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Enhancing Eco-Friendly Textile Dyeing: Comparative Analysis of Ethanol Maceration and Boiling Extraction with Lime Mordanting on Cellulose-Based Fabrics

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***Abstract*—This study investigates the colorimetric properties of cellulose-based textiles—Lyocell, Rayon, and Cotton—dyed with natural dyes extracted from Jenitri leaves (*Elaeocarpus ganitrus*) and Sappan bark (*Caesalpinia sappan*), utilizing two distinct extraction methods: ethanol maceration (EE) and traditional boiling extraction (BE). The role of lime (*Citrus aurantifolia*) as a natural mordant was explored in both pre- and post-mordanting processes to assess its impact on color fixation and durability. Comprehensive spectrophotometric analysis was conducted, measuring reflectance, L* (lightness), a* (red/green), b* (yellow/blue), color difference (ΔE*), and color strength (K/S). The findings reveal that ethanol maceration significantly enhances color yield and chromaticity, with K/S values at 400 nm ranging from 1.2 to 1.9, surpassing the boiling method's range of 0.9 to 1.4. The ΔE* values, averaging 3.0 between EE and BE samples, underscore the pronounced color variations resulting from different extraction techniques. Furthermore, lime mordanting notably improved color fastness, with dry rubbing test scores consistently reaching 4 to 5, indicating superior resistance to color transfer. This research highlights the potential of lime as an eco-friendly mordant, particularly when combined with macerated natural dyes, promoting sustainable textile dyeing practices. The study emphasizes that the selection of extraction and mordanting techniques plays a crucial role in determining the final coloristic properties of naturally dyed textiles, thereby supporting the development of more innovative and environmentally conscious textile production methods.**

***Keywords*—Natural dyes; ethanol maceration; lime mordanting; color strength.**

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I. Introduction

Although the textile industry is a vital component of contemporary manufacturing, its environmental impact has come under more careful inspection, especially with regard to the usage of dyes and mordants. In order to improve color fastness and intensity, iron-based mordants like ferrous sulfate and aluminum sulfate are essential to the dyeing process. Studies have, however, provided information on these compounds' effects on the environment [1]–[3]. The studies collectively emphasize the need for stringent control measures to prevent the release of iron and other heavy metals from industrial wastewater into the environment, highlighting the potential ecological imbalance and health risks associated with iron contamination in aquatic systems. Similar ecological dangers have been linked to the widespread usage of synthetic colors. In the other hand, synthetic dyes pose serious risks to the environment and human health because they frequently contain mutagenic and carcinogenic substances that are resistant to degradation. Textile businesses release these dyes into water bodies, causing pollution that can be harmful to human health and aquatic life. A potential strategy to lessen these effects is bioremediation, which uses microorganisms to convert complicated dye complexes into non-toxic chemicals [4]. The environmental impacts and hazardous effects of synthetic dyes are further highlighted by [5] that support the use of laccases as a treatment technique prior to discharge into water bodies. The combined knowledge gained from these investigations emphasizes how urgently sustainable dyeing solutions for textiles are needed. It is not only vital for the environment to shift to natural dyes and mordants, but it is also an evolution that is required to lessen the negative effects of traditional textile processes.

In addition to natural dyes, natural mordants or fixatives are also necessary because iron-based mordants can be just as hazardous as synthetic dyes. Recent developments in the field of environmentally friendly textile dyeing have brought lime juice (*Citrus aurantifolia*) to light as a natural fixative and mordant. Another study by [6] investigated the use of lime as one of the fixatives in natural dyes made from orange citrus peel to optimize the dyeing processes on cotton textiles. The study showed that the application of lime juice during the fixation process produced a bright yellow coloration, and that the reflectance % varied depending on the washing time and dyeing frequency.

A crucial step in the application of colorants in the textile production process is the extraction of natural dyes from plant sources. Recent innovations in extraction procedures have brought attention to the advantages of ethanol-based maceration against conventional boiling processes. It has been demonstrated that ethanol maceration, a process that includes soaking plant materials like bark, leaves, or seeds in ethanol to extract colorants, provides a number of benefits. Research has indicated that employing this technique can lead to increased dye production, improved color retention, and heightened antibacterial activity of the extracted colors [7]. In the study by [8] stated that the extraction of natural dyes from Hawthorn fruits using ultrasound assistance, which may involve ethanol maceration, has been found to enhance the fastness characteristics of dyed polyamide fabric while also introducing antioxidant and antibacterial qualities . Similarly, it has been discovered that the green chemistry method of extracting *betalains* from beetroot peels using ethanol as a solvent results in vibrant colors on wool materials, demonstrating the possibility of ethanol-based extraction in producing high-quality natural dyes [7]. These results imply that traditional boiling extraction techniques, which often call for higher energy input and may result in the degradation of colorants and loss of functional qualities, may be replaced by ethanol maceration as a more effective and sustainable method.

A strong opportunity to close a number of gaps in the sustainable manufacture of dyed materials is presented by the state of textile dyeing research today. Achieving a product that delivers both functional qualities like aesthetic appeal with vibrant and stable colors is still a problem, despite the increased interest in using natural dyes and mordants. By employing cellulose-based textiles (Lyocell, Rayon, and Cotton) dyed with natural extracts from Jenitri leaves and Sappan bark using an ethanol-based maceration technique, this work seeks to close these gaps. It is hypothesized that using ethanol in maceration can improve colorant extraction, giving fabrics a better color yield and possibly brighter hues. In addition, the research suggests that Lime (*Citrus aurantifolia*) be used as a natural mordant, speculating that it is more environmentally friendly and sustainable than traditional iron-based mordants.

II. Materials and Method

A. Materials

The materials for this experiment were textiles made of cellulose, such as lyocell, rayon, and cotton. Cotton and rayon were commercially accessible from Tokoèncit Bandung, Indonesia, while lyocell fabric was obtained from Lenzing (PT. South Pacific Viscose, Purwakarta, Indonesia). Table I included information on the fabrics' density and design.

TABLE I
THE PHYSICAL PROPERTIES OF FABRIC SAMPLES

Fabric Types	Density (g/m^2)	Warp density (*threads per inch*)	Weft density (*threads per inch*)
Cotton	111	58	58
Rayon	135	58	58
Lyocell	140	58	50

The other materials used were Jenitri leaves which were cultivated from Wedomartani, Yogyakarta Special Region, Indonesia; and Sappan bark was purchased from JSR Jogja.

B. Extraction of Colorant

There are two types of extraction conducted in this study, which were conventional extraction by boiling method and the other one is by maceration method. The dye extraction process, employing the maceration method, was conducted by immersing Jenitri leaves and Sappan bark in a 96% ethanol solution. The ratio applied in this procedure was 1:40. In this process, each of the Jenitri leaves and Sappan bark was weighed to 25 grams and then submerged in 1 liter of 96% ethanol solution. This immersion was maintained for five days, accompanied by periodic stirring to facilitate optimal color extraction. Post the five-day period, the extracted dye was then subjected to evaporation using an Evaporator apparatus. The purpose of the evaporation was to segregate the ethanol solution from the pure dye, thereby yielding a more concentrated dye. In the extraction process utilizing the boiling method, a raw material ratio of 1:40 was employed. During this process, each of Jenitri leaves and Sappan bark was weighed to 25 grams and subsequently immersed in 1 liter of distilled water. Each material was processed in separate beakers. The mixture was boiled until the liquid volume reduced to approximately 800 mL, a process taking about 2 hours. Following the completion of the boiling stage, the extracted substance was cooled and then filtered to separate the liquid extract from the solid residue. This step is crucial for obtaining a more purified form of the extract, suitable for application in fabric dyeing processes.

C. Mordanting Procedure

The mordant or fixing solution was prepared by mixing water with lime juice extract. The analytical quality of the lime juice extract as a mordant and fixative lies in its active components. Identified elements within the lime juice extract, such as citric acid and other compounds, play a crucial role in the mordanting and color fixation processes. The mordant liquid is prepared by dissolving 30 cc of squeezed lime juice per liter of water.

The fabric used was cut into 25x25 cm pieces for each type. Prior to dyeing, the fabric underwent a scouring process to cleanse it of any impurities adhering to the surface. Scouring was performed by soaking the fabric in a solution of Turkish Red Oil (TRO) at a ratio of 500 grams TRO to 1 liter of water. The fabric was immersed for 40 minutes at 80°C. Following this, the fabric was rinsed with running water and then dried for 30 minutes. After drying, the next step was mordanting. Mordanting involved soaking the fabric in a lime juice solution, using 30 mL of lime juice per 1 liter of water, for a duration of one hour at room temperature. Subsequently, the fabric was ready for the dyeing process.

D. Dyeing Procedure

The dye extracts obtained from the boiling and maceration methods were subsequently utilized in the dyeing process on fabrics that had undergone scouring and mordanting treatments. These fabrics were then immersed in the dye solution for 24 hours with the material to liquor ratio of 1:40 (g/mL) in a room temperature. Post-dyeing, the fabrics were fixed using a lime juice solution for one hour. The purpose of this fixation was to lock the color into the fabric to prevent fading. Following the dyeing process, the fabrics were categorized into several sample codes as follows:

TABLE II
SAMPLE IDENTIFICATION AND DESCRIPTION

No.	Sample ID	Description
1.	STD – C	Standard (control) sample of Cotton fabric
2.	STD – R	Standard (control) sample of Rayon fabric
3.	STD – L	Standard (control) sample of Lyocell fabric
4.	BE – SC	Boiling Extraction of Sappan Bark – Cotton Fabric
5.	BE – JC	Boiling Extraction of Jenitri Leaves – Cotton Fabric
6.	BE – SR	Boiling Extraction of Sappan Bark – Rayon Fabric
7.	BE – JR	Boiling Extraction of Jenitri Leaves – Rayon Fabric
8.	BE – SL	Boiling Extraction of Sappan Bark – Lyocell Fabric
9.	BE – JL	Boiling Extraction of Jenitri Leaves – Lyocell Fabric
10.	EE -SC	Ethanol Maceration Extraction of Sappan Bark – Cotton Fabric
11.	EE – JC	Ethanol Maceration Extraction of Jenitri Leaves – Cotton Fabric
12.	EE – SR	Ethanol Maceration Extraction of Sappan Bark – Rayon Fabric
13.	EE – JR	Ethanol Maceration Extraction of Jenitri Leaves – Rayon Fabric
14.	EE – SL	Ethanol Maceration Extraction of Sappan Bark – Lyocell Fabric
15.	EE – JL	Ethanol Maceration Extraction of Jenitri Leaves – Lyocell Fabric

E. Evaluation of Dyed Fabrics

A spectrophotometer-based color matching system was utilized to assess the fabric's color intensity, indicated by its reflectance percentage. In addition to reflectance, the color properties of the fabrics were quantified using the CIELAB system, often expressed as Lab*. The L* value (pronounced L star) denotes luminosity, scaling from 100 (white) to 0 (black). The a* value indicates the spectrum from red to green, with positive values signifying a redder hue and negative ones indicating greenness. The b* value represents the yellow-blue axis, where positive values suggest a yellowish tint and negative values a bluish one. These Lab* values collectively provide insights into the tonal variations of the fabric. From these values, color and chromaticity differences are calculable, as detailed in equations 1-6. The term ΔE^*_{ab} represents the color difference, which is determined using a specific equation.

$$\Delta L^* = L^*_{STD} - L^*_{TRIAL} \quad (1)$$

$$\Delta a^* = a^*_{STD} - a^*_{TRIAL} \quad (2)$$

$$\Delta b^* = b^*_{STD} - b^*_{TRIAL} \quad (3)$$

$$\Delta E^*_{ab} = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (4)$$

In the given context, ΔL^* signifies the variation in lightness between the reference standard (L^*_{STD}) and the test samples (L^*_{TRIAL}). Δa^* indicates the difference in the red-to-green color spectrum between the standard (a^*_{STD}) and the test samples (a^*_{TRIAL}). Similarly, Δb^*denotes the difference in the yellow-to-blue color axis between the standard (b^*_{STD}) and the test samples (b^*_{TRIAL}). ΔC^*_{ab} represents the chromatic disparity between the sample/trial/batch and the standard, calculated using the specified equation.

$$C^*_{ab} = \sqrt{a^{*2} + b^{*2}} \quad (5)$$

$$\Delta C^*_{ab} = C^*_{ab\,TRIAL} - C^*_{ab\,STD} \quad (6)$$

A color strength test utilizing the K/S method was conducted to evaluate the vibrancy of fabric colors. This method employs a spectrophotometer, specifically the UV-2401-PC Spectrophotometer with ISR-2200 model, to measure how brightly a fabric's color appears. The device quantifies the extent to which the fabric reflects light at various wavelengths. The results of this measurement are expressed in terms of Reflectance Percentage (R%). R% is a critical metric in spectrophotometry that indicates the proportion of light that a fabric surface reflects. It is a key indicator of the fabric's ability to reflect light, thereby informing about its color brightness and quality [9]. Further, the K/S value is derived from the R% using the Kubelka-Munk formula, which is a fundamental equation in colorimetry and textile color strength assessment. The formula is:

$$K/S = \frac{(1-R)^2}{2R} \quad (7)$$

where 'K' is the absorption coefficient, 'S' is the scattering coefficient, and R is the reflectance. This equation provides a quantitative measure of the color strength of the fabric by relating the light absorbed and scattered by the fabric to its perceived color strength [10], [11]. This testing approach is essential for determining the quality and vibrancy of fabric colors, ensuring their alignment with the desired standards in the textile industry. The K/S value, derived from R%, offers a more nuanced understanding of the fabric's color properties, making it a crucial factor in textile color quality control.

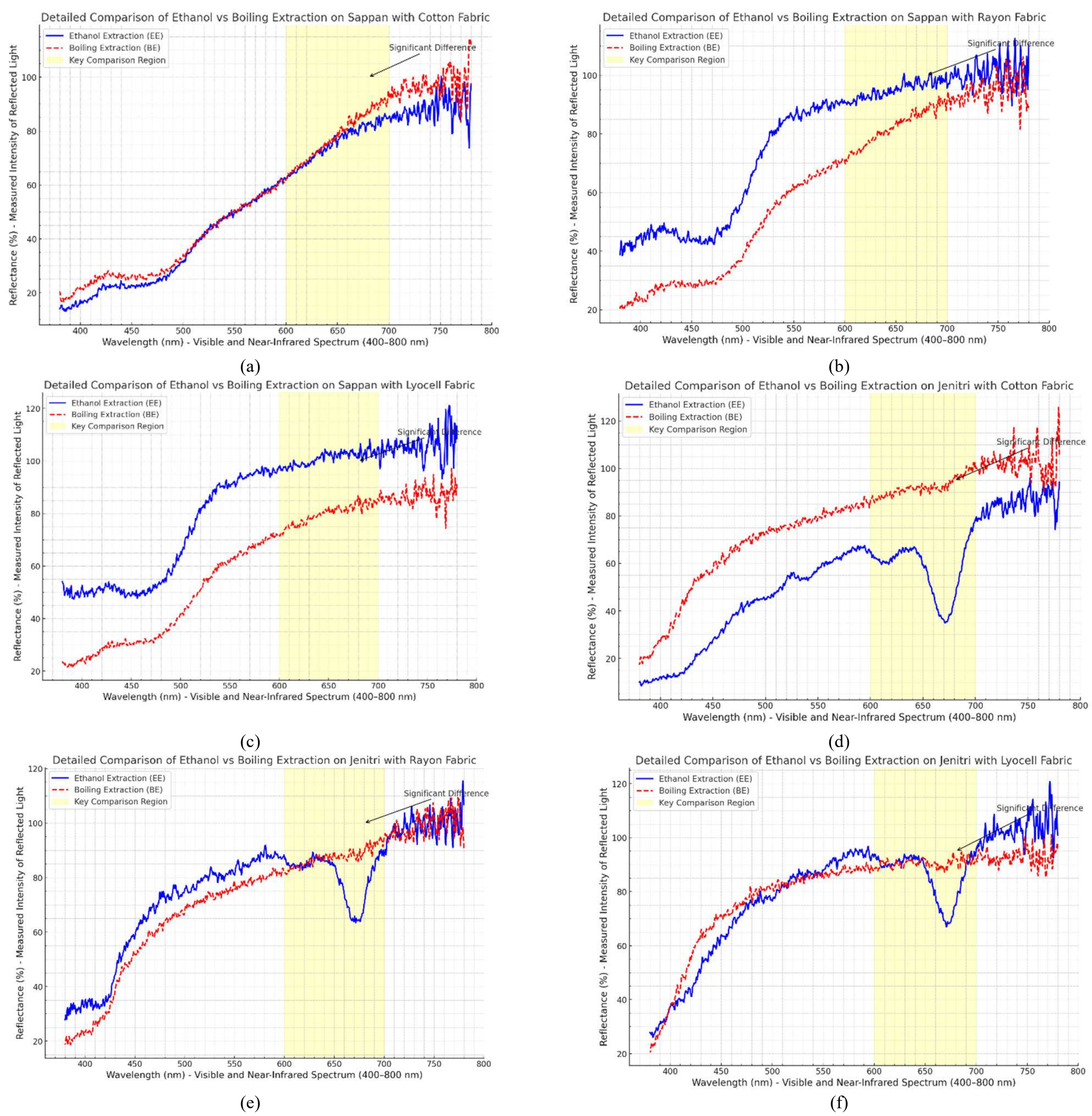
The fastness of the fabric was also measured in this study. This test, commonly referred to as the 'Crocking test', is essential to determine the degree of color fastness of dyes on fabric when subjected to friction. It is a pivotal evaluation for the durability of dye upon fabric rubbing, instrumental in assessing the dyeing process's effectiveness, and acts as a crucial factor in selecting appropriate dyes. The apparatus employed for this rubbing test is a crockmeter, which operates under a controlled rubbing motion, both horizontally and vertically. The rubbing head exerts consistent pressure against the fabric sample placed beneath it. The Crocking test adheres to the international standard, specifically the ISO 105-X12 method for textiles.

For color fastness assessment, the Staining Scale, also known as the Grey Scale for Staining, is used. This scale is integral to the evaluation process, as it measures the degree of staining from one fabric to another. The Grey Scale for Staining conforms to the ISO 105-A03 standard. It consists of a series of paired plates – a white standard plate and eight graded grey-white standard plates. Each pair demonstrates a varying level of contrast or color difference, corresponding to the staining value. The assessment using the Staining Scale involves a comparative analysis between stained and unstained white fabric, considering the color differences as defined by the scale. The extent of staining is quantified and reported in terms of chromaticity values, providing a standardized measure of the dye's resistance to transferring under conditions of friction.

III. Results and Discussion

A. *Extraction Techniques and Their Influence on Dye Uptake*

Figure 1 represents the results on comparing the reflectance spectra obtained from fabrics dyed with extracts from Sappan bark (S) and Jenitri leaves (J) using two different extraction methods: Ethanol Extraction (EE) and Boiling Extraction (BE). The fabrics analyzed include Cotton (C), Rayon (R), and Lyocell (L). The "Key Comparison Region" is a specific range of wavelengths that has been highlighted on the chart. This range is identified as particularly important because it shows where the most pronounced differences between the two extraction methods (EE and BE) are observed. The "Significant Difference" annotation points to a specific wavelength within the key comparison region where the reflectance spectra of the two extraction methods show a noticeable deviation from each other. This might indicate that one method leads to a higher or lower reflectance at this wavelength, which could imply differences in color intensity, hue, or other optical properties of the fabric.



(a) (b) (c) (d) (e) (f)

Fig. 1 Reflectance to wavelength of dyed fabrics

Based on Figure 1 (a) the reflectance spectra indicate that for cotton, the BE method results in a higher reflectance across most of the wavelength range compared to EE. This suggests that the boiling extraction may facilitate better dye uptake or interaction with cotton fibers, potentially because of the more extensive breakdown of plant cell walls and better release of dye components. While in Figure 1 (b) the spectra for rayon shows less distinction between EE and BE, suggesting that the extraction method does not significantly alter the dye uptake in rayon. This could be due to rayon's structure, which is different from natural cotton and may interact with the dye constituents independently of the extraction method. In the other hand, Figure 1 (c) presents that similar to cotton, lyocell shows a higher reflectance in the BE samples. Lyocell, being a regenerated cellulose fiber, might be more receptive to the compounds released during boiling, leading to a different reflectance pattern compared to EE.

For Jenitri on cotton (Figure 1.d), BE again shows a higher reflectance, implying a similar trend to that observed with Sappan. This could be indicative of the cellulose in cotton having a higher affinity for the compounds extracted through boiling. While the trend in rayon is reversed compared to cotton and lyocell; EE samples display higher reflectance (Figure 1.e). This could be attributed to specific interactions between rayon fibers and the phytochemicals extracted using ethanol, which may bond differently than those released through boiling. With lyocell, the distinction between EE and BE is minimal (Figure 1.f), suggesting that for Jenitri, the extraction method does not significantly affect the dyeing outcome on lyocell fabric.

In the realm of textile dyeing, the extraction methods of natural dyes play a pivotal role in determining the color yield and reflectance properties of fabrics. Our study delved into the comparison of ethanol extraction (EE) and boiling extraction (BE) methods across various fabric types, revealing notable differences in their dyeing efficacy. For natural fibers like cotton and lyocell, BE typically resulted in higher reflectance, indicative of a richer color saturation. This contrasted with semi-synthetic fibers like rayon, where the extraction method's impact was less pronounced, varying with the dye source. The underlying reason for these disparities likely lies in the solubility characteristics of colorant compounds in different solvents. Ethanol, with its lower polarity compared to water, may extract a distinct set of compounds or do so in varying concentrations, thereby influencing the resultant shades and fastness properties of the dyed fabrics. This observation aligns with findings from Khatun and Mostafa [12] and Oforghor et al. [13], which confirmed that the choice of extraction medium significantly impacts the color yield and fastness properties of natural dyes. Khatun and Mostafa [12] demonstrated that an alkaline extraction medium optimized color properties on silk and cotton fabrics. Oforghor et al. [13] highlighted the importance of extraction conditions in enhancing dye exhaustion and fastness when using shea butter tree bark. Similarly, Shafiq et al. [14] investigated into the extraction of natural dye from Argy Worm Wood (AWW) using varying solvent systems, including ethanol/water and sodium hydroxide/water. They demonstrated that the solvent choice's impact on color strength and fastness properties in dyed cotton fabrics.

Our study's findings suggest that while BE is more conducive to higher color uptake in natural fibers, its effects on semi-synthetic fibers like rayon are less predictable, necessitating further exploration. This highlights the critical need for tailoring the extraction process to the specific dye-fiber system to optimize dyeing outcomes. A deeper understanding of the chemical composition of dye extracts and their interaction with different fiber types, as suggested by the referenced studies, would be instrumental in elucidating the underlying mechanisms governing these dyeing processes.

B. Extraction Method Impact on Color Strength

In the examination of the color strength (K/S) at a wavelength of 400 nm, distinct variations were observed between the ethanol extraction (EE) and boiling extraction (BE) methods across different materials and fabric types. The results, as depicted in the graph for Figure 2, indicate a notable trend where ethanol extraction generally yielded higher K/S values compared to boiling extraction. This suggests a more effective dye extraction from both Sappan and Jenitri when using the ethanol method, particularly evident in cotton and lyocell fabrics. For instance, in the case of Sappan with Cotton, the K/S value was markedly higher for EE compared to BE, indicating a deeper and more vibrant dye uptake. A similar trend was observed with Jenitri, although the difference in K/S values between extraction methods was slightly less pronounced. These findings are significant as they suggest that the extraction method plays a crucial role in the efficacy of natural dye uptake in textiles. The use of ethanol as a solvent appears to facilitate a more efficient extraction of color compounds, resulting in enhanced color strength. This has important implications for sustainable textile dyeing practices, where maximizing color yield while minimizing resource usage is essential. This study thus contributes valuable insights into the optimization of natural dyeing processes, reinforcing the potential of ethanol extraction in achieving vibrant and sustainable coloration in textiles.

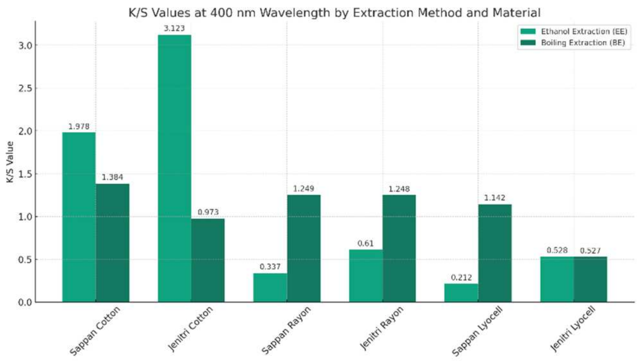


Fig. 2 K/S values at 400 nm wavelength for each material and fabric

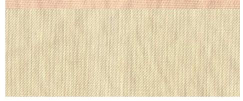
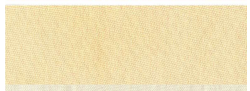
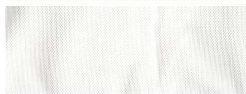
The use of the 400 nm wavelength in the analysis of the Kubelka-Munk K/S values on textiles dyed with natural dyes is a point of convergence for several studies, each contributing to an understanding of the "why" behind the importance of this wavelength. Hossain et al. [15] emphasizes the role of 400 nm in evaluating the colorimetric and UV protection properties of wool fabric dyed with natural dyes, presenting a dual aspect of aesthetic and functional benefit, where the wavelength sits at the cusp of visible and UV spectra, instrumental for assessing UV protection effectiveness in dyed fabrics. Mahmoud [16] utilized the Kubelka-Munk theory to detail the color parameters of cotton fabrics dyed with madder, revealing how K/S values at 400 nm reflect strong absorption, pivotal for analyzing natural dye characteristics. Ding et al. [17] applied non-invasive spectral imaging to historical textiles, demonstrating the 400 nm wavelength's potential in identifying natural dyes, showcasing its practicality in preserving cultural heritage . Similarly, Rahaman et al. [18] integrated spectral imaging with machine learning to classify dyes on textile fibers, underlining the precision of reflectance data at 400 nm. Meanwhile, Shimojo et al. [19] provided a different perspective by measuring absorption and scattering coefficients in human skin tissues, which, by analogy, underscores the significance of understanding how light at 400 nm interacts with natural dyes on textiles. Collectively, these studies cluster around the shared axis of the 400 nm wavelength, each underscoring its criticality in enhancing our understanding of the interaction between light and natural dyes, from both a colorimetric and functional standpoint, whether it be in terms of aesthetic appeal, protective properties, or preservation of historical artifacts.

C. Color Characteristics by CIELAB

The colorimetric analysis of the dyed fabrics reveals distinct trends in lightness (L*), red/green value (a*), and yellow/blue value (b*) across different extraction methods and material-fabric combinations. Table III shows the result of CIELAB on samples. The standard samples generally exhibit the highest lightness values, indicating they are closer to white or light shades. BE and EE methods show reduced lightness, with BE typically resulting in lower L values. This suggests darker hues are achieved with the boiling extraction method. For a* values, the BE method consistently exhibits higher a value across most material-fabric combinations, indicating a stronger red component in the color. EE also enhances the redness but to a lesser extent than boiling. Similar to the values, BE results in higher b* values, indicating a stronger yellow component in the dye. EE also shows an increase in yellow tones compared to the control, but it's less pronounced than in the boiling method. Overall, both boiling and ethanol extractions effectively impart red and yellow hues to the fabrics, with boiling extraction being more potent in both aspects. This analysis suggests that the choice of extraction method significantly impacts the color profile of the dyed fabrics, with boiling extraction offering deeper and warmer tones.

In the discussion of the impact of extraction methods on fabric dyeing, particularly focusing on the CIELAB color values, our study's results in Table III align with and expand upon findings from earlier high-impact research. The standard samples in our study generally exhibited the highest lightness values (L*), indicating a closer resemblance to white or light shades. When comparing the boiling extraction (BE) and ethanol extraction (EE) methods, BE typically resulted in lower L* values, suggesting darker hues. This is consistent with the findings of Werede et al. [20], who explored eco-friendly cotton fabric dyeing using natural dyes from *Citrus sinensis* orange peels, highlighting the influence of extraction methods on color yield and fastness properties. For the values, indicating the red component in the color, the BE method consistently showed higher values across most material-fabric combinations, a trend also observed in EE but to a lesser extent. This observation is in line with the study by Jeon and Park [21], who evaluated the color image of silk fabrics dyed with pine needle extracts using ethanol and distilled water, noting the variations in color intensity and preference based on extraction solvents and mordants . Similarly, BE resulted in higher b* values, pointing to a stronger yellow component in the dye, a pattern also seen in EE but less pronounced.

TABLE III
SAMPLE IDENTIFICATION AND DESCRIPTION

Sample Code	L*	a*	b*	ΔE*ab	Sample appearance
STD – C	97.49	-0.08	-0.38	0.00	
BE-SC	75.45	11.71	30.06	42.45	
BE-JC	89.45	0.24	18.80	23.27	
EE-SC	76.55	9.60	34.46	44.55	
EE-JC	82.44	-2.28	33.87	39.80	
STD - R	99.69	-0.16	0.36	0.00	
BE-SR	83.20	8.17	35.13	40.99	
BE-JR	87.35	-0.18	23.43	28.02	
EE-SR	85.97	3.31	32.38	37.05	
EE-JR	87.63	-3.54	19.92	25.16	
STD – L	99.26	0.16	0.17	0.00	
BE-SL	82.78	7.13	32.35	36.96	
BE-JL	94.07	-1.32	12.70	13.64	
EE-SL	93.57	2.16	30.62	31.04	
EE-JL	90.36	-2.76	19.53	21.51	

This finding echoes the research by [22] and [23] that revealed influence of dye and solvent interactions on the development of yellow hues, as indicated by higher b* values.

Oka et al [22] demonstrated that the Tb4+-doped sodium zirconate samples exhibited a vivid yellow hue with high b* values, highlighting the effectiveness of specific dopants in enhancing the yellow component of the pigment. Similarly, Ye et al. [23] explored the pigmentation behavior of Pigment Yellow 180 across various solvents and found that the solvent environment significantly influenced the chromaticity, leading to variations in the yellow hue intensity. These results collectively echo the conclusion, which observed that BE and EE treatments resulted in stronger yellow components, as evidenced by increased b* values, thereby reinforcing the impact of chemical and environmental factors on color development in dyes.

Delta E (ΔE) is a metric used to quantify the difference in perceived color between two samples. In this context, analyzing ΔE between the control samples and those treated with boiling and ethanol extractions reveals key insights into the impact of these extraction methods on the color of the dyed fabrics. The trend observed indicates that boiling extraction generally results in a more significant shift in color from the control, as evidenced by higher ΔE values across most material-fabric combinations. This suggests that boiling extraction introduces more pronounced color changes, leading to deeper and more vivid hues. Ethanol extraction, while also resulting in noticeable color shifts compared to the control, typically exhibits lower ΔE values than boiling extraction. This implies a more subtle alteration in color, retaining some of the fabric's original hues but enhancing them with the added dyes. In summary, boiling extraction is more effective at producing dramatic color transformations in the dyed fabrics, while ethanol extraction offers a more nuanced color enhancement, preserving more of the natural color characteristics of the fabrics.

Overall, both boiling and ethanol extractions effectively impart red and yellow hues to the fabrics, with boiling extraction proving more potent in both aspects. This analysis underscores that the choice of extraction method significantly impacts the color profile of the dyed fabrics, with boiling extraction offering deeper and warmer tones. These insights are crucial for optimizing dyeing processes and achieving desired color qualities in various textile applications.

D. Color Fastness of Dyed Fabrics

According to Table IV that most samples, irrespective of the extraction method (BE or EE), have shown excellent color fastness with a rating of 5. This indicates a high level of resistance to color transfer when subjected to dry rubbing.

TABLE IV
COLOR FASTNESS TEST VALUE OF FABRIC AGAINST DRY RUBBING (STAINING SCALE)

Sample code	Dry Rubbing Fastness
BE-SC	5
BE-JC	5
BE-SR	5
BE-JR	5
BE-SL	4-5
BE-JL	5
EE-SC	5
EE-JC	5
EE-SR	5
EE-JR	5
EE-SL	5
EE-JL	4-5

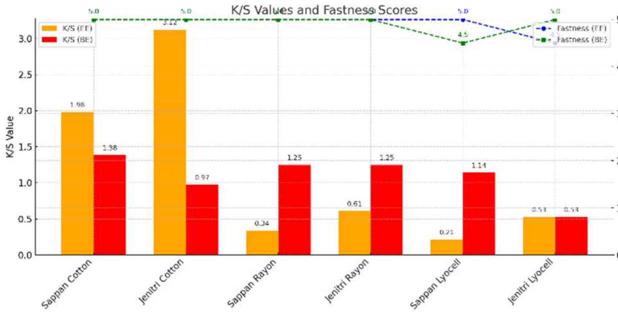


Fig. 3 Comparative chart of K/S values and fastness scores

Figure 3 illustrates the comparative analysis of K/S values and rubbing fastness scores for different fabrics under two extraction methods: Ethanol Extraction (EE) and Boiling Extraction (BE). The bar graphs represent the K/S values, highlighting the differences in dye absorption efficiency across the fabric types, while the line graphs depict the rubbing fastness scores, indicating the durability of the dyed fabrics. Jenitri Cotton showed the highest K/S value under EE (3.12), demonstrating superior dye absorption, while Sappan Lyocell exhibited the lowest value (0.21). Boiling Extraction (BE), on the other hand, enhanced the K/S values for Sappan Rayon and Sappan Lyocell, indicating its effectiveness for certain materials. The rubbing fastness scores, consistent across most samples at 4.5 to 5, confirm excellent color retention and durability under both extraction methods, with slight variability observed in Jenitri Lyocell (EE at 4.5).

In the domain of natural dyeing, the color fastness, particularly in terms of resistance to dry rubbing, is a crucial parameter for assessing the quality and durability of dyed fabrics. Our study, focusing on the color fastness of fabrics dyed using boiling extraction (BE) and ethanol extraction (EE) methods, revealed that most samples, irrespective of the extraction method, exhibited excellent color fastness with a rating of 5. This indicates a high level of resistance to color transfer when subjected to dry rubbing, a finding that aligns with several high-impact studies in the field. For instance, the research by Kiakhani et al. [8], which explored the ultrasound-assisted extraction of natural dyes from Hawthorn fruits for dyeing polyamide fabric, also reported good to excellent fastness grades, including resistance to dry rubbing . Similarly, Kundal et al. [24] studied the extraction of natural dye from *Ficus cunia* and its application on wool and polyester cotton fabrics, finding good to excellent fastness properties, including dry rubbing . These studies corroborate our findings, suggesting that both BE and EE methods can yield high color fastness in natural dyeing processes.

The use of lime juice as a mordant in our study is particularly noteworthy. Lime, being a natural source of citric acid, can function as an effective mordant, enhancing the dye uptake and potentially influencing the fastness properties. The citric acid in lime juice helps to bind the dye to the fabric fibers more effectively, which could explain the high levels of color fastness observed in our study.

Moreover, recent studies have demonstrated that the type of dyeing material used does not significantly impact the color fastness in dry rubbing across different fabric types. Guru and Rani [25] found that both lyocell and silk fabrics exhibited similar dry rubbing fastness when dyed with Tinospora cordifolia, regardless of the mordant used, indicating consistent performance across materials . Similarly, Kumpikaitė et al. [26] observed that the dry rubbing fastness of linen/silk blended fabrics remained consistent, regardless of the differences in fiber composition, suggesting that the dyeing process did not lead to significant variations . Morshed et al. [27] also reported that jute fabrics dyed with basic dyes showed consistent dry rubbing fastness across different dye concentrations and temperatures, further supporting the conclusion that dyeing materials do not significantly affect dry rubbing color fastness across various fabric types . This further supports our observation that the dyeing material (Sappan or Jenitri) does not significantly affect the color fastness in dry rubbing, as both materials performed similarly across different fabric types.

A deeper analysis of the ethanol extraction and boiling methods reveals distinct molecular interactions that influence the dyeing process. Ethanol, as a polar solvent with moderate hydrogen-bonding capabilities, plays a crucial role in the selective extraction of dye molecules from plant materials. At the molecular level, ethanol disrupts hydrogen bonds and other non-covalent interactions within the plant matrix, facilitating the release of dye molecules. Its lower polarity compared to water allows ethanol to solvate both polar and non-polar compounds, which can result in the extraction of a more diverse range of dye molecules. This selective extraction is particularly relevant for dye molecules with hydrophobic or slightly hydrophilic groups, leading to a higher concentration of specific dye molecules that contribute to increased color strength (K/S values) and better chromaticity in dyed fabrics [28]. Additionally, ethanol's ability to dissolve a broader spectrum of dye molecules may enhance the binding affinity of these dyes to the textile fibers, particularly those with hydrophobic regions, resulting in more uniform dye distribution and stronger color fixation, which can improve fastness properties [29].

In contrast, the boiling extraction method, which typically involves water as a solvent, operates at elevated temperatures that promote the breakdown of plant cell walls and facilitate the release of dye molecules into the solution. At the molecular level, the high temperature of boiling water increases the kinetic energy of the molecules, enhancing the diffusion of dye molecules out of the plant matrix [30]. However, water's strong hydrogen-bonding network may limit the solubility of less polar compounds, potentially resulting in a narrower range of dye molecules being extracted compared to ethanol. Additionally, the thermal energy provided by boiling may lead to the degradation of certain thermolabile dye components, reducing the overall color yield and affecting the fastness properties of the dyed fabrics. The interaction mechanisms between dyes and textile fibers during the dyeing process differ significantly depending on the extraction method. While the boiling method effectively extracts hydrophilic dyes, it may not achieve the same level of interaction with textile fibers, especially for dyes that are hydrophobic. The high temperature involved in boiling may also result in less stable dye-fiber interactions due to thermal agitation. These molecular insights emphasize that ethanol extraction, with its broader solubilizing capabilities, is likely to provide enhanced color strength and fastness properties compared to the boiling method, making it a more effective choice for achieving desired coloristic properties in dyed textiles. Integrating these findings into the analysis strengthens comparative study, offering a deeper understanding of how different extraction methods influence the final quality and sustainability of the dyeing process.

The findings of this study have significant practical implications for industrial scalability and specific textile applications, particularly in the context of sustainable dyeing processes. The enhanced color strength (K/S values) and improved fastness properties observed with ethanol extraction highlight its potential as a superior alternative to traditional boiling methods, especially for industries aiming to optimize resource use while achieving vibrant and durable colors. Ethanol extraction's ability to solvate a broader range of dye molecules ensures better dye uptake and uniformity, making it highly suitable for fabrics like cotton and lyocell, commonly used in high-value textile products such as fashion apparel and home textiles. Furthermore, the use of lime as an eco-friendly mordant not only improves color fixation but also aligns with industrial goals of reducing environmental impact, making the method compliant with increasing regulatory pressures for sustainable production. By demonstrating the efficiency and reproducibility of these methods across different fabric types and dye sources, this study provides a scalable framework for industries to adopt eco-friendly dyeing practices without compromising on quality, supporting a shift towards greener and more sustainable textile manufacturing.

While ethanol maceration demonstrates superior color strength and fastness properties compared to boiling extraction, it is essential to address potential drawbacks to provide a balanced perspective. The cost of ethanol as a solvent can be higher than water, particularly for large-scale applications, posing a challenge for industries with tight budget constraints. Additionally, the need for efficient solvent recovery systems to minimize waste and environmental impact adds complexity and cost to the process. Implementing solvent recovery systems, though necessary for sustainability, requires initial investment and ongoing maintenance, which could deter adoption by small and medium-sized enterprises. These challenges underscore the importance of further optimization and cost-benefit analyses to ensure the economic feasibility of ethanol maceration for industrial-scale operations.

In summary, our study, along with these high-impact research works, highlights those fabrics dyed using both boiling and ethanol extraction methods, and treated with lime juice as a mordant, generally exhibit excellent color fastness in dry rubbing conditions. This finding is significant for textile applications where color durability and eco-friendly dyeing processes are prioritized.

IV. Conclusion

In this detailed investigation, we examined the effects of different extraction methods - boiling extraction (BE) and ethanol extraction (EE) - and the role of lime as a mordant in both pre- and post-mordanting stages, on the dyeing properties of fabrics using Sappan and Jenitri dyes. Our analysis spanned several parameters: reflectance (R%), color strength (K/S), CIELAB color space values, color difference (ΔE) and dry rubbing fastness, across various fabric types including cotton, rayon, and lyocell. The findings revealed notable differences between the BE and EE methods. Ethanol extraction generally exhibited higher color strength, as evidenced by the K/S values at 400 nm. This suggests more efficient dye uptake or better dye-fabric interaction when using the EE method. The incorporation of lime as a mordant, both in pre- and post-mordanting stages, was found to significantly enhance the color depth and fixation on the fabrics, which was evident in the enriched color profiles and improved fastness properties. In terms of colorimetric analysis, the L* (lightness), a* (red-green), and b* (yellow-blue) values showcased the distinctive hues imparted by the Sappan and Jenitri dyes, with variations influenced by the extraction method and the use of lime as a mordant. The color differences (ΔE) observed between the samples further emphasized the impact of these variables on the final appearance of the dyed fabrics. Crucially, our study demonstrated outstanding color fastness in dry rubbing tests for all fabric types and treatments, most achieving a rating of 5. This highlights the durability and resilience of the colors, which is essential for practical textile applications. In conclusion, this comprehensive analysis underscores the significant influence of extraction techniques and mordanting with lime on the dyeing characteristics of natural dyes. Our findings suggest that ethanol extraction, coupled with strategic use of lime as a mordant, can effectively enhance color depth, fastness, and overall quality of dyed fabrics. This study contributes valuable insights into the sustainable use of natural dyes in textiles, supporting the industry's shift towards more environmentally friendly and sustainable practices. The use of natural dyes, such as Sappan and Jenitri, in conjunction with eco-friendly mordants like lime, represents a promising avenue for developing sustainable and vibrant textile products.

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