leather surface. Ecoprinting not only produces artistic patterns but also supports sustainability by minimizing the use of hazardous chemicals [2]. Nevertheless, a major challenge of natural dyeing lies in its relatively low color stability and colorfastness compared to synthetic dyes, which often limits its application due to poor fixation and rapid fading under light and washing conditions [3].

Beyond color-related issues, ecoprinted leather is also prone to changes in physical properties, such as tensile strength, elongation, and softness. These aspects are crucial, as mechanical properties determine the quality standards required by the leather industry (SNI 4593:2011). The mordanting and natural dyeing process can influence the collagen structure, potentially making the leather stiffer, less elastic, or even susceptible to surface cracking if not properly controlled [4]. Therefore, innovations in mordant application should consider not only improvements in color quality but also the preservation of the physical properties of leather to meet industrial requirements.

Previous studies have demonstrated that metal salt mordants, such as aluminum- and iron-based salts, enhance color fastness in eco-printed leather, while their effects on mechanical and physical properties vary depending on the type of mordant applied [5]. Other research has evaluated both natural and synthetic mordants. The use of alum crystal in the tannery process affected the physical properties of tanned leather, including tensile strength and flexural strength, indicating that mordant/tanning additives influence mechanical quality [6]. Several studies report that combining tannic acid with metallic mordants such as aluminum (from potassium aluminum sulfate) can enhance the fixation and intensity of natural dyes, likely through the formation of stable tannin–metal complexes, which improves color performance without substantially deteriorating mechanical properties of the substrate [2,7].

However, these results remain inconsistent, particularly in balancing color quality and physical properties. Thus, there is a need for mordant innovations that not only enhance aesthetic quality but also preserve the mechanical performance of leather. In natural dyeing processes, mordants function by improving the interaction between dye molecules and collagen fibers through coordination bonding. Nevertheless, the use of conventional metal-based mordants is increasingly restricted due to concerns regarding toxicity and environmental pollution from dyeing wastewater [1]. Therefore, the development of safer and more eco-friendly mordant alternatives is urgently required.

The application of eco-friendly mordants in leather processing has gained increasing attention as an alternative to conventional metal-based mordants, which often pose environmental and health risks. Previous research has reported that magnesium sulphate (Epsom salt) can act as an eco-friendly mordant due to its low toxicity and its ability to enhance the binding of natural dyes to protein-based substrates such as leather and textile fibers by facilitating dye–fiber coordination and improving dye uptake and colorfastness in natural dyeing processes [8]. Previous studies on the use of Epsom salt in leather mordanting have primarily focused on improving color absorption and surface appearance, but have provided limited evaluation of its effects on the physical and mechanical properties of livestock leather. Moreover, optimization of Epsom salt concentration to achieve both superior color performance and desirable leather strength characteristics has not been comprehensively investigated. This study therefore aims to address these limitations by evaluating the influence of different Epsom salt concentrations on both color quality and physical performance of ecoprinted sheep leather.

Research on optimizing Epsom salt concentrations as a mordant in leather ecoprinting is expected to yield sharper, more stable colors with improved fastness, while maintaining the physical properties of leather within industrial standards. This effort also aligns with the development of sustainable leather dyeing technologies that are environmentally friendly and provide higher added value [8].

These environmental concerns have encouraged the exploration of alternative mordants that are both safe and effective in leather ecoprinting. This study offers novelty by introducing Epsom salt ($MgSO_4$) as an eco-friendly mordant in the leather ecoprinting process, while simultaneously evaluating its effects on color quality, physical properties, and color fastness. Therefore, the findings are expected to provide a safer and more sustainable alternative to heavy metal–based mordants.

EXPERIMENTAL

Materials and Methods

Materials

Sheep crust leather was used as the main material in this study due to its relatively uniform fiber structure and good dye absorption properties, making it suitable for natural dyeing applications such as ecoprinting. Previous studies have shown that sheep crust leather is a common substrate for eco-printing research because of these characteristics [2].

Quercus infectoria galls contain a diverse profile of phenolic compounds, particularly hydrolysable tannins such as gallotannins, which are among the predominant bioactive constituents reported in the literature [9].

Fresh leaves of *Toona sinensis* (*A. Juss.*) M. Roem were used as printing materials due to their anthocyanin and flavonoid compounds that produce stable reddish-brown hues [10].

The mordants consisted of magnesium sulfate heptahydrate ($MgSO_4 \cdot 7H_2O$, Epsom salt, Merck ≥99% purity), sodium carbonate (Na_2CO_3, soda ash, Merck ≥99%), and aluminum sulfate ($Al_2(SO_4)_3 \cdot 18H_2O$, Merck ≥99%). All chemicals were of analytical grade.

Methods

Experimental Design

The study employed a Completely Randomized Design (CRD) [11], consisting of five Epsom salt concentration levels: 0%, 15%, 30%, 45%, and 60%. Each treatment was replicated four times, resulting in 20 experimental units.

The total amount of mordanting chemicals was maintained at 123 g per treatment, with a constant water volume of 1500 mL. The treatment compositions were as follows:

P0 (0%): 0 g Epsom salt, 20.51 g soda ash, and 102.49 g aluminum sulfate.

P1(15%): 18.45 g Epsom salt, 17.43 g soda ash, and 87.12 g aluminum sulfate.

P2(30%): 36.90 g Epsom salt, 14.35 g soda ash, and 71.75 g aluminum sulfate.

P3(45%): 55.35 g Epsom salt, 11.28 g soda ash, and 56.37 g aluminum sulfate.

P4(60%): 73.80 g Epsom salt, 8.20 g soda ash, and 41.00 g aluminum sulfate.

The mordant mixture consisted of Epsom salt ($MgSO_4$), soda ash (Na_2CO_3), and aluminum sulfate ($Al_2(SO_4)_3$). $MgSO_4$ acts as a metal ion source to form coordination bonds with natural dyes, soda ash increases the pH to open collagen fiber structures, and aluminum sulfate enhances pigment fixation by forming additional crosslinking sites.

Experimental Procedure

Sheep crust leather was cleaned, cut into 20 × 20 cm samples, and soaked in clean water for 30 minutes before mordanting. The samples were immersed in the respective mordanting solutions at room temperature (28 ± 2 °C) for 30 minutes, with gentle stirring every 10 minutes to ensure uniform penetration [12]. After treatment, the samples were rinsed and air-dried under ambient conditions.

Preparation of dye extract: Gall manjakani powder was extracted with distilled water (1:10 w/v) by boiling at 90–95 °C for 60 minutes, then filtered to obtain a tannin-rich extract [13].

Ecoprinting process: Fresh *Toona sinensis* leaves were arranged on the leather surface, tightly wrapped in plastic and kraft paper, then steamed at 70–80 °C for 120 minutes using a modified stainless-steel steamer (capacity 15 L, temperature controller ±1 °C). The natural pigments from *Toona sinensis* leaves were transferred onto the leather surface during the steaming process. The process followed the method described in [5], with minor modification. The samples were then unwrapped, rinsed, and air-dried.

Evaluation of Color and Physical Properties

Color quality was analyzed using a spectrophotometer (Minolta CM-3600d, Konica Minolta, Japan) under standard illuminant D65 and a 10° observer angle.

Color Intensity (K/S) was calculated using the Kubelka–Munk equation [14].

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

where *R* is the reflectance at the maximum absorption wavelength.

Color stability (ΔE) was determined by comparing the CIELAB color coordinates (L^*, a^*, b^*) of treated samples with the control, according to the following formula [15]:

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2}$$

where L^*, a^*, b^* are the color values of the sample and L_0^*, a_0^*, b_0^* are the reference values of the control.

Color fastness tests were conducted following ISO standards:

- Rubbing (ISO 11640:2012); Washing (ISO 105-C06:2010); Perspiration (ISO 105-E04:2013)
- Light fastness (ISO 105-B02:2014)

Physical properties were tested according to leather testing standards:

- Tensile strength and elongation (ISO 3376:2011); Tear strength (ISO 3377-2:2016); Seam strength (ISO 13936-2:2004); Softness (IUP 36:2009)

Morphological Observation

Morphological changes in the fiber structure were observed using Scanning Electron Microscopy (SEM; JEOL JSM-6510LV, Japan) at magnifications of 500× to 2000×. Samples were gold-coated using a sputter coater (Quorum Q150R) before imaging to compare fiber arrangement and pigment penetration across treatments [4].

Data Analysis

Data were analyzed using Analysis of Variance (ANOVA) under the CRD model [16]. When significant differences were detected ($p < 0.05$), Duncan's Multiple Range Test (DMRT) was applied for mean comparison. Results were interpreted based on statistical significance and descriptive comparison. No optimization analysis was applied, as the study focused on identifying the most effective range of Epsom salt concentration rather than statistical optimization.

RESULTS AND DISCUSSION

A. Effect on the Color Quality of Ecoprinted Leather

Table 1 demonstrates the effect of Epsom salt concentration on the color intensity and color stability of ecoprinted leather. The K/S value represents the color depth, while ΔE describes the degree of color change after washing and exposure.

Table 1. Effect of Epsom salt ($MgSO_4 \cdot 7H_2O$) concentration as mordant on the color intensity (K/S) and color stability (ΔE) of ecoprinted sheep leather

Epsom Salt Mordant Concentration (%)	Color Intensity (K/S)	ΔE (Color Fastness/Stability)
0	8,2	12,5
15	11,4	9,8
30	13,9	7,2
45	14,6	6,5
60	12,1	8,1

Note: K/S represents color depth based on Kubelka-Munk function; ΔE indicates color difference (lower ΔE = higher color stability).

Increasing the concentration of Epsom salt ($MgSO_4$) from 0% to 45% resulted in a consistent increase in color intensity (K/S) and a reduction in ΔE values, indicating more effective pigment fixation and improved color stability on the leather surface. These trends reflect the performance of a balanced multicomponent mordant system, where $MgSO_4$, soda ash, and aluminum sulfate interact synergistically to create favorable chemical conditions for pigment–collagen bonding.

In this formulation, Mg^{2+} ions facilitate the formation of coordination bridges with phenolic groups of natural pigments, while soda ash regulates the pH, promoting controlled fiber swelling and improved pigment diffusion [12]. Aluminum sulfate contributes to the initial stabilization of the collagen matrix, enhancing surface readiness for dye fixation [13]. The combined action of these components promotes efficient pigment uptake and uniform distribution, resulting in enhanced color depth and stability without inducing excessive rigidity.

These findings align with previous studies reporting [8] that effective mordanting in protein-based substrates is strongly dependent on balanced mordant composition, controlled pH, and appropriate ionic strength, which together optimize dye–fiber interactions and color homogeneity.

At 60% $MgSO_4$, a slight decline in both K/S and ΔE was observed, suggesting that excessive ionic concentration disrupts the optimal proportion of mordant components and may lead to surface salt accumulation, thereby hindering uniform pigment penetration. Similar effects have been reported where elevated salt concentrations altered collagen fibril organization and reduced dye anchoring efficiency [4].

Overall, the 30–45% $MgSO_4$ range represents the most effective mordanting condition, providing superior color depth and stability. This performance arises from the synergistic balance among $MgSO_4$, soda ash, and aluminum sulfate, supporting a more controlled and stable ecoprinting process that demonstrates practical potential as an environmentally promising alternative to conventional heavy-metal-based mordant systems.

B. Effect on the Physical Quality of Ecoprinted Leather

Table 2 presents the influence of varying concentrations of Epsom salt mordant on the mechanical properties of ecoprinted leather. The results show a significant effect ($p < 0.05$) on tensile strength, tear strength, and softness, indicating that mordant concentration influences both the strength and flexibility of the leather.

Table 2. Physical Properties of Ecoprinted Leather Treated with Different Epsom Salt Mordant Concentrations

Epsom Salt Concentration (%)	Tensile Strength (N/mm²)	Elongation (%)	Stitch Strength (N/mm)	Tear Strength (N/mm)	Softness (mm)
0	12.14 ± 1.32^{a}	59.47 ± 4.99^{ab}	5.23 ± 1.26^{a}	493.95 ± 77.13^{a}	16.16 ± 0.95^{a}
15	10.46 ± 1.81^{a}	64.29 ± 13.53^{b}	5.56 ± 0.40^{a}	573.63 ± 86.16^{a}	13.89 ± 1.62^{a}
30	19.36 ± 1.37^{b}	57.55 ± 5.86^{ab}	5.10 ± 0.96^{a}	550.06 ± 70.37^{a}	16.60 ± 2.07^{a}
45	22.31 ± 1.02^{c}	47.37 ± 1.33^{a}	6.43 ± 0.40^{a}	947.03 ± 91.50^{b}	24.01 ± 2.41^{b}
60	10.50 ± 0.61^{a}	71.36 ± 6.24^{b}	4.96 ± 1.01^{a}	537.71 ± 86.56^{a}	15.51 ± 1.81^{a}

Note: Values are expressed as mean ± standard deviation. Different superscript letters within the same column indicate significant differences ($p < 0.05$).

Mechanical testing results corroborate the color performance findings, demonstrating that the 30–45% $MgSO_4$ range represents the most effective mordanting condition for improving the functional performance of ecoprinted leather. Within this concentration range, significant improvements were observed in tensile strength and tear resistance, indicating reinforcement of the collagen fiber network without detrimental effects on elasticity. Stitch strength, however, remained statistically comparable across treatments, although P3 exhibited the highest numerical value. This pattern suggests that the multicomponent mordant system maintains stitch performance rather than consistently enhancing it, aligning with the statistical interpretation presented in Table 2.

Importantly, the mechanical data also reveal a clear trade-off between strength and elasticity, particularly at the extreme $MgSO_4$ concentrations. Although P3 (45%) produced the highest tensile strength, its elongation value decreased markedly (47.37 ± 1.33%), indicating a stiffer yet less elastic leather. Such characteristics may not be suitable for flexible applications such as footwear uppers, where SNI standards emphasize not only strength but also minimum elongation requirements. Conversely, P4 (60%) exhibited high elongation (71.36 ± 6.24%) but substantially reduced strength, reflecting a loss of crosslinking control within the collagen network. This strength–elasticity trade-off highlights the functional limitations of excessive ionic loading and underscores the importance of balancing mechanical criteria when interpreting compliance with SNI-based performance expectations.

These enhancements reflect the synergistic action of the multicomponent mordant system. $MgSO_4$ contributes to the formation of coordination interactions between collagen fibers and pigment molecules, while soda ash regulates the pH environment, facilitating controlled fiber swelling and increasing the accessibility of reactive sites. Aluminum sulfate supports initial fiber stabilization and improves surface cohesion, collectively promoting a more compact and mechanically resilient collagen matrix. This integrated interaction enhances stress distribution within the fiber structure, resulting in improved resistance to mechanical deformation.

Previous studies support this interpretation [4,12], reporting that moderate concentrations of metal ions improve collagen network strength and resistance to mechanical stress, while excessive ionic levels or imbalanced mordant ratios can lead to stiffness, microstructural disruption, or reduced fiber flexibility. In this study, the observed improvements in tensile strength and tear resistance are therefore best explained by the controlled balance of mordant components, rather than by Mg^{2+} alone.

At 60% $MgSO_4$, a decline in tensile and tear strength was observed, likely due to excessive ionic loading that promoted salt crystallization and disrupted fiber continuity. Such conditions reduce structural homogeneity and weaken inter-fiber bonding, as also reported in salt-treated leather systems [8].

Overall, these results demonstrate that balanced mordanting with $MgSO_4$, soda ash, and aluminum sulfate at 30–45% produces optimal mechanical integrity, providing both aesthetic and functional benefits for practical ecoprint leather applications. The mechanical stability achieved in this range is attributable to synergy among mordant components rather than consistent improvements across every mechanical parameter, especially stitch strength, which remained largely unchanged statistically.

Although aluminum sulfate is categorized as a metal-based mordant, its environmental impact is considerably lower than that of conventional chromium salts commonly used in leather processing. In this study, aluminum sulfate was applied in reduced and controlled proportions as part of a balanced mordant system, minimizing its overall environmental load while maintaining functional performance. Furthermore, unlike chromium-based mordants, aluminum compounds are less persistent and exhibit lower ecotoxicological risk. However, direct assessment of effluent parameters such as COD, BOD, and biodegradability was beyond the scope of this study and should be addressed in future research to comprehensively validate the environmental advantages of the proposed mordant system

C. Effect on the Color Fastness of Ecoprinted Leather

Table 3 shows the influence of Epsom salt concentration on various color fastness parameters of ecoprinted leather. The results indicate that increasing the mordant concentration up to 45% enhances washing, rubbing, and perspiration fastness, with ratings ranging from good to very good (4–5).

Table 3. Effect of Epsom Salt Concentration on the Color Fastness Properties of Ecoprinted Leather

Epsom Salt Concentration (%)	Washing Fastness	Wet Rubbing Fastness	Dry Rubbing Fastness	Perspiration Fastness	Light Fastness
0	2	2–3	2	2	3–4
15	3	3	2–3	3	3–4
30	4	4	3–4	4	3
45	4–5	4–5	4	4–5	3
60	3–4	3–4	3	3	3

Note: Color fastness of ecoprinted leather was evaluated using the Grey Scale with a scoring range of 1–5. A score of 1 indicates very poor fastness (severe color change), while a score of 5 indicates excellent fastness (no visible color change). Intermediate values (e.g., 2–3 or 3–4) represent performance levels between these categories.According to industrial standards for leather finishing, a minimum score of 3 or higher is generally considered acceptable for commercial applications. The obtained values in this study therefore meet the target for acceptable color fastness performance

The results in Table 3 indicate that varying concentrations of the three-component mordant mixture—$MgSO_4$, soda ash, and aluminum sulfate—significantly affected the color fastness of ecoprinted leather against washing, dry and wet rubbing, perspiration, and light exposure. The control sample (0%) showed low fastness values (washing = 2; dry rubbing = 2.5; wet rubbing = 2; light = 2), reflecting limited bonding between natural pigments and collagen fibers in the absence of mordanting agents.

The improvements observed at 30–45% $MgSO_4$ cannot be attributed to Mg^{2+} alone. Although Mg^{2+} contributes to coordination bonding with chromophoric groups of plant pigments, the enhanced color fastness is primarily due to the synergistic interaction and balanced ratio among all three mordant components:

- Mg^{2+} facilitates ionic crosslinking that enhances pigment fixation,
- Al^{3+} from alum strengthens dye–fiber interactions via coordination complexes,
- Tannins act as natural polyphenolic bridges, stabilizing the pigment–collagen matrix.

This cooperative mechanism aligns with [1,17], who reported that optimal dye affinity occurs when metal salts and tannins interact simultaneously, rather than independently.

At higher $MgSO_4$ concentrations (60%), a decline in color fastness was observed (e.g., washing = 3.5; wet rubbing = 3; light = 3). This decrease likely results from oversaturation, where excessive salt deposition interferes with pigment penetration and disrupts the balanced mordant–fiber interaction.

Although washing, rubbing, and perspiration fastness improved with increasing $MgSO_4$ proportion up to P3, the light fastness remained constant at a rating of 3 across P2–P4. This indicates that the multicomponent mordant system does not overcome the inherent photolability of natural pigments used in ecoprinting. A rating of 3 (“fair”) may be insufficient for commercial products exposed to daylight, suggesting that additional stabilization strategies—such as the use of UV absorbers or tannin-rich post-treatments—may be required to enhance light stability.

According to ISO 11640 standards for leather finishing, acceptable rubbing fastness typically ranges from 3–4. In this study, the 30–45% $MgSO_4$ condition met or exceeded this benchmark, confirming that the optimized balance of mordant components provides practical, eco-friendly color fixation suitable for sustainable leather dyeing.

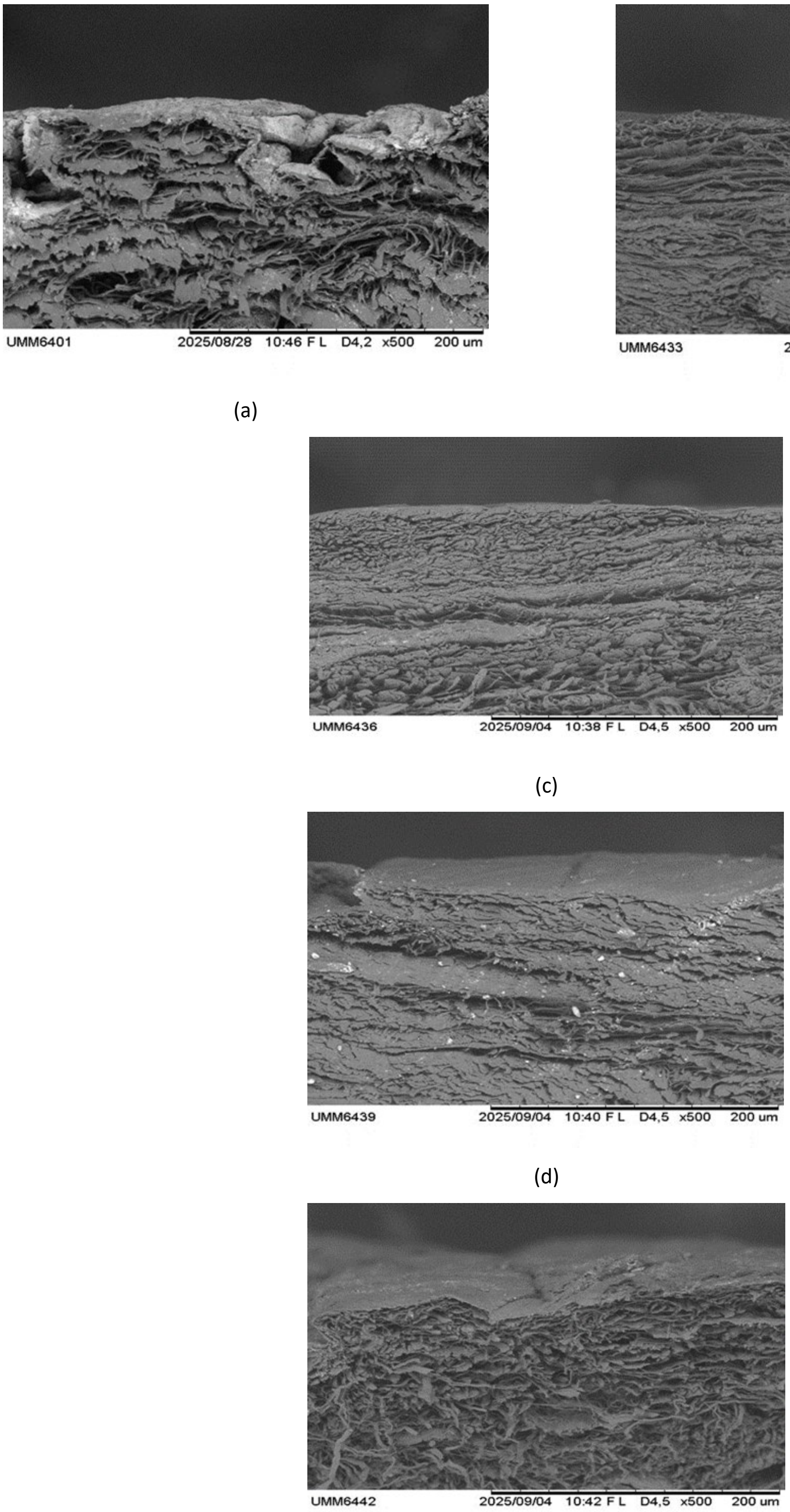
D. SEM Results of Ecoprinted Leather Cross-Sections

The SEM micrographs further substantiate the chemical and mechanical findings. Leather samples treated within the 30–45% $MgSO_4$ range showed compact and uniform collagen fiber structures with minimal inter-fibrillar voids and well-dispersed pigment deposits. Importantly, this improvement should not be attributed to Mg^{2+} ions alone, but rather to the synergistic interaction between $MgSO_4$, natural tannin-based pigments, and the mordanting environment. The balanced ratio among these components facilitates controlled ionic bridging and hydrogen bonding, resulting in stronger collagen–pigment integration and more homogeneous fixation.

Similar structural consolidation has been reported, indicating that metal mordants are effective only when supported by compatible organic complexes [5]. The dense and integrated morphology observed here corresponds directly with higher K/S values and improved color fastness, indicating that fiber compactness and pigment anchoring arise from cooperative chemical interactions, not simply an increase in Mg^{2+} concentration.

Conversely, at 60% concentration, SEM revealed surface salt aggregation and reopened voids within the fiber matrix, indicating that excess $MgSO_4$ disrupted the structural arrangement. This supports the mechanical test results showing reduced strength and the color data indicating diminished stability.

The SEM micrographs (Figures 1a–1e) illustrate the effects of increasing Epsom salt ($MgSO_4$) concentrations on the collagen fiber structure of ecoprinted leather.



(a) (b)

(c)

(d)

(e)

Figure 1. (a) Application of Epsom salt 0%; (b) Application of Epsom salt 15%; (c) Application of Epsom salt 30%; (d) Application of Epsom salt 45%; (e) Application of Epsom salt 60%

At 0% $MgSO_4$ (Figure 1a), the collagen bundles appear loose with wide inter-fibrillar spaces, indicating minimal cross-linking. The fibers are less compact, which may reduce color stability and mechanical strength. At 15% $MgSO_4$ (Figure 1b), the fibers become moderately more organized, showing initial ionic interactions that begin to enhance structural cohesion.

A clearer structural improvement is observed at 30% $MgSO_4$ (Figure 1c), where collagen fibers are more compact and uniformly arranged, suggesting an optimal level of cross-linking that promotes good mechanical properties and efficient pigment fixation. This structure supports both color stability and softness. At 45% $MgSO_4$ (Figure 1d), the collagen matrix becomes more densely packed, with reduced interfibrillar voids. While this improves firmness, it begins to reduce flexibility and may limit the leather’s handling characteristics.

At 60% $MgSO_4$ (Figure 1e), the collagen fibers appear excessively compressed and rigid, with visible aggregation and reduced porosity. These patterns confirm that the optimal performance in ecoprint leather is achieved not merely by increasing $MgSO_4$, but by maintaining the appropriate interaction balance within the mordanting system.

Taken together, the colorimetric, mechanical, and morphological analyses demonstrate that the enhancement in ecoprint leather properties results from a synergistic interplay of $MgSO_4$, natural pigment constituents, and the mordanting environment, which collectively stabilize collagen structure and pigment fixation. When this synergy exceeds the optimal ratio (above 45%), crystallization and structural stress begin to occur, reducing flexibility, aesthetic stability, and performance. Thus, the optimal mordant composition lies in the balanced interaction rather than the magnitude of any single component.

It is important to acknowledge that the experimental design involved altering the concentrations of all three mordant components simultaneously. While the observed improvements in color, mechanical properties, and color fastness strongly correlate with increasing $MgSO_4$, the optimal results may actually arise from a specific ratio of Mg^{2+}, Al^{3+}, and carbonate ions within the mordanting system. Future studies could isolate these variables individually to confirm the precise role and contribution of each component, providing a deeper understanding of the synergistic interactions in ecoprint leather processing.

Furthermore, the use of Epsom salt ($MgSO_4$), an inexpensive and widely available commodity, presents a cost-effective pathway for both industrial and small-scale (UMKM) ecoprint leather production, enhancing product quality while supporting environmental sustainability. Together, the observed improvements in leather properties reflect the synergistic balance of mordant components and practical, sustainable material choices, aligning with the study’s broader goal of environmentally friendly and industrially relevant ecoprint leather processing.

Together, these considerations highlight that the observed improvements in leather properties result from both the synergistic balance of mordant components and practical, sustainable choices in material selection, aligning with the study’s broader goal of environmentally friendly and industrially relevant ecoprint leather production.

CONCLUSION

A balanced multicomponent mordant system consisting of $MgSO_4$, Na_2CO_3, and a reduced proportion of $Al_2(SO_4)_3$—particularly at a 30–45% $MgSO_4$ ratio—provides optimal color quality and mechanical performance of ecoprinted leather. This formulation can be considered an environmentally promising alternative to conventional heavy-metal mordants, although further evaluation of wastewater characteristics is required to validate its sustainability claims.

Author Contributions

Conceptualization – Pancapalaga W, Hartati ES, and Adiyastiti BET; methodology – Pancapalaga W and Hartati ES; formal analysis – Adiyastiti BET and Fathoni RAR; investigation – Fathoni RAR; resources – Adiyastiti BET; writing-original draft preparation – Pancapalaga W, Adiyastiti BET and Hartati ES; writing-review and editing – Pancapalaga W and Hartati ES; visualization – Pancapalaga W; supervision – Pancapalaga W. All authors have read and agreed to the published version of the manuscript. All authors have read and approved the final version of the manuscript and agreed to its submission to the journal.

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Conflicts of Interest

The authors declare no conflict of interest.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist in language editing, improving clarity, and refining grammar. After using this tool, the authors carefully reviewed and revised the content to ensure accuracy and originality. The authors take full responsibility for the integrity and content of the publication.

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