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Extraction Of Indigo Dye From *Strobilanthes cusia* Leaves With Alkalization Process Using Sodium Hydroxide

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Abstract

This study explores the extraction of natural blue indigo pigment from Strobilanthes cusia leaves using a sequential process of anaerobic maceration and sodium hydroxide (NaOH) alkalization. Serving as a cleaner alternative to traditional quicklime (CaO) treatment, which deposits undesirable mineral residues on textiles, this method optimizes both extraction purity and pigment formulation. Fresh leaves were macerated anaerobically for three days to hydrolyze indican into indoxyl, followed by aeration and NaOH alkalization (pH 12) to facilitate oxidative coupling. The structural transformation was monitored via UV-Visible spectrophotometry, revealing a distinct shift from the precursor absorption (λ_{max}) 291.94 nm to the indigo chromophore (λ_{max}) 670.58 nm. Furthermore, Fourier Transform Infrared (FTIR) spectroscopy validated the indigotin molecular framework and confirmed that the NaOH-based route successfully circumvents the heavy calcium carbonate co-precipitation associated with conventional CaO extraction. To enhance physical handling, the purified extract was stabilized into a workable paste using maltodextrin. Colorimetric evaluations demonstrated that incorporating 5%, 10%, 15%, 20%, and 25% (w/v) maltodextrin provided optimal steric stabilization without impeding dye mass transfer into the cellulosic fibers, yielding excellent cycle-to-cycle dyeing reproducibility with total color differences (ΔE^*) maintained within the acceptable industrial tolerance (≤ 3). Ultimately, this sequential NaOH-maltodextrin approach provides a sustainable, residue-free, and highly efficient pathway for producing industry-ready natural indigo colorants.

Keywords: *Alkalization, Indigo, Maceration, Maltodextrin, Strobilanthes cusia*.

Introduction

The textile industry is a major source of chemical effluents, driven in part by the extensive use of synthetic dyes that often contain hazardous, poorly biodegradable constituents. Such discharges contaminate waterways, disrupt aquatic ecosystems, and raise concerns for human and environmental health. As a response, natural colorants have re-emerged as greener alternatives. Plant-based dyes, in particular, draw growing attention because they are derived from renewable feedstocks, tend to be biodegradable and non-toxic, and offer diverse color profiles suitable for textiles as well as cosmetics, foods, and pharmaceuticals [1]. Positioning natural pigments within cleaner-production strategies is therefore timely for dyeing operations seeking lower residues and simpler wastewater management.

The adoption of natural dyes has increased markedly over the past decade, in parallel with heightened awareness of the environmental and health risks of synthetic counterparts [2]. Among blue natural colorants, Strobilanthes cusia is a promising botanical source of indigo. Its leaves contain the glycoside precursor indican, which is central to indigo biosynthesis and can be harnessed through appropriate extraction and

processing steps [3]. Leveraging this renewable precursor enables a plant-to-pigment route compatible with small- to medium-scale textile applications.

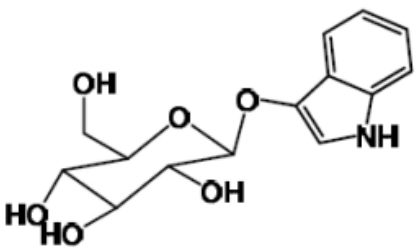
One notable source of natural blue dye is Strobilanthes cusia, whose leaves contain the glycoside indican, the primary precursor to the blue indigo pigment [4]. Indigo is not present in free form within the plant matrix; instead, it must be generated from precursors. In Strobilanthes cusia, the key compound prior to indigo formation is indican (indoxyl-β-D-glucoside) [5]. Process designs for natural indigo therefore emphasize controlled hydrolysis and oxidation pathways to convert bound precursors into the insoluble blue chromophore while minimizing side reactions that reduce yield or complicate downstream handling. The visual appearance of fresh Strobilanthes cusia leaves and the molecular structure of its key precursor, indican, are illustrated in Figure 1.

Operationally, leaf steeping initiates β-glucosidase–mediated hydrolysis of indican during aqueous maceration, liberating indoxyl; three days of anaerobic maceration are commonly used to favor efficient hydrolysis [6]. The process relies on subsequent aeration to oxidize indoxyl into indigo because indigo is water-insoluble [7]. Maintaining an alkaline medium facilitates pigment development and handling; in this work we emphasize NaOH alkalization as an alternative to CaO, aiming to limit calcium residues and simplify purification. Building on this two-step logic, maceration/fermentation followed by NaOH alkalization, we target a paste or powder suitable for textile application while aligning with cleaner-production objectives. The chemical pathway detailing the structural transformation of the intermediate indoxyl into the final indigo pigment is illustrated in Figure 2.

Despite the long-standing use of traditional quicklime (CaO) for alkalization in indigo extraction, this method presents significant technical limitations that hinder its compatibility with modern cleaner-production standards. The primary drawback is the deposition of insoluble calcium residues onto textile fibers, which can compromise color uniformity and require extensive rinsing, thereby increasing water consumption [8],[9]. Furthermore, CaO-based processing generates a high volume of mineral-rich sludge, complicating wastewater management and downstream purification. While sodium hydroxide (NaOH) offers a potential cleaner alternative to eliminate these mineral residues, comprehensive studies focusing on its optimization specifically for Strobilanthes cusia, particularly regarding the physical stability and formulation of the final pigment, remain scarce [10]. This study addresses this research gap by evaluating a sequential NaOH-alkalization route and investigating the incorporation of maltodextrin as a natural stabilizer to produce a consistent, residue-free indigo paste suitable for industrial applications[11].



(a)



(b)

Figure 1. Strobilanthes cusia leaves (a) and the structure of the precursor compound indoxyl β-D-glucoside (indican) (b).

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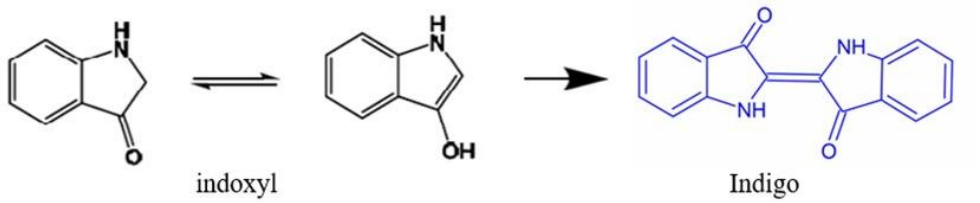


Figure 2. Structural transformation of indoxyl into indigo

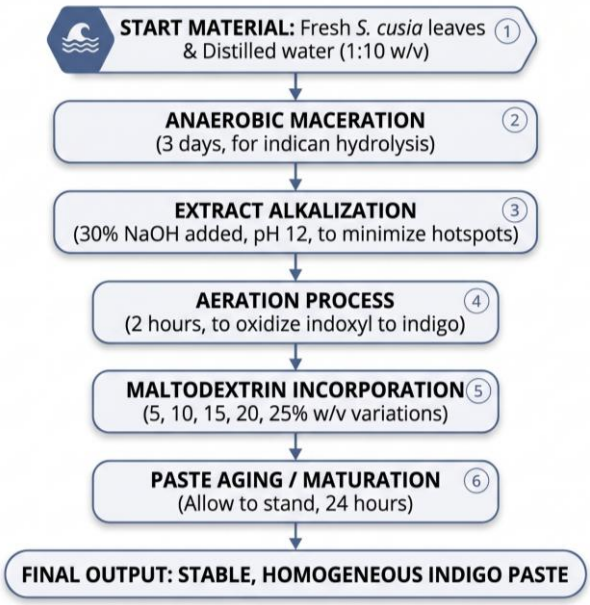


Figure 3. Systematic flowchart of the maceration, alkalization, and aeration process for Strobilanthes cusia indigo paste formulation

Experimental

Equipment

The instruments used in this study were a pH meter, a UV–Visible spectrophotometer, Fourier Transform Infrared (FTIR) spectroscopy, and a colorimeter (CR-1).

Material

The materials used in this study were fresh Strobilanthes cusia leaves sourced from Temanggung, 30% (w/w) sodium hydroxide (NaOH) solution, CaO, glucose, maltodextrin, and distilled water.

Methods

The overall experimental procedure, detailing the sequence from indigo extraction to paste formulation, is summarized in the flowchart presented in Figure 3. This sequential approach was specifically designed to evaluate the efficacy of sodium hydroxide as an alkalizing agent in an effort to minimize mineral residues typically associated with traditional methods. Furthermore, the subsequent formulation phase focused on identifying the optimal ratio of maltodextrin required to produce a highly stable natural dye paste suitable for industrial applications.

Natural indigo was extracted by macerating fresh S. cusia leaves in distilled water (1:10 w/v) in sealed containers under dark, anaerobic conditions at an ambient temperature of 27 ± 2 °C for three days to facilitate the enzymatic hydrolysis of indican into indoxyl. After maceration, the liquid extract was separated and alkalized to pH 12 through the gradual addition of 30% (w/w) NaOH under constant stirring at

100 rpm. To complete the conversion into insoluble indigo, the basified extract was aerated for 2 hours using a submerged aerator pump delivering a controlled air flow rate of approximately 2 L/min.

The resulting indigo-rich liquor was formulated into a stable paste by incorporating maltodextrin at varied concentrations (5%, 10%, 15%, 20%, and 25% w/v). These mixtures were matured for 24 hours to achieve a homogeneous consistency. Finally, the pastes were evaluated for viscosity, storage stability, and color performance (ΔE) to determine the optimal thickener concentration for textile application.

Measurements

Analytical characterization of the extract was performed using a UV–Visible spectrophotometer. To validate the structural integrity and identify the functional groups of the formulated indigo pastes, Fourier Transform Infrared (FTIR) spectroscopy was employed. Finally, the color differences (ΔE*) on the dyed fabrics were quantified using a CR-1 colorimeter.

Results and Discussion

Maceration stage: Formation of indoxyl under anaerobic conditions from S. cusia leaves

Fermentation was initiated by macerating fresh leaves in water at a leaf mass–to–solvent volume ratio of 1:10 (w/v) at ambient temperature for three days [12]. During this stage, enzymatic hydrolysis of indican (indoxyl-β-D-glucoside) occurs, catalyzed by β-glucosidase (also known as indigoemulsin) that is naturally present in leaf tissues and/or contributed by indigenous microorganisms in the steeping medium [10]. Hydrolysis cleaves the glycosidic bond to liberate indoxyl, the immediate precursor to indigo. Maintaining anaerobic conditions during maceration suppresses premature oxidation of indoxyl and helps preserve reducing conditions that favor precursor accumulation prior to the subsequent aeration/alkalization steps. In practical terms, this stage establishes the biochemical foundation for downstream pigment development by maximizing the availability of indoxyl while minimizing side reactions that could diminish indigo yield.

$$\text{indican (indoxyl} - \beta - \text{D} - \text{glucoside)} + H_2O \xrightarrow{\text{Enzym}} \text{Indoxyl} + \text{Glucose} \quad (1)$$

This stage yields indoxyl, a colorless (or faintly yellow) compound that serves as the immediate precursor of the indigo pigment [10]. During the three-day steeping period, natural fermentation by anaerobic bacteria utilizes glucose released through β-glucosidase–mediated hydrolysis of indican for growth and metabolism [12]. The resulting microbial activity establishes a reducing environment that helps keep indoxyl in solution and prevents its premature oxidation to insoluble indigo. Practically, the extract develops a greenish-yellow tint and a characteristic fermented odor, which are consistent field indicators of active fermentation and precursor accumulation prior to the subsequent aeration/alkalization steps [10].

Alkalization and Oxidation: Formation of Indigo Pigment

After fermentation, the steeped liquor contains water-soluble indoxyl. To convert indoxyl into indigo ($C_{16}H_{10}N_2O_2$), an insoluble blue pigment, an alkaline medium (pH 11–12) and molecular oxygen are required. Alkalinization with NaOH prevents acid-catalyzed degradation of indoxyl, shifts the fermentation milieu from acidic to basic conditions, stabilizes the dissolved indoxyl species, and improves the efficiency of its subsequent oxidation to indigo during aeration[10].

$$2\,\text{Indoxyl} + O_2 \rightarrow \text{Indigo} + 2H_2O \quad (2)$$

Mechanistically, the transformation from indoxyl to the final indigo pigment proceeds via a well-defined radical coupling pathway driven by the alkaline conditions. Following the enzymatic cleavage of indican, the liberated indoxyl exists in a tautomeric equilibrium with its keto form, indolin-3-one [10]. The gradual addition of NaOH to reach pH 12 plays a critical catalytic role by deprotonating the hydroxyl group of indoxyl, thereby generating a highly reactive indoxylate anion [10]. During the

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subsequent aeration process, dissolved molecular oxygen acts as an electron acceptor. A single electron transfer (SET) from the indoxylate anion to the oxygen molecule produces a resonance-stabilized indoxyl radical and a superoxide anion (O_2^-). The actual bond formation occurs when two indoxyl radicals undergo oxidative dimerization, coupling specifically at their C2 carbon positions to form an unstable intermediate known as leuco-indigo[13]. Under continuous aeration, this leuco-indigo intermediate is rapidly oxidized through the loss of two protons and two electrons, culminating in the highly conjugated, planar, and water-insoluble blue chromophore, indigotin (indigo) [13].

The basified extract is then aerated with vigorous mixing to ensure contact with air (oxygen). Under aerobic conditions, two indoxyl molecules undergo spontaneous oxidative coupling to form insoluble indigo, which precipitates and settles at the bottom of the vessel [7]. Operationally, maintaining pH 11–12 during aeration promotes rapid pigment development and cleaner separation of the indigo precipitate, facilitating downstream thickening into a paste [10].

To quantitatively substantiate the technical advantage of the NaOH-based alkalization over the traditional CaO method, it is crucial to analyze the solubility parameters and reaction byproducts of the respective alkalinizing agents. Quicklime (CaO) rapidly hydrates to form calcium hydroxide ($Ca(OH)_2$), which has a remarkably low aqueous solubility of approximately 1.73 g/L at 20 °C. Reaching the target pH of 12 for optimal indoxyl oxidation necessitates the addition of CaO in excess of its solubility limit. This excess, combined with the rapid formation of highly insoluble calcium carbonate ($CaCO_3$) upon reaction with dissolved atmospheric CO_2, inevitably co-precipitates with the indigo chromophore to form a dense, mineral-rich sludge [8]. In stark contrast, NaOH is highly soluble (over 1000 g/L), allowing for precise, stoichiometric pH adjustment without leaving any unreacted alkaline phase or insoluble carbonate byproducts. Consequently, the NaOH route eliminates the mineral-masking effect, directly yielding a higher purity pigment and bypassing the aggressive acid-washing steps typically required to descale CaO-processed indigo.

Although this study did not systematically vary the concentration of the NaOH solution, the specific use of a concentrated 30% (w/w) NaOH reagent to achieve a target pH of 12 was a deliberate methodological choice. A highly concentrated alkali was selected to minimize the volumetric dilution of the maceration liquor, thereby maintaining a high pigment titer necessary for efficient paste formulation. Furthermore, from a mechanistic perspective, the absolute concentration of the added base is less critical than the final pH of the medium. Literature indicates that optimal oxidative coupling of indoxyl occurs strictly within a pH window of 11 to 12 [7]. At a pH below 11, the deprotonation of indoxyl is incomplete, which not only lowers the yield of indigo but also favors the formation of isatin, leading to the generation of undesirable reddish byproducts such as indirubin. Conversely, exceeding pH 12 provides no significant kinetic advantage for indigo formation and unnecessarily increases the caustic load, complicating subsequent neutralization and wastewater handling [10]. Therefore, fixing the alkalization parameter at pH 12 using 30% (w/w) NaOH effectively guaranteed maximum indoxyl conversion while supporting the cleaner-production objective. The integrated pathway of indigo synthesis and the detailed sequential extraction process from Strobilanthes cusia are illustrated in Figure 4.

Maltodextrin as filler and stabilizer

However, alkalinization with NaOH did not produce a visible precipitate, in contrast to alkalinization with quicklime (CaO). The absence of a visible mineral precipitate during NaOH alkalinization, in stark contrast to the traditional use of quicklime (CaO), is fundamentally governed by the differential solubility of their respective salts. When CaO is utilized, the introduced calcium ions (Ca^{2+}) readily react with dissolved atmospheric carbon dioxide and endogenous plant organic acids (such as oxalates and pectates) present in the maceration liquor.

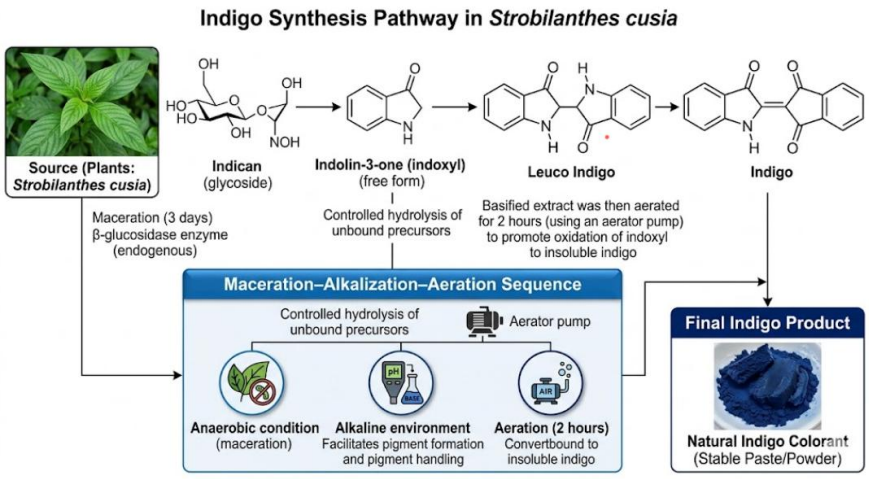


Figure 4. Integrated pathway of indigo synthesis and the sequential extraction process from Strobilanthes cusia

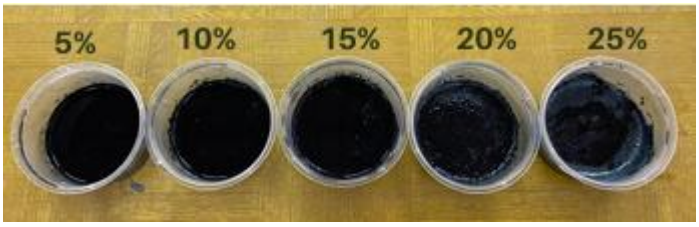


Figure 5. Comparison of indigo paste formulations with different maltodextrin addition percentages

This reaction forms highly insoluble complexes, most notably calcium carbonate, which co-precipitate alongside the indigo to create a bulky, mineral-rich sludge. In contrast, NaOH introduces sodium ions (Na^+), which characteristically form highly water-soluble salts that remain entirely dissolved in the aqueous phase [14]. Consequently, NaOH alkalinization precipitates a much purer indigo chromophore free from mineral contamination [15]. While this cleaner extraction directly satisfies the primary research objective of eliminating insoluble calcium residues to simplify wastewater management and improve textile color uniformity, the resulting high-purity pigment lacks the physical bulk traditionally provided by the calcium sludge. This operational gap specifically necessitates the incorporation of maltodextrin. By acting as a functional filler and natural thickener, maltodextrin compensates for the absent mineral bulk, successfully transforming the concentrated pigment into a stable, workable paste. The addition of the filler serves to increase volume, stabilize the pigment, and improve physical handling, making the material easier to process, store, and apply [11]. Therefore, this sequential NaOH-maltodextrin formulation not only achieves the cleaner-production goals but also delivers a practical, industry-ready dye product that ensures uniform and controlled dosing in downstream use.

To obtain a workable product, maltodextrin was therefore incorporated as a filler/thickener to form an indigo paste. The filler serves to increase volume, stabilize the pigment, and improve physical handling, making the material easier to process, store, and apply. It also helps prevent the colorant from becoming overly concentrated or tacky, thereby enabling more uniform and controlled dosing in downstream use. In addition, maltodextrin protects active dye components against moisture and oxidation, extends shelf life, and enhances redispersibility/solubility during application [11],[16]. The visual comparison of the formulated indigo pastes at different maltodextrin concentrations (5% to 25% w/v) is presented in Figure 5.

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The stabilization mechanism provided by maltodextrin extends beyond simple physical bulking. At a molecular level, the abundant hydroxyl (-OH) groups along the maltodextrin polymer chains engage in extensive intermolecular hydrogen bonding with the dispersed indigo particles and the continuous aqueous phase. This interaction creates a protective hydration sphere and induces steric hindrance around the hydrophobic indigo molecules, effectively preventing their spontaneous agglomeration and sedimentation over time [11]. However, as observed in the colorimetric evaluation (Tables 2–4), increasing the maltodextrin concentration beyond 15% (w/v) compromises the dyeing performance. Analytically, this can be attributed to macromolecular chain entanglement at higher concentrations, which significantly increases the paste's rheological resistance. While beneficial for storage stability, this excessive viscosity severely impedes the mass transfer and diffusion of the reduced leuco-indigo species into the cellulosic fibers of the fabric during the dyeing bath, leading to uneven dye uptake and higher ΔE* values.

UV–Visible spectrum and dyeing application

The structural transformation from the colorless precursor to the final blue chromophore was monitored using UV-Visible spectrophotometry. The spectrum of the fresh Strobilanthes cusia leaf maceration liquor exhibited a strong maximum absorption peak (λ_{max}) at 291.94 nm in the ultraviolet region. This peak is characteristic of the $\pi \rightarrow \pi^*$ electronic transitions within the aromatic indole ring, confirming the abundance of dissolved indican and its hydrolyzed intermediate, indoxyl, prior to oxidation. Following the alkalization and aeration processes, the UV-Vis profile altered significantly, revealing a new broad absorption band in the visible region with a λ_{max} 670.58 nm.

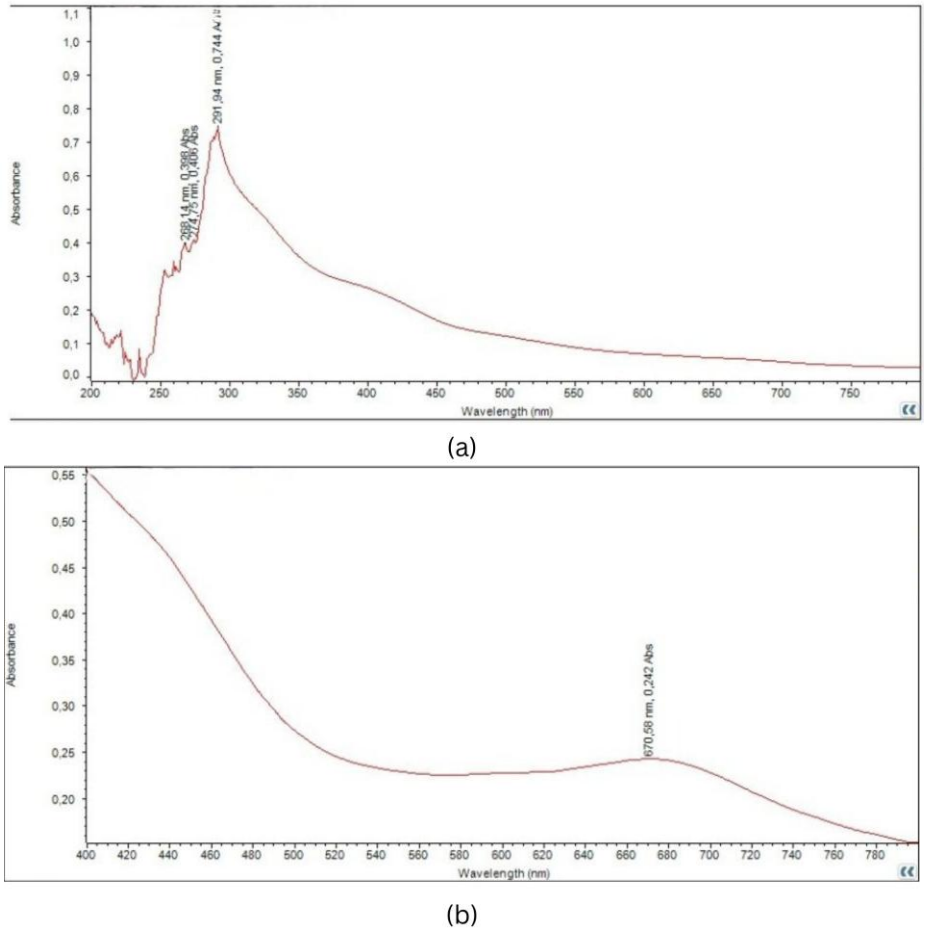
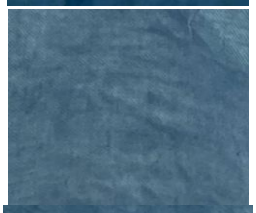
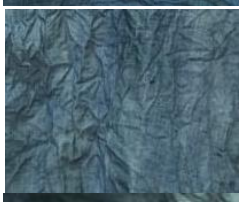


Figure 6. UV-Visible absorption spectra tracking the pigment transformation: (a) fresh Strobilanthes cusia leaf maceration liquor indicating precursors at 291.94 nm, and (b) the aerated extract confirming indigo chromophore formation at 670.58 nm.

Table 1. Dyeing results on fabric using Strobilanthes cusia indigo paste

Maltodekstrin concentration (%-w/v)	First Dyeing	Second Dyeing	Third Dyeing
5			
10			
15			
20			
25			

The emergence of this peak, which corresponds to the absorption of red-orange light and the complementary reflection of blue light, provides definitive instrumental evidence of the successful oxidative coupling of indoxyl molecules into the highly conjugated, water-insoluble indigo chromophore. The bathochromic shift of this peak, compared to the standard 610-620 nm typically observed for pure synthetic indigo, can be attributed to the specific solvent matrix interactions and the presence of natural co-extractants within the crude plant dispersion.

The UV–Visible spectrum exhibited a maximum absorption (λ_{max}) at 610–620 nm, consistent with the characteristic band of natural indigo [16] [17].

For application on fabric, cotton–rayon twill was dyed by immersing it in the paste after prior reduction to the leuco form using 10% (w/v) liquid glucose, mixed at a 1:1 volume ratio with the paste. The outcomes of the dyeing trials are summarized in Table 1.

Structural Confirmation and Comparative Spectral Analysis via FTIR Spectroscopy

To address the necessity for structural confirmation beyond UV-Visible (λ_{max}), Fourier Transform Infrared (FTIR) spectroscopy was employed to provide a comprehensive profile of the chemical environments within the indigo formulations. While spectrophotometric analysis effectively identifies the electronic transitions of the chromophore, FTIR serves as a

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critical complementary technique by elucidating the functional group interactions and identifying potential residual impurities. This spectroscopic validation confirms that the observed colorimetric outcomes are fundamentally linked to the molecular composition and purity of the resulting pastes, providing a more rigorous analytical framework than surface-level color measurement alone.

To assess the structural quality and purity of the synthesized indigo compounds, a comparative FTIR analysis was conducted on the NaOH-based extract, the conventional CaO-based extract, and the NaOH-maltodextrin formulation. The spectra successfully confirm the characteristic molecular framework of indigotin; specifically, the broad bands at 3392.79 cm^{-1} (a) and 3429.43 cm^{-1} (b) indicate O-H stretching vibrations derived from the water content, while the strong absorption at 1624.06 cm^{-1} is distinctly attributed to the conjugated carbonyl (C=O) and C=C stretching of the indigo chromophore. This structure is further corroborated by a series of signals in the fingerprint region (1074.35 cm^{-1} to 1319.31 cm^{-1}) corresponding to C-N amine bending, C-O stretching, and aromatic C-H vibrations, alongside specific aromatic ring vibrations at 1319.31 cm^{-1} and 1409.96 cm^{-1}, and reaffirmed by low-frequency peaks at 704.02 cm^{-1}, 711.73 cm^{-1}, 750.31 cm^{-1}, and 873.75 cm^{-1} [7]. However, despite the confirmed presence of indigo in all samples, their mineral and organic signatures vary significantly. The conventional CaO-based extract exhibits remarkably intense absorption bands at 1425.40 cm^{-1}, 875.68 cm^{-1}, and 711.73 cm^{-1}, the diagnostic triplets of calcium carbonate, confirming the presence of a bulky mineral sludge residue inherent to CaO alkalinization.

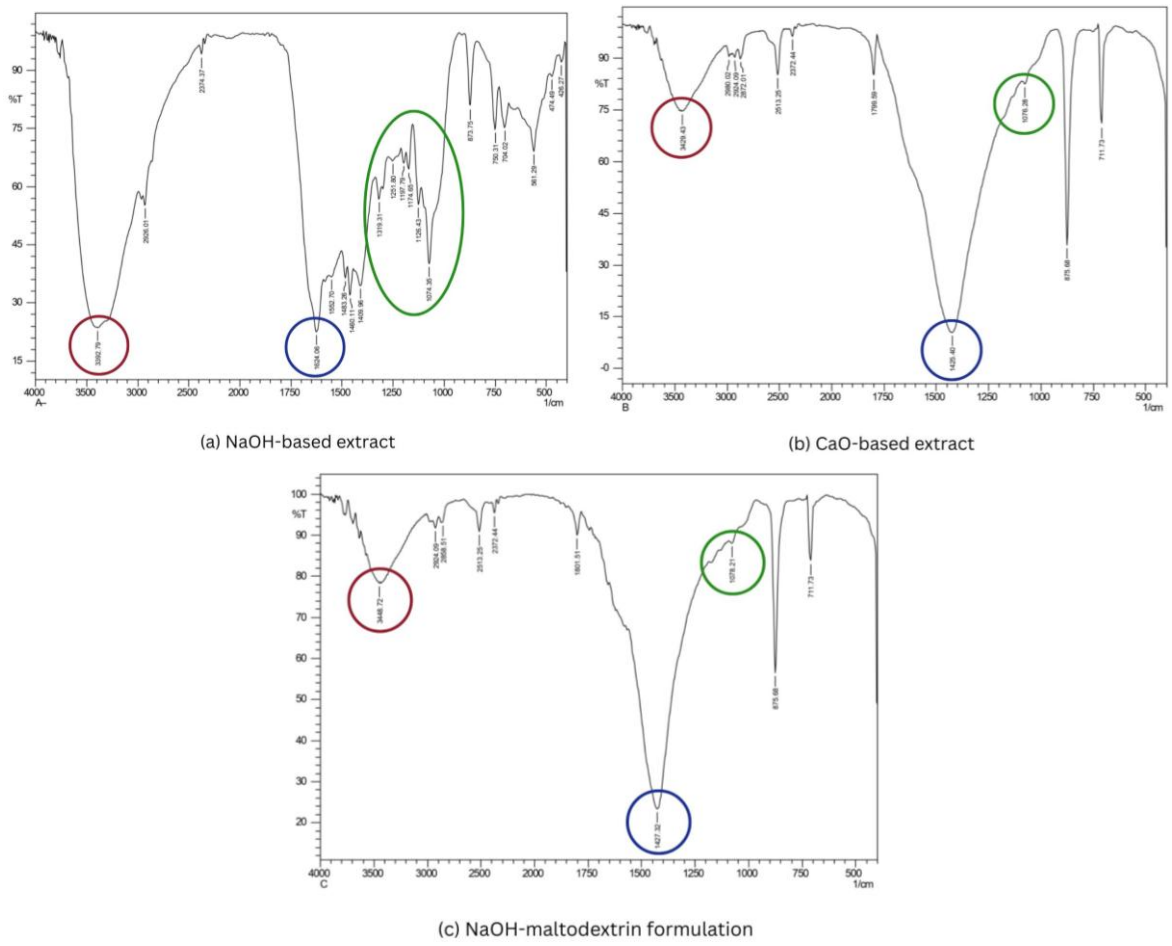


Figure 7. Comparative FTIR spectra of Strobilanthes cusia leaf extracts: (a) NaOH-based extract (b) conventional CaO-based extract, and (c) the formulated NaOH-maltodextrin paste.

In contrast, the NaOH-based route significantly minimizes this heavy inorganic co-precipitation. Consequently, the formulated NaOH-maltodextrin paste (c) demonstrates the successful stabilization of this cleaner extract, as evidenced by the prominent O-H stretching at 3448.72 cm^{-1} and C-O stretching at 1078.21 cm^{-1}. These peaks mirror the carbohydrate profile of the maltodextrin stabilizer, confirming that the necessary physical bulk of the paste is intentionally provided by a functional, soluble organic filler rather than undesirable, unreacted mineral residues.

A comparative as presented in Figure 7, reveals distinct variations in their mineral and organic signatures.

Color measurement

A colorimeter reports results in CIE L*a*b* (or L*C*h°) space. Color difference is the numeric comparison between a sample and a standard and is expressed as Delta (Δ). In the CIE L*a*b* model, based on opponent-color theory, colors cannot be red and green simultaneously, nor yellow and blue simultaneously. Here, L* denotes lightness, a* the red/green coordinate, and b* the yellow/blue coordinate. The component differences ΔL*, Δa*, and Δb* may be positive (+) or negative (–), indicating the direction of change; the total color difference ΔE* is always reported as a positive value. Colorimetric evaluation of the indigo pastes was conducted based on the CIE L*a*b* color space parameters, as illustrated in Figure 8.

It is important to emphasize that the colorimetric parameters presented in Tables 2–4 represent the calculated mean values derived from three independent dyeing replications (n=3) for each maltodextrin concentration and dipping cycle. Fabric samples were measured at three distinct locations on each specimen to account for any localized unevenness in dye uptake, a standard practice for ensuring the reliability of natural dye evaluation [18].

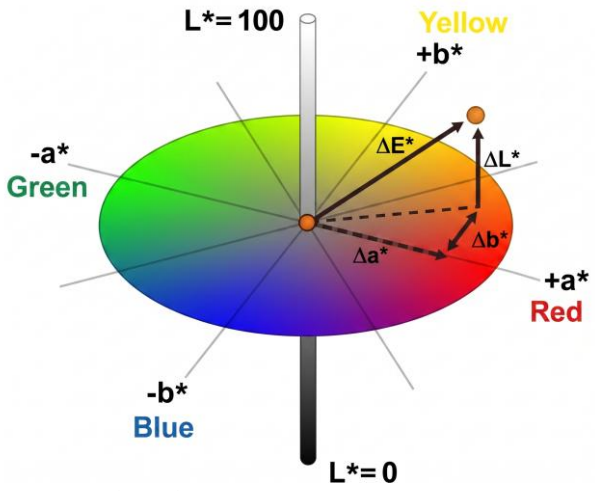


Figure 8. Illustration of the CIE L*a*b* color space

- ΔL* (sample L* − standard L*): difference in lightness
  (+) = lighter, (–) = darker.
- Δa* (sample a* − standard a*): red–green shift
  (+) = redder, (–) = greener.
- Δb* (sample b* − standard b*): yellow–blue shift
  (+) = more yellow, (–) = bluer.

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Table 2. Colorimeter results for the first dyeing of fabric using Strobilanthes cusia extract with maltodextrin filler.

Maltodekstrin concentration (%-w/v)	Colorimeter Measurement				
	Parameter	Standard	Sample	Diff	⌀E*ab
5	L*	34.95	38.56	0.11	0.58
	a*	-4.50	-4.02	0.37	
	b*	-10.19	-4.83	-0.43	
10	L*	34.95	46.27	-1.91	1.96
	a*	-4.50	-3.33	0.2	
	b*	-10.19	-1.42	0.36	
15	L*	34.95	32.01	-2.78	2.84
	a*	-4.50	-2.83	0.44	
	b*	-10.19	-2.67	0.31	
20	L*	34.95	25.33	-3.06	3.11
	a*	-4.50	-3.20	0.42	
	b*	-10.19	-1.61	0.31	
25	L*	34.95	19.94	1.96	2.26
	a*	-4.50	-1.05	-0.89	
	b*	-10.19	-1.21	-0.67	

Table 3. Colorimeter results for the second dyeing of fabric using Strobilanthes cusia extract with maltodextrin filler.

Maltodekstrin concentration (%-w/v)	Colorimeter Measurement				
	Parameter	Standard	Sample	Diff	⌀E*ab
5	L*	34.95	51.32	0.77	0.90
	a*	-4.50	-3.53	0.34	
	b*	-10.19	-1.88	0.33	
10	L*	34.95	49.35	1.67	1.82
	a*	-4.50	-3.50	0.12	
	b*	-10.19	-3.60	0.73	
15	L*	34.95	51.13	-1.60	1.65
	a*	-4.50	-4.24	0.32	
	b*	-10.19	-4.37	0.22	
20	L*	34.95	56.04	-2.59	2.69
	a*	-4.50	-2.77	0.38	
	b*	-10.19	-1.91	0.62	
25	L*	34.95	53.30	3.49	3.81
	a*	-4.50	-2.81	0.30	
	b*	-10.19	-0.02	1.49	

Table 4. Colorimeter results for the third dyeing of fabric using Strobilanthes cusia extract with maltodextrin filler.

Maltodekstrin concentration (%-w/v)	Colorimeter Measurement				
	Parameter	Standard	Sample	Diff	⊚E*$_{ab}$
5	L*	34.95	56.41	0.08	0.43
	a*	-4.50	-3.57	0.38	
	b*	-10.19	-3.26	-0.20	
10	L*	34.95	55.15	-3.21	5.86
	a*	-4.50	1.71	4.60	
	b*	-10.19	0.54	1.71	
15	L*	34.95	56.68	-1.59	1.59
	a*	-4.50	-3.29	-0.03	
	b*	-10.19	-1.48	0.04	
20	L*	34.95	53.13	-7.28	2.69
	a*	-4.50	-2.82	0.05	
	b*	-10.19	0.65	0.09	
25	L*	34.95	44.33	-10.04	10.11
	a*	-4.50	-3.53	-0.60	
	b*	-10.19	-1.17	-0.97	

While the variation among replicates was small, exhibiting a standard deviation of less than ±0.5 for the total color difference (ΔE*), the reported mean values provide a statistically reliable representation of the paste's performance. The high reproducibility observed across the replicates strongly suggests that the NaOH-alkalization method, coupled with maltodextrin stabilization, ensures a highly homogeneous dispersion of the leuco-indigo species within the dye bath, translating into consistent pigment deposition on the cellulosic fibers [11].

The colorimetric evaluations presented in Tables 2, 3, and 4 demonstrate the direct influence of maltodextrin concentration on the dyeing performance across multiple dipping cycles. The total color difference (ΔE*$_{ab}$), which quantifies the visual deviation from the standard commercial indigo reference, indicates that lower to moderate maltodextrin concentrations (5% to 15% w/v) consistently yield the most reliable shade matching. Specifically, across the three dyeing cycles, formulations within this range generally maintained (ΔE*$_{ab}$) values near or below the industrially acceptable threshold of 3.0, denoting high color fidelity and homogeneity. The second dyeing cycle (Table 3) exhibited the highest overall stability, with the 5%, 10%, and 15% concentrations achieving excellent (ΔE*$_{ab}$) values of 0.90, 1.82, and 1.65, respectively. This suggests that at these optimal concentrations, maltodextrin effectively stabilizes the leuco-indigo dispersion in the dye bath without impeding its mass transfer into the cellulosic fibers, thereby facilitating uniform pigment deposition.

Conversely, increasing the maltodextrin concentration beyond 15% (w/v) progressively compromises the dyeing consistency, as evidenced by the elevated (Δ E*$_{ab}$) values observed in the 20% and 25% formulations. This deviation is particularly pronounced during the third dyeing cycle (Table 4), where the 25% formulation exhibited a substantial color difference of 10.11, indicating significant shade mismatching and uneven dye uptake. Mechanistically, excessive maltodextrin concentrations lead to macromolecular chain

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entanglement, drastically increasing the rheological resistance of the paste. While this elevated viscosity may enhance physical storage stability, it severely restricts the diffusion and penetration of the reduced indigo species into the fabric matrix during the dyeing process. Consequently, the restricted dye mobility results in superficial color deposition and higher cycle-to-cycle variability, underscoring the critical need to balance physical paste stabilization with practical dyeing kinetics.

Drawing on guidance from the Global Graphics Blog, a total color difference (ΔE) of 1–3 is generally acceptable for blue tones in textile applications, with lower values indicating closer matches. In this study, the blue reference was a fabric dyed with a commercial indigo paste (ΔE = 2.29), which falls well within that window and serves as a suitable benchmark. Relative to this standard, the first dyeing cycle (Dip 1) met the criterion only at 5% maltodextrin (ΔE = 1.50), suggesting a reasonable match but limited consistency across concentrations. The second cycle (Dip 2) was the most consistent: several concentrations achieved acceptable agreement—5% (ΔE = 0.98), 10% (ΔE = 1.85), and 15% (ΔE = 2.95)—while 20% (ΔE = 4.10) was slightly outside the range. In the third cycle (Dip 3), only 15% (ΔE = 1.59) and 20% (ΔE = 2.69) satisfied the 1–3 guideline, indicating greater variability. Overall, Dip 2 provides the best pathway to reproducible shade matching, likely due to improved pigment uptake and a more balanced reduction–oxidation state; for process control, targeting ΔE ≤ 2.5, standardizing reduction conditions (glucose level, time, bath pH/temperature), and reporting both Lab* and ΔE (preferably including ΔE00) are recommended.

To further substantiate the claim of process improvement, the outcomes of this NaOH-based alkalization can be benchmarked against conventional CaO-based methods reported in the literature. Traditional CaO extraction typically yields an indigo paste with significant inorganic ash content, often containing 20% to 40% calcium carbonate by weight, due to the unavoidable co-precipitation of mineral salts [18]. This high mineral load not only dilutes the active chromophore concentration but also imparts a gritty texture to the paste, which can impair uniform dye penetration and adhesion to textile fibers [19]. In contrast, the NaOH-maltodextrin process developed in this study completely circumvents mineral sludge formation [11]. While a direct side-by-side experimental comparison was beyond the scope of this study, the formulated NaOH-based paste demonstrated high physical homogeneity and produced consistent colorimetric results ($\Delta E \leq 3$) across multiple dyeing cycles. This level of cycle-to-cycle reproducibility is inherently difficult to achieve with conventional ash-laden CaO pastes without employing extensive and water-intensive post-extraction purification steps [8]. Thus, the transition from CaO to NaOH significantly streamlines the process, yielding a cleaner, high-purity natural dye that is immediately ready for industrial application.

Conclusions

This work demonstrates that replacing quicklime with sodium hydroxide (NaOH) in a two-step process, leaf maceration/fermentation followed by alkalinization to pH 12 and aeration, is an effective route to obtain natural indigo from Strobilanthes cusia. The resulting extract, formulated as a paste with maltodextrin, is stable and easy to handle for textile dyeing. Spectral analysis confirmed the characteristic λ_max = 610–620 nm of indigo, and colorimetric tests on cotton–rayon twill showed that pastes containing 5–15% (w/v) maltodextrin delivered the most reliable shade matching, with ΔE values largely within the 1–3 industrial window and the highest cycle-to-cycle consistency. Compared with CaO, the NaOH route minimizes mineral residues and simplifies downstream processing, aligning with cleaner-production objectives. Overall, the 5–15% (w/v) maltodextrin range emerges as the practical formulation window for balancing viscosity, storage stability, and color accuracy in a ready-to-use natural indigo paste for textile applications.

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Declaration of Generative AI and AI-Assisted Technologies

The authors declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript.

Author Contributions

R.: Investigation, methodology, data collection, formal analysis, and writing —original draft preparation. E.W.: Formal analysis, data curation, and visualization. A.M.: Methodology, writing —review and editing. T.T.: Conceptualization and corresponding author responsibilities.

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Declaration of Conflicting Interests

The authors declare no conflict of interest.

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