COLOR AND PHYSICAL PROPERTIES OF COTTON FABRICS DYED WITH NATURAL PIGMENT EXTRACTED FROM *PERISTROPHE ROXBURGHIANA* LEAF

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This study investigates the dyeing performance of cotton fabrics using natural pigment extracted from *Peristrophe roxburghiana* (PR) leaves as a sustainable alternative to synthetic dyes. The research aims to optimize dyeing parameters, while assessing both color performance and environmental benefits within a cleaner production framework. Pigment extraction was conducted using an aqueous, low-chemical process, and dyeing was performed under varying conditions of temperature, time, pH, and mordant concentration. Color strength and fastness were evaluated using reflectance spectrophotometry and standard testing. The optimal dyeing conditions (60 °C, 60 min, mildly acidic pH) resulted in enhanced color strength (K/S). Among the mordants tested, $CuSO_4·5H_2O$ at 0.5% showed the most significant improvement in K/S values and wash fastness. Importantly, the process demonstrated reduced chemical usage and maintained acceptable fabric properties, including air permeability, wrinkle recovery, and flexural rigidity. These findings highlight PR pigment as a promising bio-based colorant for cotton textiles, supporting cleaner production strategies and environmentally responsible textile manufacturing.

Keywords: natural dyes, *Peristrophe roxburghiana* (PR), natural dyes, cotton dyeing, cleaner production, color fastness, eco-friendly mordant

INTRODUCTION

The growing awareness of the hazards associated with synthetic dyes has increased the demand for cleaner textile production, thereby intensifying the search for sustainable, plant-based natural pigments.[1,2] Natural dyes are valued for their biodegradability, non-toxicity, and renewable origins, making them increasingly attractive alternatives in the textile industry, which faces mounting pressure to adopt more sustainable practices.[3,4]

Among various plant-based dye sources, *Peristrophe roxburghiana* (PR), a shrub native to tropical and subtropical Asia, has gained attention due to its dye-yielding potential.[5] Traditionally used in folk medicine and occasionally as a coloring agent in cultural practices, PR leaves are rich in pigment compounds, such as flavonoids and polyphenols, that exhibit promising coloration properties for textile applications.[6,7] These properties make PR a strong candidate for eco-friendly cotton dyeing within a cleaner production framework.

Cotton, the most widely used natural fiber globally, is an ideal substrate for dyeing with natural pigments due to its hydrophilic nature and broad application in apparel and home textiles.[8] However, cotton presents certain dyeing challenges, primarily due to its limited affinity for many natural colorants.[9] Therefore, optimizing dyeing parameters, such as extraction method, pH, temperature, dyeing time, and mordant concentration, is essential to enhance dye-fiber interactions and improve dyeing efficiency, while maintaining environmental compatibility.[10,11]

Recent studies have investigated a wide range of botanical dye sources and dyeing methodologies aimed at improving performance, while minimizing environmental impact. For example, Sankaralingam *et al*. extracted anthocyanins from *Hibiscus sabdariffa* (L.) and demonstrated effective application on natural fibers with favorable fastness and eco-friendly potential.[12] Likewise, Amirova *et al.* investigated various plant-based dyes on natural silk, achieving vibrant shades with acceptable fastness properties.[13] Similarly, Yajie *et al.* reported that PR extract produced stable and aesthetically pleasing colors on silk under optimized mordanting conditions.[14] In general, these studies highlight that the performance of plant-based dyes on textile substrates, particularly cellulose fibers such as cotton, strongly depends on extraction techniques and mordanting strategies, which directly influence color strength, shade development, and fastness properties.[9,15,16,17]

Despite these advancements, the application of PR leaf extract as a natural dye for cotton fabrics remains largely underexplored, particularly with respect to the systematic optimization of dyeing parameters and process conditions. This study builds upon previous research by focusing on the unique dyeing properties of PR within a cleaner production framework. The novelty of this work lies in the comprehensive and systematic evaluation of PR leaf pigment for cotton dyeing, including the optimization of extraction methods, mordanting techniques, and key dyeing parameters. Pigments were extracted using aqueous, low-chemical methods and characterized by UV–Vis spectrophotometry. Dyeing experiments were conducted under controlled conditions to investigate the effects of temperature, pH, dye concentration, and mordant type on dye uptake and color performance. Selected metallic mordants were applied to improve fixation.

The dyed samples were evaluated in terms of color strength (K/S), colorimetric properties (L^*, a^*, b^*), and fastness to washing and rubbing. Through this systematic approach, the study aims to establish relationships between process parameters and dyeing performance, thereby improving reproducibility and process efficiency. The results demonstrate that optimized PR-based dyeing can produce stable and visually appealing shades with reduced chemical input. Consequently, this work reinforces the potential of PR pigment as a sustainable and cleaner alternative for cotton coloration, contributing to the development of low-impact textile dyeing technologies

EXPERIMENTAL

A systematic experimental design was employed to optimize dyeing parameters for both color performance and environmental compatibility. Plain-woven 100% cotton fabric (150 g/m^2) was used as the dye substrate. Prior to dyeing, the fabric was subjected to a sequential pre-treatment: desizing, scouring, and bleaching to ensure uniform absorbency and reproducibility. Briefly, desizing was performed using 2 g/L α-amylase at 60 °C for 60 min. The fabric was then scoured with 4 g/L NaOH and 2 g/L detergent at 90 °C for 60 min, followed by bleaching in a bath containing 5 g/L of 30% H_2O_2 at 85 °C for 45 min. After thorough rinsing and air-drying, the treated fabrics were ready for use. Fresh and dried PR leaves were collected from southern Vietnam. The mordants used in this study included copper sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$), ferrous sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$), potassium aluminum sulfate dodecahydrate ($KAl(SO_4)_2 \cdot 12H_2O$), and aluminum sulfate octadecahydrate ($Al_2(SO_4)_3 \cdot 18H_2O$), all of analytical grade. Distilled water was used for all preparations and procedures.

Pigment extraction was performed using an aqueous decoction method. Fresh or dried PR leaves (100 g) were boiled in 1,000 mL of distilled water for 60 minutes. The resulting mixture was filtered to remove solid residues, and the filtrate was cooled to room temperature prior to dyeing. Extract concentration was varied between 20% and 100% v/v to assess the effect of dye strength. Dyeing experiments were carried out in laboratory-scale dye baths with a material-to-liquor ratio of 1:20. Dyeing was conducted at various temperatures (30 °C, 45 °C, 60 °C, and 75 °C), dyeing times (30-120 minutes), and pH levels (4-9), adjusted using acetic acid or sodium hydroxide. The dyeing process was carried out using the simultaneous mordanting method with mordant concentrations of 0.2%, 0.5%, and 1.0% owf (on weight fabric). All dyeing processes were performed under constant agitation to ensure uniform dye uptake.

The pH and oxidation–reduction potential (ORP) of the dye baths were monitored using a calibrated Eutech Instruments integrated meter, and values were recorded after stabilization.

The UV-Vis absorption spectra of the dye extracts and residual dye baths were recorded using a Yoke UV1720 single-beam spectrophotometer equipped with a photometric detector system over a wavelength range from 190-1,100 nm). Spectral measurements were conducted in the range of 200-800 nm using standard 10 mm quartz cuvettes with a 10 nm optical path length.

Colorimetric properties were evaluated using two complementary instruments. The CIE $L^*a^*b^*$ values were measured using a Linshang LS173 portable colorimeter under a standard D65 illuminant and a 10° standard observer. Color strength (K/S) values were determined using an X-Rite 530 spectrophotometer (X-Rite, USA), operating in reflectance mode with specular component excluded (SCE), and calculated at the maximum absorption wavelength (λ_{max}) of the dyed samples. The ΔE values were calculated using the undyed cotton fabric as the standard white reference. To ensure measurement accuracy, each fabric sample was folded into four layers to achieve complete opacity.

Measurements were taken at a minimum of three different locations on each sample, and the average values were reported. To evaluate color durability after laundering, the total color difference (ΔE) was calculated by comparing the CIE L*a*b* coordinates of the dyed fabric before washing (reference) with those obtained after washing.

The washing fastness of the dyed cotton samples was assessed according to ISO 105-C06 using a Miele washer. The test specimens (15 cm x 15 cm) were sewn adjacent to standard multifiber fabrics and agitated in a wash bath. Color change was additionally evaluated after 1, 2, and 5 washing cycles to assess durability.

The physical properties of the dyed fabrics were also characterized to determine the impact of the dyeing process on textile performance, including air permeability (ASTM D737), moisture content, wrinkle recovery angle (ISO 2313), and bending rigidity (ASTM D1388). All experiments were performed in quintuplicate ($n = 5$) to ensure reproducibility. The experimental data are presented as the mean ± standard deviation (SD). Statistical analysis was conducted using Microsoft Excel. A p-value of less than 0.05 ($p < 0.05$) was considered statistically significant.

RESULTS AND DISCUSSION

Effect of dye concentration on color performance and process optimization

Analysis of UV-Vis spectra

Figure 1 provides insights into the composition of PR extracts and their interaction with cotton fabric based on UV-Vis spectra. The original/undyed extract (solution before dyeing) shows a strong absorption peak in the UV region of 200-205 nm, likely due to conjugated double bonds or carbonyl groups from solvents or organic compounds. In the visible region, a broad band at 330-360 nm and a distinct peak at 570-590 nm appear. The latter is characteristic of anthocyanins (*i.e.*, key pigments giving PR its purple hue). The 330-360 nm band may correspond to phenolic compounds or flavonoids common in plant extracts.

When examining the extract after dyeing cotton, the UV region (190-300 nm) shows significantly reduced absorbance and more scattering, suggesting the uptake or degradation of small UV-absorbing molecules during dyeing. In contrast, the visible region (300-700 nm) maintains a similar spectral shape, but with a noticeable decrease in absorbance at both the 330-360 nm and 570-590 nm peaks. This indicates successful transfer of anthocyanins to the cotton, confirming the dyeing process. The clear reduction in peak intensity confirms the depletion of dye molecules from the dye bath, reflecting a good dye uptake by the fabric. However, the presence of residual absorbance suggests that many anthocyanins remained in solution or that the exhaustion was not entirely complete, possibly due to the short dyeing time, high initial dye concentration, or the absence of a mordant. Optimizing dyeing conditions, such as mordant use, could further enhance anthocyanin fixation on cotton.

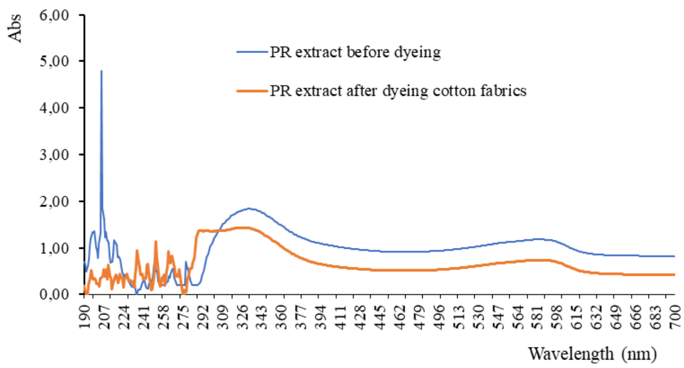


Figure 1: UV-Vis spectra of the PR extract before dyeing and after dyeing cotton fabrics

Impact of dilution ratios on K/S and ΔE

Building upon the findings from the UV-Vis spectral analysis, the macroscopic color properties of the dyed fabrics were subsequently evaluated. Figure 2 effectively illustrates the impact of different dilution ratios (DR) of PR extract on the color strength (K/S) and color difference (ΔE) of dyed cotton fabrics, without the use of mordants. The visual representation of the dyed fabric samples (ACM020 to ACM100), which correspond to the dye extracts concentrations from 20% to 100%, respectively, clearly shows a progressive increase in color intensity as the extract concentration rises (*i.e.*, as the dilution ratio decreases, moving from DR 20:80 to DR 100:0, which represents undiluted extract).

Quantitatively, this observation is strongly supported by the K/S values, which are a measure of color depth. As the concentration of the dye extract increases, the K/S value consistently rises, from 0.72 for ACM020 (DR 20:80) to 2.28 for ACM100 (DR 100:0). This trend unequivocally demonstrates that a higher concentration of the dye molecules in the extract leads to a greater amount of dye being adsorbed onto the cotton fabric. This increased dye uptake translates directly into a more saturated and intense color on the textile. The parabolic fit indicates a strong correlation and suggests that the dye uptake is not linearly proportional to the concentration, potentially hinting at saturation effects at higher concentrations or a more complex adsorption mechanism. Similarly, the ΔE values, which quantify the total color difference compared to a standard white reference, also show a clear upward trend with increasing extract concentration, ranging from 36.34 (ACM020) to 52.50 (ACM100). A larger ΔE value indicates a greater perceived color difference, confirming that the fabrics dyed with higher concentrations of the extract are visually darker and more distinct from the undyed cotton. The polynomial fit again shows a strong relationship.

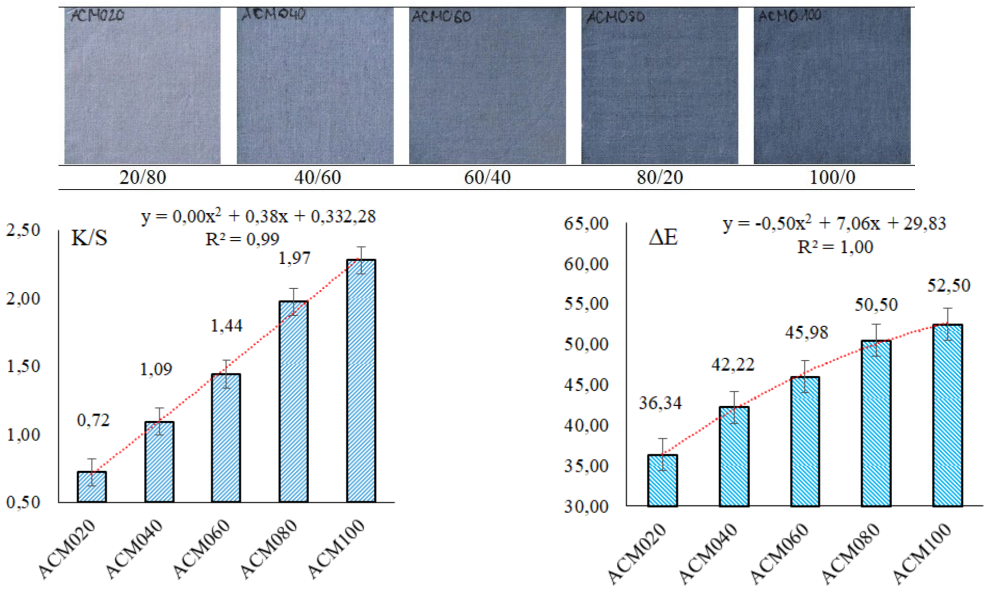


Figure 2: K/S and ΔE values of dyed cotton fabrics with PR extracts at various dilution ratios (DR) of 20/80 (ACM020), 40/60 (ACM040), 60/40 (ACM060), 80/20 (ACM080, and 100/0 (ACM100) in distilled water without mordants at 60 °C, in 30 min

These results collectively confirm that, even without mordants, the anthocyanin pigments from PR extract do adsorb onto cotton fibers, imparting color. The direct relationship between extract concentration and color depth/difference highlights the importance of dye bath concentration in achieving desired color intensity. Nevertheless, the absence of mordants means the dye-fiber interaction might primarily rely on weaker physical forces (*e.g.*, H bonding), which typically results in lower dye exhaustion and potentially poorer wash/light fastness compared to mordanted dyeing processes. The continuous increase in K/S and ΔE with higher concentrations suggests that a saturation point for dye uptake without mordants has not been reached within the tested range, implying that higher concentrations would still yield darker shades, though potentially less efficiently. These results indicate that an optimal dye concentration can achieve sufficient color depth without excessive pigment use, thereby supporting resource efficiency and cleaner textile production.

Optimization of dyeing temperature and time for cotton fabrics

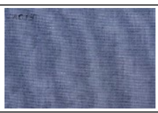
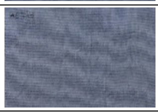
The dyeing performance of cotton fabrics with PR extracts under varying exhaust dyeing temperatures (30 °C to 75 °C) and dyeing durations (30 to 120 minutes) was analyzed using CIELAB color coordinates, color difference (ΔE), and color strength (K/S) values.

The temperature-dependent results in Table 1 demonstrate that as dyeing temperature increases from 30 °C to 75 °C, L* values slightly increase, indicating a trend toward lighter shades. It should be noted that the Moiré pattern visible in the sample photographs of Table 1 is merely a digital optical artifact resulting from the camera's interaction with the fabric's woven structure, rather than an indication of uneven dyeing (referring to Fig. 2). The a* and b* values, representing red/green and yellow/blue hues, respectively, shift slightly, suggesting minor changes in hue, but remaining within a similar color range. The ΔE values decrease from 49.02 (ACT30) to 45.34 (ACT75), implying a reduced perceptual color difference between the samples at higher temperatures. Similarly, K/S values, which indicate dye uptake or color depth, show a declining trend from 3.67 at 30 °C to 3.48 at 75 °C. This suggests that while higher temperatures may improve dye penetration and evenness (lower ΔE), they slightly reduce color depth, likely due to degradation or desorption of colorants at elevated temperatures.

Figure 3 presents the effect of dyeing duration (30 to 120 min) on ΔE and K/S. As dyeing time increases, both ΔE and K/S values rise. ΔE increases from 45.02 at 30 min (ACg30) to 46.86 at 120 min (ACg120), indicating a slightly greater deviation in color perception, possibly due to deeper shade development. The K/S values increase significantly, from 1.42 to 1.64, reflecting enhanced dye uptake over time. This aligns with diffusion-controlled dyeing behavior, where prolonged time facilitates better interaction between dye molecules and the fiber.

Table 1

ΔE and K/S values of cotton fabrics dyed with PR extracts at various temperatures (30, 45, 60 and 75 °C) at a DR of 80/20 in 30 min according to the CIELAB color space

Sample	Photos	L*	a*	b*	ΔE±SD	K/S±SD
ACT30		51.21	4.63	-17.07	49.02±0.01	3.67±0.02
ACT45		51.91	4.63	-15.10	47.64±0.03	3.59±0.01
ACT60		52.32	2.82	-12.92	46.58±0.02	3.55±0.03
ACT75		53.05	2.77	-10.77	45.34±0.01	3.48±0.01

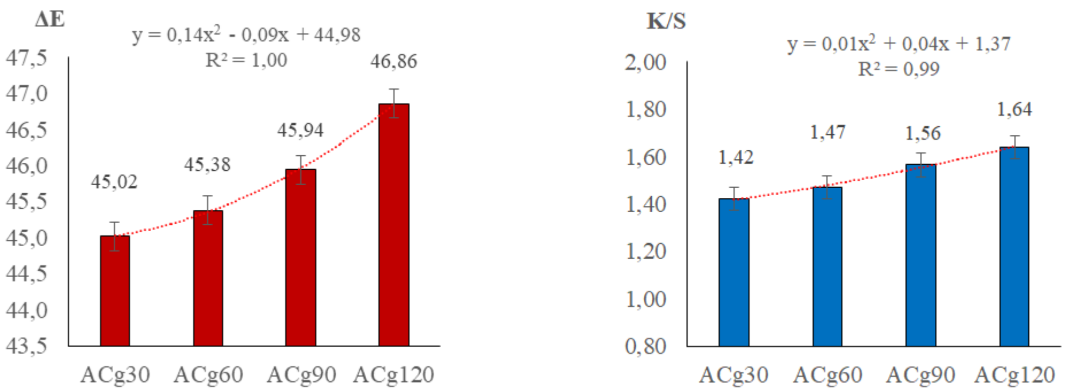


Figure 3: ΔE and K/S values of cotton fabrics dyed with PR extracts in 30, 60, 90 and 120 minutes at 60 °C and a DR of 80/20 (no pH adjustment), noted as ACg30, ACg60, ACg90 and ACg120, respectively

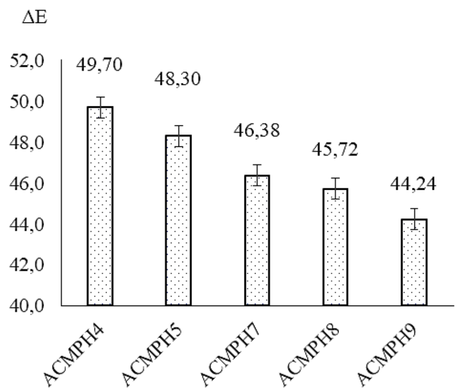


Figure 4: ΔE values of cotton fabrics dyed with PR extract at pH = 4, 5, 7, 8, and 9 at 60 °C, using a DR of 80/20 for 60 min, labelled as ACMPH4, ACMPH5, ACMPH7, ACMPH8 and ACMPH9, respectively

The regression equations with high R^2 values (1.00) for ΔE and for K/S (0.99) confirm the reliability of these polynomial fits, indicating a strong relationship between time and both color difference and strength. Obviously, dyeing cotton with PR extracts shows that lower temperatures yield deeper color strength but less uniformity, while longer dyeing times enhance both depth and noticeable color changes. Optimal dyeing conditions would thus balance temperature and time to achieve desirable shade and fastness. Accordingly, a dyeing temperature of 60 °C and a duration of 60 min were identified as optimal conditions, enabling effective dye uptake, while minimizing energy consumption, consistent with cleaner production principles.

Effect of pH on dye fixation and process sustainability

Figure 4 illustrates the ΔE values of cotton fabrics dyed with PR extracts under varying pH conditions, labeled as ACMPH4 through ACMPH9. ΔE quantifies the visual difference between colors; lower values indicate greater color uniformity and similarity to the target shade. From the chart, ΔE consistently decreases with increasing pH, starting at 49.70 at pH 4 and reducing to 44.24 at pH 9. This trend suggests that dyeing in more alkaline environments enhances color consistency and possibly better dye-fiber bonding. The most significant improvement occurs between pH 4 and pH 7, indicating a shift from unstable dye fixation in acidic media to more effective dye absorption under neutral to mildly alkaline conditions. Overall, the results indicate that a higher pH, particularly near pH 9, significantly influences the color strength (K/S values) and shade variations of the cotton fabric dyed with PR extracts. The use of mildly acidic to neutral pH conditions not only enhances dye fixation, but also reduces the need for strong chemicals, aligning the process with environmentally responsible textile manufacturing.

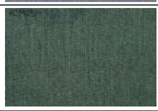
Role of mordants in optimizing dye fixation and cleaner production

Types of mordanting agents

Table 2 presents the influence of different mordants on the dyeing performance of cotton fabrics using PR extracts, evaluating ΔE, K/S, pH, and ORP. The control sample without mordant (ACMNO) showed a moderate K/S value of 3.60, suggesting a reasonable dye uptake under neutral pH (7.68) and a reducing environment (ORP -40.40 mV), which prevents the oxidation of the dye molecules and facilitates better dye exhaustion onto the fabric. As $KAl(SO_4)_2 \cdot 12H_2O$ was used as a mordant (ACMKA), ΔE value significantly decreased to 5.44, indicating high color uniformity. However, this came at the expense of color strength, with K/S value dropping to 3.23. The near-neutral pH (7.50) and moderate ORP (-29.10 mV) likely favored consistent, but less intense coloration. $CuSO_4 \cdot 5H_2O$, used in ACMCU, produced the highest K/S value of 4.40, indicating strong dye fixation and a deep shade, but it also resulted in the highest ΔE value of 19.32, reflecting a notable shift in hue, as observed in the greenish fabric appearance. The pH (7.53) and ORP (-30.40 mV) provided a favorable setting for dye-metal complex formation, enhancing depth but sacrificing color consistency. $Al_2(SO_4)_3 \cdot 18H_2O$, applied in ACMAL, resulted in moderate K/S value of 3.37 and a ΔE of 6.88, balancing dye uptake and color evenness. A slightly lower ORP (-

16.80 mV) may indicate weaker reducing conditions affecting bonding. Meanwhile, $FeSO_4·7H_2O$ in sample ACMFE led to a higher K/S value (3.67) and a ΔE of 9.78, producing a somewhat darker tone characteristic of iron mordants, which typically dull shades. The dyeing condition remained mildly reducing (ORP -28.20 mV) at pH 7.48. Overall, the use of mordants clearly modifies both the dye intensity and visual uniformity of PR-colored fabrics. While alum is effective for achieving consistent shades, copper sulfate enhances color strength but alters hue, and iron sulfate offers a good compromise between depth and stability.

Table 2
ΔE, K/S, pH and oxidation-reduction potential (ORP) values of the PR dye bath in the presence of mordants including $KAl(SO_4)_2.12H_2O$ (ACMKA), $CuSO_4.5H_2O$ (ACMCU), $Al_2(SO4)_3.18H_2O$ (ACMAL), $FeSO_4.7H_2O$ (ACMFE) at 60 °C, using a DR of 80/20 for 60 min, with a mordant concentration of 1.0% owf

Sample	Mordant	Photo	ΔE±SD	K/S±SD	pH	ORP
ACMNO	None		-	3.60±0.01	7.68	-40.40
ACMKA	$KAl(SO_4)_2.12H_2O$		5.44±0.04	3.23±0.01	7.50	-29.10
ACMCU	$CuSO_4.5H_2O$		19.32±0.01	3.40±0.01	7.53	-30.40
ACMAL	$Al_2(SO4)_3.18H_2O$		6.88±0.03	3.37±0.00	7.28	-16.80
ACMFE	$FeSO_4.7H_2O$		9.78±0.02	3.67±0.01	7.48	-28.20

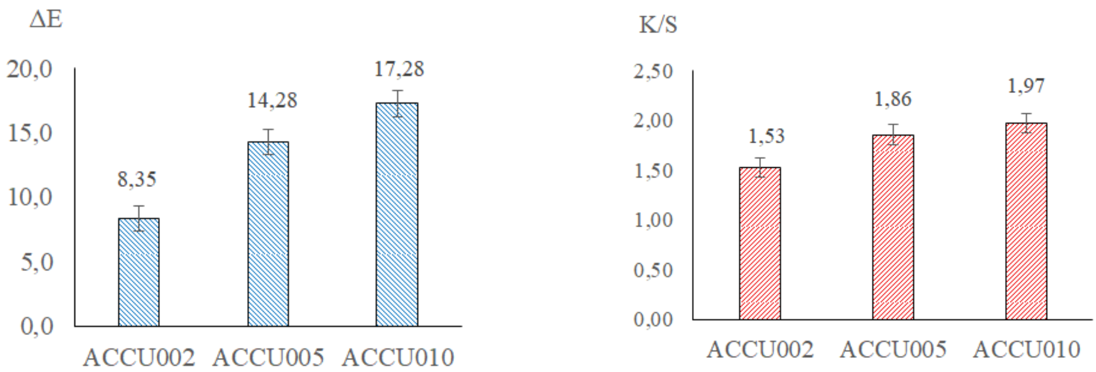


Figure 5: ΔE and K/S values of samples dyed at 0.2, 0.5 and 1.0% owf of $CuSO_4.5H_2O$ at 60 °C and a DR of 80/20 (no pH adjustment)

Impact of mordanting content on ΔE and K/S values

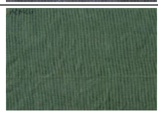
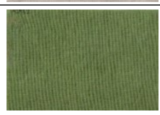
Figure 5 illustrates the influence of $CuSO_4·5H_2O$ mordant concentrations (0.2, 0.5 and 1.0% owf) on ΔE and K/S of cotton fabrics dyed with PR extracts. The results show a clear trend as the mordant concentration increases, both ΔE and K/S values rise significantly. At 0.2% owf (ACCU002), ΔE value is 8.35, indicating minimal color deviation, and K/S value is 1.53, reflecting moderate dye uptake. When the concentration increases to 0.5% owf (ACCU005), ΔE nearly doubles to 14.28, and K/S increases to 1.86, indicating enhanced dye absorption, but with greater deviation from the base shade. At the highest concentration of 1.0% owf (ACCU010), ΔE reaches 17.28, and K/S peaks at 1.97, demonstrating the most intense coloration, but with the least color uniformity. This suggests that higher $CuSO_4·5H_2O$ content promotes stronger dye-fiber interactions, possibly through complex formation, which improves dye fixation. However, it also alters the original color significantly. Thus, while increasing mordant concentration enhances color depth, it compromises color consistency. Optimal mordant levels should therefore balance between achieving deep coloration and maintaining desirable shade fidelity. These findings suggest that a moderate mordant concentration (0.5% owf) is sufficient to achieve optimal color strength and fastness, thereby avoiding excessive chemical usage and supporting cleaner production strategies.

Fixation of mordanting agents on cotton fabrics dyed with PR extracts under different washing conditions

While achieving satisfactory color strength is crucial, the practical application of natural dyes heavily depends on their durability. Therefore, the washing and rubbing fastness properties of the treated fabrics were assessed. The results presented in Table 3 and Figure 6 illustrate the effects of different mordants on the color fastness based on ΔE values and K/S values of cotton fabrics dyed with PR extract, both before and after washing. Four mordants were used as $KAl(SO_4)_2·12H_2O$ (KA), $Al_2(SO_4)_3·18H_2O$ (AL), $FeSO_4·7H_2O$ (FE), and $CuSO_4·5H_2O$ (CU). The ΔE values indicate the total color difference before and after washing. Among the mordants, KA showed the highest ΔE (33.82), followed by AL (31.56) and FE (25.34), suggesting that fabrics mordanted with these compounds experienced substantial color change after washing. In contrast, CU exhibited the lowest ΔE (14.64), implying better color retention and thus higher wash fastness. Before washing, $CuSO_4·5H_2O$ (CU) yielded the highest K/S value (2.40), indicating it provided the most intense coloration among the mordants tested. $FeSO_4·7H_2O$ (FE) also showed a relatively high initial K/S (1.67). However, after washing, the K/S values for KA, AL, and FE dropped significantly, particularly for FE, which fell to 0.40. This sharp decline correlates with their high ΔE values and indicates poor dye fixation. In contrast, K/S value of CU remained relatively high after washing (1.46), demonstrating better color retention and mordanting efficiency. This is consistent with its low ΔE value and visually less faded appearance, as shown in the image. Accordingly, $CuSO_4·5H_2O$ appears to be the most effective mordant among those tested, providing both strong initial coloration and superior color fastness to washing.

Table 3

ΔE values of cotton fabrics dyed with PR extract and mordanted with $KAl(SO_4)_2.12H_2O$ (KA), $Al_2(SO_4)_3.18H_2O$ (AL), $FeSO_4.7H_2O$ (FE), and $CuSO_4.5H_2O$ (CU) at a DR of 80/20, 60 °C, and 60 min (no pH adjustment), before and after washing

Sample	Mordants	Before	After	ΔE±SD
KA	$KAl(SO_4)_2.12H_2O$			33.82±0.01
AL	$Al_2(SO4)_3.18H_2O$			31.56±0.01
FE	$FeSO_4.7H_2O$			25.34±0.01
CU	$CuSO_4.5H_2O$			14.64±0.01

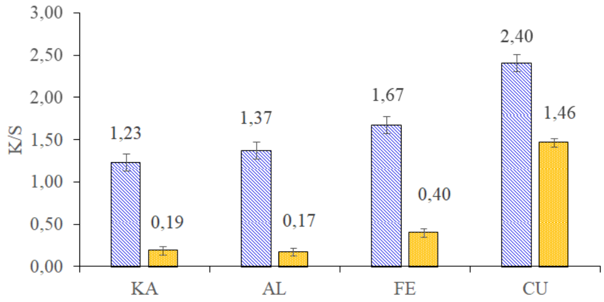


Figure 6: K/S values of cotton fabrics dyed with PR extract and mordanted with $KAl(SO_4)_2 \cdot 12H_2O$ (KA), $Al_2(SO_4)_3 \cdot 18H_2O$ (AL), $FeSO_4 \cdot 7H_2O$ (FE), and $CuSO_4 \cdot 5H_2O$ (CU), before and after washing

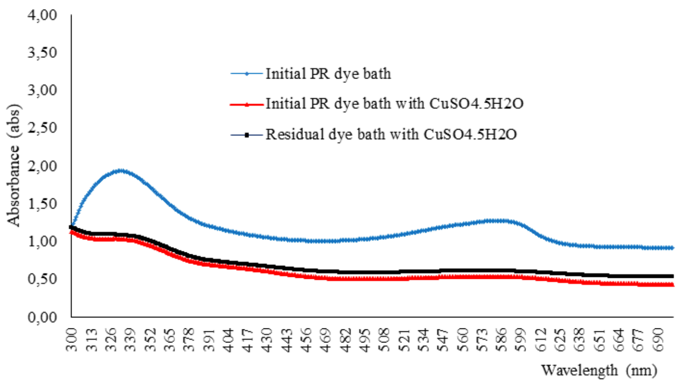


Figure 7: UV-Vis spectra of residual PR dye bath after dyeing cotton with 0.5% owf of $CuSO_4 \cdot 5H_2O$

Figure 7 presents the UV–vis spectra of the PR extract under three conditions: pure extract, extract with $CuSO_4 \cdot 5H_2O$, and extract with both $CuSO_4 \cdot 5H_2O$ and cotton fabric. The pure PR extract exhibits a pronounced absorption band in the near-UV region around 320-340 nm, along with a broad and relatively weak absorption tail extending across the visible range (approximately 350-650 nm). These features indicate the presence of chromophoric compounds, such as flavonoids and anthocyanins, whose conjugated systems enable π–π^* electronic transitions.

Upon addition of $CuSO_4 \cdot 5H_2O$, a clear decrease in absorbance intensity is observed across the entire wavelength range, particularly in the UV region, demonstrating a hypochromic effect. This behavior suggests the formation of dye–metal complexes through coordination between Cu^{2+} ions and functional groups, such as hydroxy or carboxy groups in the pigment molecules, leading to modifications in their electronic structure. When both $CuSO_4 \cdot 5H_2O$ and cotton fabric are introduced, the absorbance decreases further, indicating the depletion of dye species from the solution, which reflects the dye uptake by the fabric. This confirms effective dye uptake, likely facilitated by coordination interactions involving the metal ion, dye molecules, and cellulose functional groups. Overall, the observed spectral changes confirm the role of $CuSO_4 \cdot 5H_2O$ as an effective mordant and support the applicability of PR extract as a natural dye for cotton fabrics, contributing to improved dye fixation and potential fastness enhancement. Thus, $CuSO_4 \cdot 5H_2O$ at an optimized concentration offers an effective balance between color performance and environmental compatibility, reinforcing its suitability for sustainable cotton dyeing.

Effect of $CuSO_4 \cdot 5H_2O$ mordant concentration on color strength and fastness

Figure 8 and Table 4 illustrate the impact of mordant concentration and dilution ratios on the color difference and washing fastness of cotton fabrics dyed with PR extracts. Figure 8, a bar chart, displays the total color difference (ΔE) after a washing cycle for cotton samples dyed at 0.2, 0.5, and 1.0% owf of $CuSO_4.5H_2O$, labeled ACCU002, ACCU005, and ACCU010 respectively. The ΔE values are 24.62 for ACCU002, 20.84 for ACCU005, and 13.20 for ACCU010. This trend indicates that increasing the concentration of $CuSO_4.5H_2O$ as a mordant generally leads to a lower color difference after washing, suggesting improved color fastness at higher mordant concentrations. A lower ΔE signifies less color change, implying better retention of the original color after washing. Table 4 further elaborates on the washing fastness by comparing the color and color difference (ΔE) of cotton fabrics dyed with PR extracts at various DR of PR/H_2O, mordanted at 0.5% owf of $CuSO_4.5H_2O$. The table presents images of both unwashed and washed samples, along with their K/S values (for unwashed samples) and ΔE values for both unwashed and washed states. For unwashed samples, as the DR of PR/H_2O decreases (*i.e*., higher concentration of PR extract), the K/S values increase from 0.57 (20/80) to 2.19 (100/0), indicating a deeper color. Correspondingly, the ΔE values for the unwashed samples also increase significantly from 32.08 to 50.18, reflecting the substantial initial color achieved with higher PR extract concentrations. After washing, the ΔE values for all samples are significantly lower compared to their unwashed counterparts, ranging from 3.82 (20/80) to 23.22 (100/0).

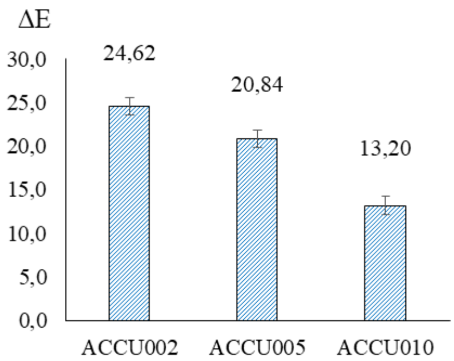


Figure 8: Color difference between cotton samples dyed at 0.2, 0.5 and 1.0% owf of $CuSO_4.5H_2O$ at a DR of 80/20, 60 °C, and 60 min (no pH adjustment), after a washing cycle

Table 4
Washing fastness of cotton fabrics dyed with PR extracts at different dilution ratios of PR/H_2O (20/80, 40/60, 60/40, 80/20, and 100/0) at a DR of 80/20, 60 °C, and 60 min (no pH adjustment)

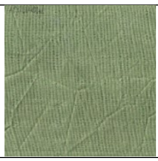
Sample	Dilution ratio (DR) of PR/H_2O with 0.5% owf of $CuSO_4.5H_2O$ mordant				
	20/80	40/60	60/40	80/20	100/0
Unwashed					
K/S±SD	0.57±0.01	1.39±0.00	1.70±0.00	1.96±0.01	2.19±0.01
ΔE±SD	32.08±0.02	43.90±0.01	46.56±0.01	48.54±0.01	50.18±0.01
Washed					
ΔE±SD	3.82±0.04	12.28±0.02	18.26±0.02	21.36±0.01	23.22±0.01

Table 6
Some physical properties of cotton fabrics dyed with PR extracts
(at a DR of 80/20, 60 °C for 60 min, no pH adjustment)

Physical properties	Original sample	Dyed sample	Change (%)
Moisture content (%)	5.35±0.02	4.95±0.02	- 7.42
Water permeability (m/s)	1.18±0.01	1.25±0.01	- 5.84
Crease recovery angle (°)	55.60±0.06	58.82±0.09	- 5.79
Flexural stiffness (g/cm)	0.04±0.02	0.05±0.02	- 8.53

This reduction in ΔE after washing, although present across all ratios, shows that while a higher concentration of the PR extract initially yields a deeper color, it also results in a greater color loss upon washing, as evidenced by the increasing ΔE values in the washed state with increasing PR extract concentration. Therefore, achieving a balance between initial color depth and washing fastness is crucial, with more dilute PR extract solutions demonstrating better color retention after washing, despite their lighter initial shade.

Impact of optimized dyeing conditions on fabric performance

To evaluate the effect of PR dyes on cotton fabrics, the physical properties were measured, such as moisture content, water vapor permeability, dry and wet rubbing fastness, crease recovery, and stiffness.

Table 6 presents a comparative analysis of cotton fabrics dyed with PR dyes against original samples. The physical properties examined include moisture content, water vapor permeability, crease recovery angle, and flexural stiffness, with changes expressed as percentages. Regarding moisture content, the original sample had a value of 5.35%, while the dyed sample showed a lower value of 4.95%. This corresponds to a decrease of -7.42%, indicating a reduction in moisture content after dyeing. For water vapor permeability, the original fabric measured 1.18 m/s, which increased to 1.25 m/s after treatment. This corresponds to a change of -5.84%, indicating an improvement in the fabric's ability to allow water vapor to pass through. The crease recovery angle, a measure recovery from creasing, was 55.60° for the original sample and improved to 58.82° for the dyed fabric. This change of -5.79% signifies that the PR dye treatment enhanced the crease recovery of fabric. Finally, the flexural stiffness, which indicates a fabric's resistance to bending, increased from 0.04 g/cm in the original sample to 0.05 g/cm in the dyed sample. This reflects a negative change of -8.53%, suggesting that the PR dye treatment made the fabric stiffer. In summary, the PR dye treatment appears to positively influence several key physical properties of cotton fabric. It leads to a minor decrease in moisture content, an improvement in water vapor permeability and crease recovery, and an increase in flexural stiffness. These alterations suggest that PR dyes can modify the handle and performance characteristics of cotton textiles, potentially offering benefits such as enhanced breathability and wrinkle resistance, albeit with a slight increase in stiffness. These results confirm that the optimized dyeing process preserves key fabric properties, ensuring functional performance while maintaining environmental sustainability.

Despite the promising results regarding the dyeing potential of PR extracts on cotton, several limitations of this study should be acknowledged. Firstly, the chemical composition and dye yield of natural extracts are inherently variable, depending on factors such as harvesting season and geographical origin. These variations can significantly affect color consistency and reproducibility, as pigment content is strongly influenced by plant phenology and environmental conditions.[18,19] Secondly, although simultaneous mordanting with $CuSO_4 \cdot 5H_2O$ significantly enhances color strength, the potential environmental risks associated with residual metal ions in dye effluents remain a critical concern, particularly for large-scale industrial applications where effective wastewater treatment and metal ion management are essential.[20] Finally, as the present work was conducted under controlled laboratory conditions, further investigations are required to evaluate process scalability, economic feasibility, and applicability in pilot-scale or continuous dyeing systems. To further contextualize the performance of the PR extract, its dyeing behavior on cotton was compared with that reported in previous studies using other plant-based colorants. Specifically, when evaluated against our earlier works utilizing extracts such as red cabbage pigments,[21] mangosteen rind,[22] and *Bougainvillea glabra* flowers[23] under similar mordanting conditions, the PR extract demonstrated highly competitive dyeing performance. While these plant-based dyes generally provided moderate color depth and acceptable washing fastness on cellulosic fibers, the application of PR extract in combination with $CuSO_4 \cdot 5H_2O$ in the present study resulted in enhanced color strength along with excellent washing and rubbing fastness properties. These findings highlight the strong potential of PR as an effective and sustainable natural dye, capable of delivering both high color performance and durability. Moreover, the improved dyeing efficiency observed in this study suggests that the PR extract may serve as a promising eco-friendly alternative to conventional natural dyes, contributing to the advancement of low-impact and sustainable textile coloration technologies.

CONCLUSION

This study demonstrates that optimized dyeing of cotton fabrics using *Peristrophe roxburghiana* (PR) leaf pigment can achieve high color strength and fastness, while reducing chemical usage and energy demand, supporting cleaner textile production. Optimal dyeing conditions (60 °C for 60 minutes at slightly acidic pH) were established, and the inclusion of 0.5% $CuSO_4 \cdot 5H_2O$ significantly improved dye uptake and fastness performance. The dyed fabrics exhibited stable physical properties, confirming their suitability for textile use. These outcomes suggest a strong potential for incorporating this natural pigment into eco-friendly textile processing. As environmental concerns intensify, such alternatives offer promising pathways for reducing chemical use and resource consumption in the dyeing industry. Future work should address the long-term durability of dyed textiles and the scalability of this method for industrial adoption.

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