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Analysis of the Effect of Fixators and pH Conditions on the Color Absorption of Cotton with Natural Teak Leaf Dyes (*Tectona grandis Linn. f.*)

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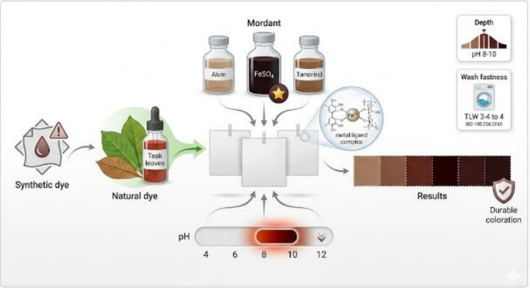
ABSTRACT



Growing concern about the environmental impacts of synthetic dyes has renewed interest in plant-based colorants for sustainable textile dyeing. Teak leaves (Tectona grandis Linn. f.) are rich in polyphenolic compounds with strong chromophoric properties, but the influence of fixation conditions and dye-bath pH on fabric performance requires further clarification. This study evaluated the effects of mordant type and dye-bath pH on color intensity and washing fastness of cotton fabrics dyed with teak leaf extract. Cotton samples were dyed at pH 4, 6, 8, 10, and 12, then post-mordanted using alum, ferrous sulfate, or tamarind extract. Color characteristics were quantified using the CIE Lab* system, and washing fastness was assessed following SNI ISO 105-C06:2010. Ferrous sulfate consistently produced the darkest shades and the highest washing fastness ratings (TLW 3–4 to 4), likely due to stable metal ligand complex formation among Fe^{2+} ions, dye molecules, and cellulose fibers. Mildly alkaline dye baths (pH 8–10) enhanced color depth, whereas extreme alkalinity (pH 12) decreased dye uptake, presumably because stronger electrostatic repulsion limited adsorption. Overall, teak leaf extract shows strong potential as an eco-friendly natural dye, and the results emphasize that careful mordant selection and pH optimization are essential to achieve durable coloration for sustainable textile processing.

Keywords: *Mordan; cotton fabric; teak leaves; pH; natural dye.*

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INTRODUCTION

Synthetic dyes have long dominated the global textile industry because they provide strong color intensity, broad chromatic range, high stability, and excellent fastness on many fiber types. Large scale dyeing and finishing activities have also become a major driver of environmental degradation linked to industrial effluents. Textile dyeing and finishing processes contribute up to 20% of global industrial water pollution, and approximately 200,000 tons of synthetic dyes are released into aquatic ecosystems each year [1]. Many synthetic dyes persist in the environment because their molecular structures resist biodegradation and remain stable under natural conditions. Aromatic amines and heavy metals present in some dye formulations further elevate ecological and human health risks [2]. Environmental pressure and regulatory concerns have therefore intensified efforts to reduce synthetic dye pollution and seek safer alternatives.

Natural plant derived dyes have gained renewed attention as sustainable substitutes because they are generally biodegradable, less toxic, and associated with lower environmental impact than many synthetic dyes [3]. Natural colorants can be extracted from leaves, roots, bark, flowers, and fruits, which enables diverse chromophore sources and local resource utilization. Application of natural dyes, however, often faces technical limitations that reduce industrial adoption. Low dye to fiber affinity, weaker color strength, and poor wash fastness are common challenges, especially on cellulose based fibers such as cotton [4]. Improvement of dye uptake and durability frequently requires additional chemical assistance during dyeing. Mordanting remains a key strategy to enhance fixation by promoting stronger interactions between dye molecules and fiber surfaces [5], [6].

Mordants improve dye performance by forming coordination bonds that stabilize the dye fiber complex and strengthen shade durability. Metal salt mordants such as alum ($KAl(SO_4)_2 \cdot 12H_2O$) and iron salts ($FeSO_4$, $FeCl_3$) remain widely used because they can increase color depth and improve fastness. Concerns about the environmental burden of some metal salts have also driven exploration of greener mordanting approaches. Bio mordants derived from tannin rich plant extracts, including pomegranate rind, oak galls, and tamarind, have emerged as promising alternatives with lower toxicity and improved sustainability profiles [6]. Tannin based systems can contribute functional groups that interact with both dye molecules and fibers, supporting fixation without heavy metal dependence. Selection of an appropriate mordant therefore becomes essential for balancing performance, safety, and sustainability in natural dyeing processes.

Teak leaves (Tectona grandis Linn. f.) represent one of the natural dye sources receiving increasing research attention because they contain diverse phenolic compounds with strong chromophoric properties [7]. Traditional applications have used teak leaves to produce reddish brown shades, indicating their practical dyeing potential. Recent studies have supported teak leaf extract as a viable dye for cotton, wool, and silk fabrics under various dyeing conditions [8]. Flavonoids, anthraquinones, tannins, and related phenolics contribute to the extract color profile and its interaction behavior with textile substrates [7]. Major components such as tectochrysin, luteolin derivatives, and naphthoquinones provide reactive sites that can support stronger binding on cellulose when mordants are present [9]. Teak leaf dye therefore offers a relevant model for investigating how process variables control shade formation and fixation outcomes.

Dye bath pH strongly influences natural dyeing by affecting dye solubility, ionization, fiber swelling and penetration, and chromophore stability [10], [11]. Plant based dyes often show different shades across acidic, neutral, and alkaline conditions because phenolic groups undergo structural changes that modify light absorption [12]. Teak leaf extract contains pH sensitive polyphenols, where moderate alkalinity can improve dye uptake through enhanced dissociation, while very high alkalinity can trigger dye degradation or electrostatic repulsion that reduces fixation and shade stability [11], [12]. pH control is therefore essential for achieving reproducible color depth and durable fastness in teak leaf dyeing.

Current literature rarely examines the combined influence of mordant type and dye bath pH on teak leaf dye performance, even though both variables strongly affect fixation and shade stability. Many studies focus only on mordant effects, which limits interpretation of how mordanting interacts with dye ionization states [13], [16]. Other studies emphasize pH effects without systematically comparing different mordant systems under equivalent dyeing conditions [14]. Reviews on natural dye chemistry highlight the need for integrated investigations that evaluate mordant selection and pH control simultaneously to improve reproducibility and strengthen mechanistic understanding [15]. Limited use of standardized washing fastness protocols such as ISO 105 C06 also reduces comparability across teak leaf dye studies [8].

This study investigates the combined effects of fixators and dye bath pH on color absorption and washing fastness of cotton dyed with teak leaf extract. Alum, ferrous sulfate, and tamarind extract are evaluated as fixators, while pH is adjusted to 4, 6, 8, 10, and 12. Characterization includes phytochemical screening, UV Vis spectroscopy, ATR FTIR, SEM, and CIE Lab colorimetric analysis to link composition, bonding, surface morphology, and color outcomes. Novelty lies in a controlled integrated framework that tests mordant type and pH variation together for teak leaf dyeing. Outcomes are expected to identify conditions that maximize color depth and durability while supporting sustainable textile coloration aligned with green chemistry priorities [19], [20].

METHODS

1. Materials

Teak leaves (*Tectona grandis* Linn. f.) were used as the natural dye source, while bleached plain-woven cotton fabric served as the dye substrate. Teak leaves were selected due to their high content of flavonoids, tannins, and related polyphenolic compounds known for their chromophoric properties [7], [9]. Reagents used in this study included 1 M acetic acid, 1 M sodium hydroxide, alum ($KAl(SO_4)_2 \cdot 12H_2O$), ferrous sulfate ($FeSO_4 \cdot 7H_2O$), and tamarind extract prepared from dried tamarind pulp. ECE detergent was used for washing fastness testing according to the SNI ISO 105-C06:2010 standard. Instruments included a digital pH meter, digital colorimeter (CIE Lab*), UV–Vis spectrophotometer, ATR–FTIR spectrometer, SEM microscope, and SPSS software for statistical analysis.

2. Dye Extraction Procedure

Freshly collected teak leaves were washed, cut into small pieces, and boiled in distilled water at a leaf-to-water ratio of 1:20

(50 g in 1000 mL) for 45 minutes. This method follows recommended extraction procedures for polyphenolic dyes to maximize chromophore release while preventing thermal degradation [3], [5]. The extract was filtered through muslin cloth and Whatman No. 1 paper, producing a clear dye solution. The dye extract was stored at 4°C until further use.

3. Preparation of Dye Bath (pH Adjustment)

Teak leaf extract was adjusted to pH 4, 6, 8, 10, and 12 using 1 M acetic acid and 1 M sodium hydroxide to examine the role of dye bath chemistry. A digital pH meter calibrated with standard buffer solutions at pH 4, 7, and 10 was used to verify measurement accuracy. Dye bath pH adjustment is essential because phenolic chromophores undergo ionization changes that alter solubility, molecular structure, and fiber affinity [10], [11].

4. Mordant Preparation

Three mordants were used: alum (10% w/v), ferrous sulfate (5% w/v), and tamarind extract prepared by steeping 30 g of dried tamarind pulp in 300 mL of hot water (1:10 w/v). The solutions were filtered to remove insoluble residues. Metal mordants such as alum and iron salts increase dye-fiber interactions through coordination bonding [5], [16], while tamarind extract serves as an eco-friendly natural bio-mordant rich in organic acids and tannins [6].

5. Dyeing Procedure

Cotton fabric samples (5 × 5 cm; ±1 g) were immersed in 100 mL of teak leaf extract at the designated pH levels and dyed at 90°C for 45 minutes under continuous stirring to ensure uniform penetration. Dyed fabrics were rinsed under running water and gently pressed to remove excess liquid, then post mordanted by immersion in each mordant solution at 60°C for 20 minutes using a liquor ratio of 1:20 (fabric:solution, w/v). Samples were rinsed again and dried at room temperature, following a sequential post mordanting procedure commonly applied in natural dyeing of cellulose fibers to improve color fixation [3], [17].

6. Colorimetric Analysis

Color measurements were performed using a calibrated digital colorimeter operating under the CIE L*ab** color system. A standard white tile was used for instrument calibration. Three readings were taken at different points on each fabric sample, and mean values of L*, a*, and b* were recorded. Colorimetric evaluation provides quantitative insight into shade depth, hue variation, and chromatic differences among treatments [8], [15].

7. Washing Fastness Testing

Washing fastness was assessed according to SNI ISO 105-C06:2010, using 4 g/L ECE detergent. Fabric specimens were washed at 40°C for 30 minutes, rinsed, dried, and evaluated using grayscale ratings for color change and staining. This procedure provides standardized performance assessment for natural dyes under laundering conditions.

8. Phytochemical Screening

Qualitative phytochemical screening was conducted to identify the presence of flavonoids, tannins, and other polyphenolic constituents within the teak leaf extract. These compounds play key roles in dye behavior, shade development, and mordant interaction [7], [9].

9. UV–Vis Spectroscopy

UV–Vis analysis was performed on the dye extract within the 200–800 nm wavelength range to observe absorbance characteristics and pH-dependent spectral shifts. Such measurements elucidate chromophore stability, electron delocalization, and bathochromic or hypsochromic effects associated with dye-bath conditions.

10.ATR–FTIR Spectroscopy

ATR–FTIR spectroscopy was carried out in the 400–4000 cm^{-1} region to analyze chemical interactions between dye molecules and cellulose fibers. Specific attention was given to O–H stretching, aromatic C=C vibrations, and shifts indicative of hydrogen bonding or metal–ligand coordination involving mordants [15], [17].

11.Scanning Electron Microscopy (SEM)

SEM imaging was performed at 10 kV to examine morphological changes on the cotton fiber surface before and after dyeing and mordanting. SEM analysis provides visual confirmation of dye particle deposition, surface roughening, and potential structural alterations induced by the dyeing process [18].

12.Statistical Analysis

Quantitative results, including L*, a*, b* values and washing fastness ratings, were analyzed using two-way ANOVA to evaluate the effects of pH and mordant type. Tukey HSD post hoc testing was applied when results were significant ($p < 0.05$), using SPSS version 25, consistent with common practice in natural dyeing studies [6], [11]. Ethical approval was not required because the study involved no human or animal subjects.

RESULT AND DISCUSSION

This study utilized young teak leaves (*Tectona grandis* Linn. f) as a natural dye for cotton fabric. The research was carried out through three main stages: (i) the preparation stage, (ii) the optimization stage, and (iii) the characterization stage. The focus of this research was to evaluate the color fastness to washing under different dye bath pH variations and mordant types in a single dyeing process.

1. Phytochemical Analysis

Phytochemical screening of the teak leaf extract was conducted as a preliminary test to identify the presence of secondary metabolites. The tests performed included flavonoid and tannin identification. The results of the phytochemical screening are presented in Table 1.

Table 1. Phytochemical Screening Results of Teak Leaf Extract (*Tectona grandis L.f*) Extract

Phytochemical Test	Reagent used	Color change	Result
Flavonoids	Concentrated HCl + Mg Powder	Orange-red	(+)
Tannins	1% $FeCl_3$ Solution	Greenish-black	(+)

2. Phytochemical and UV–Visible Spectral Analysis of Teak Leaf Extract

The flavonoid test of the teak leaf extract was performed by mixing 1 mL of extract with 0.1 g of magnesium powder followed by the addition of 2–3 drops of concentrated HCl. The appearance of an orange to reddish coloration indicated the presence of flavonoid compounds. The resulting orange-red color confirmed that the teak leaf extract contained flavonoids of the flavone type. The presence of tannins in the teak leaf extract was identified using a 1% $FeCl_3$ solution. The formation of a greenish-black or dark blue color after adding $FeCl_3$ indicated a positive result for tannins [14]. When the teak leaf extract, prepared using distilled water as a solvent, was treated with 1% $FeCl_3$, a greenish-black color was observed. This color change confirmed that the extract contains tannin compounds.

3. Qualitative Analysis Using UV–Visible Spectrophotometry

UV–Visible spectrophotometry was employed to qualitatively analyze the teak leaf extract and identify the chromophoric groups present. The diluted extract (100× dilution) was scanned over a wavelength range of 220–600 nm. The teak leaf extract exhibited two characteristic absorption maxima (λ_{max}) at 274 nm (band II) and 335 nm (band I). These absorption bands correspond to the spectral characteristics of flavonoid compounds, specifically the flavone class [20].

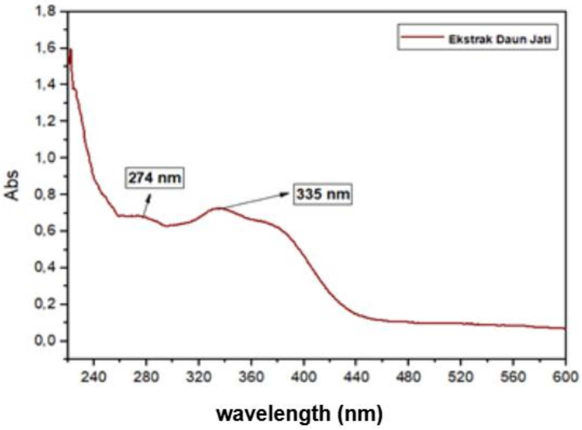


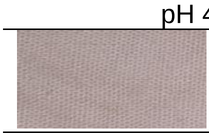
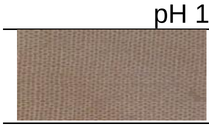
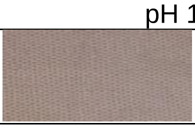
Figure 1. UV Visible Spectrum of Teak Leaf (*Tectona grandis L.f*) Extract

The spectrum in Figure 1 reveals that absorption around 250–280 nm is associated with π → π* electronic transitions, typically arising from conjugated C=C double bonds in aromatic rings. The second absorption band observed between 260–350 nm is attributed to n → π* transitions, representing the presence of C=O chromophoric groups. The presence of these characteristic absorption peaks confirms that the teak leaf extract contains conjugated systems and chromophores typical of flavonoid structures, supporting the results obtained from the phytochemical analysis.

4. Optimization Results and Fixation Analysis

Optimization of the dyeing and fixation process was carried out by cutting the fabric into 20 pieces, each measuring 20 cm × 20 cm. The fabrics were immersed in the dye bath at 70 °C for 90 minutes [17]. The high-temperature dyeing process aimed to enhance the diffusion of dye molecules from teak leaf extract into the fibers, as the fibers undergo swelling and the dye molecules in the solution dissociate into larger particles [21]. Cotton fabrics were dyed using teak leaf extract under various pH conditions acidic (pH 4 and 6) and basic (pH 8, 10, and 12) with one repetition for each treatment. The results of the dyeing process and the CIE Lab color analysis, conducted using the ColorGrab application on an OPPO A5 2020 device, are presented in Table 2.

Table 2. Dyeing Results and CIE Lab Analysis

pH 4		pH 6		pH 8	
	L^* = 68,5 a^* = 6,4 b^* = 2,9		L^* = 61,4 a^* = 4,4 b^* = 8,1		L^* = 56,9 a^* = 4,9 b^* = 11,4
pH 10		pH 12			
	L^* = 58,1 a^* = 5,6 b^* = 7,5		L^* = 64,1 a^* = 5,2 b^* = 3,1		

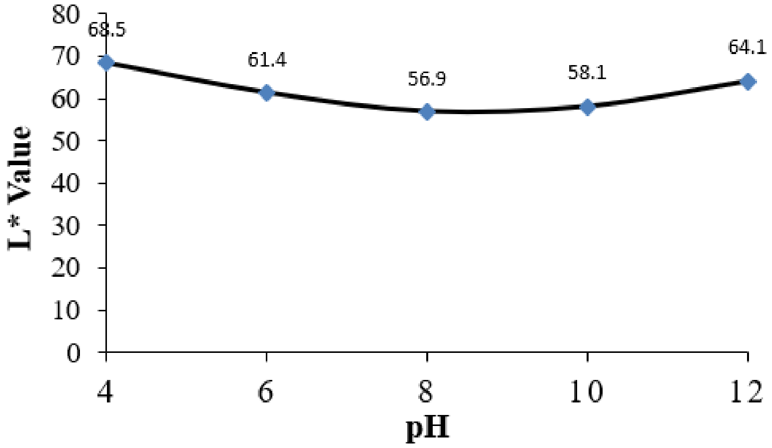


Figure 2. Effect of pH on L* Value of Dyed Cotton Fabric

The results of cotton dyeing with teak leaf extract showed that dye bath pH significantly influenced color depth, as reflected by L* values. Higher L* indicates lighter shades and lower L* indicates darker shades. Dyeing at pH 4, 10, and 12 produced lighter colors with L* values of 68.5, 58.5, and 64.1, while pH 6 and 8 produced darker shades with L* values of 61.4 and 56.9. Figure 2 presents the relationship between dye bath pH and L* values.

Figure 2 shows that lower L* values correspond to reduced fabric brightness and therefore darker shades. Color depth increased as dye bath pH rose from 4 to 10, while a slight decrease in intensity appeared at pH 12. Dyeing at pH 4 produced a noticeably lighter shade than dyeing at pH 6, 8, 10, and 12. Mamun et al, [23] reported that pH strongly influences color depth in natural dyeing, with alkaline conditions (pH 8 to 10) generally producing darker shades due to stronger dye fiber interactions, while acidic conditions (pH 4 to 6) tend to yield lighter shades. A decline in color depth at very high alkalinity is also consistent with the explanation of Tayade and Adivarekar [22]. Deprotonation of dye molecules above pH 9 increases the number of negatively charged O^- groups, which enhances the negative charge on cellulose fibers and promotes electrostatic repulsion, thereby reducing dye absorption.

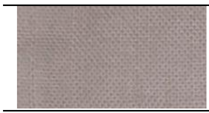
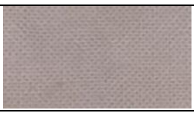
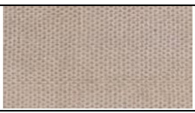
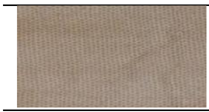
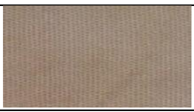
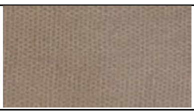
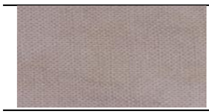
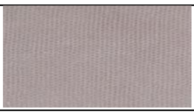
5. Fixation Results

Following the dyeing process, post-mordanting (fixation) was carried out to improve the color fastness and bonding of the dye molecules to the cotton fibers. The mordants used were alum ($KAl(SO_4)_2$), tamarind extract, and ferrous sulfate ($FeSO_4$). Fixation was performed by immersing the dyed fabric in a mordant solution with a concentration of 5 g/L at room temperature for 60 minutes [18]. The appearance of the cotton fabrics after fixation and the corresponding CIE Lab color analysis are presented in Table 3.

Table 3 shows that dyed cotton fabrics treated with different mordants alum, ferrous sulfate (tunjung), and tamarind extract displayed different color brightness (L*) across pH conditions. Lower L* values indicate darker shades, while higher L* values indicate lighter tones. Alum mordanting produced relatively lighter shades, with L* values ranging from 57.2 to 62.5. This trend may relate to alum forming strong interactions with dye molecules but weaker interactions with the cotton fiber, which can limit effective dye fixation at the fabric surface and increase the likelihood of fading [23]. Tamarind extract produced even higher L* values, ranging from 58 to 66, compared with other mordants and the unmordanted sample. Increased brightness under tamarind treatment may result from H^+ released by citric and tartaric acids, which lowers the dye bath pH and shifts coloration toward lighter tones [10].

Ferrous sulfate (tunjung) produced darker shades, reflected by lower L* values between 54 and 60, suggesting greater dye uptake and stronger fixation. Ferrous sulfate can form coordination complexes with dye molecules due to its ability to provide multiple coordination sites. Coordination sites that remain available after dye binding can interact with hydroxyl (OH) groups in cellulose, enabling ternary complex formation among mordant, dye, and fiber [23]. This coordination mechanism strengthens dye fiber bonding and supports deeper, more intense coloration.

Table 3. The Results of Cotton Fabric Dyeing After Fixation

Cotton + Teak Leaf Extract (pH 4)					
Alum		Tamarind		Ferrous Sulfate	
	L^* = 65,1 a^* = 4,6 b^* = 3,4		L^* = 66,6 a^* = 4,4 b^* = 3,9		L^* = 60,0 a^* = 3,4 b^* = 11,9
Cotton + Teak Leaf Extract (pH 6)					
Alum		Tamarind		Ferrous Sulfate	
	L^* = 62,5 a^* = 4,7 b^* = 5,9		L^* = 58,0 a^* = 5,0 b^* = 9,6		L^* = 58,2 a^* = -0,1 b^* = 14,9
Cotton + Teak Leaf Extract (pH 8)					
Alum		Tamarind		Ferrous Sulfate	
	L^* = 59,7 a^* = 3,7 b^* = 10,9		L^* = 61,4 a^* = 4,7 b^* = 8,8		L^* = 57,1 a^* = 0 b^* = 6,2
Cotton + Teak Leaf Extract (pH 10)					
Alum		Tamarind		Ferrous Sulfate	
	L^* = 61,7 a^* = 4,2 b^* = 7,5		L^* = 60,9 a^* = 4,2 b^* = 7,5		L^* = 54,2 a^* = 1,5 b^* = 14,4
Cotton + Teak Leaf Extract (pH 12)					
Alum		Tamarind		Ferrous Sulfate	
	L^* = 57,2 a^* = 10,9 b^* = 7,2		L^* = 63,2 a^* = 4,4 b^* = 4		L^* = 54,0 a^* = 1,9 b^* = 16,4

6. Characterization of Teak Leaf Extract and Dyed Cotton Fabric

The teak leaf extract was qualitatively analyzed using Fourier Transform Infrared (FTIR) spectroscopy to identify the functional groups present. The FTIR spectrum was recorded in the wavenumber range of 4000–600 cm⁻¹, as shown in Figure 3.

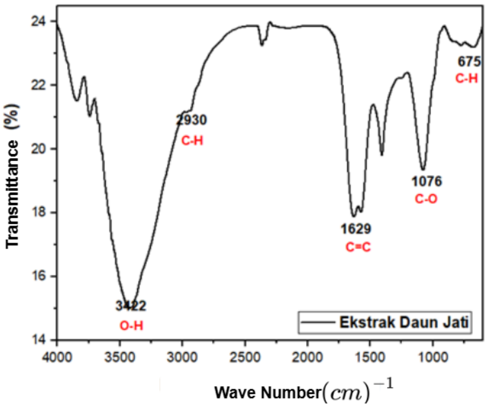


Figure 3. FTIR Spectrum of Teak Leaf Extract

Figure 3 shows an absorption band at 3422 cm⁻¹, which corresponds to O–H stretching vibrations of hydroxyl groups and is characteristic of flavonoid compounds that contribute to chromophore activity and color binding sites [24]. Two distinct peaks at 1629 cm⁻¹ and 1574 cm⁻¹ indicate aromatic C=C stretching vibrations [25]. A strong band at 1076 cm⁻¹ represents C–O stretching vibrations associated with alcohol groups [26]. These spectra confirm that teak leaf extract contains dominant functional groups O–H, C=C, and C–O, consistent with polyphenolic constituents such as flavonoids and tannins that support natural dyeing performance.

7. ATR-FTIR Characterization of Cotton Fabric

The ATR-FTIR characterization was conducted to identify the functional groups present in the cotton fabric before and after the dyeing process using teak leaf extract within the wavenumber range of 4000–600 cm⁻¹. The spectra of untreated, pre-mordanted, and dyed cotton fabrics are shown in Figure 4.

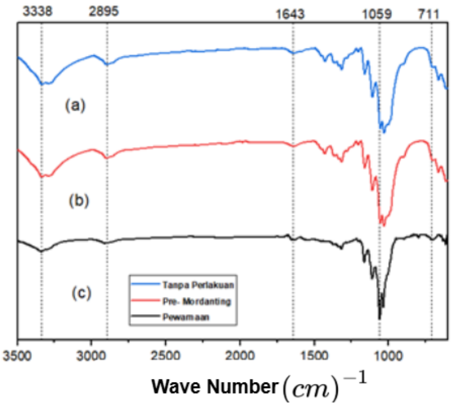


Figure 4. ATR-FTIR Spectra of Cotton Fabric: (a) Untreated; (b) Pre-mordanted; (c) Dyed with Teak Leaf Extract

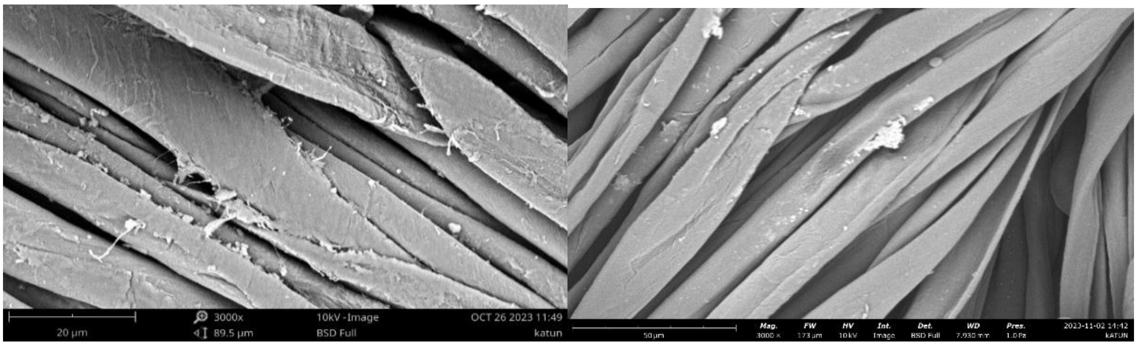
The ATR FTIR spectrum of untreated cotton showed six major absorption peaks at 3333, 2897, 1637, 1314, 1107, and 1028 cm⁻¹. The broad band at 3333 cm⁻¹ corresponds to O–H stretching vibrations of cellulose hydroxyl groups. The absorption at 2897 cm⁻¹ indicates C–H stretching, supported by CH_2 bending at 1314 cm⁻¹. The peak at 1637 cm⁻¹ is attributed to H–O–H bending of bound water, while the strong band at 1028 cm⁻¹ represents C–O stretching of alcohol groups in cellulose. This set of peaks confirms the typical absorption profile of cellulose based cotton fibers.

The pre mordanted cotton fabric exhibited a very similar profile, with bands at 3334, 2898, 1639, 1314, 1107, and 1029 cm⁻¹. The O–H and C–H stretching bands remained dominant, indicating preservation of the cellulose functional groups. The sharp C–O stretching peak also persisted with only a slight shift compared with the untreated sample. Similarity between spectra suggests that mordanting did not significantly modify the cellulose backbone and primarily involved limited surface level interactions. Minor shifts can reflect weak bonding or adsorption at the fiber surface rather than structural transformation of cellulose.

The dyed cotton fabric showed clearer spectral changes after treatment with teak leaf extract, with peaks at 3341, 2899, 1643, 1315, 1108, and 1058 cm⁻¹. The O–H stretching band shifted to 3341 cm⁻¹, indicating contributions from both cellulose hydroxyl groups and phenolic hydroxyl groups from teak leaf polyphenols. The band at 1643 cm⁻¹ suggests the presence of aromatic C=C or carbonyl C=O stretching associated with flavonoid structures. The C–O stretching region shifted to 1058 cm⁻¹, consistent with additional alcohol or ether functionalities from the dye components. Shifts and new spectral features support the formation of new interactions between dye molecules and cellulose, most plausibly through hydrogen bonding between hydroxyl rich structures. The results indicate effective adsorption and retention of teak leaf dye constituents on cotton, supporting its potential as an eco friendly natural dye source.

8. SEM Analysis of Cotton Fabric

SEM micrographs in Figure 4 and Figure 5 show clear morphological differences in cotton fibers before and after dyeing. Cotton fibers before dyeing display a smooth and clean surface with distinct natural convolutions. Surface features indicate that the cellulose structure remains intact and free of visible surface deposits. Fiber contours appear well defined and relatively uniform, suggesting minimal external coating. The micrographs also show larger inter fiber spacing that reflects the original fiber arrangement. These characteristics represent the typical morphology of untreated cotton.



(a) (b)

Figure 5. SEM Images of Cotton Fabric: (A) Before Dyeing, (B) After Dyeing (3000×)

Cotton fibers after dyeing exhibit marked surface modification, as shown in Figure 4 and Figure 5. Fiber surfaces appear rougher with fine particles and irregular deposits distributed along the outer layer. Surface deposits indicate that dye components adhered to and interacted with cellulose during dyeing. Relatively uniform coverage suggests effective penetration and fixation across the fiber surface. Different interaction mechanisms can contribute to the observed coating, including pigment adsorption for natural dyes and hydrogen bonding or van der Waals interactions for direct dyes, while reactive dyes may involve covalent attachment. These SEM observations support successful dye uptake by cotton, reflected by increased surface roughness, reduced inter fiber spacing, and the appearance of dye related deposits absent in the untreated sample.

9. Color Fastness to washing test

The color fastness to washing was evaluated according to SNI ISO 105-C6:2010. The test results for dyed cotton fabrics, both with and without fixatives at pH 4,6,8,10,and 12 are presented in Table 4. The color fastness of cotton fabrics dyed with teak leaf extract was evaluated according to SNI ISO 105-C6:2010. The results (Table 4) indicate that the degree of color fastness varies with pH and the type of mordant used. Fabrics without mordant (control) showed moderate fastness at acidic pH (3–4 at pH 4) but poor resistance under alkaline conditions. Fabrics treated with alum (tawas) exhibited good fastness at pH 4 (rating 4) but declined significantly at higher pH levels. The tamarind (asam jawa) mordant produced good results at pH 10 (rating 4), suggesting improved dye fixation in mildly basic conditions. Meanwhile, ferrous sulphate (tunjung) provided the best overall performance, maintaining good fastness (ratings 3-4 to 4) across most pH levels, indicating strong dye–fiber bonding through metal–ligand complex formation.

Table 4. Result of color fastness to washing test

pH	Type of Mordant	Color Fastness Rating	Description
4	Control	3–4	Fairly Good
6		2–3	Poor
8		1–2	Bad
10		1–2	Bad
12		3	Fair
4	Alum	4	Good
6		3–4	Fairly Good
8		1–2	Bad
10		1–2	Bad
12		1–2	Bad
4	Tamarind	3	Fair
6		1–2	Bad
8		1–2	Bad
10		4	Good
12		2	Poor
4	Ferrous Sulphate	4	Good
6		3–4	Fairly Good
8		4	Good
10		1–2	Bad
12		4	Good

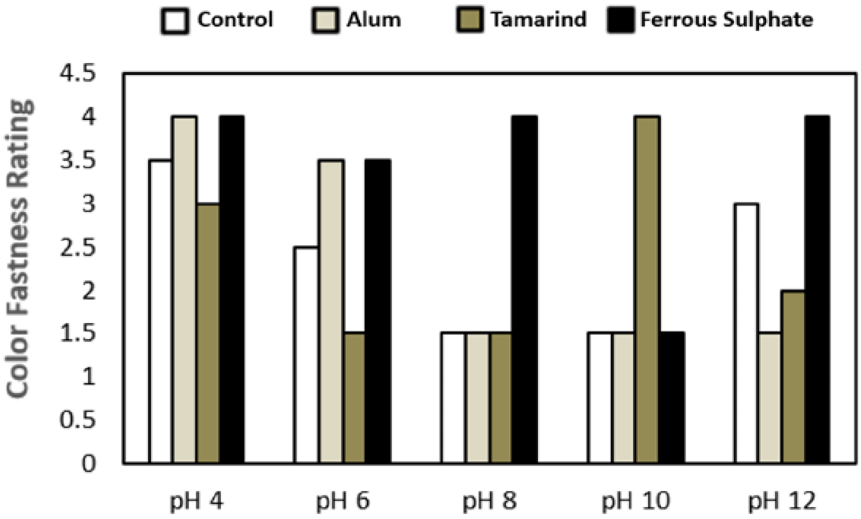


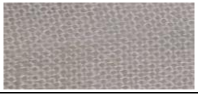
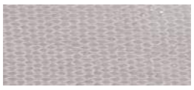
Figure 6. Effect of Mordant Type and pH Variation on Color Fastness

Figure 6 shows that cotton fabrics mordanted with ferrous sulphate (tunjung) exhibited the best color fastness at pH 4, 6, 8, and 12, while alum mordant resulted in poor fastness at pH 8, 10, and 12. Based on the analysis, the order of color fastness from best to worst was tunjung > tamarind > without mordant > alum, consistent with the findings of Hudu et al [27]. However, a slight deviation was observed in this study, as tamarind produced poorer fastness than alum, possibly due to the unstable nature of natural dyes, low pigment concentration, or uneven fabric mordanting during testing. Among the pH variations, fabrics dyed with acidic dye solutions (pH 4) demonstrated better fastness compared to those dyed under alkaline conditions [28].

10. Color Difference Test

Color stability after the washing fastness test was evaluated using color difference (ΔE) analysis. Color changes after washing can occur due to partial desorption of dye components from the fiber and chemical changes in chromophore groups. Ionization or decomposition of hydroxyl (O–H) and carbonyl (C=O) groups in the dye molecules can alter chromophore structure and reduce shade intensity, contributing to measurable color variation after laundering [29]. CIE Lab* coordinates were used to quantify color before and after washing, while ΔE represents the overall magnitude of the color difference. Visual results of the color difference evaluation are presented in Table 5 and Table 6.

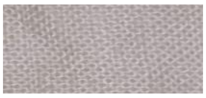
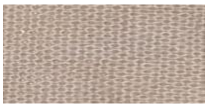
Table 5. CIE-Lab Values of cotton fabric (Without Mordant) After Testing

Cotton Fabric + Teak Leaf Extract					
pH 4		pH 6		pH 8	
	L^* =68,7 a^* = 4,3 b^* = 1,6		L^* = 69,3 a^* = 3,4 b^* = 1,8		L^* = 72,6 a^* = 3,4 b^* = 0,6
pH 10		pH 12			
	L^* =69,3 a^* = 3,4 b^* = 1,8		L^* = 65,1 a^* = 4,8 b^* = 1,7		

Visually, Table 5 shows clear differences in fabric color before and after washing. Cotton fabrics that were not subjected to mordanting exhibited high L* values after washing, indicating a shift toward lighter shades. The highest L* value was observed at pH 8, whereas the lowest L* value occurred at pH 12.

Table 6, shows that fabrics treated with different mordants exhibited varying brightness levels (L*) after the washing test. Fabrics dyed at pH 4 through pH 12 and mordanted with tamarind extract consistently showed the highest L* values, indicating lighter or whitish shades. In contrast, fabrics mordanted with ferrous sulfate (tunjung) showed the lowest L* values across all pH levels, reflecting darker shades due to stronger dye fixation [30]. The differences in brightness indicate that each mordant interacts differently with the dye and cotton fibers. Tamarind extract tends to reduce color depth, while ferrous sulfate enhances dye absorption and darkens the fabric. Alum produced intermediate results. The effect of pH and mordant type on post-washing L* values is illustrated in Figure 7.

Table 6. CIE-Lab Values of Cotton Fabric (With Mordant) After Washing

Cotton Fabric + Teak Leaf Extract (pH 4)					
Alum		Tamarind		Ferrous Sulphate	
	L* = 66,3 a* = 3,3 b* = 2,3		L* = 67,6 a* = 5,6 b* = 2,6		L* = 58,6 a* = 2,5 b* = 6,3
Cotton Fabric + Teak Leaf Extract (pH 6)					
Alum		Tamarind		Ferrous Sulphate	
	L* = 67,4 a* = 3,3 b* = 2,3		L* = 68,1 a* = 3,2 b* = 1,2		L* = 63,7 a* = 3,0 b* = 7,0
Cotton Fabric + Teak Leaf Extract (pH 8)					
Alum		Tamarind		Ferrous Sulphate	
	L* = 72,7 a* = 3,7 b* = 0,8		L* = 72,6 a* = 3,4 b* = 0,6		L* = 63,8 a* = 3,4 b* = 10,0
Cotton Fabric + Teak Leaf Extract (pH 10)					
Alum		Tamarind		Ferrous Sulphate	
	L* = 66,9 a* = 2,9 b* = 2,2		L* = 73,0 Tawas b* = 1,3		L* = 57,8 a* = 2,6 b* = 7,5
Cotton Fabric + Teak Leaf Extract (pH 12)					
Alum		Tamarind		Ferrous Sulphate	
	L* = 70,1 a* = 3,6 b* = 1,3		L* = 70,5 a* = 4,1 b* = 0,9		L* = 63,8 a* = 3,6 b* = 7,8

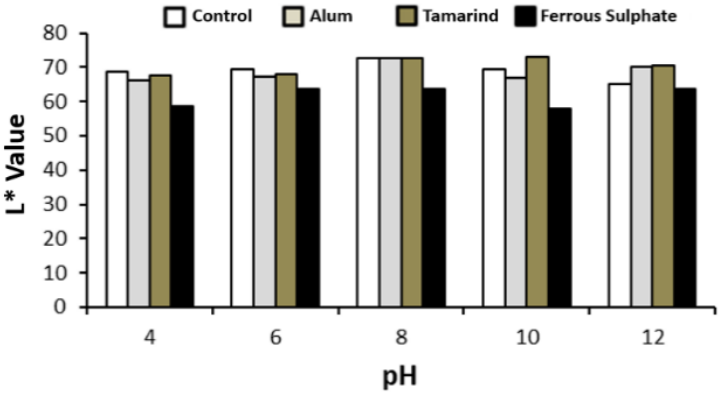


Figure 7. Effect of pH and Mordant Type on L* Values After Washing

Figure 7, shows the highest L* values were observed in cotton fabrics dyed at pH 8 using alum, tamarind extract, and without any mordant, indicating lighter shades. In contrast, the lowest L* value occurred at pH 10 in fabrics mordanted with ferrous sulphate (tunjung). Chemically, tunjung contains Fe^{2+} ions, which readily form coordination complexes with both fiber functional groups and dye molecules [31][32]. This strong interaction enhances dye fixation, resulting in lower brightness (L*) and darker, more saturated fabric color. After determining the CIE Lab* values and assessing washing fastness, the dyed cotton fabrics were further analyzed for color difference (ΔE) to quantify the degree of color change after washing. The ΔE values and their corresponding color change categories are presented in Table 7.

Table 7. Categories and Criteria for Color Difference (ΔE)

Category	Color Difference (ΔE)	Criteria
I	ΔE < 0.2	No visible change
II	0.2 < ΔE < 2.0	Very slight change
III	2.0 < ΔE < 3.0	Slight change (visible under high-quality observation)
IV	3.0 < ΔE < 6.0	Moderate change (visible under high-quality filter)
V	6.0 < ΔE < 12.0	Large change (clearly different color)
VI	ΔE > 12.0	Very large change (markedly different color)

Table 8. ΔE Values of Cotton Fabric After Washing Fastness Testing

Mordant Type	pH	Before Washing	After Washing	ΔE	Color Change
		L* a* b*	L* a* b*		
Control	4	68.5 / 6.4 / 2.9	68.7 / 4.3 / 1.6	2.4	Small
	6	61.4 / 4.4 / 8.1	69.3 / 3.4 / 1.8	10.1	Large
	8	56.9 / 4.9 / 11.4	72.6 / 3.4 / 0.6	19.1	Very Large
	10	58.1 / 5.6 / 7.5	69.3 / 3.4 / 1.8	12.7	Very Large
	12	64.1 / 5.2 / 3.1	65.1 / 4.8 / 1.7	1.7	Very Small
Alum	4	65.1 / 4.6 / 3.4	66.3 / 3.3 / 2.3	2.0	Small
	6	62.5 / 4.7 / 5.9	67.4 / 3.3 / 2.3	6.2	Large
	8	59.7 / 3.7 / 10.9	72.7 / 3.7 / 0.8	16.4	Very Large
	10	61.7 / 4.2 / 7.5	66.9 / 2.9 / 2.2	7.5	Large
	12	57.2 / 10.9 / 7.2	70.1 / 3.6 / 1.3	15.9	Very Large
Tamarind	4	66.6 / 4.4 / 3.9	67.6 / 5.6 / 2.6	2.0	Small
	6	58.0 / 5.0 / 9.6	68.1 / 3.2 / 1.2	13.2	Very Large
	8	61.4 / 4.7 / 8.8	72.6 / 3.4 / 0.6	13.9	Very Large
	10	60.9 / 4.2 / 7.5	73.0 / 3.6 / 1.3	13.6	Very Large
	12	63.2 / 4.4 / 4.0	70.5 / 4.1 / 0.9	7.9	Large
Ferrous sulphate	4	60.0 / 3.4 / 11.9	58.6 / 2.5 / 6.3	5.8	Moderate
	6	58.2 / –0.1 / 14.9	63.7 / 3.0 / 7.0	10.1	Large
	8	57.1 / 0.0 / 16.2	63.8 / 3.4 / 10.0	9.7	Large
	10	54.2 / 1.5 / 14.4	57.8 / 2.6 / 7.5	7.8	Large
	12	54.0 / 1.9 / 16.4	63.8 / 3.6 / 7.8	13.1	Very Large

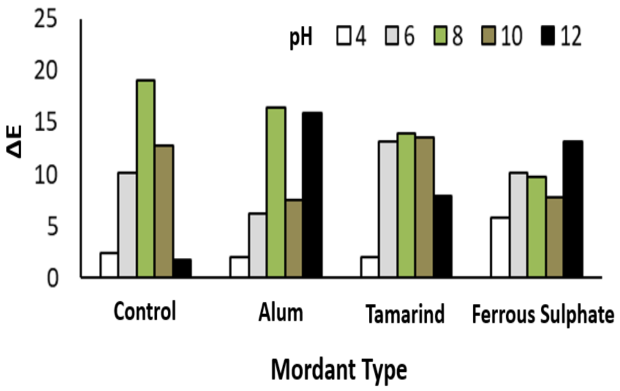


Figure 8. Effect of pH and Mordant Type on Color Difference (ΔE)

Table 8 shows that mordant type strongly influenced the magnitude of color change (ΔE) under different dyeing conditions. Mildly acidic conditions produced the smallest color differences in alum treated fabrics, tamarind treated fabrics, and unmordanted samples (ΔE ≈ 2.0 to 2.4), indicating slight but perceptible shade shifts. Moderately acidic to neutral conditions showed the lowest ΔE for alum mordanting (ΔE = 6.2), which still falls within the “large” color change category. Slightly alkaline conditions produced the most stable color with ferrous sulphate (tunjung), indicated by ΔE = 9.7, which remained a significant shift but was smaller than the changes observed for alum or tamarind. Figure 8 illustrates the relationship between pH, mordant type, and ΔE trends [33].

Higher alkalinity increased color instability in several treatments, particularly for alum mordanting, which showed ΔE values of 7.5 to 12.7 and therefore substantial to very substantial differences. The smallest color change under strongly alkaline conditions occurred in the unmordanted sample (ΔE = 1.7), categorized as “very slight,” indicating minimal perceptible alteration [31]. These findings highlight strong pH sensitivity of teak leaf dyes and confirm that mordant chemistry plays a critical role in final color stability. Ferrous sulphate tended to improve fixation more consistently across conditions, while alum and tamarind extract showed reduced stability as pH increased. The overall pattern emphasizes the need to optimize mordant selection together with pH control to achieve more stable teak leaf dye coloration [33].

CONCLUSION

This study confirms that teak leaf extract is a viable natural dye for cotton fabrics when supported by optimized dyeing conditions. Dye baths adjusted to pH 8–10 produced the deepest shades, indicating improved chromophore activation and fiber affinity. Ferrous sulfate emerged as the most effective mordant, resulting in the highest color depth and washing fastness. Spectroscopic and microscopic analyses further verified strong dye–fiber interactions and stable complex formation under these conditions. In contrast, extreme alkalinity (pH 12) reduced dye uptake and durability due to chromophore degradation. These findings provide clear guidelines for enhancing the performance of plant-based dyes through pH and mordant optimization. Overall, the study supports teak leaf extract as a promising eco-friendly colorant for sustainable textile applications.

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