ASIAN J NAT PROD BIOCHEM
Volume 23, Number 2, December 2025
Pages: 153-163

P-ISSN: 2775-4189
E-ISSN: 2775-4197
DOI: 10.13057/biofar/f230207

Natural dye plants in traditional batik production and their potential as plant-derived pigments

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Manuscript received: 20 September 2025. Revision accepted: 24 December 2025.

Abstract. *Hapsari AN, Nurrizqi AY, Nurrosidah AN, Maharani AC, Indrawan M, Saensouk S, Setyawan AD. 2025. Natural dye plants in traditional batik production and their potential as plant-derived pigments. Asian J Nat Prod Biochem 23: 153-163.* Plant-derived natural dyes have attracted renewed interest as alternative pigment sources due to growing concerns over the environmental and health implications of synthetic dyes. Traditional dyeing practices offer process-based systems in which pigment extraction, transformation, and application are achieved using low-input operational controls. This study documents plant species used as natural dyes in traditional batik production at Batik Tjap Tiga Negeri, Laweyan Batik Village, Surakarta, Central Java, Indonesia, and discusses their relevance as plant-derived pigment sources within a natural product and biochemical context. Observations were conducted during active dye production to record plant species utilized, plant parts used, extraction methods, dye application procedures, and handling of residual materials. A total of seven plant species were identified as components of the dyeing system, including *Indigofera tinctoria*, *Caesalpinia sappan*, *Cudrania javanensis*, *Swietenia mahagoni*, *Symplocos fasciculata*, *Tectona grandis*, and *Acacia* spp. Dye extraction involved fermentation or aqueous heat-based processes, while dye application relied on repeated dipping and drying cycles. Variation in color intensity was associated with differences in dyeing duration and the number of application cycles. The results indicate that traditional dyeing systems function as low-input pigment processing frameworks in which color outcomes are regulated through process variables such as fermentation, pH adjustment, and repeated application. Literature-based synthesis further shows that the documented dye plants are associated with reported pigment classes, including indigoids, homoisoflavonoids, flavonoid-related pigments, and tannin-rich polyphenols. Although no chemical analyses were performed, the study highlights traditional dyeing systems as low-input pigment processing models and identifies candidate plant sources for future biochemical characterization and natural product research.

Keywords: Batik dyeing, natural pigments, plant-derived dyes, process-controlled coloration, traditional dyeing systems

INTRODUCTION

Synthetic dyes have been extensively used in the textile industry due to their color uniformity, reproducibility, and high production efficiency. However, their widespread application has raised serious environmental and health concerns, particularly related to the release of non-biodegradable effluents, high Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), and the formation of toxic aromatic amines during degradation (Ardila-Leal et al. 2021; Al-Tohamy et al. 2022; Islam et al. 2023). These issues have motivated increasing regulatory pressure and scientific interest in developing safer and more sustainable alternatives for textile coloration. Recent studies emphasize that synthetic dye residues contribute significantly to aquatic toxicity and long-term ecosystem degradation, especially in regions dominated by small-scale textile industries with limited wastewater treatment infrastructure (Moreira et al. 2022; Periyasamy 2024).

In response to these challenges, plant-derived natural pigments have re-emerged as promising alternatives due to their renewable origin, lower toxicity, and potential biodegradability. Advances in green chemistry and sustainable materials research highlight natural pigments as key components in environmentally responsible production systems (Fried et al. 2022; Pizzicato et al. 2023; Renita et al. 2023). In addition to their environmental advantages, plant-based pigments are increasingly valued for their aesthetic complexity and compatibility with eco-friendly processing routes. Reviews published in some scientific journals consistently report growing scientific and industrial interest in natural colorants derived from higher plants (Bechtold and Mussak 2009; Shahid et al. 2013).

Despite these advantages, the large-scale adoption of natural pigments remains constrained by variability in color yield, stability, and processing efficiency. Consequently, understanding traditional dyeing systems that have historically optimized plant pigment use under low-input conditions may provide valuable insights for contemporary natural product and biochemical research.

Several plant species traditionally used in textile dyeing are well documented in the literature as sources of chemically distinct pigment classes. *Indigofera tinctoria* is widely recognized as a primary source of indigoid pigments, particularly indigo and indirubin, which are formed through enzymatic hydrolysis and subsequent oxidation of indican precursors (Fried et al. 2022; Castillo-Suárez et al. 2023). Indigoid compounds have attracted biochemical interest due to their redox behavior and chromophoric properties (Maugard et al. 2001; Bechtold et al. 2003).

Caesalpinia sappan has been reported as a major source of brazilin and its oxidized derivative brazilein, phenolic pigments responsible for red to reddish-brown hues. These compounds belong to the homoisoflavonoid group and are known for their pH-dependent color transitions and metal-binding behavior, making them relevant to studies on pigment stability and mordant interactions (Pizzicato et al. 2023; Wouyou et al. 2025). Similarly, *Cudrania javanensis* and related dye plants have been associated with flavonoid-related yellow pigments, which contribute to color diversity and exhibit sensitivity to processing conditions (Alegbe and Uthman 2024).

Importantly, these pigment associations are reported in the literature and are not derived from chemical analyses conducted in the present study. Nevertheless, identifying plant species traditionally selected for dyeing provides an empirical basis for linking botanical sources with known pigment classes of biochemical relevance.

Traditional textile dyeing systems rely on process variables that directly influence pigment release, transformation, and fixation onto textile fibers. Fermentation is commonly employed to convert precursor compounds into chromophoric forms, particularly in indigo-based systems where microbial or enzymatic activity facilitates pigment solubilization prior to oxidation. Another critical variable is pH adjustment, often achieved through the addition of alkaline materials such as calcium oxide (CaO). The pH plays a decisive role in pigment ionization, solubility, and affinity for textile fibers, thereby affecting color intensity and stability (Shahid et al. 2013). Repeated dipping and drying cycles further enhance pigment deposition by promoting gradual accumulation and fixation.

Viewed from a natural product perspective, these traditional practices can be conceptualized as integrated pigment processing systems governed by fermentation, pH control, and repeated application. Understanding these process-dependent effects is essential for translating traditional knowledge into biochemical and natural product research frameworks.

This study aims to document plant species used as natural dyes in traditional batik production and to discuss their potential relevance as plant-derived pigment sources for natural product and biochemical studies. We hypothesized that color intensity in traditional batik dyeing increases with longer dyeing duration and a higher number of repeated dipping cycles, reflecting process-controlled modulation of plant-derived pigments rather than chemical modification of pigment composition.

MATERIALS AND METHODS

Study site and dye production system

The study was conducted at Batik Tjap Tiga Negeri, a traditional batik production unit located in Laweyan, Surakarta, Central Java, Indonesia. The site represents an active batik workshop that applies plant-based natural dyes as part of its regular production process. Observations were carried out during ongoing dyeing activities to capture operational practices under real production conditions.

The dye production system at the study site is characterized by small-scale, manual processing and the use of plant-derived materials prepared on-site. Natural dyes are processed through a sequence of steps that include plant material preparation, aqueous extraction or fermentation, dye bath conditioning, and repeated application to textile fibers. All procedures are conducted under ambient conditions without the use of synthetic auxiliaries or industrial-scale equipment.

Plant materials used for dyeing are sourced from cultivated plants or local suppliers, depending on availability. Dye preparation methods vary according to plant species and targeted color outcomes and include fermentation, boiling, decoction, soaking, or grinding. In indigo-based dyeing, alkaline conditions are achieved through the controlled addition of calcium oxide to facilitate dye application prior to oxidation. These procedures form an integrated dye production system in which color development is regulated through operational control rather than chemical modification.

The dye application process involves repeated immersion and air-drying cycles to achieve gradual color accumulation on textile fibers. Adjustments in dyeing duration and repetition are made empirically by practitioners based on visual assessment of color development. Handling of residual materials is incorporated into routine production activities and does not involve secondary chemical treatment.

The study site was treated as a process-oriented unit of analysis, focusing on the operational steps relevant to pigment extraction, transformation, and application. Historical, cultural, and spatial aspects were not included, as the primary objective was to document dyeing practices with relevance to plant-derived pigment research.

Plant material identification

Plant species used as natural dye sources were identified based on direct observation of dye preparation and application activities at the study site, combined with information provided by practitioners regarding local plant names and plant parts utilized. The identification process focused on establishing the correct scientific names of plant taxa relevant to dye production.

Initial identification was conducted using regional and national floristic references, including standard botanical handbooks and floras relevant to Indonesian plant taxa (Backer and van den Brink 1980; Whitmore et al. 1986; Suheryanto 2017). These printed sources were used to match local plant names with macroscopic morphological descriptions and accepted scientific names prior to verification using online taxonomic databases.

To ensure taxonomic accuracy and nomenclatural consistency, scientific names were subsequently verified using authoritative online plant taxonomic resources, including Plants of the World Online (POWO 2026; https://powo.science.kew.org), the Global Biodiversity Information Facility (GBIF 2026; https://www.gbif.org), and the International Plant Names Index (IPNI 2026; https://www.ipni.org). These databases were consulted to confirm accepted names, authorship, and higher-level taxonomic placement.

Plant identification was limited to species actively used in the dyeing process during the observation period. No plant specimens were collected for herbarium deposition, and no microscopic or molecular identification was performed. Consequently, species determination relied on macroscopic morphological characteristics, local usage information, and cross-validation with floristic literature and online taxonomic references.

This identification approach aimed to produce a validated list of plant species relevant to the dyeing system while maintaining methodological transparency appropriate for a process-oriented natural product study.

Observation of dye preparation and application

Observation of dye preparation and application was conducted through direct, non-intrusive monitoring of routine dyeing activities at the study site. The observations aimed to document operational steps and key process variables involved in the use of plant-based natural dyes under real production conditions, without measuring pigment composition or performance quantitatively. This approach is commonly used in process-oriented studies of traditional dyeing systems to capture practice-based knowledge (Cardon 2007; Bechtold and Mussak 2009).

The observation covered sequential stages of dyeing activities, including plant material preparation, dye extraction or fermentation, dye bath conditioning, and application of dyes to textile fibers. For indigo-based dyeing, particular attention was given to leaf fermentation, alkalization, and oxidation, as these stages regulate pigment availability and dye uptake in traditional indigo systems (Maugard et al. 2001; Bechtold et al. 2003; Castillo-Suárez et al. 2023).

For non-indigo dye plants, observations focused on aqueous extraction methods such as boiling or decoction of bark, wood, or leaves. Heat-assisted extraction is widely reported as an effective approach for releasing phenolic and flavonoid-related pigments from plant tissues used in natural dyeing (Vankar 2000; Samanta and Agarwal 2009). Extraction duration and handling of dye solutions prior to application were recorded descriptively to characterize process variability.

The use of plant-based mordants was also noted, including the sequence and timing of mordant application relative to dyeing. Natural mordants derived from plant materials have been reported to influence pigment-fiber interactions without the use of synthetic additives (Shahid et al. 2013).

Dye application was observed during repeated immersion and air-drying cycles. Key variables recorded included dyeing duration, number of dipping cycles, and general dye bath conditions such as perceived alkalinity. Repeated application is known to facilitate gradual pigment accumulation and improved color fixation in plant-based dyeing systems (Pizzicato et al. 2023; Renita et al. 2023).

All observations were conducted under ambient production conditions without intervention, aligning with established process-based investigations of traditional dyeing systems (Cardon 2007; Fried et al. 2022).

Data analysis

Data analysis was conducted using a descriptive and process-oriented framework to synthesize observational information related to plant species utilization, dye preparation procedures, and dye application practices. The analytical approach was designed to organize field observations systematically without applying quantitative statistical inference or laboratory-based pigment measurements.

Information obtained from observations was categorized according to major components of the dyeing system, including plant material characteristics, extraction or fermentation techniques, application procedures, and handling of residual materials. Process variables such as dyeing duration, number of dipping cycles, and general dye bath conditions were documented to enable comparison across different dye types. This form of qualitative categorization is widely used in studies aiming to understand traditional production systems and process-driven material behavior (Bechtold and Mussak 2009; Ling et al. 2022).

Color intensity was assessed using an observational ordinal scale based on visual evaluation during routine production. Such qualitative scaling methods are commonly employed in traditional dyeing studies where color outcomes are controlled empirically and instrumental colorimetric measurements are not available (Renita et al. 2023; Negi 2025). The analysis focused on identifying consistent patterns between operational variables and observed color development rather than on quantifying pigment concentration or color metrics.

Comparative interpretation of dyeing practices emphasized process-response relationships, allowing evaluation of how variations in operational control influenced dye application outcomes. Interpretation was limited to patterns observable across repeated production cycles and did not extend to causal or mechanistic claims at the molecular level. This constraint ensured a clear distinction between observational findings and literature-based biochemical interpretation.

Literature-based synthesis was applied separately during the discussion stage to relate observed dye plants and processing practices to reported pigment classes and biochemical behavior. By maintaining this separation, the analytical framework preserved methodological transparency and avoided conflation between primary observational data and secondary literature interpretation (Snyder et al. 2019; Fried et al. 2022; Pizzicato et al. 2023).

RESULTS AND DISCUSSION

Plant species used as natural dye sources

Observation of dye production activities at Batik Tjap Tiga Negeri identified a set of plant species consistently used as sources of natural dyes in traditional batik production. These species represent the primary botanical materials employed for generating different color tones and for supporting dye fixation during the dyeing process. The documented plant species, plant parts used, color outcomes, and extraction methods are summarized in Table 1.

A total of seven plant species were recorded as active components of the dyeing system. The species utilized include *I. tinctoria*, *C. sappan*, *C. javanensis*, *Swietenia mahagoni*, *Symplocos fasciculata*, *Tectona grandis*, and *Acacia* spp. Each species was associated with a distinct role within the dyeing process, either as a primary source of color or as a supporting material for color fixation.

Leaves of *I. tinctoria* were used as the sole source of blue coloration. The dye preparation involved a fermentation-based process followed by oxidation, resulting in a characteristic indigo hue applied as a base layer in the dyeing sequence. Other dye plants primarily utilized woody tissues, including bark or heartwood, which were processed through boiling or decoction to obtain aqueous dye solutions. These species contributed red, yellow, brown, or dark brown tones depending on the plant material and extraction method employed.

In addition to pigment-producing plants, *S. fasciculata* bark was recorded as a natural mordant source. Rather than contributing a distinct color, this species was used to support dye fixation through alum-related compounds released during grinding and soaking. The inclusion of a plant-based mordant highlights the integrated nature of the dyeing system, in which color development and fixation are achieved using botanical materials.

Across all documented species, extraction methods were limited to low-input aqueous processes, including fermentation, boiling, decoction, grinding, and soaking. No synthetic chemicals or industrial additives were applied during plant material processing. The recorded plant species and associated extraction techniques together form the botanical foundation of the natural dyeing system observed in this study.

Dye extraction and application processes

The dye extraction and application processes observed at Batik Tjap Tiga Negeri followed a structured sequence of plant material preparation, aqueous extraction or fermentation, dye bath conditioning, and repeated application to textile fibers. Although specific procedures varied among plant species, the overall workflow showed consistent operational stages across different dye types.

For indigo-based dyeing derived from *I. tinctoria*, dye preparation involved a fermentation stage using fresh leaves immersed in water. The fermentation process produced a soluble dye intermediate, which was subsequently subjected to oxidation during application. Prior to dyeing, alkaline conditions were established through the addition of small amounts of calcium oxide (CaO) to the dye bath. This step facilitated pigment solubilization before oxidation and application. The sequential stages of fermentation, alkalization, oxidation, and dye application were consistently applied during indigo dyeing, as illustrated in Figure 1.

Extraction of dyes from non-indigo plant species relied primarily on aqueous heat-based methods. Woody materials such as the bark or wood of *C. sappan*, *C. javanensis*, *S. mahagoni*, and *Acacia* spp. were processed through boiling or decoction to release color-bearing compounds into the dye solution. Following extraction, solid residues were removed by simple filtration, and the resulting dye solutions were used directly for fabric dyeing without further modification.

In the case of *S. fasciculata*, bark material was processed by grinding and soaking to obtain a solution used as a natural mordant. This solution was applied prior to or in conjunction with dyeing to support color fixation. The mordanting step was integrated into the dyeing sequence without the use of synthetic additives.

Application of natural dyes to textiles involved repeated dipping and air-drying cycles. Each cycle allowed gradual accumulation of color on the fabric surface, while intermediate drying facilitated fixation. Dyeing was conducted under ambient conditions, and the duration and number of dipping cycles were adjusted according to the desired color depth. Variations in these parameters were recorded as part of the observation process and are addressed in subsequent sections.

To synthesize the observed dye preparation and application procedures, the individual operational steps were integrated into a simplified workflow representing the general structure of plant-based dyeing systems. This workflow is summarized in Figure 2, highlighting common stages shared across different dye types.

Table 1. Plant species used as natural dye sources in traditional batik production

Scientific name	Local name	Plant part used	Color obtained	Extraction method
Indigofera tinctoria	Indigo / Tarum	Leaves	Blue	Fermentation followed by oxidation
Caesalpinia sappan	Secang	Wood	Red	Boiling
Cudrania javanensis	Tegeran	Wood	Yellow	Decoction
Swietenia mahagoni	Mahoni	Bark	Brown	Boiling
Symplocos fasciculata	Jambal	Bark	Mordant source (alum)	Grinding and soaking
Tectona grandis	Jati	Leaves	Reddish brown	Hot extraction
Acacia spp.	Kayu akasia	Bark	Dark brown	Boiling

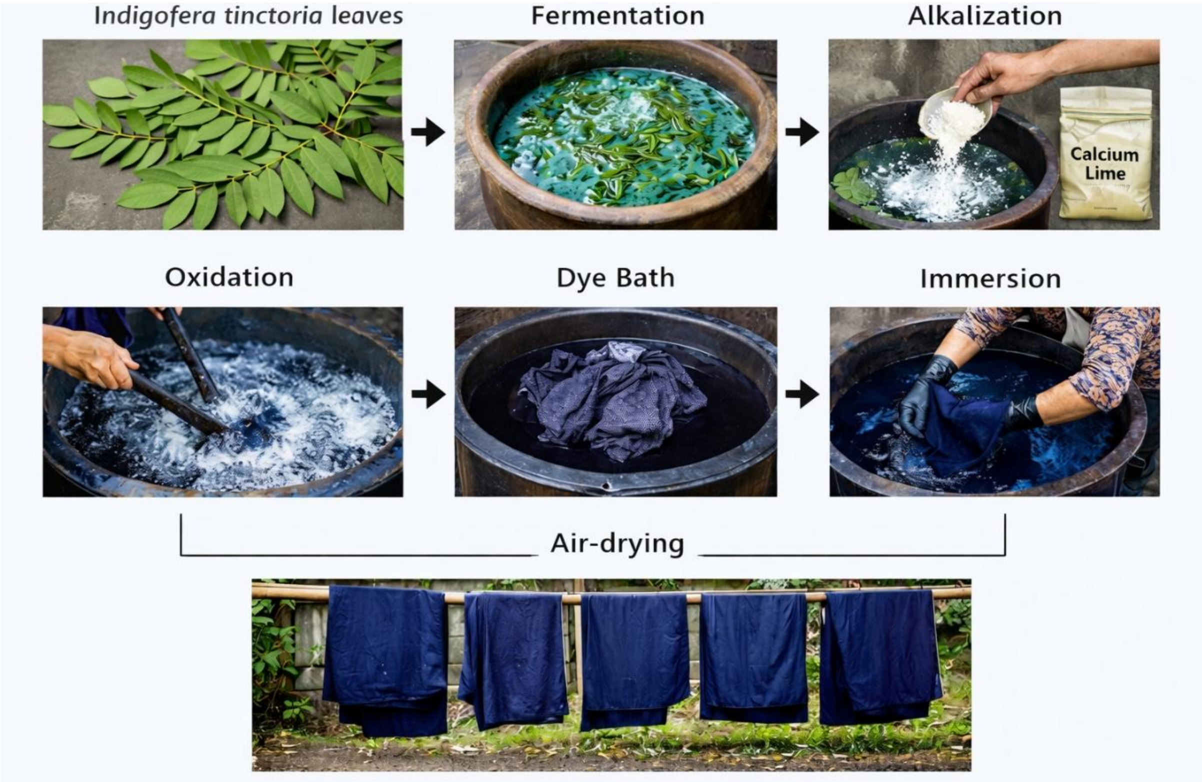

Figure 1. Indigo-based dye preparation and application process derived from *Indigofera tinctoria*

Figure 2. Simplified workflow of plant-based natural dye preparation and application in traditional batik production

Influence of processing parameters on color intensity

Variation in color intensity observed during natural dyeing was closely associated with differences in processing parameters, particularly dyeing duration and the number of repeated dipping cycles. Practitioners consistently adjusted these parameters to achieve the desired color depth across different dye types. Observed relationships between processing conditions and resulting color intensity are summarized in Table 2.

Across all dye plants, increased dyeing duration and a higher number of dipping cycles were associated with progressively deeper color tones. Fabrics subjected to a single or limited number of dipping cycles generally exhibited lighter coloration, whereas repeated application resulted in darker and more saturated hues. This pattern was most pronounced in indigo-based dyeing, where incremental color buildup was achieved through successive dipping and oxidation cycles.

For non-indigo dye plants, including *C. sappan*, *C. javanensis*, and *S. mahagoni*, color development followed a similar trend, although the rate of intensity increases varied among species. Short extraction and dyeing times produced pale or moderate tones, while extended exposure and repeated application enhanced color depth. These observations indicate that color intensity is not solely dependent on plant species but is strongly influenced by operational control during dye application.

Color intensity was recorded using an observational ordinal scale, reflecting practical assessments made during routine production. This scale captured relative differences in color depth rather than quantitative pigment concentration. The summarized relationships between dyeing duration, dipping frequency, and observed color intensity are presented in Table 2, while a visual representation of these trends is provided in Figure 3.

The observed patterns demonstrate that traditional dyeing systems rely on process-based modulation to control color outcomes. Rather than altering dye composition through chemical modification, practitioners achieve color variation by adjusting exposure time and repetition, allowing gradual pigment accumulation on textile fibers. These findings highlight the role of processing parameters as key determinants of color intensity within plant-based dyeing systems.

Handling of residual dye materials within the dyeing process

Handling of residual materials generated during the dyeing process was systematically documented based on the type of residue produced and the applied handling practice. Residual materials were classified into liquid and solid forms originating from different stages of dye preparation and application. The observed types of residual materials and their corresponding handling practices are summarized in Table 3.

Table 2. Observed the relationship between processing parameters and color intensity in natural dyeing

Dye plant source	Dyeing duration	Number of dipping cycles	Observed color intensity*
Indigofera tinctoria	Short	Low	Light blue
Indigofera tinctoria	Moderate	Medium	Medium blue
Indigofera tinctoria	Extended	High	Deep blue
Caesalpinia sappan	Short	Low	Light red
Caesalpinia sappan	Moderate	Medium	Medium red
Caesalpinia sappan	Extended	High	Dark red
Cudrania javanensis	Short	Low	Pale yellow
Cudrania javanensis	Moderate	Medium	Yellow
Cudrania javanensis	Extended	High	Deep yellow

Note: *: Color intensity was assessed using an observational ordinal scale based on routine production evaluation

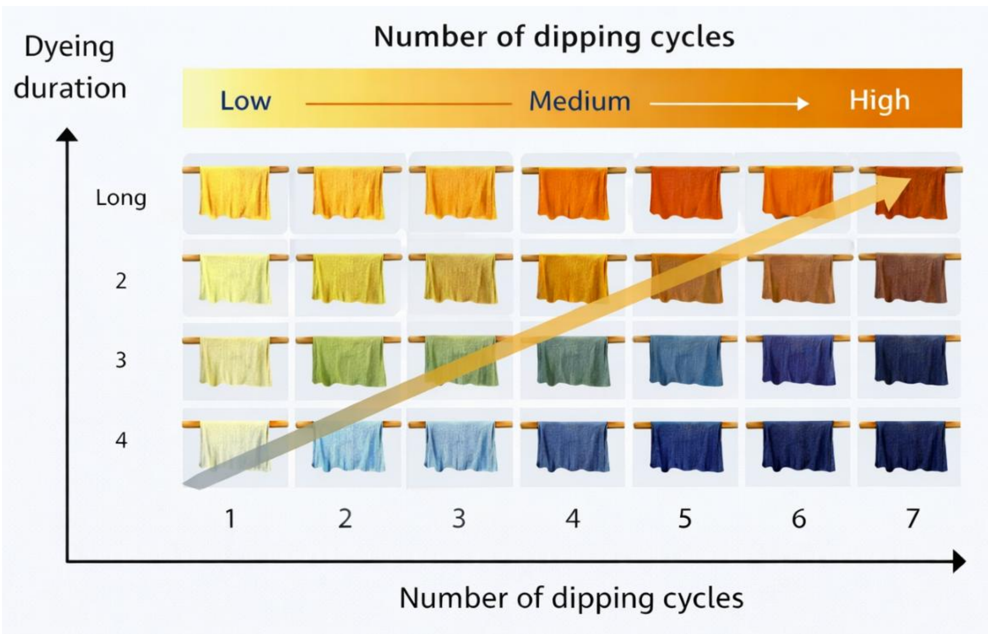

Figure 3. Relationship between dyeing duration, number of dipping cycles, and observed color intensity in plant-based natural dyeing

Table 3. Types of residual materials generated during dyeing and their observed handling practices

Residual type	Source process	Physical form	Observed handling practice
Spent indigo dye solution	Leaf fermentation and dyeing	Liquid	Reused when possible; settled before discharge
Spent dye solution (non-indigo)	Boiling/decoction of plant materials	Liquid	Settled before discharge
Fermented leaf residues	Indigo dye preparation	Solid	Manually removed; disposed of as organic waste
Bark and wood residues	Boiling/decoction processes	Solid	Manually removed; disposed of as organic waste

Liquid residues consisted primarily of spent dye solutions derived from indigo fermentation and aqueous extraction of non-indigo dye plants. These residues were temporarily retained and reused when visible color potential remained, particularly in indigo-based dyeing systems. Once reuse was no longer feasible, liquid residues were subjected to basic settling prior to discharge.

Solid residues included spent leaves, bark, and wood fragments remaining after fermentation or boiling processes. These materials were manually separated from dye solutions and handled as organic waste. No chemical additives or secondary processing steps were applied to either liquid or solid residues during handling.

The classification presented in Table 3 demonstrates that residual material handling was embedded within routine dyeing operations and followed consistent, low-input practices across different dye types.

Discussion

Reported pigment classes associated with dye plants

The plant species documented in this study as natural dye sources (Table 1) are widely reported in the literature to contain distinct classes of plant-derived pigments with biochemical relevance. Although no chemical analyses were conducted in the present work, linking the observed dye plants with previously reported pigment classes provides a contextual framework for interpreting traditional dyeing practices within natural product research.

Indigofera tinctoria is consistently reported as a primary source of indigoid pigments, particularly indigo and indirubin. These pigments originate from indican precursors that undergo enzymatic hydrolysis followed by oxidation, yielding the characteristic blue chromophore widely used in natural dyeing systems. Indigoid compounds are of long-standing interest in pigment chemistry due to their redox-dependent color expression and stability under alkaline conditions (Maugard et al. 2001; Bechtold et al. 2003). The exclusive use of *I. tinctoria* for blue coloration observed in this study aligns with these well-documented biochemical properties.

Caesalpinia sappan has been extensively reported as a source of brazilin and its oxidized derivative brazilein, belonging to the homoisoflavonoid group. These phenolic pigments exhibit pronounced color changes depending on oxidation state and pH, producing red to reddish-brown hues commonly exploited in traditional dyeing. Beyond their chromophoric role, brazilin-type compounds have attracted attention due to their metal-binding behavior and sensitivity to processing conditions (Pizzicato et al. 2023; Vij et al. 2023). The use of *C. sappan* wood as a red dye source in the present study is therefore consistent with reported pigment chemistry.

Yellow dyes derived from *C. javanensis* have been associated in previous studies with flavonoid-related pigments, a broad class of polyphenolic compounds known for their structural diversity and color variability. Flavonoids typically display yellow coloration resulting from conjugated aromatic systems and are sensitive to extraction method and pH conditions (Mansour 2018). Although the exact pigment composition of *C. javanensis* was not analyzed here, its application as a yellow dye source corresponds with these reported characteristics.

Other dye plants recorded in this study, including *S. mahagoni*, *T. grandis*, and *Acacia* spp., are reported to contain phenolic compounds and tannin-related pigments that contribute to brown or dark color tones. Tannins and related polyphenols are commonly associated with bark- and wood-derived dyes and are known for their affinity to textile fibers and role in color fixation (Samanta and Konar 2011; Pisitsak et al. 2016). The use of these species as sources of brown coloration observed in the present work reflects this broader pattern.

In addition to pigment-producing plants, *S. fasciculata* is widely reported as a natural source of alum-related mordant compounds, rather than as a direct pigment source. Its inclusion in the dyeing system supports color fixation by enhancing pigment-fiber interactions, a role well documented in traditional dyeing literature (Shahid et al. 2013). This functional distinction underscores the integrated use of different plant materials within traditional dyeing systems.

The reported pigment classes associated with each dye plant documented in this study are summarized in Table 4. Importantly, this table represents a synthesis of published literature rather than the results of chemical characterization conducted in the present work. By explicitly distinguishing observational findings from literature-based pigment associations, this study maintains methodological transparency while situating traditional dye plants within a biochemical and natural product context.

Table 4. Reported pigment classes associated with plant species used as natural dyes

Plant species	Plant part used	Reported pigment class	Representative compounds (reported)	Key literature sources
Indigofera tinctoria	Leaves	Indigoid pigments	Indigo, indirubin	Bechtold et al. (2003), Maugard et al. (2001) and Arista et al. (2024)
Caesalpinia sappan	Wood	Homoisoflavonoids	Brazilin, brazilein	Vij et al. (2023) and Pizzicato et al. (2023)
Cudrania javanensis	Wood	Flavonoid-related pigments	Flavones, flavonols	Darshi et al. (2019) and Maula et al. (2025)
Swietenia mahagoni	Bark	Phenolic compounds/ tannins	Condensed tannins	Syame et al. (2022) and Bakar et al. (2023)
Tectona grandis	Leaves	Phenolic pigments	Anthraquinone- and flavonoid-related compounds	Godghate and Sawant (2014) and Montri et al. (2025)
Acacia spp.	Bark	Tannin-rich polyphenols	Catechin-based tannins	Haslam (1989), Seigler (2003) and Pizzi (2008)
Symplocos fasciculata	Bark	Alum-related mordant compounds	Aluminum-containing mineral complexes	Cardon (2007) and Laksono and Subiyati (2021)

Traditional dyeing as a low-input pigment processing system

Traditional dyeing practices observed in this study can be interpreted as low-input pigment processing systems, in which color development and fixation are achieved through the manipulation of physical and chemical process variables rather than through synthetic modification of dye molecules. Fermentation, pH adjustment, and repeated dye application function collectively to regulate pigment solubility, transformation, and deposition on textile fibers. This process-based control mechanism distinguishes traditional dyeing from industrial dye production, where pigment properties are typically standardized through chemical synthesis and auxiliary additives.

Fermentation plays a central role in indigo-based dyeing systems and represents a biologically mediated transformation process. In indigo dyeing, enzymatic or microbial hydrolysis converts precursor compounds into soluble intermediates that can later be oxidized to form the insoluble indigo pigment. Similar fermentation-driven transformations have been described in traditional dyeing systems across Asia and Africa, where microbial activity governs pigment availability under ambient conditions (Maugard et al. 2001; Bechtold et al. 2003; Cardon 2007). From a biochemical perspective, such systems provide natural examples of redox-controlled pigment chemistry occurring without external catalysts or high-energy inputs.

Adjustment of dye bath pH, commonly achieved using alkaline materials such as calcium oxide, represents another key variable influencing pigment behavior. pH governs pigment ionization state, solubility, and affinity for textile fibers, thereby directly affecting color intensity and stability. Numerous studies on plant-derived pigments have demonstrated strong pH sensitivity, particularly for indigoids, flavonoids, and phenolic compounds (Vankar 2000; Saxena and Raja 2014; Mansour 2018). In traditional dyeing, pH adjustment is conducted empirically, yet the observed outcomes mirror fundamental principles of pigment chemistry described in laboratory-based studies.

Repeated dipping and drying cycles further illustrate how traditional systems achieve color modulation through incremental pigment accumulation. Rather than relying on high pigment concentrations in a single application, color depth is gradually built through successive exposure and oxidation or fixation steps. This approach parallels adsorption-based models of pigment deposition, where repeated contact enhances binding efficiency and uniformity (Kamel et al. 2005; Renita et al. 2023). Such process-driven control offers an alternative perspective to conventional dye chemistry, emphasizing temporal modulation over compositional alteration.

Compared with synthetic dye systems, which prioritize uniformity and reproducibility through chemically defined formulations, plant-based dyeing systems exhibit inherent variability. However, this variability is not random; it is structured by controllable process parameters such as time, pH, and repetition. Recent discussions in green chemistry and sustainable materials research highlight that such variability can be reframed as functional adaptability rather than as a limitation, particularly when low environmental impact and resource efficiency are prioritized (Kant 2012; Periyasamy 2024).

The low-input nature of traditional dyeing systems also aligns with broader efforts to develop sustainable pigment processing strategies. The absence of synthetic auxiliaries, operation under ambient conditions, and reliance on aqueous extraction and biological transformation position traditional dyeing as a practical model for eco-compatible pigment utilization. Studies in natural product research increasingly recognize traditional processing knowledge as a valuable source of insight for designing alternative pigment systems that balance functionality with sustainability (Al-Tohamy et al. 2022; Islam et al. 2023).

Taken together, the observed dyeing practices demonstrate that traditional systems operate as integrated pigment processing frameworks, in which fermentation, pH regulation, and repeated application collectively govern pigment behavior. These systems provide empirically validated examples of how plant-derived pigments can be effectively processed and applied using minimal inputs, offering conceptual relevance for contemporary natural product and biochemical studies focused on pigment stability, transformation, and application.

Comparison with synthetic dyes from a pigment perspective

From a pigment perspective, synthetic dyes and plant-derived dyes represent two fundamentally different paradigms of color generation and control. Synthetic dyes are designed to achieve high consistency, reproducibility, and predictability, with chromophoric structures chemically engineered to deliver specific color properties under standardized conditions. The production and application of synthetic pigments typically rely on controlled chemical synthesis, precise formulation, and the use of auxiliary agents to stabilize color expression and fiber binding. This approach enables uniform coloration at an industrial scale but requires substantial material inputs and tightly regulated processing conditions (Periyasamy 2024; Negi 2025).

In contrast, plant-derived dyes operate within a process-controlled framework rather than a compositionally fixed system. Dynamic interactions between pigment precursors, extraction conditions, pH, and application sequence shape color outcomes in plant-based dyeing. Variability in color intensity and hue is therefore an inherent feature of plant-derived pigments, reflecting differences in processing rather than inconsistency in pigment identity. Recent discussions in *Green Chemistry* and *Molecules* emphasize that such variability can be strategically managed through process optimization, without requiring chemical modification of pigment structures (Bechtold and Mussak 2009; Kant 2012; Renita et al. 2023).

The contrast between chemical control and process control is particularly evident in how color stability is achieved. Synthetic dyes rely on molecular design and stabilizing additives to maintain color performance across diverse conditions. Plant-derived dyes, by contrast, achieve functional stability through repeated application, controlled exposure, and the use of natural mordants or pH adjustments. Although these approaches differ fundamentally, both systems aim to regulate pigment-fiber interactions to achieve durable coloration. Conceptually, traditional dyeing systems thus demonstrate alternative strategies for pigment stabilization that do not depend on synthetic auxiliaries (Bechtold et al. 2007; Yusuf et al. 2017).

From a natural product research perspective, the distinction between synthetic and plant-derived pigments highlights complementary strengths rather than a binary hierarchy. Synthetic pigments offer benchmarks for consistency and scalability, while plant-derived pigments provide models for studying pigment behavior under biologically and chemically dynamic conditions. Reviews in *Green Chemistry* and *Molecules* increasingly recognize plant-based pigments as valuable systems for exploring structure-function relationships, particularly in relation to pH sensitivity, redox behavior, and process-driven modulation of color expression (Castañeda-Ovando et al. 2009; Yusuf et al. 2017).

Importantly, the present study does not attempt to evaluate the efficiency or environmental performance of plant-derived dyes relative to synthetic dyes. Instead, the comparison is framed at a conceptual level, focusing on how different pigment systems achieve color control through distinct mechanisms. By situating traditional dyeing practices within this comparative framework, plant-based dyeing can be understood as a process-centered pigment system with relevance to contemporary discussions on alternative pigment technologies.

Implications for natural product and biochemical research

The findings of this study highlight the relevance of traditional dye plants not only as cultural or artisanal materials, but also as candidate sources of plant-derived pigments with potential importance for natural product and biochemical research. By documenting plant species actively used in dyeing systems and linking them with reported pigment classes, this work provides a structured foundation for identifying botanical candidates suitable for further biochemical investigation.

Traditional dye plants represent model systems for studying pigment behavior under process-driven conditions. Unlike laboratory-isolated pigments examined under controlled analytical settings, pigments in traditional dyeing systems undergo transformation, deposition, and stabilization through dynamic interactions with pH, redox conditions, and repeated exposure. Such systems offer empirical contexts for examining pigment stability and transformation pathways that are often simplified or abstracted in experimental models (Samanta and Agarwal 2009; Iqbal and Ansari 2021).

One area of particular relevance is pH-dependent color expression, a defining characteristic of many plant-derived pigments, including indigoids, flavonoids, and phenolic compounds. Traditional practices involving alkaline conditioning and repeated oxidation steps provide natural analogs for studying how pH influences pigment solubility, chromophore structure, and color manifestation. These process-induced responses mirror fundamental biochemical principles governing pigment behavior and can inform experimental designs in pigment chemistry (Maugard et al. 2001; Pizzicato et al. 2023).

Additionally, the observed reliance on process-driven pigment modulation-such as repeated dipping and controlled exposure-underscores the importance of application dynamics in determining color outcomes. Rather than treating pigment performance as an intrinsic chemical property alone, traditional dyeing systems emphasize the role of operational variables in shaping functional expression. This perspective aligns with emerging research trends that frame pigment behavior as an interaction between molecular structure and processing context (Yusuf et al. 2017; Renita et al. 2023).

From a methodological standpoint, the present study delineates clear boundaries between observational documentation and biochemical inference. While no analytical characterization was conducted here, the documented dye plants and processing conditions provide clear targets for future biochemical validation, including chromatographic profiling, spectroscopic characterization, and stability assessment under controlled conditions. Such follow-up studies could elucidate structure-function relationships and quantify pigment responses to pH, redox state, and processing intensity.

In this context, traditional dyeing systems can be viewed as knowledge-rich platforms that inform hypothesis generation rather than as substitutes for analytical research. Integrating observational data from traditional practices with modern biochemical techniques offers a promising pathway for advancing the study of plant-derived pigments within natural product research.

In conclusion, this study documents the use of seven plant species as natural dye sources in traditional batik production at Batik Tjap Tiga Negeri, Laweyan, Surakarta. The recorded species-*I. tinctoria*, *C. sappan*, *C. javanensis*, *S. mahagoni*, *S. fasciculata*, *T. grandis*, and *Acacia* spp.- provide pigments derived from leaves, bark, and wood tissues. Indigo dyeing relied exclusively on *I. tinctoria* leaves through fermentation, alkalization, and oxidation, while non-indigo dyes were obtained via aqueous heat-based extraction of woody materials. The findings indicate that color outcomes are primarily governed by processing parameters, including fermentation, pH adjustment, and repeated application, rather than chemical modification of pigment structures. These practices represent low-input processing strategies that allow modulation of color intensity through operational control. By integrating observational evidence with literature on indigoids, flavonoid-related pigments, and tannin-rich polyphenols, this study provides a framework for understanding process-driven pigment behavior. Future research combining analytical characterization with traditional process knowledge is needed to validate pigment composition and evaluate the generality of process-color relationships across batik systems.

REFERENCES

Alegbe EO, Uthman TO. 2024. A review of history, properties, classification, applications, and challenges of natural and synthetic dyes. Heliyon 10 (13): e33646. DOI: 10.1016/j.heliyon.2024.e33646.

Al-Tohamy R, Ali SS, Li F, Okasha KM, Mahmoud YAG, Elsamahy T, Sun J. 2022. A critical review on the treatment of dye-containing wastewater: Ecotoxicological and health concerns of textile dyes and possible remediation approaches for environmental safety. Ecotoxicol Environ Saf 231 (1): 1-17. DOI: 10.1016/j.ecoenv.2021.113160.

Ardila-Leal LD, Poutou-Piñales RA, Pedroza-Rodríguez AM, Quevedo-Hidalgo B. 2021. A brief history of colour, the environmental impact of synthetic dyes, and removal by using laccases. Molecules 26 (13): 3813. DOI: 10.3390/molecules26133813.

Arista NDI, Aziz SA, Kurniawati A. 2024. Natural dye of Indigofera tinctoria for the textile industry. J Environ Sci Sustain Dev 7 (1): 578-598. DOI: 10.7454/jessd.v7i1.1249.

Backer CA, van den Brink RCB. 1980. Flora of Java Vol I-III. Wolters-Noordhoff, Groningen.

Bakar MA, Islam MI, Mia R, Ahmed T, Mahmud ST, Toki GFI, Haque MA. 2023. Exploring the potential of mahogany extract as a natural dye for the coloration of jute fabric. Heliyon 9 (9): e19464. DOI: 10.1016/j.heliyon.2023.e19464.

Bechtold T, Mahmud-Ali A, Mussak R. 2007. Natural dyes for textile dyeing: A comparison of methods to assess the quality of Canadian goldenrod plant material. Dyes and Pigments 75 (2): 287-293. DOI: 10.1016/j.dyepig.2006.06.004.

Bechtold T, Mussak R. 2009. Handbook of Natural Colorants. John Wiley & Sons, Chichester, USA. DOI: 10.1002/9780470744970.

Bechtold T, Turcanu A, Ganglberger E, Geissler S. 2003. Natural dyes in modern textile dyehouses - how to combine experiences of two centuries to meet the demands of the future? J Clean Prod 11 (5): 499-509. DOI: 10.1016/S0959-6526(02)00077-X.

Cardon D. 2007. Natural Dyes: Sources, Tradition, Technology and Science. Archetype Publications, London.

Castañeda-Ovando A, Pacheco-Hernández ML, Páez-Hernández ME, Rodríguez JA, Galán-Vidal CA. 2009. Chemical studies of anthocyanins: A review. Food Chem 113 (4): 859-871. DOI: 10.1016/j.foodchem.2008.09.001.

Castillo-Suárez LA, Sierra-Sánchez AG, Linares-Hernández I, Martínez-Miranda V, Teutli-Sequeira EA. 2023. A critical review of textile industry wastewater: Green technologies for the removal of indigo dyes. Intl J Environ Sci Technol 20 (9): 10553-10590. DOI: 10.1007/s13762-023-04810-2.

Darshi C, Lestari DW, Pratiwi D, Indrianingsih AW, Rosyida VT, Apriyana W, Nisa K, Hayati SN, Handayani S, Purnami M. 2019. Dyeing of cotton fabric with natural dye from *Cudrania javanensis* using soka (*Ixora javanica*) leaves extract as bio-mordant. Din Kerajinan Batik 36 (2): 105-112. DOI: 10.22322/dkb.v36i2.4149.

Fried R, Oprea I, Fleck K, Rudroff F. 2022. Biogenic colourants in the textile industry - a promising and sustainable alternative to synthetic dyes. Green Chem 24 (1): 13-35. DOI: 10.1039/D1GC02968A.

GBIF. 2026. Global Biodiversity Information Facility. https://www.gbif.org.

Godghate AG, Sawant RS. 2014. Phytochemical analysis of leaves of *Tectona grandis* Linn. Intl J Pharma Bio Sci 5 (1): 355-359.

Haslam E. 1989. Plant Polyphenols: Vegetable Tannins Revisited. Cambridge Univ Press, Cambridge, UK.

IPNI. 2026. International Plant Names Index. https://www.ipni.org.

Iqbal S, Ansari TN. 2021. Extraction and application of natural dyes. In: Rather LJ, Shabbir M, Haji A (eds). Sustainable Practices in the Textile Industry. Wiley, Hoboken. DOI: 10.1002/9781119818915.ch1.

Islam T, Repon MR, Islam T, Sarwar Z, Rahman MM. 2023. Impact of textile dyes on health and ecosystem: A review of structure, causes, and potential solutions. Environ Sci Pollut Res 30 (4): 9207-9242. DOI: 10.1007/s11356-022-24398-3.

Kamel MM, El-Shishtawy RM, Yussef BM, Mashaly H. 2005. Ultrasonic assisted dyeing: III. Dyeing of wool with lac as a natural dye. Dyes Pigments 65: 103-110. DOI: 10.1016/j.dyepig.2004.06.003.

Kant R. 2012. The textile dyeing industry is an environmental hazard. Nat Sci 4 (1): 22-26. DOI: 10.4236/ns.2012.41004.

Laksono AI, Subiyati S. 2021. Pengaruh metode mordan alam daun Simplokos pada pencapan kain kapas dengan zat warna alam daun marenggo (*Chromolaena odorata* L). Pros Semin Nas Ind Kerajinan Batik (SNIKB) 2021. Yogyakarta, 6-7 Oktober 2021. [Indonesian]

Ling TC, Inta A, Armstrong KE, Little DP, Tiansawat P, Yang YP, Phokasem P, Tuang ZK, Sinpoo C, Disayathanoowat T. 2022. Traditional knowledge of textile dyeing plants: A case study in the Chin ethnic group of western Myanmar. Diversity 14 (12): 1065. DOI: 10.3390/d14121065.

Mansour R. 2018. Natural dyes and pigments: Extraction and applications. In: Yusuf M (eds). Handbook of Renewable Materials for Coloration and Finishing. Wiley, Hoboken. DOI: 10.1002/9781119407850.ch5.

Maugard T, Enaud E, Choisy P, Legoy MD. 2001. Identification of an indigo precursor from leaves of *Isatis tinctoria* (woad). Phytochemistry 58 (6): 897-904. DOI: 10.1016/S0031-9422(01)00335-1.

Maula VA, Rahayuningsih E, Mindaryani A. 2025. Dyeing and isotherm adsorption of natural dye from tegeran (*Cudrania javanensis* Trecul) on cotton fabric. AIP Conf Proc 3295: 060006. DOI: 10.1063/5.0272993.

Montri N, Wanapat M, Kang S, Cheas S, Cherdthong A, Gunun P, Nirwan G, Foiklang S, Kongmun P, Polyorach S. 2025. Exploring *Tectona grandis* Linn. f. leaf extract as a functional feed additive with antioxidant and nutraceutical potential for livestock. Animals 15 (23): 3498. DOI: 10.3390/ani15233498.

Moreira VR, Lebron YAR, Couto CF, Maia A, Moravia WG, Amaral MCS. 2022. Process development for textile wastewater treatment towards zero liquid discharge. Process Saf Environ Prot 157 (1): 537-546. DOI: 10.1016/j.psep.2021.10.037.

Negi A. 2025. Natural dyes and pigments: Sustainable applications and future scope. Sustain Chem 6 (3): 23. DOI: 10.3390/suschem6030023.

Periyasamy AP. 2024. Recent advances in the remediation of textile-dye-containing wastewater. Sustainability 16 (2): 1-41. DOI: 10.3390/su16020495.

Pisitsak P, Hutakamol J, Thongcharoen R, Phokaew P, Kanjanawan K, Saksang N. 2016. Improving the dyeability of cotton with tannin-rich

natural dye through pretreatment with whey protein isolate. Ind Crop Prod 79: 47-56. DOI: 10.1016/j.indcrop.2015.10.043.
Pizzi A. 2008. Tannins: Major sources, properties, and applications. In: Belgacem MN, Gandini A (eds). Monomers, Polymers, and Composites from Renewable Resources. Elsevier, Oxford. Pp 179-199. DOI: 10.1016/B978-0-08-045316-3.00008-9.
Pizzicato B, Pacifico S, Cayuela D, Mijas G, Riba-Moliner M. 2023. Advancements in sustainable natural dyes for textile applications: A review. Molecules 28 (16): 1-22. DOI: 10.3390/molecules28165954.
POWO. 2026. Plants of the World Online. Royal Botanic Gardens, Kew. https://powo.science.kew.org.
Renita AA, Gajaria TK, Sathish S, Kumar JA, Lakshmi DS, Kujawa J, Kujawski W. 2023. Progress and prospects of the industrial development and applications of eco-friendly colorants. Foods 12 (7): 15-21. DOI: 10.3390/foods12071521.
Samanta AK, Agarwal P. 2009. Application of natural dyes on textiles. Indian J Fibre Text Res 34: 384-399.
Samanta AK, Konar A. 2011. Dyeing of textiles with natural dyes. In: Akcakoca Kumbasar EP (eds). Natural Dyes. IntechOpen, London. DOI: 10.5772/21341.
Saxena S, Raja ASM. 2014. Natural dyes: Sources, chemistry, application, and sustainability issues. In: Muthu S (eds). Roadmap to Sustainable Textiles and Clothing. Textile Science and Clothing Technology. Springer, Singapore. DOI: 10.1007/978-981-287-065-0_2.
Seigler DS. 2003. Phytochemistry of *Acacia*-sensu lato. Biochem Syst Ecol 31 (8): 845-873. DOI: 10.1016/S0305-1978(03)00082-6.
Shahid M, Shahid-ul-Islam, Mohammad F. 2013. Recent advancements in natural dye applications: A review. J Clean Prod 53: 310-331. DOI: 10.1016/j.jclepro.2013.03.031.
Snyder H. 2019. Literature review as a research methodology: An overview and guidelines. J Bus Res 104: 333-339. DOI: 10.1016/j.jbusres.2019.07.039.
Suheryanto D. 2017. Natural Dyes: Ensiklopedia Zat Warna Alami dari Tumbuhan untuk Industri Batik. Andi Offset, Yogyakarta. [Indonesian]
Syame SM, Mohamed SM, Elgabry EA. 2022. Chemical characterization, antimicrobial, antioxidant, and cytotoxic potentials of *Swietenia mahagoni*. AMB Expr 12: 77. DOI: 10.1186/s13568-022-01406-w.
Vankar PS. 2000. Chemistry of natural dyes. Resonance 5: 73-80. DOI: 10.1007/BF02836844.
Vij T, Anil PP, Shams R, Dash KK, Kalsi R, Pandey VK, Harsányi E, Kovács B, Shaikh AM. 2023. A comprehensive review of bioactive compounds found in *Caesalpinia sappan*. Molecules 28 (17): 6247. DOI: 10.3390/molecules28176247.
Whitmore TC, Tantra IGM, Sutisna U. 1986. Tree Flora of Indonesia: Checklist for Sumatra. Forest Research and Development Centre, Bogor, Indonesia.
Wouyou HG, Avocevou-Ayisso C, Idohou R, Assogbadjo SC, Houndonougbo JSH, Assogbadjo AE. 2025. Current knowledge and prospects of African plants providing natural dyes: A systematic review. Discover Plants 2 (1): 1-71. DOI: 10.1007/s44372-025-00234-z.
Yusuf M, Shabbir M, Mohammad F. 2017. Natural colorants: Historical, processing and sustainable prospects. Nat Prod Bioprospect 7: 123-145. DOI: 10.1007/s13659-017-0119-9.