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Chemical Study of Mordanting and Fixation Processes in Indigo, Sappanwood, and Tannin Natural Dyes Using Visual and UV-Vis Spectroscopic Analysis

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ABSTRACT

Ecoprint is an eco-friendly textile dyeing technique whose color quality is strongly influenced by mordanting and fixation processes. However, inconsistent mordant–fixative systems often result in unstable color intensity and poor standardization. This study aimed to evaluate the effect of different mordant and fixative combinations on the color characteristics of ecoprint fabrics dyed with indigo (*Indigofera tinctoria*), sappanwood (*Caesalpinia sappan*), and tannin extracts. Cotton fabrics were treated with either conventional mordant or color mordant, followed by fixation using vinegar, bone lime, lime, clear ferrous sulphate, or ferrous sulphate. Color properties were analyzed using UV-Vis spectroscopy (200-800 nm) and RGB evaluation. Iron-containing mordant systems significantly enhanced absorbance intensity in the visible region. It reduced the RGB lightness values, indicating deeper, more stable colors. Indigo showed maximum absorption at 647-672 nm, with the darkest blue obtained with the color mordant combined with ferrous sulphate fixation. Sappanwood showed maximum absorbance in the 482-491 nm range, under iron-assisted treatments. Tannin dyeing produced the most pronounced darkening effect due to tannin–iron complex formation. Overall, iron-assisted mordant–fixative systems under controlled pH conditions provided the most optimal and reproducible color performance, offering a scientific basis for standardizing the ecoprint process in sustainable textile production.

INTRODUCTION

Ecoprint is an artistic textile-dyeing technique that uses natural materials to produce unique, aesthetically valuable patterns. Its popularity has continued to increase alongside growing public awareness of environmentally friendly textile products (Faridatun, 2022). The ecoprint process uses a printing technique that employs natural dyes derived from leaves, roots, flowers, and bark. This technique can generate natural patterns on various media, including fabrics, paper, clay, glass, and leather; however, cotton and silk remain the most commonly used substrates

(Lubis et al., 2024). The development of patterns and color quality in ecoprint fabrics is influenced by several controlling factors, particularly the type of natural dye source and the pH conditions of the fabric following the mordanting process. The selection of appropriate natural dyes as base colors, combined with proper mordanting, results in distinctive color characteristics that harmonize with the natural motifs derived from leaves and flowers. Furthermore, the fixation stage plays a critical role in determining the fabric's final color appearance. The color fastness of ecoprint fabrics is achieved through the synergistic interaction between optimal mordanting and fixation processes (Wahyuningsih et al., 2020).

The mordanting stage is a crucial preliminary step before the dyeing process. Mordanting is conducted by immersing the fabric in a mordant solution to enhance the fiber's ability to absorb dye molecules effectively. This stage plays a decisive role in ecoprint dyeing, as it determines the degree of dye–fiber adhesion and resistance to color fading (Wahyuningsih et al., 2025). When properly performed, mordanting results in colors that are more durable and fade-resistant, even after repeated washing or prolonged exposure to sunlight (Wulandari et al., 2025). In addition, the dyed patterns appear sharper, more detailed, and well-defined, with no color bleeding, thereby producing clear, aesthetically appealing motifs. Color intensity is also enhanced and better aligned with the inherent characteristics of the natural dyes used, leading to a more optimal final appearance (Nadiah and Adriani, 2025). Consequently, appropriate mordanting can significantly enhance the aesthetic value of ecoprint products. In parallel, the fixation stage is equally important in determining the final color outcome. Through this stage, vivid, detailed, non-overlapping, and highly durable base colors are achieved, resulting in ecoprint fabrics with superior aesthetic quality and performance (Kusumaningtyas and Wahyuningsih, 2021; Rahmawati et al., 2024).

Despite these advantages, artisan-made ecoprint products still frequently experience color instability. Variations in color intensity and durability contribute to difficulties in standardizing color and pattern quality in ecoprint fabrics (Nada and Widowati, 2020). One of the primary factors underlying this issue is the improper dosage of mordants and fixatives during the dyeing process. Insufficient dosages weaken dye–fiber bonding, leading to poor color fastness, whereas excessive use of mordants and fixatives may induce undesirable color changes, reduce motif clarity, and potentially damage the fabric fibers (Agustin and Hidayati, 2024). Therefore, achieving consistent dyeing results and determining optimal dosages are critical aspects that require systematic investigation and development. Efforts to advance ecoprint products should focus on improving dyeing quality through scientifically grounded approaches, including optimizing mordant and fixative dosages and color composition, while adhering to green chemistry principles.

Beyond enhancing visual quality, the development of controlled dyeing techniques with optimized mordant and fixative dosages also has the potential to improve production efficiency, reduce excessive chemical use, and expand the market reach of ecoprint batik fabrics. However, previous studies have primarily focused on a single type of natural dye or a single mordant treatment (Arsa and Adriani, 2024). Moreover, investigations integrating visual evaluation with quantitative analytical approaches remain limited. The success of such innovations can be quantitatively evaluated through colorimetric analysis using UV-visible spectroscopy to monitor color variation and stability (Wahyuningsih et al., 2022). Therefore, the present study aims to comprehensively examine the influence of various mordant and fixative systems on the color characteristics of ecoprint textiles using three chemically distinct natural dyes: indigo, sappanwood, and tannin. The evaluation was conducted through a combined visual assessment and UV–Vis spectroscopic analysis to gain a deeper understanding of the relationships among the chemical conditions of the dyeing process, color intensity, and dye stability. Alongside improvements in management practices and more efficient production systems, advancements in ecoprint dyeing technology and innovation are expected to positively impact community empowerment and strengthen local partnerships, while simultaneously reinforcing ecoprint's position as a competitive, environmentally friendly textile product.

RESEARCH METHODS

Materials and Equipments

The materials used in this study included cotton fabric, soda ash (Na_2CO_3), alum ($Al_2(SO_4)_3$), sodium bicarbonate ($NaHCO_3$), ferrous sulphate ($FeSO_4$), clear ferrous sulphate, vinegar (CH_3COOH), lime, bone lime, sappanwood dye, indigo dye, tannin, and water. The instruments used were spoons, buckets, a digital camera, and a UV-Vis spectrophotometer (PerkinElmer Lambda 365+).

Fabric Preparation

The initial stage began with a scouring process to remove impurities and natural oils from the fabric. The fabric was immersed in a soda ash solution (5 tablespoons per 10 L of water) for 10 min and subsequently boiled for approximately 30 min. Afterward, the fabric was removed and air-dried under direct sunlight until completely dry. The mordanting process was then conducted to enhance the fabric's affinity toward natural dyes. The composition of the mordant solution is presented in Table 1.

Table 1. Types of mordants and compositions used in ecoprint dyeing

Types of Mordants	Ingredients	Total Volume (L)
Ordinary mordant	150 g $Al_2(SO_4)_3$ 50 g $NaHCO_3$ 30 g Na_2CO_3	5
Color mordant	150 g $Al_2(SO_4)_3$ 50 g $FeSO_4$ 50 g CH_3COOH 50 g $NaHCO_3$ 30 g Na_2CO_3	5

The fabric was immersed in the mordant solution for 10-15 min, gently kneaded to ensure uniform absorption, and then dried again under sunlight.

Fabric Dyeing Optimization

The natural dyes employed for color pattern optimization included sappanwood, tannin, and indigofera. After completion of the base dyeing stage and subsequent drying, the fabric was further treated with a fixation process using five fixatives: vinegar, bone lime, lime, clear ferrous sulphate, and ferrous sulphate. The dye solutions were analyzed using a UV-Vis spectrophotometer over a wavelength range of 200-800 nm with a 1 cm path length cuvette, using distilled water as the blank. Each sample measurement was conducted in triplicate to ensure reproducibility.

RESULTS AND DISCUSSION

Indigo dye derived from *Indigofera tinctoria* is one of the most stable natural blue colorants and has been utilized for thousands of years, commonly obtained through fermentation or extraction processes (Hakiim and Sari, 2018). Fundamentally, this dye does not require mordanting or fixation, as it operates through unique physical and chemical mechanisms distinct from those of other natural dyes. Indigo dyeing is highly dependent on the chemical conditions of the dye bath (Madina et al., 2024). Indigo is inherently insoluble in water and must therefore be reduced to its colorless, soluble form, leuco-indigo (indigo white), in a reducing solution, typically employing sugar and lime or fructose as reducing agents (Lestari and Riyanto, 2004). During dyeing, the fabric is immersed for 2–5 min and subsequently removed; upon exposure to air, leuco-indigo is rapidly oxidized back to its insoluble blue form, which becomes physically trapped within the amorphous regions of textile fibers. The corresponding reactions can be expressed as follows (Huang and Hecht, 2023):

Reduction reaction: Indigo + $2e^-$ + $2H^+$ → Leuco-indigo

Oxidation reaction: Leuco-indigo + $12O_2$ → Indigo

Visually, a clear distinction was observed between the mordant solutions (Figure. 1A(i)) and the dyed fabrics subjected to conventional mordanting and color mordanting treatments (Figure. 1A and B). The color mordant, containing additional ferrous sulphate ($FeSO_4$) and vinegar (CH_3COOH), produced deeper blue to bluish-green hues compared to the conventional mordant, resulting in paler, less contrasting blue shades. From a chemical perspective, Fe^{2+}/Fe^{3+} ions can interact weakly with indigo molecules via coordination to carbonyl groups, thereby increasing dye aggregation and affinity for the textile fiber surface (Beck and Sünkel, 2020). On the other hand, vinegar helps maintain chemical stability and accelerates oxidation during dyeing. The influence of fixatives on the final color was also pronounced. Samples without fixation (ii) exhibited relatively weak coloration. The use of vinegar as a fixative (iii) resulted in stronger and more stable blue hues, indicating that acidic conditions favor the oxidation of leuco-indigo into its insoluble and more stable indigo form. In contrast, fixation using bone lime (iv) and lime (v), both alkaline, caused the color to shift toward paler or greenish tones, likely due to disruption of the indigo oxidation process or the formation of less stable precipitates on the fiber surface. Conversely, iron-based fixatives, namely clear ferrous sulphate (vi) and ferrous sulphate (vii), produced the darkest and most intense colors, particularly when combined with color mordanting, highlighting strong interactions between indigo chromophores and iron ions.

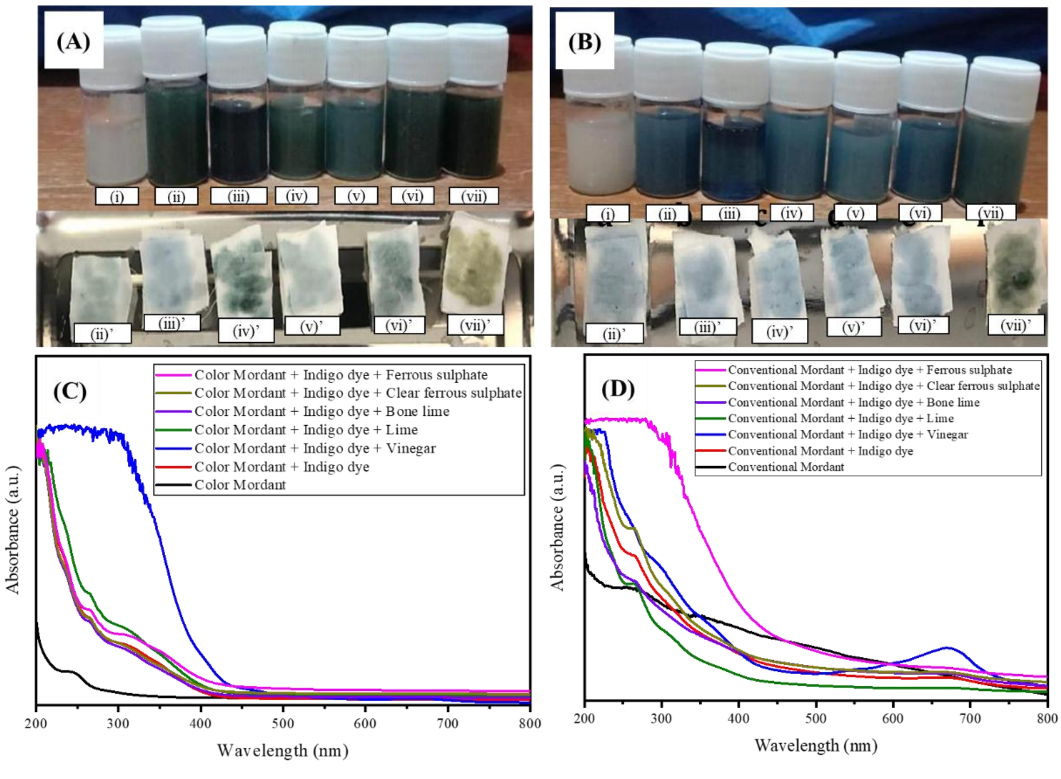

Figure 1. Indigo dyeing using (A) color mordant and (B) conventional mordant: (i) mordant solution, (ii) without fixation, (iii) vinegar fixative, (iv) lime fixative, (v) bone lime fixative, (vi) clear ferrous sulphate fixative, and (vii) ferrous sulphate fixative; UV-Vis spectral analysis of indigo dyeing under (C) color mordant and (D) conventional mordant

UV-Vis spectroscopic analysis (Figure. 1C and D) supports these observations, where samples treated with ferrous sulphate and/or vinegar fixatives exhibited the highest absorbance values, reflecting enhanced dye stability. In contrast, samples subjected to alkaline fixatives showed a more pronounced decrease in absorbance, consistent with the visually observed faded coloration. Variations in the absorption curve profiles reflect differences in indigo chromophore concentration and stability arising from distinct chemical environments during mordanting and fixation. Moreover, Table 2 demonstrates variations in the maximum absorption wavelength within the visible region. These shifts are closely associated with changes in color direction, as reflected in the Red-Green-Blue (RGB) values, which are influenced by the system's chemical conditions, particularly through redox mechanisms in indigo dyeing.

Table 2. Summary of maximum wavelengths and colors produced from indigo dyeing

Sample	Maximum wavelength (nm)		Color at maximum wavelength in RGB	Complimentary color in RGB
	UV	Vis		
Color mordant	246	-	-	-
Color mordant + indigo dye	265	652	248, 0, 0	0, 248, 248
Color mordant + indigo dye + vinegar	261	664	238, 0, 0	0, 238, 238
Color mordant + indigo dye + lime	264	668	234, 0, 0	0, 234, 234
Color mordant + indigo dye + bone lime	266	662	239, 0, 0	0, 230, 230)
Color mordant + indigo dye + clear ferrous sulphate	266	662	239, 0, 0	0, 239, 239
Color mordant + indigo dye + ferrous sulphate	269	672	230, 0, 0	0, 239, 239
Conventional mordant	251	-	-	-
Conventional mordant + indigo dye	258	662	239, 0, 0	0, 239, 239
Conventional mordant + indigo dye + vinegar	254	670	232, 0, 0	0, 232, 232
Conventional mordant + indigo dye + lime	263	652	248, 0, 0	0, 248, 248
Conventional mordant + indigo dye + bone lime	258	656	245, 0, 0	0, 245, 245
Conventional mordant + indigo dye + clear ferrous sulphate	264	660	241, 0, 0	0, 241, 241
Conventional mordant + indigo dye + ferrous sulphate	279	647	252, 0, 0	0, 252, 252

In contrast, sappanwood dye (*Caesalpinia sappan*), which is highly popular in ecoprint applications due to its attractive color, also presents intriguing chemical properties. Sappanwood contains brazilin, a chromophoric compound that is oxidized to brazilein, producing red to orange hues (Khasanah and Widowati, 2022). However, these color variations are strongly influenced by the type of mordant or fixative applied during the dyeing process. The use of acidic mordants or fixatives tends to preserve the yellowish tones of sappanwood, as acidic conditions stabilize the brazilein pigment. In contrast, alkaline mordants or fixatives generally induce a shift toward red coloration. Meanwhile, metal-based mordants can further darken the sappanwood color to purplish-red or deeper shades by interacting with the dye pigment (Meutia et al., 2019).

Visually (Figure. 2A and B), both the dye solutions and the dyed fabrics treated with color mordants exhibited more intense, darker hues with a dark yellow nuance, whereas those treated with conventional mordants yielded brighter pink to purplish tones. The addition of ferrous sulphate to the color mordant promoted the formation of complexes between Fe^{2+}/Fe^{3+} ions and brazilein pigments in sappanwood (Wongsooksin et al., 2008). This complexation led to a shift toward darker coloration and enhanced color stability on the fabric. In parallel, the presence of vinegar in the color mordant helped regulate the pH, thereby enabling a more controlled metal–dye complexation.

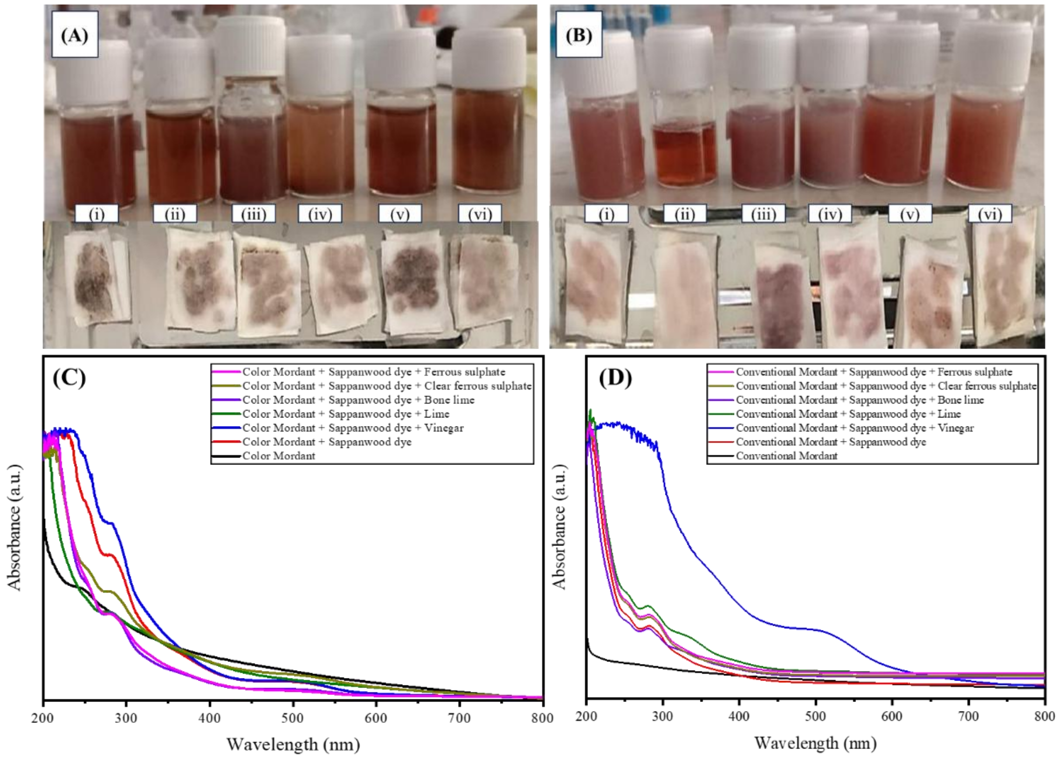

Figure 2. Sappanwood dyeing using (A) color mordant and (B) conventional mordant: (i) without fixation, (ii) vinegar fixative, (iii) lime fixative, (iv) bone lime fixative, (v) clear ferrous sulphate fixative, and (vi) ferrous sulphate fixative; UV-Vis spectral analysis of sappanwood dyeing under (C) color mordant and (D) conventional mordant

UV-Vis spectroscopic analysis further corroborated these visual observations (Figure. 2C and D), where samples treated with color mordants and vinegar fixatives exhibited the highest absorbance values among all treatments. Elevated absorbance indicates a higher chromophore concentration and stronger interactions between the dye molecules and the textile fibers. Conversely, samples treated with alkaline fixatives showed a more rapid decline in absorbance, consistent with the visually observed color fading. This behavior closely parallels the trends observed for indigo dyeing. Variations in RGB values further represent the direction and magnitude of color shifts, as summarized in Table 3. The predominance of the red (R) component, accompanied by variations in the green (G) and blue (B) components, indicates modulation of color intensity toward red to brownish hues in the sappanwood dyeing system.

Table 3. Summary of maximum wavelengths and colors produced from sappanwood dyeing

Sample	Maximum wavelength (nm)		Color at maximum wavelength in RGB	Complimentary color in RGB
	UV	Vis		
Color mordant	246	-	-	-
Color mordant + sappanwood dye	279	484	0, 230, 255	255, 26, 0
Color mordant + sappanwood dye + vinegar	282	485	0, 234, 255	255, 21, 0
Color mordant + sappanwood dye + lime	277	483	0, 226, 255	255, 30, 0
Color mordant + sappanwood dye + bone lime	280	488	0, 247, 255	255, 9, 0

Color mordant + sappanwood dye + clear ferrous sulphate	280	482	0, 222, 255	255, 34, 0
Color mordant + sappanwood dye + ferrous sulphate	280	491	0, 255, 245	255, 0, 9
Conventional mordant	251	-	-	-
Conventional mordant + sappanwood dye	282	489	0, 251, 255	255, 4, 0
Conventional mordant + sappanwood dye + vinegar	291	485	0, 234, 255	255, 21, 0
Conventional mordant + sappanwood dye + lime	280	488	0, 247, 255	255, 9, 0
Conventional mordant + sappanwood dye + bone lime	280	490	0, 255, 255	255, 0, 0
Conventional mordant + sappanwood dye + clear ferrous sulphate	282	484	0, 230, 255	255, 26, 0
Conventional mordant + sappanwood dye + ferrous sulphate	282	486	0, 239, 255	255, 17, 0

Tannins, which are natural dyes widely found in various plant sources, are also widely used in ecoprint techniques (Haq, 2025). Tannins are polyphenolic compounds with multiple hydroxyl groups, enabling them to interact effectively with macromolecules, impart color, and enhance dye fixation on textile fibers (Ristiani and Sulistyaningsih, 2022). In addition to their affinity toward macromolecules, tannins readily react with metal ions, particularly iron ions (Fe^{2+} or Fe^{3+}) present in ferrous sulphate fixatives (Abdullahi et al., 2019). The reaction between tannins and iron ions results in the formation of dark-colored tannin–iron complexes, accompanied by precipitates exhibiting gray, dark blue, or olive-green hues, depending on concentration and pH (Halimu et al., 2017). In addition, tannins can form hydrogen bonds with textile fibers, further enhancing dye fixation (Wilson et al., 2012).

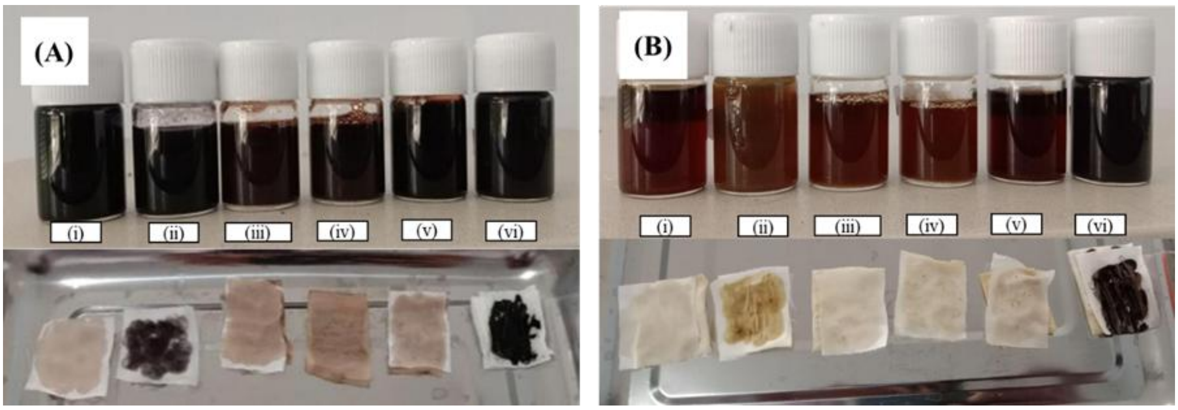

Figure 3. Tanin dyeing using (A) color mordant and (B) conventional mordant: (i) without fixation, (ii) vinegar fixative, (iii) lime fixative, (iv) bone lime fixative, (v) clear ferrous sulphate fixative, and (vi) ferrous sulphate fixative

Figure 3 illustrates the pronounced differences in dye solution color and fabric dyeing outcomes between the color mordant treatment (A) and the conventional mordant treatment (B). The color mordant containing ferrous sulphate ($FeSO_4$) produced markedly darker to nearly black hues in both the dye solutions and the fabrics compared to the conventional mordant, which yielded light brown to reddish-brown tones. This phenomenon indicates the formation of tannin–

iron complexes. The presence of vinegar in the color mordant further helped regulate the solution pH, thereby facilitating a more effective complexation reaction between tannins and iron ions. The use of iron-based fixatives, namely clear ferrous sulphate (v) and ferrous sulphate (vi), resulted in the most significant color changes, producing highly contrasted dark brown to black shades. These results further confirm the formation of strong coordination bonds between tannins and iron ions during the fixation process, leading to more permanent entrapment of the dye molecules within the textile fibers. The resulting colors were more homogeneous and exhibited superior coverage compared to other treatments.

CONCLUSION

Overall, the study confirms that iron-containing color mordants combined with appropriately selected fixatives represent the most effective strategy for enhancing color intensity and stability across different natural dyes. However, the underlying mechanisms differ (redox entrapment for indigo, metal–brazilein complexation for sappanwood, and metal–tannin coordination for tannins). For indigo dyeing, the best results were obtained with the color mordant combined with iron-based fixatives (ferrous sulphate or clear ferrous sulphate). This combination produced the darkest and most stable blue shades. For sappanwood dye, the best color intensity and stability were achieved with the color mordant, followed by vinegar or iron-based fixation. This treatment generated darker reddish to brownish hues. For tannin-based dyeing, the most significant color development occurred when iron-containing mordants and iron-based fixatives were applied. The formation of strong tannin–iron coordination complexes resulted in dark brown to black shades with superior homogeneity and coverage. From an industrial perspective, these findings provide a scientific basis for process standardization in ecoprint production. For industrial implementation, it is recommended that ecoprint producers adopt iron-assisted mordant systems with controlled pH, while carefully optimizing metal salt concentrations to balance color performance and environmental impact.

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