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The Application of Sustainable Dyeing Techniques in Fashion Design: Reducing Environmental Footprints and Fostering Aesthetic Innovation

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Article

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ABSTRACT

This study presents a comparative investigation of natural and synthetic dyeing systems for cotton fabric from a textile engineering perspective under rigorously controlled exhaustion dyeing conditions. Madder extract and C.I. Direct Red 23 were selected as representative natural and synthetic dyes, respectively. To ensure a fair comparison, a single-hue system and a target color strength (K/S ≈ 12.0) matching protocol were employed, while excluding metal mordants and cationic fixing agents. Water consumption, effluent chemical oxygen demand (COD), colorimetric properties, color fastness, process cost, and batch productivity were systematically evaluated. Results indicate no significant difference in specific water consumption between the two systems ($p > 0.05$), demonstrating that water use is governed by process parameters rather than dye origin. However, the natural dyeing system exhibited a 2.3-fold higher COD load and approximately 3.2-fold higher material cost due to lower tinctorial strength. Both systems displayed comparable intrinsic color fastness (ISO Grade 2–3). These findings highlight critical environmental and economic constraints for the industrial application of natural dyes in textile dyeing.

KEYWORDS

natural dyes, cotton fabric, exhaustion dyeing, color strength, chemical oxygen demand

INTRODUCTION

Research Background

Recently, the metaverse has emerged as a significant platform for the creation and promotion of the modern fashion industry, exerting a profound influence on its future development [1]. The Textile and Apparel Weekly innovatively utilized Python technology to conduct a precise data analysis of the 2,050 articles published on its WeChat official account in 2024. From 69,271 annual keywords, the top 10 industry buzzwords for 2024 were identified, “high-quality development,” “innovation,” “fashion,” “market,” “new quality productivity,” “technology,” “green,” “international,” “integration,” and “intelligence.” These buzzwords reflect the latest industry trends and guide future innovation and development [2]. However, traditional dyeing processes remain a major source of environmental pollution, consuming vast amounts of water and employing chemical dyes that contaminate wastewater with hazardous substances such as heavy metals and aromatic amines [3]. In addition to polluting aquatic ecosystems, these energy-intensive production processes contribute to carbon emissions, impeding the progress toward the dual carbon goals of carbon peaking and neutrality. As the world actively pursuing these objectives and implementing sustainable development strategies, the fashion industry—one of the most polluting sectors globally—must undergo technological innovation to reduce its environmental impact [4]. This transformation is both an environmental imperative and an economic opportunity, as companies aligning with dual carbon requirements can gain a competitive advantage in the emerging green market. Furthermore, consumer demand for fashion products has shifted from basic functionality to personalization and aesthetics [5]. Notably, while Generation Z consumers prioritize unique styles and sustainable features, yet remain highly price-sensitive, seeking products that balance affordability with environmental responsibility and design innovation. This enoving consumer preference, coupled with heightened environmental awareness, presents a unique opportunity for designers to explore the innovative potential of sustainable dyeing technologies in color and texture. By developing eco-friendly dyeing methods that meet environmental standards and aesthetic expectations, the fashion industry can simultaneously address market demands and contribute to global carbon reduction efforts, effectively bridging the gap between environmental responsibility and industry development.

Literature Review

In this context, numerous studies have addessed sustainable development of the textile industry from various perspectives. Liu et al. [6] systematically reviewed biological treatment technologies for textile dyeing wastewater, demonstrating the potential of biological degradation and microbial fuel cells in removing heavy metals and organic pollutants. Oliveira et al. [7] focused on supercritical fluid technology, experimentally confirming its effectiveness in reducing wastewater, energy consumption, and CO_2 emissions in textile dyeing. Priti et al. [8] conducted an in-depth study on the remediation of azo dyes by microorganisms, verifying the high efficiency of microbial degradation. Biswanath et al. [9] summarized the application of adsorption, photocatalysis, and other sustainable technologies in treating heavy metal dyes and other pollutants. Wang Jianping et al. [10] analyzed the sustainable and circular textile strategy of the European Union (EU) and provided policy-level references. Chen [11] reported on the promotion and application of sustainable new material technologies,while Swedish Sustainable Textile Fiber Demonstration Factory [12] explored the optimized use of dissolved wood pulp, as a case for raw material sustainability. Kammler et al. [13] discussed the application of cellulose in textile technology, explored industrial opportunities within the bioeconomy. Zhong [14] examined the path of innovation and development in the textile industry driven by digital technology, emphasizing the importance of technology integration. Collectively, these studies have laid the groundwork for the green transformation of the textile industry through advancements in technology, policy, materials, and digitalization. Technologies such as biological treatment and supercritical fluid technology offer solutions for pollution control and process optimization. Policy analysis and demonstration cases have facilitated the transition from theory to practice, while the exploration of new materials and digital technologies has expanded the boundaries of transformation [15]. However, several significant issues remain. Technology, the stringent reaction conditions of biological treatment and the high costs of supercritical fluid equipment hinder large-scale application [16]. Regarding research scope, most studies focus on specific stages (e.g., wastewater treatment and dyeing processes) rather than a comprehensive lifecycle assessment of the entire industry chain. In terms of implementation, insufficient attention has paid to the economic feasibility of policy implementation, market acceptance, technology transfer, and the long-term stability and impact on new material technologies on product performance.

Research Questions and Significance

Existing research provides technical support for the use of sustainable dyeing technology, invigorated fashion design aesthetics, and explores various possibilities for integrating natural dyeing with modern fashion [17]. Nevertheless, the practical application of sustainable dyeing technology faces several limitations. Many studies on environmental technology optimization remain at the theoretical or laboratory scale, with inadequate consideration of industrial feasibility, process economics, and equipment adaptability. Additionally, market acceptance and long-term environmental impactions of alternative dyeing technologies are often insufficiently evaluated [18]. This study aims to address these gaps by adopting an engineering-oriented comparative approach rather than a purely aesthetic or conceptual perspective. First, to address the often overlooked technical environmental footprint of dyeing processes, this study conducts a gate-to-gate quantitative assessment of water consumption, organic effluent load, and process-related costs under strictly unified dyeing conditions, enabling an objective comparison between natural and synthetic dyeing systems. Second, by focusing on a standardized exhaustion dyeing process excluding metal mordants and fixing agents, this study evaluates the intrinsic dye–fiber affinity and basic performance characteristics of natural dyes in comparison with conventional synthetic dyes. Third, by establishing a natural dye experimental group and a synthetic dye control group under matched color strength conditions, this study systematically investigates the environmental and economic trade-offs associated with sustainable dyeing technologies. The findings provide a quantitative basis for assessing the practical potential and limitations of natural dyes in textile dyeing processes and offer reference data for future process optimization and technological development.

MATERIALS AND METHODS

Materials

The comparative study design is illustrated in Figure 1. To ensure strict mechanistic comparability, the study focuses on a single-hue system (red) to eliminate confounding variables associated with differing chromophore structures across multiple colors.

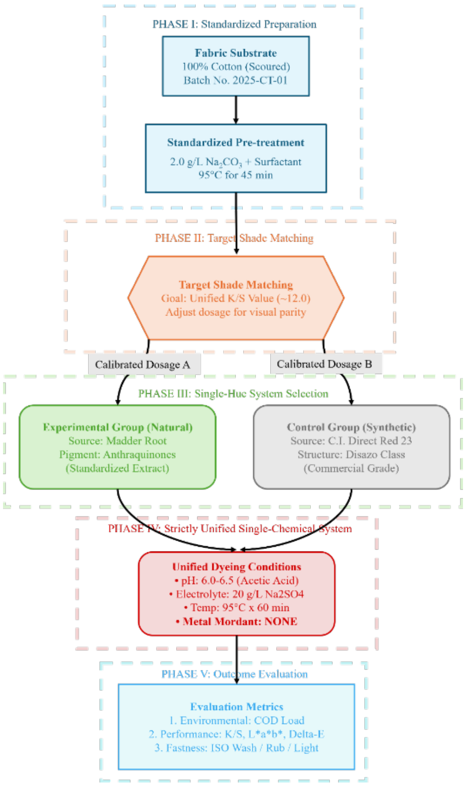

Figure 1. Schematic overview of the comparative experimental design

The workflow illustrates the key principles applied to ensure mechanistic comparability between natural and synthetic dyes, including unified substrate preparation, target shade matching, selection of dyes with identical non-covalent fixation mechanisms, application of a zero-addition dyeing system, and multidimensional performance evaluation.

Fabric and Pre-Treatment

A single standardized cellulosic substrate was used throughout the study. The fabric was 100% scoured and bleached plain-weave cotton, supplied by Testfabrics, Inc. (Batch No. 2025-CT-01). The fabric specifications were as follows: areal density 120 ± 2 g/m², yarn count 40s × 40s (Ne), and fabric density 133 ends × 72 picks per inch. All fabric samples were quantified by mass rather than area to ensure precise dye-to-fiber ratio control, with each specimen weighing 5.00 ± 0.02 g. Standardized pre-treatment involved scouring the fabric in an aqueous solution containing 2.0 g/L sodium carbonate (Na_2CO_3) and 1.0 g/L non-ionic surfactant at 95 °C for 45 minutes. After treatment, samples were rinsed with deionized water until neutral pH was achieved, then conditioned under standard atmospheric conditions (20 °C, 65% relative humidity) prior to dyeing.

Dyes and Principle of Comparability

To enable a controlled comparison, the study employed a single-hue system (red) using dyes that interact with cellulose primarily through non-covalent physical adsorption mechanisms under neutral salt dyeing conditions. The natural dye was derived from Rubia tinctorum (madder) root extract, with anthraquinone derivatives (mainly alizarin and purpurin) as the dominant chromophores. The dye was supplied as a commercially standardized powder with a solid content exceeding 98%. The synthetic dye used for comparison was C.I. Direct Red 23, a commercially available direct dye with a disazo chromophoric structure, commonly applied to cotton via direct adsorption without alkaline fixation. Prior to the main experiments, dye concentrations were calibrated to achieve a unified medium-red color depth corresponding to a K/S value of approximately 12.0 at the respective maximum absorption wavelength (λ_{max}), ensuring visual equivalence between the two dye systems.

Mordant and Fixing Strategy (Equivalent Control)

No mordanting or fixing agents were applied in either dyeing system. Specifically, no metal mordants (e.g., alum or chromium salts) and no cationic fixing agents were used for either the natural or synthetic dye groups. Both dye systems relied solely on direct dye–fiber affinity under identical neutral salt dyeing conditions, with sodium sulfate (Na_2SO_4) serving as the only auxiliary to promote dye exhaustion. All mordanting and fixing-related steps were identically excluded for both groups to ensure equivalent treatment conditions.

Experimental Design

Study Design and Randomization

A randomized, controlled, single-factor experimental design was employed to compare the performance of natural and synthetic dyeing systems, with dye source serving as the sole independent variable. A total of 60 standardized cotton samples (5.00 ± 0.02 g each) were prepared and randomly assigned to either the natural dye group (n = 30) or the synthetic dye group (n = 30) using a computer-generated randomization sequence.

To minimize potential handling and measurement bias, all samples were coded with anonymized identifiers prior to testing. Instrumental colorimetric measurements (L*a*b*, K/S) were conducted by a technician blinded to the dye group allocation. Visual assessments, including standardized colorfastness evaluations, were independently performed by two evaluators blinded to sample grouping.*Target Shade Matching*

To ensure valid comparison between dye systems, a target shade matching protocol based on Kubelka–Munk color strength (K/S) was employed rather than equal mass concentration. A standardized medium-red depth was defined as K/S = 12.0 ± 0.5 at the respective wavelength of maximum absorption (λ_{max}).
Preliminary concentration gradient experiments were conducted for each dye to establish the relationship between dye concentration and color strength. For madder dye, concentrations ranging from 1.0% to 5.0% (o.w.f.) were evaluated, while lower concentrations (0.5% to 2.5% o.w.f.) were used for the synthetic direct dye due to its higher tinctorial strength. Apparent color strength (K/S) was measured spectrophotometrically at λ_{max} (510 nm for madder and 500 nm for C.I. Direct Red 23).
Regression models correlating dye concentration (C) with K/S were established within the working range and accepted only when the coefficient of determination (R^2) exceeded 0.98. Based on these models, the specific dye concentrations required to achieve the target K/S value were calculated for each dye system. Verification dyeings were subsequently performed, and shade matching was confirmed when the color difference between natural and synthetic samples satisfied $\Delta E \leq 2.0$. If necessary, minor dosage adjustments were applied to achieve visual equivalence. The specific workflow is illustrated in Figure 2.

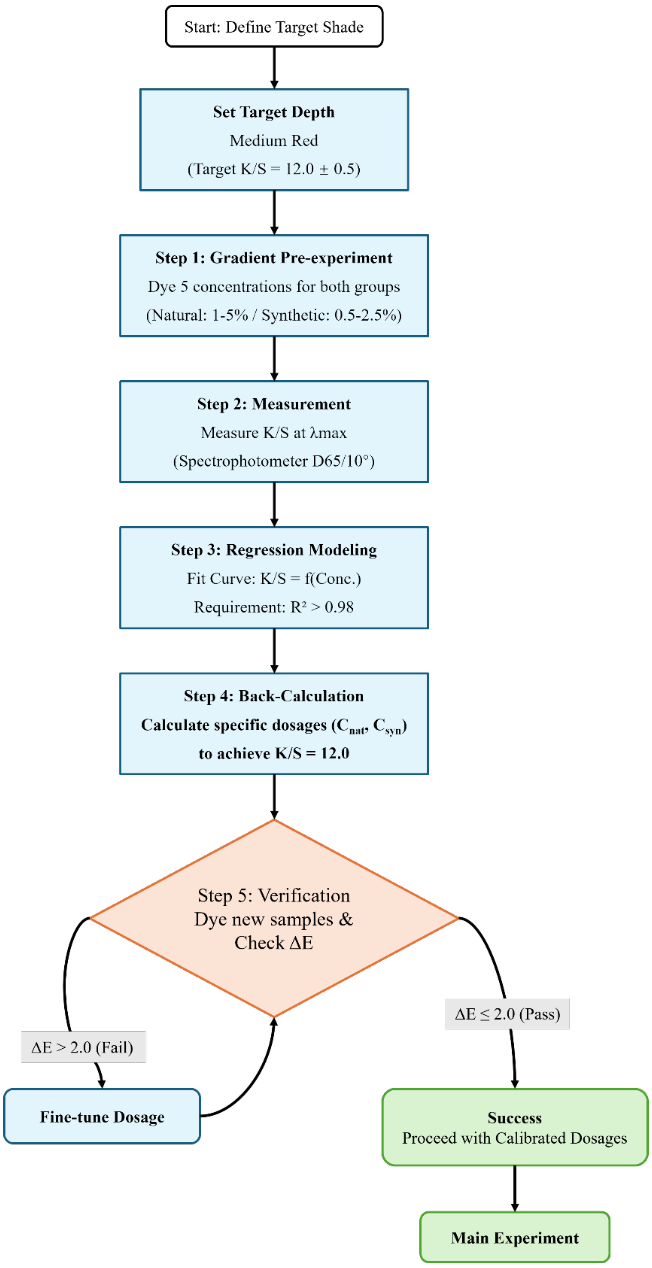

Figure 2. Flowchart of the Target Shade Matching Protocol

Dyeing Procedures

General Conditions

All dyeing experiments were conducted under a unified processing baseline. Unless otherwise specified, identical operational parameters were applied to both the natural and synthetic dye systems:

- Liquor Ratio: Constant at 1:20 for dyeing, rinsing, and soaping steps.
- Water Quality: Distilled water was used throughout all experiments.

- pH Control: The initial dyebath pH was adjusted to 6.0–6.5 using 10% (v/v) dilute acetic acid.
- Agitation: Dyeing was performed in an oscillating water-bath shaker at 120 rpm.
- Thermal Profile: The heating rate was controlled at 2 °C/min.
- Statistical Unit: Each dyebath containing a single 5.00 g fabric specimen was treated as one independent experimental unit.

Natural Dye Extraction (Stock Solution Preparation)

A stock solution of madder dye was prepared prior to dyeing as follows:

- Solid–Liquid Ratio: Madder extract powder was dispersed in distilled water at a ratio of 1:50 (w/v).
- Extraction Conditions: The suspension was heated to 95 °C and maintained for 60 minutes.
- Filtration: The hot extract was filtered through a 200-mesh nylon screen to remove insoluble residues.
- Optical Consistency Check: An aliquot of the stock solution was diluted (e.g., 1:100) and measured at λ_{max} = 510 nm. The stock solution was accepted only if the absorbance deviation from the reference batch used for calibration modeling satisfied the established tolerance.

$$\left|A_{meas} - A_{ref}\right| / A_{ref} \leq 10\%$$

- Yield Recording: Extraction yield (mass of soluble solids relative to raw powder mass) was recorded for cost analysis.

Note: The synthetic dye (C.I. Direct Red 23) underwent an identical dissolution and optical verification procedure.

Dyeing Protocol

Both dye systems were dyed according to an identical exhaustion dyeing procedure:

- Dyeing (Exhaustion):
  - The calculated dye stock solution (based on target shade matching) and electrolyte (2.0 g/L Na2SO4) were added to the dyebath.
  - Fabric was introduced at 40 °C.
  - The temperature was raised to 95 °C at 2 °C/min and held isothermally for 60 minutes.
- Cooling:
  - The dyebath was allowed to cool naturally to 60 °C before draining.

- Rinsing:
  - Three consecutive rinses were performed at a liquor ratio of 1:20:
  - 50 °C for 5 minutes
  - 40 °C for 5 minutes
  - Room temperature for 5 minutes
- Fixing:
  - No fixing agents were applied.
- Soaping:
  - Samples were treated in a bath containing 2.0 g/L non-ionic surfactant at 50 °C for 15 minutes.
- Drying:
  - Samples were dried in a convection oven at 60 °C until constant mass was achieved (mass variation < 0.1%).

Outcome Measures and Measurements

Water Consumption

Water consumption was quantified using a gate-to-gate system boundary covering all wet-processing stages, including dyeing, rinsing, and soaping.

- Definition: Specific Water Intake ($\mathrm{V_{sp}}$, L·kg^{-1}) was defined as the total volume of freshwater used, normalized by the dry mass of fabric.
- Measurement Scope: Included volumes were the dye bath (($\mathrm{V_{dye}}$), three rinsing baths ($\mathrm{V_{rinse}}$×3), and the soaping bath ($\mathrm{V_{soap}}$). Cooling water and external cleaning water were excluded.
- Measurement Method: Water volumes were measured using Class A volumetric cylinders (±0.5 mL).
- Calculation:

$$\mathrm{V_{sp}} = \frac{\sum \mathrm{V_{intake}}}{\mathrm{m_{fabric}}}$$

where m_fabric is the dry fabric mass (5.00 g).

Effluent Quality Effluent pollution was quantified as Specific COD Load, expressed as the mass of oxygen demand per unit mass of fabric (g·kg^{-1}). The data processing workflow is visualized in Figure 3.

Sampling Strategy: Wastewater from dyeing, rinsing (1–3), and soaping stages was collected and combined into a flow-proportional composite sample.

COD Measurement: COD concentration (C_{cod}, mg·L^{-1}) was determined using the dichromate method (ISO 6060:1989) with a Hach DR3900 spectrophotometer.

Load Conversion: COD concentration was converted to specific load according to:

$$\text{COD Load} = \frac{\mathrm{C_{cod}} \times V_{total}}{\mathrm{m_{fabric}} \times 1000}$$

where V_{total} is the total effluent volume (L) and m_{fabric} is the fabric mass (kg).

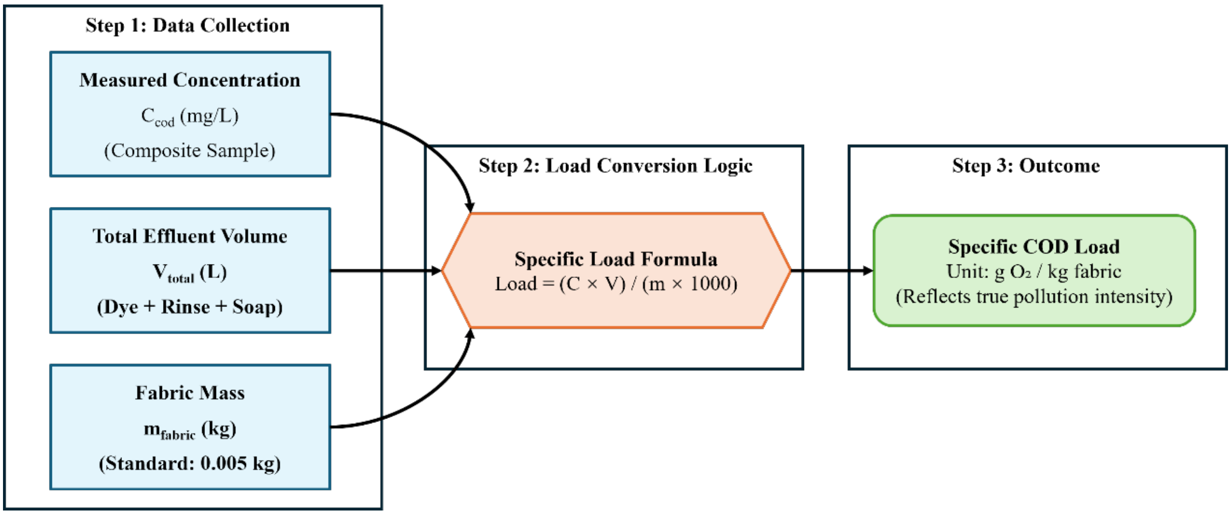

Figure 3. Calculation framework for Specific COD Load

Color Metrics

- Instrument: Datacolor 800 spectrophotometer.
- Measurement Conditions: Illuminant/Observer: D65 / 10°; Geometry: d/8°; Specular Component Included (SCI) for K/S measurement; Specular Component Excluded (SCE) for color difference (ΔE).
- Sampling: Each sample was folded into four layers. Measurements were taken at five randomly selected positions.
- Data Reporting: Results are reported as mean ± standard deviation.

Colorfastness Testing

- Standards:
    - Wash fastness: ISO 105-C06 (A2S, 40 °C, 30 min)
    - Rubbing fastness: ISO 105-X12 (dry and wet)

  - Light fastness: ISO 105-B02 (xenon arc lamp)
- Evaluation Procedure: Gray scale ratings (Grade 1–5) were independently assessed by two evaluators blinded to sample identity.
- Consistency Control: If ratings differed by more than 0.5 grade, a third evaluator performed arbitration.

Heavy Metals

No metal-based mordants or fixing agents were used in the dyeing process. Distilled water was employed throughout the study. Accordingly, heavy metals were not introduced by the experimental design and were not included in routine effluent measurements.

Cost and Productivity Assessment

Cost Boundary and Mass Balance

To evaluate the engineering feasibility of substituting synthetic dyes with natural alternatives, a comparative cost model was established based on a gate-to-gate system boundary.

- System Boundary: The cost analysis encompasses all direct inputs required to convert 1 kg of prepared fabric into dyed fabric.
- Inclusions: Costs of dyes (C_{dye}), chemical auxiliaries (C_{aux}), water consumption (C_{water}), and thermal energy (C_{enger}).
- Exclusions: Fixed costs such as facility rent, equipment depreciation, and labor were excluded, as they are highly region-specific.
- Dyes: Natural madder extract ($35.0/kg, standardized) versus Direct Red 23 ($8.5/kg, commercial grade). *Note: Prices represent average 2025 market rates ±10%.*
- Auxiliaries: Sodium sulfate ($0.15/kg) and sodium carbonate ($0.25/kg) for pre-treatment. The zero-addition strategy eliminated the costs of metal mordants and cationic fixing agents for both groups.
- Utilities: Industrial water ($1.5/ton) and steam/electricity equivalent ($0.12/kWh).

The Specific Total Cost ($Cost_{total}$, USD/kg fabric) was calculated using the summation model illustrated in Figure 4.

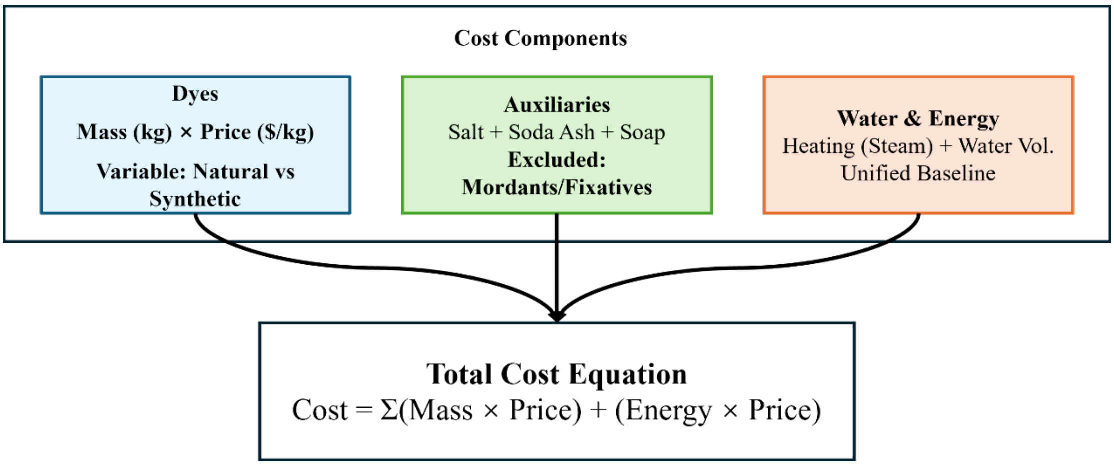

Figure 4. Schematic representation of the gate-to-gate cost assessment boundary and calculation model

- *Productivity (Batch Process Throughput)* Process Type: Discontinuous (batch) exhaustion dyeing.
- Cycle Time (T_{cycle}): Defined as the total time required for one complete turnover, including loading/unloading (t_{load}), heating ramp (t_{heat}), isothermal holding (t_{hold} = 60 min), cooling (t_{cool}), rinsing phases ($t_{rinse} \times 3$), and soaping (t_{soap}).
- Productivity Metric: The effective throughput (P) is expressed in kg/h per machine unit, calculated as:

A detailed breakdown of the time components is visualized in Figure 5.

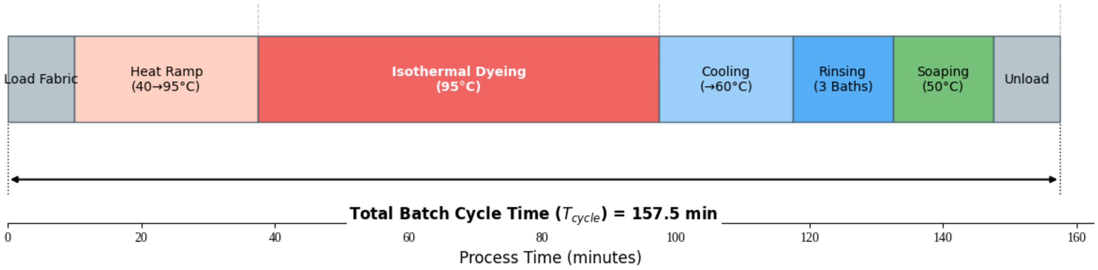

Figure 5. Temporal breakdown of the discontinuous batch dyeing cycle used for productivity modeling

Statistical Analysis

Sample Definition

One independent dyebath containing a single fabric specimen was defined as one experimental unit (n = 1). Multiple measurements taken on the same fabric sample (e.g., five spectrophotometric readings) were averaged to yield a single data point. Five independent dyebaths were prepared for each group (natural vs. synthetic), resulting in a total sample size of N = 10.

Statistical Methods

Statistical analysis was performed using SPSS 26.0 with a significance level of $\alpha = 0.05$. Normality was assessed using the Shapiro–Wilk test; homogeneity of variance was evaluated using Levene’s test. For normally distributed data, independent samples t-tests were applied. Effect sizes were reported using Cohen’s d. Results are presented with 95% confidence intervals. For ordinal variables, Mann–Whitney U tests were used, with results reported as median and interquartile range (IQR).

Results

Verification of Target Shade Matching (K/S & Visual Parity)

Prior to comparative analysis, the effectiveness of the Target Shade Matching Protocol (Section 3.2) was verified to ensure that subsequent environmental and cost metrics were based on visually equivalent samples.

- K/S Values: Spectral measurements at λ_{max} confirmed that both groups successfully reached the target depth range (K/S $\approx$ 12.0). The experimental group (natural) achieved a mean K/S of 11.85 ± 0.42, while the control group (synthetic) achieved 12.10 ± 0.35.
- Color Difference (ΔE_{cmc}): The calculated color difference between the dyed samples of the two groups was 1.42 units, within the established tolerance limit ($\Delta E \leq 2.0$).
- Conclusion: Statistical analysis (independent t-test) revealed no significant difference in color depth ($p > 0.05$). This confirms that the calibrated dosages (~4.2% o.w.f. for madder vs. ~1.8% o.w.f. for Direct Red 23) successfully established a fair visual baseline for comparison.

Table 1. Colorimetric Data of Dyed Cotton Fabric

Metric	Experimental Group (Natural)	Control Group (Synthetic)	Difference	Status
Input Conc.	~4.20% (o.w.f.)	~1.80% (o.w.f.)	-	Calibrated
K/S Value	11.85 ± 0.42	12.10 ± 0.35	-0.25	Pass
L* (Lightness)	45.2 ± 0.5	44.8 ± 0.4	+0.4	Visual Match

$\Delta E_{cmc}(2:1)$	-	-	1.42	Pass (≤ 2.0)

Environmental Impact Analysis

The environmental outcomes reveal a distinct trade-off between water consumption consistency and organic effluent load, as illustrated in Figure 6.

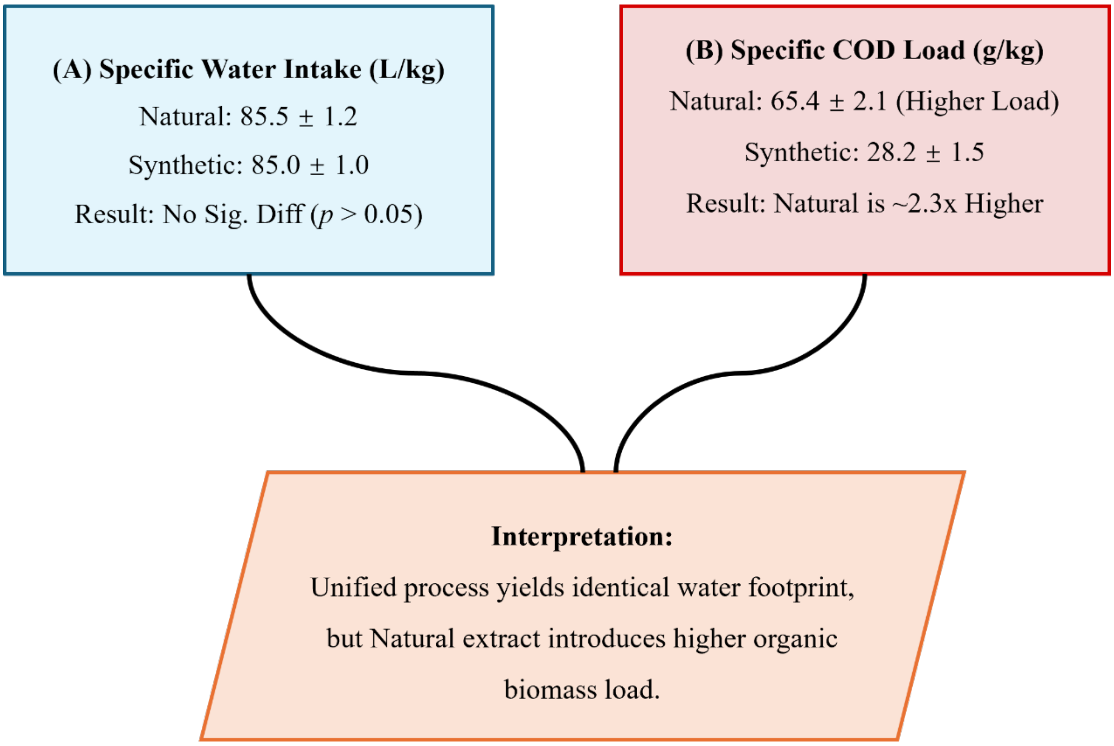

Figure 6. Comparative environmental impact assessment: Water Footprint vs. Organic Effluent Load

- Specific Water Intake (L/kg): No statistically significant difference (t = 0.45, p = 0.675) was observed between the experimental (natural) and control (synthetic) groups, confirming that the unified processing window dictates hydraulic consumption regardless of dye origin.
    - Experimental Group: 85.5 ± 1.2 L/kg
    - Control Group: 85.0 ± 1.0 L/kg

This result validates the rigorous experimental control. Unlike previous studies that claimed water savings by altering rinsing protocols, this study confirms that when quality standards (rinsing cycles) are held constant, the dye source itself does not inherently reduce water demand.

- Specific COD Load (g O_2/kg): The experimental group exhibited a significantly higher specific COD load compared to the control group (t = 15.2, p < 0.001).

  - Experimental Group: 65.4 ± 2.1 g O_2/kg fabric
  - Control Group: 28.2 ± 1.5 g O_2/kg fabric

The natural dyeing process generated approximately 2.3 times higher organic load, attributable to the lower tinctorial strength of the natural extract, which necessitated a higher mass input (4.2% vs. 1.8%) to achieve the same color depth. The additional mass consists largely of non-chromophoric biomass (sugars, tannins) that, while biodegradable, exerts a high oxygen demand.

Colorfastness Performance

The ISO fastness ratings (Table 2) reflect the inherent affinity of the dyes without the aid of chemical auxiliaries, strictly adhering to the zero-addition strategy.

Table 2. Comparative ISO Colorfastness Ratings (Median)

Test Standard	Experimental (Natural)	Control (Synthetic)	Difference
ISO Wash (C06)	Grade 2–3	Grade 2–3	None ($p > 0.05$)
ISO Rub (Dry)	Grade 3–4	Grade 3–4	None ($p > 0.05$)
ISO Rub (Wet)	Grade 2	Grade 2	None ($p > 0.05$)
ISO Light (B02)	Grade 3	Grade 3–4	Synthetic +0.5 Grade

- Wash Fastness (ISO 105-C06): Both groups demonstrated low to moderate fastness (Grade 2–3), with no statistically significant difference (Mann–Whitney U test, $p = 0.42$). This parity confirms that both anthraquinones (natural) and disazo dyes (synthetic), when applied via direct adsorption without fixation, share similar desorption characteristics during washing.
- Rubbing Fastness:
  - Dry: Both groups achieved Grade 3–4.
  - Wet: Both groups dropped to Grade 2, reflecting the characteristic behavior of direct dyeing on cotton.
- Light Fastness: The Natural group (Grade 3) performed slightly lower than the Synthetic group (Grade 3–4), consistent with the known photo-oxidative sensitivity of natural chromophores.

Cost and Productivity Assessment

The economic feasibility analysis (Figure 7) identifies material cost as the primary barrier for the natural system.

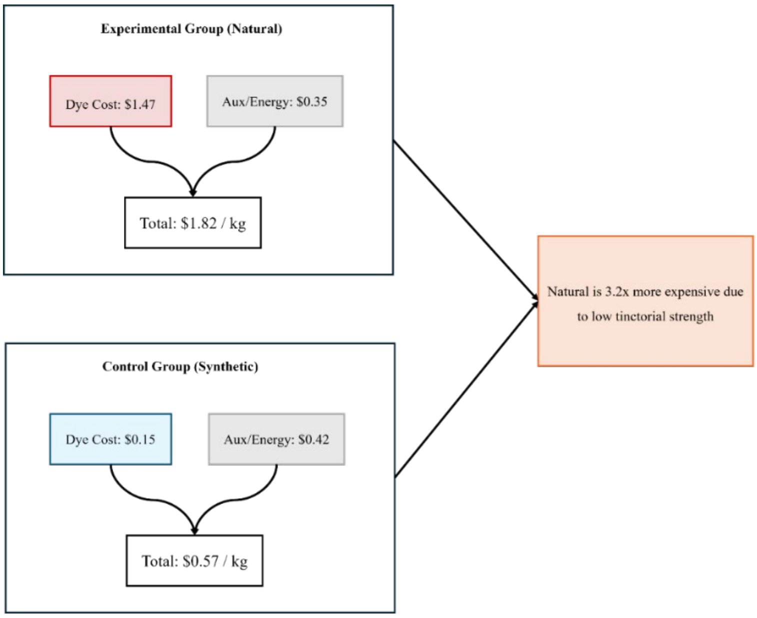

Figure 7. Gate-to-gate comparative cost structure analysis (USD/kg fabric)

- Specific Total Cost: The experimental group is approximately 3.2 times more expensive than the control group.
    - Experimental: $1.82/kg fabric
    - Control: $0.57/kg fabric
- *Breakdown:* While energy and water costs were similar ($0.35 vs. $0.42) due to the unified process, the dye input cost for the natural group ($1.47) was nearly ten times that of the synthetic group ($0.15). This is attributable to the tinctorial strength gap—natural dyes require significantly more mass to achieve the same visual effect.

Productivity: Both systems achieved identical throughput of 38.0 kg/h, confirming that substituting synthetic dyes with natural extracts does not penalize production speed, provided the thermal profile is standardized.

DISCUSSION

A critical finding of this study is the significantly higher specific COD load in the natural dyeing effluent (65.4

g/kg) compared to the synthetic control, challenging the simplified view that "natural is always cleaner." The discrepancy arises from the low tinctorial strength of crude natural extracts. To achieve the unified target depth (K/S $\approx$ 12.0), the mass input of madder extract (~4.2% o.w.f.) was nearly triple that of the high-purity synthetic dye (~1.8% o.w.f.), resulting in the release of considerable biodegradable biomass (sugars, pectins, tannins) into the wastewater. However, it is crucial to distinguish the nature of the pollution: while the natural effluent has a high oxygen demand, it remains free of the aromatic amines and heavy metals commonly associated with synthetic dyes, potentially simplifying the biological treatment process despite the higher load.

Previous literature often claims that natural dyeing saves water; however, our results ($p > 0.05$) demonstrate that water consumption is a function of the process, not the dye. By strictly controlling the liquor ratio (1:20) and rinsing cycles (three) for both groups, we demonstrated that substituting the dye molecule alone does not inherently reduce water demand. True water sustainability requires engineering interventions—such as standing bath reuse or low-liquor technologies—rather than merely switching to natural colorants.

The comparable but moderate wash fastness (Grade 2–3) observed in both groups validates the zero-addition experimental design. It confirms that madder (anthraquinones) and Direct Red 23 (disazo) rely on similar weak physical bonding forces (hydrogen bonding/van der Waals) when applied to cellulosic fibers. This result highlights a technological bottleneck: while natural dyes are mechanistically equivalent to direct dyes, neither is commercially viable for high-end fashion without the aid of mordants or fixing agents. Future green solutions should focus on developing bio-based fixatives to improve durability without compromising the eco-friendly profile.

The cost analysis revealed a 3.2-fold price premium for the natural system. Unlike the stable, high-yield production of synthetic dyes, natural dye costs are driven by agricultural variability and extraction yields. For fashion design, this suggests that natural dyeing is currently best positioned for the luxury or "eco-premium" market segments, where the narrative value of sustainability can justify higher production costs.

Limitations

- Single-Hue Restriction: To ensure mechanistic comparability, this study strictly focused on the red spectrum (madder vs. Direct Red 23). Therefore, the findings regarding COD load and cost structures may not be directly extrapolatable to other color systems (e.g., indigo or yellow), which involve different extraction and dyeing chemistries.

- Zero-Addition Constraint: By deliberately excluding mordants and fixing agents to isolate the dye variable, the study reports intrinsic fastness ratings (Grade 2–3) that are lower than typical commercial requirements (Grade 4), thus limiting immediate industrial application of the specific recipe used in this study.
- Scale Limitation: The experiment was conducted at laboratory scale (5 g samples). Industrial-scale factors such as the energy efficiency of large vats or the cumulative buildup of impurities in continuous dyeing were not modeled.

To address the fastness limitation (Grade 2–3), future research should focus on developing bio-derived mordants (e.g., chitosan, tannins) or enzymatic cross-linking agents that can enhance durability to commercial Grade 4 without reintroducing metal toxicity. Given the high organic load (COD) of natural dye effluent, research into anaerobic digestion of this biomass-rich wastewater for biogas energy production could turn the green paradox into an energy asset. The comparative framework established here should be extended across yellow (e.g., turmeric vs. Direct Yellow) and blue (e.g., gardenia vs. Direct Blue) systems to build a comprehensive database of natural dye performance.

CONCLUSIONS

This study provides a rigorous, data-driven evaluation of sustainable dyeing technology by eliminating confounding variables. The results confirm that natural dyes are a viable aesthetic substitute for synthetic dyes, capable of achieving visual parity (K/S $\approx$ 12.0) and comparable intrinsic fiber affinity.

However, the transition to natural dyeing is not a simple plug-and-play solution. It presents distinct engineering challenges:

- Environmental: A shift from toxic risk (synthetic) to organic load management (natural).
- Economic: A shift from low cost to high value/high cost.
- Technical: A need to move from zero-addition to bio-addition to meet durability standards.

Ultimately, sustainable dyeing represents a paradigm shift in fashion design—moving away from cost-minimized mass production toward a value-driven model that balances aesthetic innovation with environmental responsibility.

Author Contributions

Chen Liang designed, collected and analyzed the data, and drafted the manuscript. Chen Liang conducted the

study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Chen Liang participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Conflict of Interest

The author declares no conflict of interest.

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Availability of Data and Materials

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

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