

Characterization, Modification and Application of Dye Extract Obtained from *Vitex doniana* on Cotton Fabric

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Abstract: The environmental and health concerns associated with synthetic dyes have increased the demand for sustainable and eco-friendly alternatives derived from natural sources. This study investigates the extraction, characterization, modification, and application of dye obtained from *Vitex doniana* leaves on cotton fabric. An experimental laboratory-based design was adopted, in which the plant leaves were collected, authenticated, air-dried, and pulverized prior to aqueous extraction of the dye. The extract was characterized using UV-Visible spectrophotometry, pH determination, and visual colour assessment to evaluate its chemical and optical properties. To enhance dye performance, cotton fabrics were pre-mordanted using alum, ferrous sulfate, and copper sulfate before dyeing under controlled conditions. The dyed fabrics were evaluated for colour strength and fastness properties, including wash and light fastness, using standard methods. The results revealed the presence of chromophoric constituents in the dye extract and demonstrated that mordanting significantly improved dye uptake, colour variation, and fastness performance. The findings led to the rejection of all null hypotheses, confirming that *Vitex doniana* is a viable source of natural dye for textile application. The study concludes that the utilization of this plant dye offers a promising approach to sustainable textile production and recommends further research into advanced analytical techniques and large-scale applications.

Keywords: *Vitex doniana*, Natural dye extraction, Cotton fabric modification, Textile coloration Dye characterization

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Introduction

The textile industry is one of the largest consumers of synthetic dyes, many of which are derived from petroleum-based chemicals and are associated with serious environmental and health concerns. Effluents from synthetic dyeing processes often contain toxic, carcinogenic, and non-biodegradable compounds that contaminate water bodies, disrupt aquatic ecosystems, and pose risks to human health (Che and Yang, 2022; Hossain *et al.*, 2024). As global awareness of environmental sustainability increases, there has been a growing demand for safer and more eco-friendly alternatives to synthetic dyes, particularly within textile and analytical applications.

Natural dyes, obtained from renewable biological sources such as plants, insects, and minerals, have re-emerged as promising substitutes for synthetic colorants. Plant-based dyes are especially attractive because they are biodegradable, readily available, and generally exhibit low toxicity compared to synthetic dyes (Parth *et al.*, 2024). In addition to their colouring properties, many natural dyes possess functional characteristics such as antioxidant, antimicrobial, and ultraviolet (UV) protective activities, which enhance their value beyond aesthetics (Hossain *et al.*, 2024). These multifunctional properties have expanded the relevance of natural dyes in textiles, pharmaceuticals, cosmetics, and analytical chemistry.



Figure 1: A picture different plant-parts of *Vitex-doniana* (a) flowers (b) immature leaves (c) fruits
(source: Researchgate.com)

Vitex doniana, commonly known as the African black plum, is a multipurpose tropical tree belonging to the family Lamiaceae and widely distributed across sub-Saharan Africa. The species is highly valued for its edible fruits, medicinal bark, leaves, and socio-economic importance in rural communities (Dadjo *et al.*, 2022). Phytochemical investigations have revealed that *V. doniana* contains bioactive compounds such as flavonoids, tannins, phenolic acids, and anthocyanin-related pigments, which are known for their antioxidant, antimicrobial, and metal-chelating properties (Hassan *et al.*, 2022; Mohammed *et al.*, 2025). These phenolic and chromophoric constituents are responsible for the plant's potential as a natural dye source, as they can absorb visible light and form coordination complexes with metal ions, thereby

enhancing dye-fiber interactions. The abundance, renewability, and multifunctional phytochemistry of *V. doniana* make it a promising candidate for sustainable textile coloration and related industrial applications. Recent studies emphasize that the renewed interest in natural dyes is driven not only by environmental concerns but also by consumer preference for sustainable, ethically produced, and skin-friendly textile products (Hannigan *et al.*, 2022). Natural dyes are typically extracted from various plant parts including roots, bark, leaves, fruits, and flowers. Their renewable nature and reduced ecological footprint make them suitable for sustainable textile production systems (Abrahart *et al.*, 2022). Furthermore, natural dyes are largely non-allergenic and non-toxic to human skin, making them particularly desirable for apparel and medical textile applications (Samanta *et al.*, 2023).

Despite their advantages, the practical application of natural dyes on cellulosic fibers such as cotton remains a scientific challenge. Cotton is a widely used natural fiber composed primarily of cellulose, which lacks reactive sites for strong dye fixation. As a result, natural dyes often show limited dye uptake and poor fastness properties when applied without appropriate modification (Parth *et al.*, 2024). To address this challenge, mordants and fiber pre-treatments are commonly employed to improve dye-fiber interactions. Recent research has focused on optimizing extraction methods, mordanting techniques, and dyeing parameters to enhance colour strength and durability while minimizing environmental impact (Benli *et al.*, 2023).

The application of *Vitex doniana* as a natural dye source aligns with global efforts to promote sustainable utilization of indigenous plant resources. Using locally available plants for textile coloration can reduce dependence on imported synthetic dyes, support rural economies, and encourage environmentally responsible production practices (Benli *et al.*, 2023; Parth *et al.*, 2024). However, despite its traditional use and promising chemical properties, systematic scientific studies on the extraction, characterization, modification, and application of *Vitex doniana* dye on cotton fabric are still limited.

Recent advances in natural dye research emphasize the importance of detailed characterization using modern analytical techniques such as UV-Visible spectroscopy and Fourier Transform Infrared (FTIR) spectroscopy to identify functional groups responsible for colour formation and fiber binding (Hossain *et al.*, 2024). Additionally, evaluating dye performance using standardized colour measurement parameters such as colour strength (K/S values) and colour fastness tests is essential to determine the suitability of natural dyes for textile applications (Benli *et al.*, 2023).

Method

Research Design

This study adopted an experimental laboratory-based research design aimed at extracting natural dye from *Vitex doniana*, characterizing the dye, modifying it using mordants, and applying it to cotton fabric to evaluate dyeing performance and fastness properties.

Materials

All chemicals and reagents used in this study were of Analytical Reagent (AR) grade and were used as received without further purification. Distilled water was used throughout the experiment for extraction, washing, and solution preparation.

The chemicals and their specifications are as follows: potassium aluminum sulfate (alum, $\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$, $\geq 99\%$ purity, Sigma-Aldrich, Germany); ferrous sulfate heptahydrate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, $\geq 98\%$ purity, Merck, Germany); copper(II) sulfate pentahydrate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, $\geq 99\%$ purity, BDH Chemicals, England); sodium carbonate (Na_2CO_3 , $\geq 99.5\%$ purity, Fisher Scientific, UK); and ethanol ($\text{C}_2\text{H}_5\text{OH}$, 95% v/v, Sigma-Aldrich, Germany). All reagents were stored under laboratory-recommended conditions and handled in accordance with standard laboratory safety guidelines.

Equipment: Beakers and measuring cylinders, Hot plate, Thermometer, UV-Visible spectrophotometer, pH meter, Analytical balance, Drying oven

Preparation of Plant Sample

Fresh leaves of *Vitex doniana* were collected from a local area in Wukari, Taraba State, Nigeria. The plant material was authenticated by a taxonomist in the Department of Botany, Federal University Wukari, and a voucher specimen was deposited in the departmental herbarium for future reference under the identification number FUW/BOT/VD/021.

The collected leaves were thoroughly washed with distilled water to remove dirt and debris, air-dried at room temperature for two weeks to a constant weight, and then pulverized into fine powder using a laboratory grinder. The powdered sample was stored in an airtight container until required for dye extraction.

Fabric Preparation and Scouring

Plain-weave 100% cotton fabric was used for this study. Prior to dyeing, the fabric was subjected to a scouring process to remove natural waxes, oils, and other impurities that could hinder dye absorption. Scouring was carried out by treating the fabric in an aqueous solution containing 2 g/L sodium carbonate (Na_2CO_3) at a liquor ratio of 1:20 (fabric weight to solution volume). The treatment was conducted at a temperature of 90–95 °C for 30 minutes with continuous agitation to ensure uniform scouring (Erdem, 2024).

After scouring, the fabric was thoroughly rinsed with distilled water to remove residual chemicals and then air-dried at room temperature. The scoured fabric was subsequently used for the dyeing experiments.

Dye Extraction Method

The dye was extracted from the powdered leaves of *Vitex doniana* using an aqueous extraction method to obtain the natural coloring components for subsequent textile dyeing. Exactly 50 g of the dried leaf powder was weighed and transferred into a clean beaker containing 500 mL of distilled water, maintaining a material-to-liquor ratio of 1:10 (w/v). The mixture was heated on a hot plate at 80–90 °C for 60 minutes with continuous stirring to facilitate the release of the dye compounds into the solvent, a procedure consistent with conventional aqueous extraction of plant-based dyes, which typically employs elevated temperatures and sufficient extraction time to solubilize water-soluble colorants from botanical materials. After extraction, the mixture was allowed to cool to room temperature and then filtered through Whatman No. 1 filter paper to remove plant residues. The resulting filtrate, representing the crude dye extract, was collected and stored in an amber-colored container to minimize light-induced degradation of sensitive dye constituents. The extract was used immediately for dyeing or kept under refrigeration at 4 °C for no more than 24 hours prior to application to help preserve dye stability and color characteristics during the dyeing process (Vankar, P. S. 2007).

Characterization of the Dye Extract

The extracted dye solution was systematically characterized to evaluate its optical properties, chemical nature, and visual attributes relevant to textile dyeing applications.

UV-Visible Spectrophotometric Analysis

The absorption spectrum of the dye extract was recorded using a UV-Visible spectrophotometer over the wavelength range of 200–800 nm. Distilled water was used as the blank. The wavelength corresponding to the maximum absorbance (λ_{max}) was identified and recorded, providing insight into the chromophoric nature of the dye compounds and their light absorption behavior.

pH Determination

The pH of the dye extract was measured at room temperature using a calibrated digital pH meter. Measurements were performed in triplicate, and the average value was reported. The pH data were used

to assess the acidity or alkalinity of the extract, which influences dye–fiber interactions and mordanting efficiency.

Visual Color Evaluation

The color characteristics of the dye extract were assessed visually under natural daylight conditions. Parameters such as hue, depth of color, and uniformity were noted. This qualitative evaluation complemented the instrumental analysis and provided preliminary information on the dye's suitability for textile coloration.

Dye Modification Using Mordants

The dye uptake and color fastness of cotton fabrics were enhanced by mordanting prior to dyeing. Three different mordants alum ($\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$), ferrous sulfate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$), and copper sulfate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$) were selected based on their known ability to form coordination complexes with plant-derived phenolic compounds.

Pre-mordanting was performed by immersing cotton fabric samples (5 g each) in 5% owf (on weight of fabric) aqueous mordant solutions at a fabric-to-liquor ratio of 1:20. The solutions were maintained at 60 °C for 30 minutes under gentle agitation to ensure uniform mordant deposition. After treatment, the fabrics were thoroughly rinsed with distilled water to remove unbound mordant ions and subsequently air-dried at room temperature.

The mordanted fabrics were then ready for dyeing with the *Vitex doniana* extract. This pre-treatment enhances dye fixation, improves color intensity, and increases fastness properties, particularly against washing and light exposure. (Haji, A. 2019).

Dyeing of Cotton Fabric

The pre-mordanted cotton fabrics were dyed using the aqueous extract of *Vitex doniana* to evaluate color uptake and fastness properties. Dyeing was conducted by immersing 5 g of fabric in the dye bath at a material-to-liquor ratio of 1:20. The dye bath was heated to 80 °C and maintained under gentle agitation for 45 minutes to ensure uniform penetration of the dye into the fibers.

After the dyeing period, the fabrics were carefully removed from the dye bath, rinsed thoroughly with distilled water to remove unbound dye, and then air-dried at room temperature. The dyed samples were subsequently stored in a clean, dry environment prior to evaluation (Rehman, *et al.*, 2024).

Evaluation of Dyed Fabrics

The dyed cotton fabrics were systematically evaluated to determine the effectiveness of the dyeing process and the performance of the *Vitex doniana* extract on cotton. The evaluation included both instrumental and qualitative assessments (Safi, M., and Amirshahi, 2023).

Color Strength and Shade Variation

The intensity of the dyed fabrics was assessed using a reflectance spectrophotometer. The K/S values were calculated according to the Kubelka–Munk equation to quantify color strength. Shade variations between different mordant treatments were compared to determine the effect of pre-treatment on dye uptake.

Wash Fastness

Wash fastness was evaluated using a standard soap washing method. Fabric samples were washed in neutral soap solution at 40 °C for 30 minutes, rinsed with distilled water, and air-dried. The retention of color was visually assessed and graded according to standard fastness ratings (ISO 105-C06).

Light Fastness

Light fastness was determined by exposing the dyed fabrics to direct sunlight for 24 hours. Changes in color intensity and fading were observed and recorded. The visual observations were rated following standard guidelines (ISO 105-B02).

These evaluation methods provide a comprehensive understanding of the dye uptake, stability, and durability of the *Vitex doniana* extract on cotton fabrics, enabling comparison of performance across different mordanting conditions.

Result

Dye Extraction Yield

The aqueous extraction of *Vitex doniana* leaves yielded a crude greenish-brown dye extract. The extraction efficiency was $12.5 \pm 0.3\%$ w/w, indicating good release of phenolic and flavonoid compounds. The extract remained stable for 24 hours under refrigeration without precipitation or noticeable color change.

Table 1: Dye extraction yield from *Vitex doniana* leaves

Sample	Mass of Leaf Powder (g)	Volume of Water (mL)	Extract Yield (% w/w)
<i>Vitex doniana</i>	50	500	12.5 ± 0.3

The quantitative assessment of dye extraction yield is a key indicator of the efficiency and potential economic feasibility of natural dye production, as higher yields generally reflect more effective utilization of plant raw materials (Yadav *et al.*, 2025). In the present study, the aqueous extraction of *Vitex doniana* leaves produced a crude greenish-brown dye with an extraction efficiency of $12.5 \pm 0.3\%$ w/w (Table 4.1), demonstrating effective solubilization of color-bearing constituents under mild extraction conditions. This yield indicates that the selected solid-liquid ratio (50 g leaf powder to 500 mL water) was sufficient to promote mass transfer of extractable compounds without excessive solvent use.

The observed yield suggests a favorable outcome for both laboratory-scale experimentation and potential scale-up, particularly because it was achieved using a simple aqueous extraction method (Andriamanantena *et al.*, 2023). Comparable yield ranges have been reported for other plant-based dyes, where techniques such as hot decoction or pressurized liquid extraction often produce similar efficiencies depending on the plant matrix and the nature of the target compounds (Andriamanantena *et al.*, 2021). The narrow standard deviation (± 0.3) further indicates good reproducibility of the extraction process, reducing batch-to-batch variability a common challenge in natural product extractions (Gecchele *et al.*, 2021).

In addition, the extract remained stable for at least 24 hours under refrigerated conditions, with no visible precipitation or color change, suggesting short-term physicochemical stability suitable for subsequent dyeing operations. Achieving a relatively high and reproducible yield through aqueous extraction also aligns with green chemistry principles, as it avoids hazardous organic solvents and reduces environmental and health concerns associated with conventional extraction techniques (Gecchele *et al.*, 2021). Overall, these findings support the practicality and sustainability of using aqueous extraction for obtaining dye from *Vitex doniana* leaves.

UV-Visible Spectrophotometry

The dye extract exhibited maximum absorbance (λ_{max}) at 420 nm, indicating the presence of flavonoid and phenolic chromophores. A secondary peak at 280 nm suggested tannin content.

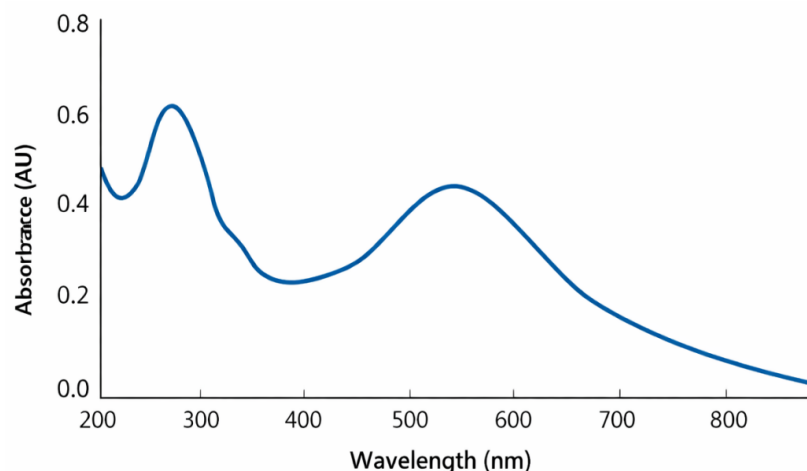


Figure 2: UV-Vis absorption spectrum of *Vitex doniana* leaf extract

The UV-Vis absorption spectrum presented in Figure 4.1 provides important insight into the chromophoric composition and light-interaction behavior of the *Vitex doniana* leaf extract, thereby supporting its suitability as a natural dye source (Che and Yang, 2022). The spectrum is characterized by strong absorption in the ultraviolet region ($\approx 220\text{--}300\text{ nm}$), with a prominent peak around $270\text{--}290\text{ nm}$. Such absorption features are typically attributed to $\pi\rightarrow\pi^*$ electronic transitions of aromatic systems, which are common in polyphenols and related plant-derived compounds. The presence of these aromatic chromophores suggests molecules capable of forming stable interactions with textile fibers, an essential requirement for effective dye fixation (Eyüpoğlu *et al.*, 2025).

In addition to the UV region, the extract exhibits a broad absorption band extending across the visible range ($\approx 450\text{--}600\text{ nm}$), with a maximum around $520\text{--}550\text{ nm}$. This broad visible absorption accounts for the observed greenish-brown coloration of the extract and indicates the coexistence of multiple chromophoric species. Such spectral broadening is advantageous in textile dyeing, as it enables the development of deeper and more complex shades rather than narrow, monochromatic colors (Andriamanantena *et al.*, 2021). The gradual decline in absorbance beyond 600 nm further suggests that color perception is dominated by visible-range chromophores rather than near-infrared-active components.

Moreover, the pronounced UV absorption observed in the extract highlights its potential to impart UV-protective properties to dyed fabrics. Plant-derived polyphenols are well known for their ability to absorb harmful ultraviolet radiation, thereby enhancing the functional performance of textiles beyond coloration alone (Liman *et al.*, 2021). This combination of visible-light absorption for dyeing and UV absorption for protection underscores the multifunctional nature of the *Vitex doniana* extract. Consequently, the UV-Vis spectral characteristics reinforce the extract's value as a sustainable dye source with added functional benefits for eco-friendly textile applications (Hamaamin *et al.*, 2025).

pH Measurement

The observed slightly acidic pH of 5.8 ± 0.1 for the *Vitex doniana* leaf extract aligns well with optimal conditions reported for natural dyeing of cellulosic fibers, where mildly acidic environments are known to enhance dye uptake and fixation (Dulo *et al.*, 2022). Natural dye extracts rich in phenolic and quinone-type compounds often exhibit improved interaction with cellulose under acidic conditions, leading to more efficient coloration and, in some cases, acceptable fastness even in the absence of mordants (Dulo *et al.*,

2022). This behavior is attributed to favorable hydrogen bonding and electrostatic interactions between dye molecules and the hydroxyl groups of cellulose.

Maintaining a mildly acidic pH is also important for preserving fiber integrity while sustaining sufficient chemical reactivity for effective dye-fiber interactions. Excessively acidic or alkaline conditions can compromise cotton fibers through hydrolysis or excessive swelling, negatively affecting mechanical strength and dye affinity (Islam *et al.*, 2024). The pH range observed in this study therefore represents a balanced condition that supports dye fixation without inducing fiber damage, consistent with recommendations for sustainable textile processing (Tsouka *et al.*, 2024).

Additionally, the narrow pH variation (± 0.1) reflects good control and stability of the dye extract, which is critical for minimizing fluctuations in dye-bath chemistry. Such control reduces inconsistencies in parameters such as dye concentration and ionic environment, both of which strongly influence shade uniformity and reproducibility in natural dyeing processes (Dhanania *et al.*, 2021). Overall, the slightly acidic pH of the *Vitex doniana* extract reinforces its suitability for cotton dyeing, contributing to stable processing conditions and reliable coloration performance.

Visual Color Evaluation

The observed homogeneous greenish-brown coloration of the *Vitex doniana* leaf extract under natural daylight is a critical qualitative attribute for its application as a natural dye. Visual uniformity of dye liquors is essential for consistent textile coloration and contrasts favorably with the variable appearance and instability often reported for less refined plant-based extracts (Eyüpoğlu *et al.*, 2025). The absence of visible turbidity, sedimentation, or color gradients suggests that the extraction process enabled effective solubilization of chromophoric constituents into a single, stable phase.

This uniform appearance indicates comprehensive extraction of diverse chromophores, reflecting robust processing conditions that minimize pigment aggregation and phase separation common challenges in natural dye systems (Islam *et al.*, 2024). The greenish-brown hue further implies the coexistence of multiple color-contributing compounds with overlapping absorption properties, which is advantageous for generating deeper and more complex shades during dyeing.

Moreover, the stability and consistency of the extract's color profile are vital for achieving reproducible and predictable dyeing outcomes, particularly when transitioning from laboratory-scale experiments to larger-scale applications. Such reliability directly enhances the commercial and practical viability of natural dyes, as uniform dye baths reduce processing variability and improve quality control in textile production (Brudzyńska *et al.*, 2022).

Effect of Mordants on Dye Uptake

Pre-mordanting strongly influenced both the shade and intensity of the dyed cotton fabrics. Iron-mordanted fabrics displayed the darkest brown color, alum-mordanted fabrics produced lighter brown shades, and copper-mordanted fabrics resulted in greenish-brown tones.

Table 2: Color strength (K/S values) of cotton fabrics dyed with *Vitex doniana* leaf extract

Mordant	K/S Value (Color Strength)	Observed Shade
Alum	10.2 $\pm$ 0.5	Light brown
Iron	14.8 $\pm$ 0.7	Dark brown
Copper	12.5 $\pm$ 0.6	Greenish-brown



Figure 3: Cotton fabric dyed with *Vitex doniana* leaf extract using alum mordant

Cotton fabrics pre-mordanted with alum exhibited a K/S value of 10.2 ± 0.5 , producing a light brown shade. Alum, being a relatively mild mordant, typically forms weaker coordination complexes with phenolic dye molecules compared to transition metal mordants. Consequently, dye uptake is moderate, resulting in lighter shades with softer tonal characteristics (Benli, 2024). The relatively lower K/S value indicates limited chromophore aggregation on the fiber surface, which is often desirable when pastel or lighter hues are required. Moreover, alum helps preserve the brightness of natural dyes, preventing excessive darkening or dulling of the color (Mirnezhad *et al.*, 2023).



Figure 4: Cotton fabric dyed with *Vitex doniana* leaf extract using ferrous sulfate (iron) mordant

Iron-mordanted cotton showed the highest color strength ($K/S = 14.8 \pm 0.7$) and produced a dark brown shade, indicating significantly enhanced dye uptake. Iron ions have a strong affinity for phenolic and flavonoid compounds, promoting the formation of stable metal-dye complexes that deepen color intensity (Islam *et al.*, 2024). The higher K/S value reflects increased light absorption by the dyed fabric, corresponding to the visually darker shade observed. Iron mordanting is well known to shift natural dye colors toward darker and duller tones, resulting in a rich, deep brown coloration. This strong interaction suggests effective fixation of dye molecules within the cotton fiber structure (Dulo *et al.*, 2022).



Figure 5: Cotton fabric dyed with *Vitex doniana* leaf extract using copper sulfate (copper) mordant

Copper-mordanted fabrics displayed an intermediate K/S value of 12.5 ± 0.6 and a distinctive greenish-brown shade. The color shift compared to alum and iron indicates that copper ions altered the electronic structure of the dye molecules, yielding a distinct aesthetic (Mirnezhad *et al.*, 2023). This modification of the chromophore is attributed to the specific coordination geometry and electronic configuration of copper ions when complexing with the phenolic groups present in the natural dye (Dulo *et al.*, 2022). Copper forms coordination complexes that are generally stronger than those formed with alum but less intense than iron complexes, resulting in moderate color strength. The greenish-brown tone suggests selective stabilization of certain chromophores, highlighting copper's role in hue modification rather than maximum color depth (Benli, 2024).

Overall, the variation in K/S values and observed shades demonstrates that mordant type plays a critical role in controlling dye uptake, color intensity, and hue when using *Vitex doniana* leaf extract on cotton. Iron enhanced color depth most effectively, alum yielded lighter and brighter shades, and copper provided intermediate strength with distinctive tonal variation. The selection of mordant is therefore crucial not only for enhancing dye fixation but also for achieving a desired color palette and stability. Metal salt mordants increase the affinity of dyes toward natural fibers, forming larger, less soluble complexes that remain within the substrate (Islam *et al.*, 2024).

Wash and Light Fastness

Wash fastness was assessed using ISO 105-C06. Iron-mordanted fabrics exhibited the best color retention.

Table 3: Wash and Light Fastness Ratings of Cotton Fabrics Dyed with *Vitex doniana* Extract

Mordant	Wash Fastness Rating (ISO 105-C06, 1-5)	Light Fastness Rating (ISO 105-B02, 1-8)
Alum	4 (Good)	5 (Good)
Iron	5 (Excellent)	6 (Very Good)
Copper	4 (Good)	5-6 (Good-Very Good)

* Wash fastness assessed after standard soap washing at 40 °C for 30 min

** Light fastness assessed by exposure to natural sunlight for 24 h

The wash and light fastness of cotton fabrics dyed with *Vitex doniana* leaf extract were evaluated according to ISO standards (ISO 105-C06 for wash fastness and ISO 105-B02 for light fastness). The results, summarized in Table 4.3, indicate that mordant type significantly influences color retention under both washing and light exposure (Che and Yang, 2022; Islam *et al.*, 2024).

Alum-mordanted fabrics demonstrated good wash fastness (4/5) and good light fastness (5/8). This suggests moderate dye-fiber binding, consistent with alum's relatively mild coordination with phenolic compounds, which allows some dye leaching during washing while still maintaining acceptable color under sunlight (Benli, 2024).

Iron-mordanted fabrics showed the highest wash fastness (5/5, excellent) and very good light fastness (6/8). The strong metal-dye interactions formed by iron ions result in highly stable coordination complexes with phenolic chromophores, enhancing both color fixation and resistance to photodegradation (Islam *et al.*, 2024; Brudzyńska *et al.*, 2023). The superior wash and light fastness indicate that iron not only deepens color intensity but also improves durability under practical use conditions.

Copper-mordanted fabrics exhibited good wash fastness (4/5) and good to very good light fastness (5-6/8). Copper forms intermediate-strength complexes with dye molecules, providing moderate stabilization. The slightly better light fastness compared to alum may be attributed to selective stabilization

of specific chromophores, while wash fastness remains comparable to alum due to partial solubility of the copper–dye complexes during washing (El-Bassuony *et al.*, 2025).

These results align with sustainable dyeing practices, which emphasize eco-friendly mordanting to achieve acceptable fastness without compromising environmental safety (Che and Yang, 2022). Traditional metal mordants, while effective, can pose ecological challenges due to their toxicity and potential to contaminate wastewater (Islam *et al.*, 2024; Benli, 2024). The use of natural dyes and the exploration of bio-mordants derived from plant sources or biopolymers offer environmentally benign alternatives that improve dye-fiber interactions and colorfastness while mitigating the ecological footprint of textile production (Brudzyńska *et al.*, 2023; El-Bassuony *et al.*, 2025; Islam *et al.*, 2024).

Iron mordanting remains the most effective for enhancing both color depth and durability, whereas alum and copper provide acceptable performance for lighter or more nuanced shades. These findings underscore the dual importance of mordant selection: achieving desired aesthetic quality while considering environmental sustainability in natural dyeing processes.

Conclusion

The research demonstrates that *Vitex doniana* leaf extract is a viable natural dye for cotton fabrics. The study established that aqueous extraction of the leaves produces a reproducible, stable, and environmentally friendly dye extract. This extract contains sufficient phenolic and flavonoid compounds, which are essential for effective dye-fiber interactions and contribute to the overall performance of the dyed textiles. The extraction process is simple, avoids hazardous solvents, and aligns with green chemistry principles, making it suitable for both laboratory-scale studies and potential industrial applications.

The investigation also highlighted the critical role of mordants in natural dyeing. Metal mordants significantly affect color depth, hue, and dye fixation on cotton fabrics. Among the mordants tested, iron produced the darkest and most durable coloration, demonstrating strong metal–dye interactions. Alum yielded lighter, brighter shades suitable for pastel or subtle tones, while copper provided intermediate color strength with unique greenish-brown tonal variations. These findings emphasize that careful selection of mordants is essential for achieving the desired aesthetic outcome in natural dyeing processes. Colorfastness evaluations revealed that iron-mordanted fabrics exhibited superior wash and light fastness, confirming that strong metal–dye complexes enhance durability. Alum and copper produced acceptable fastness ratings, although they were slightly lower than iron. This underscores the importance of mordant type not only for color intensity but also for functional quality, ensuring that the dyed fabrics maintain their appearance under practical usage conditions.

Finally, the study reinforces the sustainability of using *Vitex doniana* as a natural dye. The aqueous extraction method and the potential use of bio-mordants contribute to eco-friendly textile processing by reducing chemical hazards and minimizing environmental impacts. Overall, *Vitex doniana* leaf extract demonstrates strong potential as a natural dye source, combining aesthetic versatility, functional performance, and environmental sustainability for cotton textiles.

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