

Natural Color Characteristics of Teak Leaves (*Tectona grandis*): Effects of Particle Size on Physicochemical and Optical Properties

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Teak leaves (*Tectona grandis*) are a potential source of natural dyes for textiles. This study investigated how dried teak-leaf powder particle size (40, 60, 80, and 100 mesh) affects the optical characteristics, pH, and hot-water-extractable content of aqueous extracts and examined their application to cotton fabric. A completely randomized design with three replicates per particle-size treatment was used. Extracts were prepared in distilled water at approximately 60 °C for 1 h using a solid-to-liquid ratio of 1:10 (g/mL). Optical responses were measured using UV-Vis-NIR spectrometry over 350–950 nm, while pH and extractive content were evaluated using one-way analysis of variance. The largest absorption coefficients observed among the individual measurements were 4.192 cm⁻¹ at 391.1 nm and 4.075 cm⁻¹ at 575 nm, both in replicate II of the 100-mesh treatment. Particle size significantly affected extract pH ($F(3, 8) = 18.96, p < 0.001$), whereas its effect on extractive content was not statistically significant ($F(3, 8) = 1.60, p = 0.264$). The extracts colored alum-treated cotton fabrics, with visually observable differences among treatments. These findings indicate that particle-size selection can influence the optical response and pH of teak-leaf dye extracts; however, compound identification and quantitative textile colorfastness require further testing.

Keywords: *tectona grandis*; particle size; natural dyes; optical absorption; UV-Vis-NIR spectroscopy



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1. INTRODUCTION

Teak (*Tectona grandis*) has been studied extensively for its growth responses to climatic variability, including the use of tree rings to reconstruct past hydroclimatic conditions (Managave et al., 2010; D'Arrigo et al., 2011; Zaw et al., 2020; Nurhati et al., 2024). Beyond its timber value, teak foliage contains secondary metabolites of potential industrial interest, including phenolic compounds and flavonoids (Chávez-Salgado et al., 2022). These compounds make teak leaves a promising source of plant-derived colorants, particularly because residual leaf biomass could be utilized as a value-added raw material.

Colorants are widely used in textiles, cosmetics, and other industrial products. Although synthetic dyes generally offer consistent coloration, affordability, and convenient processing, their production and wastewater discharge may pose environmental challenges depending on their chemical composition and waste-treatment practices. Consequently, plant-derived dyes have attracted interest as alternative colorants, particularly when produced from readily available agricultural residues. However, their practical application remains constrained by variability in extraction efficiency, color intensity, dye uptake, shade reproducibility, and resistance to fading (Silaturahmi et al., 2021). Understanding the

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processing parameters that control these properties is therefore essential for improving the reproducibility of natural dye production.

Previous studies have demonstrated the potential of teak leaves as natural colorants for textiles and other applications (Murwati et al., 2011; Rahayu et al., 2025). Several color-associated constituents, including phenolic compounds, tannins, and other plant pigments, have also been reported in teak leaves (Zulfa et al., 2014; Rizquna et al., 2024). In addition, Charoensit et al. (2021) investigated the recovery of natural pigments from teak leaves, providing an important basis for their potential utilization. Nevertheless, the optical characteristics of plant-derived extracts are influenced not only by their chemical constituents but also by extraction conditions. Furthermore, although UV–Vis spectroscopy can reveal absorption features associated with different chromophore groups, overlapping spectral bands do not permit definitive identification of individual compounds without complementary chemical analysis.

Particle size is an important processing parameter because it affects the accessible surface area and mass-transfer processes during solid–liquid extraction. Reducing particle size may facilitate solvent penetration and pigment release, although the resulting response may be influenced by particle aggregation, extraction conditions, and the stability of extracted compounds. Previous studies have examined the influence of particle size on the extraction characteristics of other plant materials (Yanti et al., 2019; Rahmadhani et al., 2020). However, these findings cannot necessarily be generalized to teak leaves because the composition and distribution of extractable compounds differ among plant materials.

Despite previous investigations into teak-leaf pigments and their potential applications, the available studies cited above do not establish how controlled variations in dried teak-leaf particle size simultaneously influence the physicochemical properties, optical absorption characteristics, and resulting coloration of cotton fabric under standardized aqueous extraction conditions. In particular, the relationship between particle-size reduction and optical absorption is not necessarily straightforward because higher extractive yield does not always correspond to stronger absorption at a particular wavelength. Similarly, changes in extract pH may influence pigment behavior without producing statistically significant changes in total extractive content. Consequently, evaluating these responses separately and comparatively is necessary to determine whether particle-size reduction consistently improves the characteristics relevant to natural dye production.

The specific research gap addressed in this study is therefore the limited integrated experimental evidence linking teak-leaf particle size to extract pH, hot-water-extractable content, wavelength-dependent optical response, and qualitative textile coloration within a single controlled extraction framework. Addressing this gap is important from a physical perspective because it helps distinguish changes in total extractable material from changes in the interaction between light and the resulting dye solution. Such information can provide a basis for selecting particle-size treatments that produce desirable optical characteristics without assuming that finer particles necessarily yield higher pigment concentrations or better textile performance.

Accordingly, this study aimed to investigate the influence of dried teak-leaf particle size on the physicochemical and optical characteristics of aqueous natural dye extracts. Four particle-size fractions were evaluated using 40 mesh (approximately 425 μm), 60 mesh (250 μm), 80 mesh (180 μm), and 100 mesh (150 μm) sieves. Under standardized heated-water extraction conditions, the resulting extracts were characterized in terms of pH, extractive content, and UV–Vis–NIR absorption behavior. Their application to cotton fabric was also examined qualitatively to assess observable coloration differences and changes following sun exposure. The study tested the hypothesis that particle-size variation influences extract pH, extractive content, and optical absorption characteristics, while recognizing that these responses may not follow the same particle-size dependence. By distinguishing statistically evaluated physicochemical properties from descriptive optical and fabric observations, this work provides an experimentally grounded assessment of particle size as a processing variable for teak-leaf-derived natural dyes.

2. METHOD

Experiments were conducted at the Forest Products Technology Laboratory, Department of Forestry, Faculty of Agriculture, Pattimura University, and the Elim Advanced Technology Research

Laboratory (EAT Lab), Center for Archipelago Physics, Department of Physics, Faculty of Science and Technology, Pattimura University. Sample preparation, aqueous extraction, pH determination, optical measurements, and cotton-fabric dyeing were performed as described below.

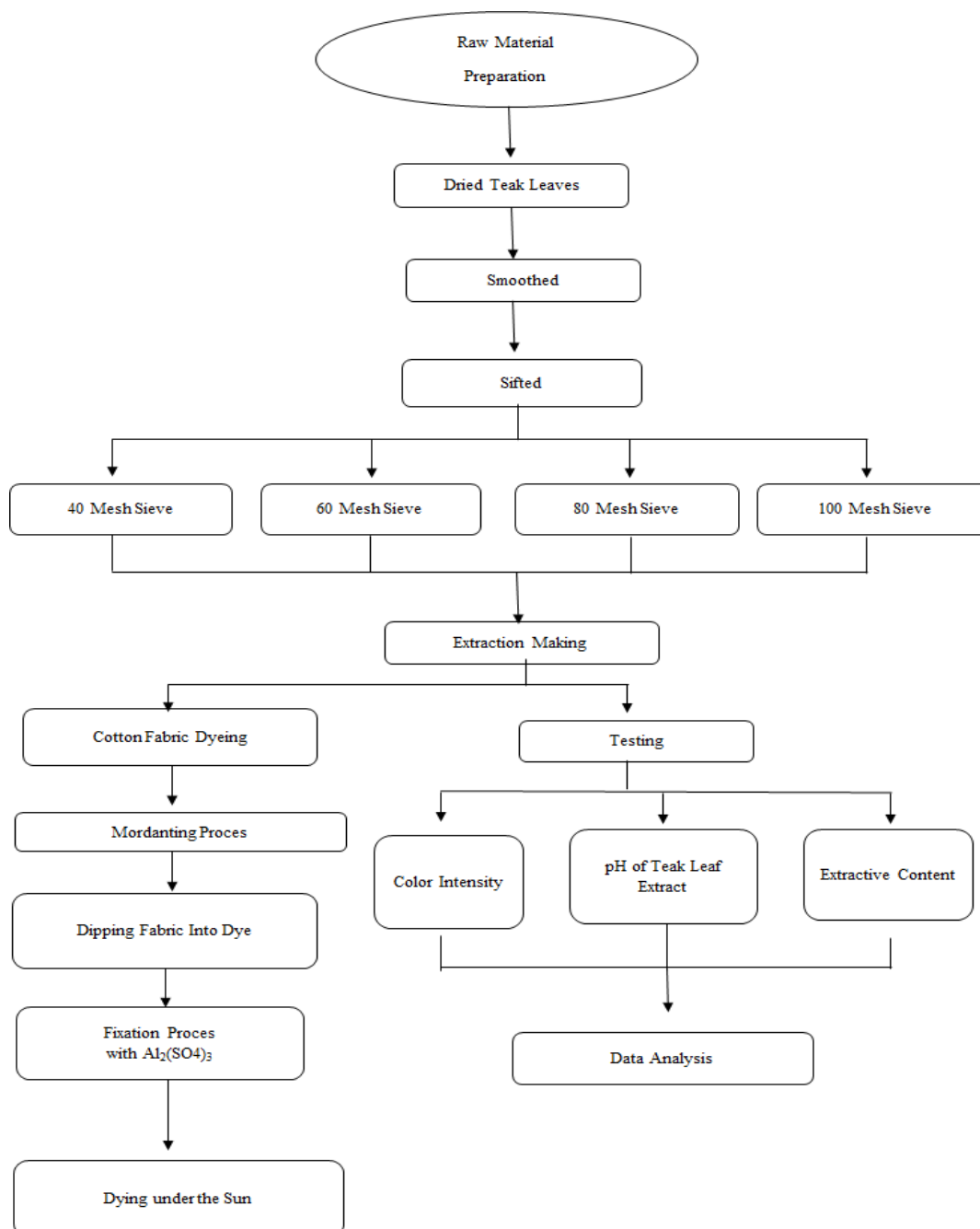


Figure 1. Experimental workflow for the preparation and characterization of teak-leaf dye extracts.

2.1 Equipment and Materials

Preparation of the dried teak-leaf powder and aqueous extracts involved scissors, a blender, 40-, 60-, 80-, and 100-mesh sieves, an analytical balance, a measuring cylinder, Erlenmeyer flasks, a stainless-steel vessel, a hot plate, a thermometer, stirring rods, a funnel, and filter paper. Extractive-content determination employed an analytical balance, a water bath, an oven, and a desiccator. Optical and acidity measurements were conducted using a UV–Vis–NIR spectrometer with sample cuvettes and a pH meter, respectively. Cotton mordanting, dyeing, and fixation were performed in suitable vessels with stirring equipment and an analytical balance for preparing the alum solutions.

2.2 Materials

Dried teak leaves (*Tectona grandis*) were collected near the Animal Husbandry Department, Faculty of Agriculture, Pattimura University. Distilled water was used for aqueous extraction and as the spectrometric blank; additional water was used for rinsing and fabric processing. Cotton fabric and alum (aluminum sulfate, $\text{Al}_2(\text{SO}_4)_3$) were used for the dyeing, mordanting, and fixation procedures.

2.3 Preparation of Dye Extracts

The experimental procedure consisted of several sequential stages, beginning with the collection and preparation of dried teak leaves (*Tectona grandis*). The leaves were cleaned, ground into powder, and separated into four particle-size fractions using 40, 60, 80, and 100 mesh sieves. Each fraction was subjected to heated-water extraction under controlled temperature and extraction time. The resulting extracts were filtered and subsequently analyzed to determine their optical absorption characteristics, pH values, electrical conductivity, and extractive contents. The extracts were also applied to cotton fabrics to evaluate their dyeing performance and visual color stability after sun exposure, as illustrated in Figure 1.

2.4 Experimental Procedures

2.4.1 Preparation of Raw Materials

Collected dried teak leaves were cleaned, ground using a blender, and sieved through 40-, 60-, 80-, and 100-mesh screens. Approximately 50 g of powder was prepared for each particle-size treatment. Mesh values describe the sieve fraction and should not be interpreted as a measurement of each particle's actual diameter.

2.4.2 Aqueous Extraction

Powder from each sieve fraction was extracted with distilled water at approximately 60 °C for 1 h with occasional stirring (Uzwatania et al., 2024). A solid-to-liquid ratio of 1:10 (g/mL) was used, equivalent to 10 mL of water per gram of leaf powder. The resulting suspension was filtered through filter paper to remove solid residue. Extracts were kept in closed containers protected from direct sunlight before measurement.

2.4.3 Cotton-Fabric Dyeing

Cotton fabric (1 × 1 m) was divided into 24 pieces and pre-wetted in water for 15 min. For mordanting, 100 g of alum was dissolved in 1 L of water by heating to approximately 100 °C. The fabric pieces were soaked in the alum solution for 24 h, rinsed until the rinse water became clear, squeezed, and sun-dried. Mordanting was intended to promote interaction between the extracted colorants and cotton fibers.

The dried fabric pieces were immersed in teak-leaf extract for 30 min and then air-dried; this immersion–air-drying sequence was repeated 10 times. While still damp, the dyed fabrics were immersed for 30 min in an alum fixation bath prepared at 100 g/L and subsequently air-dried. The procedure was used consistently across the four particle-size treatments.

2.5 Characterization and Data Analysis

2.5.1 Optical Measurements

Approximately 4 mL of each aqueous extract was transferred to a cuvette. Distilled water was used as the spectrometric blank, and the optical path length was 1 cm. The absorbance spectrum was recorded using a UV–Vis–NIR spectrometer, and representative absorption-band positions were tabulated. Optical results are reported for individual replicates; no inferential statistical test of spectral differences was reported.

2.5.2 Extra pH

Approximately 30 mL of each extract was used for pH measurement. Before measurement, the pH meter was checked against a pH 7.00 buffer, and the pH of each replicate was recorded. For reliable reproducibility, the authors should also specify the measurement temperature and whether additional calibration buffers were used.

2.5.3 Hot-Water-Extractable Content

Approximately 2 g of powder from each particle-size fraction was oven-dried to constant mass and weighed (*A*). The powder was placed in an Erlenmeyer flask containing 200 mL of hot distilled water and heated in a water bath at approximately 100 °C for 3 h, with stirring every 15 min. The residue was recovered by filtration, rinsed with hot distilled water until the rinse was clear, oven-dried to constant mass, cooled, and weighed (*B*). Extractive content was estimated from the loss of dry mass as given in Eq. (1). This gravimetric measure represents hot-water-extractable material and is not specific to any pigment class.

$$\text{Extractive content (\%)} = \left[\frac{(A - B)}{A} \right] \times 100\% \quad (1)$$

where *A* represents the initial oven-dry mass of the teak-leaf powder and *B* represents the oven-dry mass of the extracted residue, both expressed in grams.

2.5.4 Sun-Drying Observation

After mordanting, dyeing, and fixation, the air-dried fabrics were exposed to direct sunlight for 5 h and visually compared with corresponding samples kept indoors. The comparison was qualitative; no calibrated color coordinates, exposure intensity, or standard colorfastness measurements were reported.

2.5.5 Experimental Design

A one-factor completely randomized design (CRD) was used with four particle-size treatments and three replicates per treatment (12 observations per parameter). One-way ANOVA was applied to extract pH and extractive content. Individual spectral measurements and cotton-fabric photographs were analyzed descriptively.

Four particle-size fractions were evaluated: 40 mesh (UP1), 60 mesh (UP2), 80 mesh (UP3), and 100 mesh (UP4), with three independent replicates for each treatment.

The statistical model for the completely randomized design was:

$$Y_{ij} = \mu + \tau_i + \varepsilon_{ij} \quad (2)$$

where Y_{ij} is the measured response for treatment *i* in replicate *j*, μ is the overall mean, τ_i is the effect of the *i*th particle-size treatment, and ε_{ij} is the corresponding experimental error.

2.5.6 Statistical Analysis and Mean Comparisons

One-way analysis of variance (ANOVA) was conducted at a significance level of $\alpha = 0.05$ for the four particle-size treatments (40, 60, 80, and 100 mesh), with three replicates each. When a significant overall treatment effect was detected, Fisher's least significant difference (LSD; locally referred to as BNT) test was used for pairwise comparisons at the 5% level. Interpretation should also consider the small number of replicates and the assumptions of independent errors, approximate normality, and homogeneous variances ($\alpha = 0.05$).

$$LSD = t_{(\alpha/2; df_{\text{error}})} \times \sqrt{\frac{2 \times MS_{\text{error}}}{r}}, \quad (3)$$

where LSD denotes the least significant difference, $t_{(\alpha/2; df_{\text{error}})}$ is the critical Student's *t* value for the residual degrees of freedom, MS_{error} is the residual mean square from ANOVA, and $r = 3$ is the number of replicates per treatment.

A pairwise difference in treatment means was considered statistically significant when its absolute magnitude exceeded the calculated LSD at $\alpha = 0.05$; otherwise, it was considered non-significant.

2.5.7 Analysis of UV-Vis-NIR Spectra

The Beer–Lambert relationship describes attenuation of a light beam through an absorbing sample. For an optical path length *L* and attenuation coefficient α , the transmitted intensity is expressed as follows (Elim, 2019):

$$I = I_0 \exp(-\alpha L) \quad (4)$$

where I_0 is the incident light intensity, I is the transmitted intensity, α is the linear attenuation coefficient (cm^{-1}), and L is the optical path length (cm). Transmittance is $T = I/I_0$, while decadic absorbance is $A_{10} = -\log_{10}(T)$. Hence $\alpha = -\ln(T)/L = (\ln 10)A_{10}/L$. With $L = 1$ cm, the reported coefficients can be calculated from absorbance. Because the extracts may also scatter light, the resulting quantity should be interpreted as an apparent attenuation coefficient rather than an unambiguous measure of pigment concentration.

3. RESULTS AND DISCUSSION

3.1 Color Intensity

Absorption features of the teak-leaf extracts were observed between 390.5 and 394 nm (Table 1). This spectral interval overlaps with ultraviolet absorption bands reported for some flavonoid-related chromophores; however, spectral position alone cannot confirm the identity or abundance of flavonoids. UV–Vis spectrometry is useful for characterizing plant-derived dyes, but its selectivity is limited when several absorbing constituents are present (Loum et al., 2020). Accordingly, the 390.5–394 nm region is discussed here as a putative flavonoid-associated band rather than definitive chemical evidence.

A second group of absorption features occurred between approximately 525 and 575 nm (Table 2), within the visible spectral region in which certain anthocyanin-containing solutions may absorb. These bands may be influenced by pH and by other co-extracted compounds. The assignments to anthocyanin-related absorption should therefore be regarded as tentative until corroborated by compound-specific analysis (Baharuddin et al., 2015).

Table 1. UV–Vis–NIR optical properties and electrical conductivity of teak-leaf extracts near 391–394 nm.

Treatment	Repli- cation (Sample Code)	Wave- length (nm)	Conduc- tivity ($\mu\text{S}/\text{cm}$)	Absor- bance (a.u)	Transmittance (fraction) (%)	α (cm^{-1})
40 Mesh	I (11)	393.5	792	1.537	0.029	3.538
	II (12)	393.5	988	1.46	0.035	3.361
	III (13)	393.5	1160	1.288	0.052	2.963
60 Mesh	I (21)	393.5	1938	1.339	0.046	3.082
	II (22)	393.5	2128	1.526	0.030	3.515
	III (23)	393.5	1774	1.217	0.061	2.802
80 Mesh	I (31)	393.5	1570	1.731	0.018	3.992
	II (32)	393.5	1746	1.392	0.041	3.205
	III (33)	394	1568	1.594	0.026	3.669
100 mesh	I (41)	390.5	1764	1.399	0.040	3.221
	II (42)	391.1	1952	1.02	0.015	4.192
	III (43)	391.1	1502	1.392	0.041	3.203

Among the individual measurements in Table 1, replicate II of the 100-mesh treatment (sample 42) had the highest apparent attenuation coefficient, $\alpha = 4.192 \text{ cm}^{-1}$, at 391.1 nm. The absorbance (1.02), transmittance (0.015), and attenuation coefficient (4.192 cm^{-1}) reported for this replicate are not

mutually consistent under the Beer–Lambert relationship. An additional mismatch affects the absorbance (1.625), transmittance (0.017), and attenuation coefficient (4.075 cm^{-1}) recorded for sample 42 at 575 nm in Table 2. Both rows require verification against the original instrument records. Electrical conductivity also varied among samples, but the present design does not isolate the contribution of ionic solutes from that of particle-size fraction. It is therefore not justified to infer a monotonic relationship between particle size, conductivity, and pigment concentration. The optical response and conductivity should be considered separate, measured extract properties.

Table 2. UV–Vis–NIR optical properties and electrical conductivity of teak-leaf extracts near 525–575 nm.

Treatment	Detes- tation	Wave- lenght (nm)	Conduc- tivity ($\mu\text{s/cm}$)	Absor- bance (a.u)	Transmittance (fraction) (%)	α (cm^{-1})
40 Mesh	I	562.5	792	1.250	0.050	2.996
	II	575	988	1.125	0.075	2.590
	III	562.5	1160	1.143	0.100	2.303
60 Mesh	I	562.5	1938	1.100	0.073	2.617
	II	562.5	2128	1.250	0.065	2.733
	III	525	1774	0.880	0.120	2.119
80 Mesh	I	568.7	1570	1.560	0.039	3.247
	II	550	1746	1.098	0.085	2.464
	III	575	1568	1.250	0.063	2.766
100 Mesh	I	550	1764	1.062	0.075	2.590
	II	575	1952	1.625	0.017	4.075
	III	550	1502	1.000	0.075	2.590

3.2 Effect of Particle Size on Extract pH

The measured extract pH values were close to neutral, ranging from 6.82 to 7.06 across individual replicates (Table 3). Mean pH was 6.91 for the 40-mesh fraction, 6.85 for 60 mesh, 7.02 for 80 mesh, and 7.01 for 100 mesh. Although these numerical differences are modest, pH can alter the spectral behavior of some natural colorants and may contribute to variations in extracted shade (Rahayu et al., 2025). Because particle-size effects are not strictly monotonic, the results should not be described as a continuous increase in pH with decreasing particle size.

Table 3. Extract pH values for teak-leaf (*Tectona grandis*) extracts prepared using different particle-size treatments.

Treatment (Particle Size)	Replicate			Quantity	Average
	I	II	III		
40 Mesh	6.92	6.92	6.88	20.72	6.91
60 Mesh	6.85	6.82	6.88	20.55	6.85
80 Mesh	6.97	7.02	7.06	21.05	7.02
100 Mesh	7.03	6.98	7.01	21.02	7.01
Total				83.34	6.95

One-way ANOVA indicated a significant effect of sieve fraction on extract pH ($F(3, 8) = 18.96$, $p = 0.00054$; Table 4). The treatment sum of squares calculated from the reported replicate measurements was approximately 0.0583, compared with an error sum of squares of approximately 0.0082. Statistical significance does not necessarily imply a large practical color difference: the largest difference between treatment means was approximately 0.17 pH units.

Table 4. One-way analysis of variance (ANOVA) of the effect of teak-leaf particle size on extract pH.

SV	DF	SS	MS	F-value	Critical F-value	
					0.05	0.01
Treatment	3	0.06	0.019	18.96**	4.07	7.59
Error	8	0.01	0.001			
Total	11	0.07				

Note: ** indicates a statistically significant treatment effect at $p < 0.01$; tabulated 5% and 1% values are critical F thresholds, not p-values.

Fisher's LSD test at the 5% significance level identified two distinct groups of particle-size treatments based on extract pH (Table 5). The 40- and 60-mesh treatments formed one group, while the 80- and 100-mesh treatments formed another. Differences within each group were not statistically significant, whereas comparisons between groups indicated significant differences. Nevertheless, the relatively small differences in mean pH (6.85–7.02) suggest that statistical significance should not be interpreted as evidence of substantial practical differences in dye coloration, particularly given the limited number of replicates.

Table 5. Comparison of mean extract pH among teak-leaf particle-size treatments using Fisher's least significant difference (LSD) test at the 5% significance level.

Treatment	Average	Notation
UP1	6.91	a
UP2	6.85	a
UP3	7.02	b
UP4	7.01	b
Treatment	Average	Notation
UP1	6.91	a
UP2	6.85	a
UP3	7.02	b
UP4	7.01	b

Note: Means sharing the same letter are not significantly different at $\alpha = 0.05$.

3.3 Hot-Water-Extractable Content

Hot-water-extractable content represents the mass fraction of soluble or removable constituents extracted from dried teak-leaf powder under the specified experimental conditions, rather than the concentration of individual pigment compounds. As shown in Table 6, the highest mean extractive content was obtained from the 60-mesh treatment (34.14%), followed by the 80-mesh (31.04%), 100-mesh (30.95%), and 40-mesh (30.52%) treatments. Although the 60-mesh fraction exhibited the highest numerical mean, the differences among treatments were not statistically significant ($F(3, 8) = 1.60$, $p = 0.264$). Furthermore, no consistent monotonic relationship was observed between particle size and extractive content. These findings suggest that reducing particle size within the investigated range does

not necessarily increase the total amount of hot-water-extractable material. Therefore, particle-size selection should not be based solely on extractive yield but should also consider the optical characteristics and intended dyeing performance of the resulting extracts.

Table 6. Hot-water-extractable content of teak-leaf (*Tectona grandis*) powder under different particle-size treatments.

Treatment (Particle Size)	Replicate			Quantity	Average
	I	II	III		
40 Mesh	31.38	30.93	29.25	91.56	30.52
60 Mesh	37.12	34.78	30.53	102.43	34.14
80 Mesh	34.06	30.09	28.97	93.12	31.04
100 Mesh	30.05	32.23	30.57	92.84	30.95
Total				379.96	31.66

The recalculated one-way ANOVA yielded $F(3, 8) = 1.60$ ($p = 0.264$), indicating no statistically significant evidence of different mean extractive contents across the four fractions (Table 7). Accordingly, post hoc LSD comparisons are not warranted for this response. This non-significant outcome does not establish equivalence among fractions; rather, it indicates that the available measurements did not detect a treatment difference at $\alpha = 0.05$.

Table 7. One-way analysis of variance (ANOVA) of the effect of teak-leaf particle size on hot-water-extractable content.

SV	DF	SS	MS	F-value	Critical F-value	
					0.05	0.01
Treatment	3	25.066	8.355	1.601NS	4.006	7.591
Error	8	41.752	5.219			
Total	11	66.818				

3.4 Application to Cotton Fabric

Cotton is a cellulose-rich textile material capable of interacting with natural dye constituents through adsorption and other dye–fiber interactions. The effectiveness of coloration depends on the chemical composition of the extract, dye uptake, and processing conditions. Alum mordanting and fixation may enhance dye retention by modifying interactions between the colorant and textile fibers (Pujilestari, 2014). However, because the present study did not independently evaluate the effects of mordant concentration, repeated dyeing, or extraction conditions, their individual contributions to the observed coloration could not be determined.

Figures 2–5 illustrate the visual appearance of cotton fabrics dyed with teak-leaf extracts prepared from four particle-size treatments. Variations in color intensity and shade were observed among treatments and individual replicates. Notably, the second replicate of the 100-mesh treatment (sample 42) exhibited a comparatively darker appearance, consistent with its relatively high apparent optical attenuation coefficients at selected wavelengths. This qualitative correspondence suggests a possible relationship between the optical characteristics of the extract and the resulting fabric coloration. Nevertheless, because optical attenuation of the liquid extract does not directly quantify dye uptake or color strength on cotton fibers, this relationship cannot be considered conclusive. Furthermore, photographic differences may be influenced by lighting conditions, camera settings, and image processing. Quantitative colorimetric measurements, such as CIELAB coordinates and Kubelka–Munk

color-strength (K/S) values, are required to establish statistically reliable differences in textile coloration.

Visual inspection of the fabrics before and after approximately 5 h of sunlight exposure did not reveal conspicuous color changes under the conditions examined. However, this preliminary observation should not be interpreted as evidence of high lightfastness or durable dye–fiber bonding because the exposure conditions were not standardized and color changes were not quantified. The observed coloration supports the potential utilization of teak-leaf biomass as a source of natural textile dyes, consistent with previous investigations of plant-derived colorants (Pujilestari, 2014; Charoensit et al., 2021). Further studies involving standardized lightfastness and washfastness testing, quantitative colorimetry, and controlled mordanting conditions are necessary to evaluate the reproducibility and practical suitability of these extracts for textile applications.



Figure 2. Cotton fabric dyed using the 40-mesh extract before and after 5 h of sunlight exposure.



Figure 3. Cotton fabric dyed using the 60-mesh extract before and after 5 h of sunlight exposure.

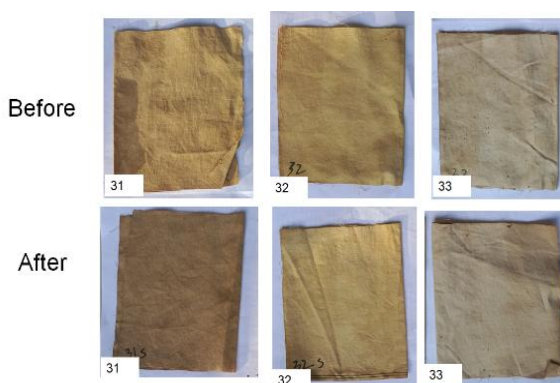


Figure 4. Cotton fabric dyed using the 80-mesh extract before and after 5 h of sunlight exposure.

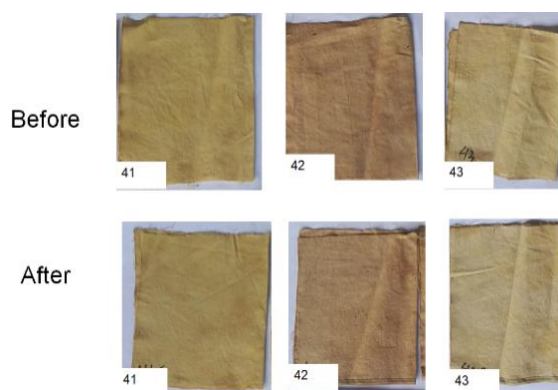


Figure 5. Cotton fabric dyed using the 100-mesh extract before and after 5 h of sunlight exposure.

4. CONCLUSION

This study demonstrates that particle-size variation influences selected physicochemical and optical characteristics of aqueous teak-leaf (*Tectona grandis*) extracts, although these properties do not exhibit a uniform response to particle-size reduction. UV–Vis–NIR measurements revealed distinct absorption features at approximately 391–394 nm and 525–575 nm. The highest individual apparent attenuation coefficients were recorded for the 100-mesh treatment (sample 42), reaching 4.192 cm^{-1} at 391.1 nm and 4.075 cm^{-1} at 575 nm. However, these individual maxima do not establish the superiority of the 100-mesh treatment across all replicates. Statistical analysis confirmed a significant effect of particle size on extract pH ($F(3, 8) = 18.96$, $p < 0.001$), whereas the effect on hot-water-extractable content was not significant ($F(3, 8) = 1.60$, $p = 0.264$). These findings indicate that changes in extract physicochemical properties and optical attenuation do not necessarily correspond to changes in total extractive yield.

The principal scientific contribution of this study is the integrated evaluation of particle-size-dependent physicochemical and optical responses under standardized aqueous extraction conditions. The results highlight the importance of distinguishing optical attenuation from total extractive content when assessing natural dye characteristics, providing an experimental basis for further optimization of teak-leaf extraction processes. The successful visual coloration of alum-treated cotton also indicates the potential of teak-leaf biomass as an alternative natural dye resource. Nevertheless, spectral band assignments remain tentative, and the qualitative textile observations do not establish dye durability or colorfastness. Further investigations should verify the spectral measurements, identify the responsible chromophores using complementary analytical techniques, quantify color characteristics and dye uptake, and evaluate light- and washfastness using standardized procedures. Such investigations are essential for determining the reproducibility, performance, and practical feasibility of teak-leaf-derived colorants for textile applications.

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AUTHOR CONTRIBUTIONS

Conceptualization, L.F.N., H.I.E., and H.S.; methodology, L.F.N. and H.S.; validation, H.I.E. and H.S.; formal analysis, L.F.N. and H.I.E.; investigation, L.F.N.; resources, H.S. and H.I.E.; data curation, L.F.N.; writing—original draft preparation, L.F.N.; writing—review and editing, H.I.E. and H.S.; visualization, L.F.N. and H.I.E.; supervision, H.I.E. and H.S.; project administration, L.F.N. and

H.S.; funding acquisition, not applicable. All authors have read and agreed to the published version of the manuscript.

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DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

ARTIFICIAL INTELLIGENCE (AI) USAGE DECLARATION

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist with English-language proofreading, editorial restructuring, and wording refinement.

REFERENCE

- Baharuddin, A., Aisyah, A., Saokani, J., & Risnah, I. A. (2015). Karakterisasi zat warna daun jati (*tectona grandis*) fraksi metanol:n-heksana sebagai photosensitizer pada dye sensitized solar cell. *Chimica et Natura Acta*, 3(1), 37–41. <https://doi.org/10.24198/cna.v3.n1.9174>
- Charoensit, P., Sawasdipol, F., Tibkawin, N., Suphrom, N., & Khorana, N. (2021). Development of natural pigments from *Tectona grandis* (teak) leaves: Agricultural waste material from teak plantations. *Sustainable Chemistry and Pharmacy*, 19, Article 100365. <https://doi.org/10.1016/j.scp.2020.100365>
- Chávez-Salgado, L., Vandenbossche, V., & Vilarem, G. (2022). *Tectona grandis* Linn. f. secondary metabolites and their bioactive potential: a review. *IForest - Biogeosciences and Forestry*, 15(2), 112–120. <https://doi.org/10.3832/for3714-015>
- D'Arrigo, R., Palmer, J., Ummenhofer, C. C., Kyaw, N. N., & Krusic, P. (2011). Three centuries of Myanmar monsoon climate variability inferred from teak tree rings. *Geophysical Research Letters*, 38(24), Article L24705. <https://doi.org/10.1029/2011GL049927>
- Elim, H. I. (2019). *Metode Fisika Eskperimen: Pelengkap Teori Fisika* (J. P. Haumahu, Ed.). Pattimura University Press.
- Loum, J., Byamukama, R., & Wanyama, P. A. G. (2020). UV–Vis Spectrometry for Quantitative Study of Tannin and Flavonoid Rich Dyes from Plant Sources. *Chemistry Africa*, 3(2), 449–455. <https://doi.org/10.1007/s42250-020-00135-6>
- Managave, S. R., Sheshshayee, M. S., Borgaonkar, H. P., & Ramesh, R. (2010). Past break-monsoon conditions detectable by high resolution intra-annual $\delta^{18}\text{O}$ analysis of teak rings. *Geophysical Research Letters*, 37(5), Article L05702. <https://doi.org/10.1029/2009GL041172>
- Murwati, E. S., Pristiwati, E., & Nugroho, L. P. A. (2011). Teknik pewarnaan agel dengan zat warna alam dari daun jati. *Dinamika Kerajinan dan Batik*, 28(1), 31–36. <https://doi.org/10.22322/dkb.v28i1.1010>
- Nurhati, I. S., Evans, M. N., Cahyarini, S. Y., D'Arrigo, R. D., Yoshimura, K., & Herho, S. H. S. (2024). $\delta^{18}\text{O}$ of Marine-Influenced *Tectona grandis* L. f. From Equatorial Indonesia: A Local Rainfall Amount and Remote ENSO Indicator. *Paleoceanography and Paleoclimatology*, 39(5), Article e2023PA004758. <https://doi.org/10.1029/2023PA004758>
- Pujilestari, T. (2014). Pengaruh ekstraksi zat warna alam dan fiksasi terhadap ketahanan luntur warna pada kain batik katun. *Dinamika Kerajinan dan Batik*, 31(1), 31–40. <https://doi.org/10.22322/dkb.v31i1.1058>
- Rahayu, S., Lestari, S. D., Budianto, A., Alaydrus, A. T., & Akhyar, H. (2025). Studi Pengaruh pH Terhadap Stabilitas Warna dan Kuat Tarik Kain Katun dengan Pewarna Alami Antosianin. *Kappa Journal*, 9(1), 43–48. <https://doi.org/10.29408/kpj.v9i1.29595>
- Rahmadhani, R., Ganda Putra, G. P., & Suhendra, L. (2020). Karakteristik ekstrak kulit biji kakao (*Theobroma cacao* L.) sebagai sumber antioksidan pada perlakuan ukuran partikel dan waktu maserasi. *Jurnal*

- Rekayasa dan Manajemen Agroindustri*, 8(2), 246–256.
<https://doi.org/10.24843/JRMA.2020.v08.i02.p09>
- Rizquna, S. A., Maulida, S. N., Hannifah, Syakuron, A. A., Muflihati, I., & Suhendriani, S. (2024). Penggunaan Ekstrak Dari Tiga Jenis Daun Jati (Daun Jati Lokal, Daun Jati Super, dan Daun Jati Belanda) sebagai Pewarna Alami pada Sirup. *JURNAL TRITON*, 15(1), 207–220. <https://doi.org/10.47687/jt.v15i1.532>.
- Silaturahmi, Wiraningtyas, A., & Ruslan. (2021). Ekstraksi zat warna dari daun jati muda (*Tectona grandis* Linn. F.) dan aplikasinya pada benang tenunan Bima. *Jurnal Redoks: Jurnal Pendidikan Kimia dan Ilmu Kimia*, 4(1), 1–9. <https://doi.org/10.33627/re.v4i1.512>
- Uzwatania, F., Ma'ruf, A., & Jumadi. (2024). Pengaruh suhu dan waktu ekstraksi pada metode digesti terhadap aktivitas jahe merah (*Zingiber officinale* var. Rubrum) di PT. X. *Jurnal Teknologi Pangan dan Gizi*, 23(2), 104–112. <https://doi.org/10.33508/jtpg.v23i2.4992>
- Yanti, G. A. K. D. P., Wartini, N. M., & Antara, N. S. (2019). Pengaruh ukuran partikel dan suhu ekstraksi terhadap karakteristik ekstrak pewarna alami bunga kenikir (*Tegetes erecta* L.). *IPTEKMA*, 8(1), 17–24. <https://doi.org/10.24843/iptekma.2019.v08.i01.p03>
- Zaw, Z., Fan, Z. X., Bräuning, A., Xu, C. X., Liu, W. J., Gaire, N. P., Panthi, S., & Than, K. Z. (2020). Drought Reconstruction Over the Past Two Centuries in Southern Myanmar Using Teak Tree-Rings: Linkages to the Pacific and Indian Oceans. *Geophysical Research Letters*, 47(10), Article e2020GL087627. <https://doi.org/10.1029/2020GL087627>
- Zulfa, L., Kumalaningsih, S., & Effendi, M. (2014). Ekstraksi pewarna alami dari daun jati (*Tectona grandis*) (kajian konsentrasi asam sitrat dan lama ekstraksi) dan analisa tekno-ekonomi skala laboratorium. *Industria: Jurnal Teknologi dan Manajemen Agroindustri*, 3(1), 62–72. <https://industria.ub.ac.id/index.php/industri/article/view/156>