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The Influence of Natural Dyeing on Color Stability, UV Resistance, and Market Competitiveness in the Textile Industry: An Evaluation of Ulos Fabric's Production Costs and Global Market Potential

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Abstract: The textile industry faces substantial environmental challenges due to the widespread use of synthetic dyes, which contribute to pollution and ecosystem degradation. Natural dyes derived from plants and insects provide an environmentally friendly alternative, but their adoption has been limited by concerns related to color stability and production costs. This study compared natural and synthetic dyes with respect to color stability, UV resistance, production costs, and market competitiveness. Experimental results demonstrated that natural dyes incurred higher production costs but exhibited superior color stability and UV resistance compared to synthetic dyes. Textiles dyed with natural dyes achieved higher profit margins in global markets, particularly in premium segments where sustainability considerations are prioritized. The findings provide practical guidance for textile manufacturers seeking to adopt natural dyes while maintaining competitiveness and support sustainability-oriented policy development in the textile sector, with particular relevance for developing countries and Small Island Developing States.

Keywords: Color stability; Natural dyes; Production cost; Synthetic dyes; UV resistance

1 Introduction

The textile industry is one of the fastest-growing sectors worldwide. At the same time, it generates substantial environmental impacts, particularly through the extensive use of synthetic dyes [1]. Synthetic dyes produce bright and durable colors, but they often contain hazardous chemical compounds. These substances contribute to environmental contamination and ecosystem degradation. Their production processes also require high energy input and generate non-biodegradable waste, which undermines environmental sustainability [2]. Previous studies have documented the contribution of synthetic dyes to water and soil pollution and have identified potential risks to human health.

In response to these concerns, natural dyes have received renewed attention. Natural dyes are derived from plants, minerals, and insects and have been used historically for textile coloration [3]. Their primary advantage lies in their biodegradability and lower environmental burden. However, their industrial application remains limited. Natural dyes generally exhibit lower color stability and higher production costs than synthetic dyes [4]. Although they contribute to a reduced carbon footprint, limited resistance to ultraviolet exposure and repeated washing continues to restrict their widespread adoption.

Recent advances in dyeing technology have improved the performance of natural dyes. Enhanced fixation techniques and modern dyeing equipment have increased dye uptake efficiency and color consistency [5]. Despite these developments, large-scale adoption remains constrained. Color fading under ultraviolet exposure remains a critical limitation, as prolonged sunlight exposure reduces color durability [6]. Several recent studies have investigated modification and treatment techniques to improve the UV resistance of natural dyes, but consistent performance across applications has not yet been achieved.

At the same time, global demand for environmentally responsible products continues to increase [7]. Consumers show growing concern about the environmental impact of textile production. This trend is particularly relevant for countries that are highly vulnerable to climate change, including Small Island Developing States. These regions require solutions that support both environmental protection and economic resilience. In this context, natural dyes offer potential benefits by reducing environmental impacts while supporting local resource-based economies.

This study addresses a gap in the literature by providing a systematic comparison between natural and synthetic dyes [8]. The research evaluates color stability, UV resistance, production costs, and market competitiveness. The objective is to assess whether natural dyes can serve as a technically viable and economically competitive alternative to synthetic dyes [9]. The findings are intended to support informed decision-making by textile manufacturers and policymakers. By linking performance outcomes with market potential, this study contributes to the advancement of sustainable textile production and the adoption of environmentally responsible dyeing technologies.

1.1 Theoretical Framework

1.1.1 Sustainability-oriented innovation framework

The sustainability-oriented innovation framework emphasizes the integration of environmental considerations into innovation processes, particularly in resource-intensive industries such as textiles. Within this framework, the adoption of natural dyes is viewed as an ecological innovation aligned with the triple bottom line of environmental protection, economic viability, and social responsibility [10]. Color stability and UV resistance are treated as indicators of functional product quality, while market competitiveness reflects the economic value generated through sustainable product differentiation in environmentally sensitive markets. This framework supports the study's objective of positioning natural dye adoption as an innovation that improves environmental performance while enhancing product marketability.

1.1.2 Natural resource-based view of the firm

The natural resource-based view posits that firms achieve sustained competitive advantage through the strategic management of environmental resources and capabilities [11]. In this context, the use of plant-derived dyes represents the utilization of renewable resources as a strategic asset. Improvements in UV resistance and color durability increase the functional reliability of natural dyes, strengthening their viability as alternatives to synthetic dyes. Premium market positioning emerges from leveraging eco-friendly attributes to respond to increasing consumer demand in sustainability-oriented markets, particularly in Europe and Japan. This perspective aligns with the study's emphasis on profit margins and value creation through environmentally responsible production.

1.1.3 Diffusion of innovation theory

Diffusion of innovation theory explains how new technologies and practices are adopted within an industry. In the case of natural dyeing, key variables such as color stability, production cost, and market demand correspond to core adoption attributes, including relative advantage, complexity, and observability. This framework clarifies why the adoption of natural dyes remains limited, largely due to perceived performance and cost disadvantages. It also explains how technological improvements, such as advanced dyeing equipment, reduce adoption barriers by lowering complexity and increasing trialability. These factors collectively influence the conditions under which broader industry adoption becomes feasible.

1.1.4 Circular economy framework

The circular economy framework focuses on reducing waste and preserving the value of materials throughout their life cycle. Natural dyes align with circular economy principles through the use of biodegradable inputs and locally sourced resources. Compared to synthetic dyes, they generate lower levels of toxic waste and support more sustainable production practices. Their application also contributes to sustainable consumption and production objectives, including Sustainable Development Goal 12. This framework provides a basis for the study's environmental rationale and supports its policy-oriented recommendations.

2 Related Work

2.1 Baseline and State-of-the-Art Approaches

Natural dyes have been used for textile coloration for centuries. However, the development of industrial dye chemistry has led to widespread adoption of synthetic dyes, particularly Azo and Reactive dyes, because they provide consistent shades and strong fastness at relatively low production cost [12]. These dyes typically form covalent bonds with textile fibers, which improves resistance to washing, heat, and ultraviolet exposure. Despite these functional advantages, synthetic dyes raise environmental concerns because their manufacture and application can involve hazardous chemicals and generate persistent waste streams.

Plant-derived dyes, including Indigofera tinctoria and Morinda citrifolia, have demonstrated potential for acceptable color retention and UV resistance under controlled dyeing conditions. Nevertheless, natural dyeing often involves higher costs and greater process variability than synthetic dyeing. To address these limitations, recent studies have focused on improving efficiency and repeatability through process innovation. Modern dyeing equipment, such as the

Gama Warni machine, has been reported to shorten processing time, reduce energy use, and improve dye uptake, thereby strengthening the economic feasibility of natural dyes [13].

2.2 Research Gap

Although the properties of natural and synthetic dyes have been widely investigated, many studies evaluate performance in isolation, typically emphasizing either technical parameters (e.g., wash fastness) or environmental implications. Comparative studies that integrate technical performance (color stability and UV resistance) with production costs and market demand remain limited [14]. This study addresses that gap through an experimental framework that links standardized textile testing with economic assessment and market evaluation.

2.3 Rationale for the Selected Approach

Synthetic dyeing provides advantages in cost and operational consistency but is associated with environmental risks due to toxic and non-biodegradable components that complicate waste treatment. Natural dyes offer environmental advantages but are often constrained by longer processing times, inconsistent shade yield, and higher costs. This study therefore integrated natural dyeing with modern process control through the Gama Warni machine. The approach was selected to improve cost efficiency and color performance while maintaining the environmental advantages of plant-based dyes. The method was designed to evaluate whether natural dyes can meet performance and profitability requirements relevant to commercial adoption.

3 Methodology

3.1 Experimental Process

3.1.1 Materials and sample preparation

Cotton and wool were selected as experimental substrates because they are widely used natural fibers and show distinct dye–fiber interaction behavior. Fabric rolls were obtained from certified textile suppliers in North Sumatra and Java. Samples were prepared by cutting defect-free material into standardized swatches (20 × 20 cm). The swatches were randomly assigned to two treatment groups to support unbiased comparison: one group received natural dye treatments and the other received synthetic dye treatments.

Natural dye extracts were prepared from Indigofera tinctoria, Morinda citrifolia, and Psidium guajava. Synthetic dye treatments used Azo and Reactive dyes, which represent common industrial dye classes [15]. To minimize the influence of substrate variation, all fabrics were selected to meet uniform construction and weight specifications consistent with textile testing practice.

3.1.2 Representativeness of fabrics

The fabric selection was intended to reflect common commercial substrates. Cotton represents mass-market production used in garments and home textiles, whereas wool represents higher-value applications such as formalwear and outerwear. Both substrates are compatible with natural and synthetic dye classes, enabling direct comparison across fiber types. In the Indonesian context, cotton is widely used in batik and daily textiles, while wool is sometimes blended into ceremonial and premium fabric products, including selected Ulos variants. This selection therefore supports both industrial relevance and regional contextual relevance.

3.1.3 Inclusion criteria and quality control

Only fabrics meeting predefined criteria were included to reduce variability unrelated to dye performance. Cotton samples were 100% cotton and wool samples were 100% wool. All fabrics were untreated, plain woven, and free from finishing agents (e.g., anti-wrinkle treatments, optical brighteners, or sizing). Fabric weight was standardized at 120 ± 5 g/m^2 for cotton and 160 ± 10 g/m^2 for wool. Each fabric roll was visually inspected, and only defect-free portions were used. This quality control reduced the likelihood that physical defects or surface treatments would confound dye uptake and fastness outcomes.

3.2 Dyeing Procedure and Performance Assessment

3.2.1 Dyeing procedure

Dyeing was carried out by immersing fabric swatches in dye baths under controlled conditions. Dye bath pH, temperature, and dyeing duration were regulated to ensure consistent processing and replicability. Natural dye treatments were performed using the Gama Warni machine, which provides controlled agitation and improved process stability and is intended to enhance dyeing efficiency [16]. Synthetic dye treatments were performed using comparable controlled dyeing conditions to support fair performance comparison.

3.2.2 Color stability and UV resistance testing

Color stability was assessed as color difference (ΔE) measured using a spectrophotometer after 10 and 20 standardized washing cycles. These measurements quantified resistance to fading during repeated laundering. UV resistance was assessed by measuring color degradation after exposure to controlled ultraviolet radiation for a defined duration. Together, these tests captured key durability properties relevant to practical textile use.

3.2.3 Production cost and market assessment

Production costs were estimated for each treatment by accounting for raw materials, labor, energy consumption, and waste treatment. Total production cost per unit area (IDR/m^2) was calculated for each dyeing method, and profit margins were estimated using the corresponding market selling price assumptions. Market demand was evaluated through a structured survey involving textile manufacturers and distributors operating in domestic markets and in international markets, including Europe and Japan. The market assessment emphasized willingness to pay, perceived value of eco-friendly attributes, and demand trends relevant to adoption of naturally dyed textiles.

3.3 Study Design

3.3.1 Factorial design and variables

A factorial experimental design was used to examine how dye type and process conditions influence dye performance. Dye type had two levels (natural and synthetic). Process parameters included pH (4.0, 6.5, 8.5), dyeing temperature (60°C, 75°C, 90°C), and dyeing duration (45, 60, 75 min). Cotton and wool were used as substrates to evaluate whether process effects differ across fiber types. The dependent variables were color stability, UV resistance, production cost, and market demand indicators. Each experimental condition was replicated three times (n = 3) to support reliability and reduce random error. The dyeing process parameters and their experimental levels are summarized in Table 1.

Table 1. Dyeing process parameters and experimental levels

Variable	Levels
pH	4.0 (acidic), 6.5 (neutral), 8.5 (alkaline)
Temperature (°C)	60, 75, 90
Dyeing duration (min)	45, 60, 75

3.3.2 Experimental control and standardization

All experiments were performed under standardized laboratory conditions (28 ± 2°C; 50 ± 5% relative humidity). Fabrics were prewashed to remove residues that could affect dye absorption. A constant liquor ratio of 1:40 was maintained across treatments. Dye bath pH was adjusted using acetic acid or sodium carbonate and verified with a calibrated pH meter. Dyeing temperature was controlled using thermostatic equipment, and dyeing time was monitored using digital timers. Measurement instruments were calibrated prior to testing, and procedures followed recognized standards to ensure comparability and replicability.

3.4 Instruments and Standards

ΔE was measured using a spectrophotometer in the CIE Lab color space after standardized wash cycles. UV resistance was measured using an accelerated UV exposure chamber with UV-A radiation (340 nm). Wash fastness testing followed ISO 105-C06, and UV exposure testing followed ASTM G154. Absorbance shifts under different pH conditions were measured using a UV-Visible spectrophotometer to support interpretation of dye behavior across acidity and alkalinity. A summary of instruments and testing standards used in this study is provided in Table 2.

Table 2. Instruments and standards used for dye performance assessment

Test Parameter	Instrument/Standard	Description
Color stability	Spectrophotometer (CIE Lab*, ΔE)	Evaluated after 10 and 20 wash cycles (ISO 105-C06)
UV resistance	Accelerated UV Chamber (UV-A, 340 nm)	24-hour UV exposure test (ASTM G154)
Absorbance shift	UV-Visible Spectrophotometer	Measurement of pH-dependent absorbance variations

3.5 Data Collection and Procedure

Data collection followed a standardized workflow. Fabric swatches were prepared and randomly assigned to treatment groups. Dyeing was conducted under predefined pH, temperature, and time settings for each experimental condition. After dyeing, samples underwent washing cycles and UV exposure tests, and ΔE and UV degradation values were recorded at the specified intervals. Production costs were compiled from recorded resource inputs and processing requirements. Market data were collected through structured interviews and summarized to describe demand patterns across domestic and international markets. The experimental period lasted eight weeks, and measurements were recorded on a weekly schedule to maintain consistent documentation.

3.6 Data Analysis

Descriptive statistics (means, standard deviations, and ranges) were calculated for ΔE, UV resistance, production costs, and profit margins to summarize overall patterns and group differences [17]. Inferential analysis used factorial analysis of variance (ANOVA) to evaluate main effects and interaction effects of dye type and process parameters on color stability and UV resistance. When variance homogeneity assumptions were not met, Welch's ANOVA was applied. Independent samples t-tests were used to compare economic outcomes between natural and synthetic dye treatments. When equal variance assumptions were violated, Welch's t-test was applied.

Assumption testing included Shapiro-Wilk tests for normality and Levene's tests for homogeneity of variance. Independence of observations was ensured through random assignment and independent processing of samples. When assumptions were violated, logarithmic or square-root transformations were applied. If violations persisted, non-parametric alternatives were used, including the Mann-Whitney U test for two-group comparisons and the Kruskal-Wallis test for multi-group comparisons. All analyses were conducted using SPSS, with statistical significance defined at $\alpha = 0.05$.

4 Results

This section presents a comprehensive comparison between natural and synthetic dyes based on experimental results. The analysis focuses on color difference, UV resistance, production costs, market competitiveness, and physicochemical mechanisms influencing dye performance. Results are discussed in relation to baseline practices and state-of-the-art natural dyeing technologies, providing both technical and economic perspectives [18].

4.1 Comparison with Baseline Dyeing Methods

4.1.1 Color stability and UV resistance performance

Color stability and UV resistance were evaluated after 20 standardized washing cycles. Table 3 summarizes the performance of natural and synthetic dyes. Natural dyes consistently exhibited lower ΔE values, indicating better color retention. The mean ΔE value for natural dyes was 3.2, whereas synthetic dyes exhibited a mean ΔE of 6.75, reflecting more pronounced fading [19].

Table 3. Color stability and UV resistance of natural and synthetic dyes after 20 washing cycles

Dye Type	Color Difference (ΔE)	UV Resistance (%)	Mean ΔE	Mean UV Resistance (%)
Indigofera tinctoria	3.2	90	3.2	90.0
Morinda citrifolia	4.5	88	3.2	90.0
Psidium guajava	5.0	85	3.2	90.0
Swietenia macrophylla	3.8	87	3.2	90.0
Synthetic dye (Azo)	7.0	72	6.75	71.5
Synthetic dye (Reactive)	6.5	70	6.75	71.5

In addition to washing durability, natural dyes showed superior resistance to ultraviolet radiation. The mean UV resistance of natural dyes reached 90.0%, compared with 71.5% for synthetic dyes. ANOVA confirmed that these differences were statistically significant ($p < 0.05$), demonstrating that dye type had a significant effect on both color stability and UV resistance [20].

These findings indicate that, despite common assumptions regarding the inferior durability of natural dyes, selected plant-based dyes particularly those derived from Indigofera tinctoria can outperform conventional synthetic dyes under controlled dyeing conditions [21].

4.1.2 Production cost analysis

Production cost components for natural and synthetic dyeing are presented in Table 4. Natural dyeing resulted in higher total production costs (60,000 IDR/m^2) compared with synthetic dyeing (37,000 IDR/m^2). The cost difference was primarily associated with raw material preparation, longer processing time, and higher labor input for natural dye extraction and handling [22].

However, higher production costs were offset by higher selling prices and profit margins. Naturally dyed textiles achieved a selling price of 120,000 IDR/m^2, generating a profit margin of 60,000 IDR/m^2. In contrast, synthetic dye-based products yielded a lower profit margin of 38,000 IDR/m^2.

These results demonstrate that production cost alone does not determine economic feasibility. Market positioning and consumer willingness to pay for sustainable products play a critical role in profitability.

Table 4. Production costs and profit margins of natural and synthetic dyeing

Cost Component	Natural Dye (IDR/m^2)	Synthetic Dye (IDR/m^2)
Raw materials	25,000	15,000
Labor	20,000	12,000
Energy	10,000	8,000
Waste treatment	5,000	2,000
Total production cost	60,000	37,000
Selling price	120,000	75,000
Profit margin	60,000	38,000

4.1.3 Market potential and consumer demand

Market survey results are summarized in Table 5. Demand for eco-friendly textiles was strongest in international markets, particularly Europe (85%) and Japan (78%). Naturally dyed Ulos fabrics achieved significantly higher selling prices in these markets compared with synthetic alternatives [23].

Table 5. Market demand and pricing for natural and synthetic dye-based textiles

Market	Demand for Eco-Friendly Products (%)	Natural Dyes (IDR/m^2)	Synthetic Dyes (IDR/m^2)
Europe	85	120,000	75,000
Japan	78	110,000	72,000
Domestic	65	90,000	68,000

Domestic demand was lower but still showed a positive trend toward sustainable products. These findings indicate that natural dyes are particularly competitive in premium and environmentally conscious markets, where sustainability attributes influence purchasing decisions.

4.2 Comparison with State-of-the-Art Natural Dyeing Methods

4.2.1 Improvements in color stability and UV resistance

Advanced natural dyeing methods using improved process control and modern equipment further enhanced performance. As shown in Table 6, Indigofera tinctoria achieved the lowest ΔE value (2.8) and the highest UV resistance (92%). These values exceeded those observed for both baseline natural dyeing and synthetic dyes [24].

Table 6. Performance of modern natural dyeing methods

Dye Type	Color Difference (ΔE)	UV Resistance (%)
Indigofera tinctoria	2.8	92
Morinda citrifolia	3.5	89
Psidium guajava	4.0	86
Swietenia macrophylla	3.2	88
Synthetic dyes	>6.5	≤ 72

The improvements can be attributed to better dye penetration, enhanced fixation, and optimized dye-fiber interactions under controlled temperature and pH conditions.

4.2.2 Cost efficiency of modern natural dyeing technology

The introduction of modern dyeing equipment reduced natural dyeing costs to 46,000 IDR/m^2, as shown in Table 7. While still higher than synthetic dyeing, this reduction significantly improved economic viability. The resulting profit margin increased to 64,000 IDR/m^2, exceeding both baseline natural dyeing and synthetic dyeing margins [25].

Table 7. Cost comparison of modern natural dyeing and synthetic dyeing

Method	Total Cost (IDR/m^2)	Selling Price (IDR/m^2)	Profit Margin (IDR/m^2)
Modern natural dyeing	46,000	110,000	64,000
Synthetic dyeing	37,000	75,000	38,000

4.2.3 Global market competitiveness

Modern natural dyeing further increased international market demand. As shown in Table 8, demand in Europe reached 90%, with selling prices increasing to 125,000 IDR/m^2. These results confirm that improvements in technical performance and cost efficiency directly enhance market competitiveness [26].

Table 8. Market potential of textiles dyed using modern natural dyeing methods

Market	Demand for Eco-Friendly Products (%)	Natural Dyes (IDR/m^2)	Synthetic Dyes (IDR/m^2)
Europe	90	125,000	75,000
Japan	85	115,000	72,000
Domestic	70	95,000	68,000

4.3 Stability Mechanisms of Natural and Synthetic Dyes

Table 9 compares dye bonding mechanisms and stability characteristics. Many natural dyes rely on hydrogen bonding, resulting in moderate stability. In contrast, indigotin binds through a redox mechanism, providing higher resistance to heat and light. Synthetic dyes form covalent bonds, explaining their high stability but also their persistence in the environment [27].

Table 9. Bonding mechanisms and stability characteristics of dyes

Dye Type	Source	Bonding Mechanism	Heat Stability	Light Stability
Anthocyanins	Plants	Hydrogen bonding	Low	Low
Flavonoids	Plants	Hydrogen bonding	Medium	Medium
Carotenoids	Plants	Hydrophobic bonding	High	Medium
Indigotin	Plants	Redox reaction	High	High
Synthetic dyes	Synthetic	Covalent bonding	High	High

4.4 Effect of pH on Natural Dye Stability

Absorbance measurements demonstrated increased color intensity at higher pH levels (Table 10). Both henna and indigo extracts exhibited improved stability under alkaline conditions, indicating stronger dye-fiber interactions [28].

Table 10. Absorbance changes of natural dyes at different pH levels

Dye Type	pH 2	pH 4	pH 6	pH 8
Henna extract	0.370	0.394	0.410	0.430
Indigo extract	0.650	0.700	0.720	0.740

4.5 Effect of Temperature on Dye Stability

Lower storage temperatures enhanced dye stability. As shown in Table 11, absorbance values increased at cold temperatures, indicating reduced degradation and improved color retention [29].

Table 11. Effect of temperature on dye absorbance

Dye Type	Room Temperature (28°C)	Cold Temperature (6°C)
Henna extract	0.651	1.016
Indigo extract	0.864	1.038

4.6 Summary of Findings

Overall, natural dyes demonstrated superior color stability, UV resistance, and market appeal compared with synthetic dyes. Modern dyeing technologies further improved performance and reduced costs. Dye stability was strongly influenced by bonding mechanisms, pH, and temperature. These findings support the feasibility of natural dyes as competitive and sustainable alternatives in textile production [30].

5 Discussion

5.1 Interpretation of the Results

This study provides empirical evidence that selected natural dyes can perform competitively relative to synthetic dyes. The results indicate that natural dyes achieved higher UV resistance and, under optimized conditions, stronger color retention [31]. In addition, the market data suggest that natural dye products can attain price premiums that support profitability in sustainability-oriented segments. The factorial design enabled evaluation of technical performance together with economic outcomes, allowing a consolidated interpretation of feasibility and competitiveness [32].

5.2 Functional Performance and Alignment with Previous Studies

Factorial ANOVA indicated statistically significant differences ($p < 0.05$) in color stability and UV resistance between natural and synthetic dyes. Natural dyes, particularly Indigofera tinctoria and Morinda citrifolia, showed higher UV resistance and lower ΔE values under controlled dyeing conditions. Performance improved most clearly under alkaline conditions (pH 8.5) and elevated temperatures (75–90°C). These findings are consistent with prior studies reporting that redox-based or phenolic-rich botanical dyes can produce relatively stable dye-fiber interactions under optimized conditions [33].

The findings also refine a common industrial assumption that synthetic dyes consistently offer superior durability. In this study, synthetic dyes produced more uniform outcomes across variable pH and temperature settings [34]. However, their UV resistance values remained lower than those of the better-performing natural dyes. This suggests that synthetic dyes may be less suitable for applications where photostability is a primary requirement, such as outdoor textiles or products exposed to prolonged sunlight.

5.3 Process Optimization and Industrial Relevance

The results confirm that dyeing parameters significantly influence performance outcomes. Interaction effects between dye type, pH, and temperature were evident, indicating that natural dye performance depends strongly on process control. This observation supports prior work emphasizing the need for optimized dye bath conditions when natural dyes are used at commercial scale [35]. The contribution of this study lies in its comparative scope: four natural dyes were evaluated across two fiber types (cotton and wool) using a consistent experimental framework.

These findings highlight an operational implication. Natural dyeing cannot be treated as a uniform substitute for synthetic dyeing without process adaptation. Instead, process settings should be tailored to dye chemistry and fiber characteristics. Such customization is necessary to improve repeatability and to reduce performance gaps between natural and synthetic dye applications [36].

5.4 Economic Trade-Offs and Market Differentiation

The cost analysis indicates that natural dyeing incurred substantially higher production costs than synthetic dyeing. This difference was driven by higher raw material inputs, labor demands, and waste management requirements. However, the market results indicate that natural dye products achieved higher selling prices, which increased profit margins despite higher production costs. This pattern aligns with economic evidence that eco-friendly textiles can remain commercially viable when positioned within premium markets where sustainability attributes influence purchasing behavior [37].

The domestic market results showed moderate demand relative to international markets. This suggests that adoption may vary by consumer segment and purchasing power. A practical implication is that manufacturers may benefit from a tiered strategy. Premium export segments can be prioritized for natural dye product lines, while process improvements and cost reduction efforts can be pursued to improve affordability for domestic markets [38].

5.5 Consumer Trends and Strategic Positioning

The market survey results indicate that consumer willingness to pay for sustainable textiles is strongest in international markets. These findings are consistent with broader evidence that eco-labeling, environmental awareness, and sustainability-oriented purchasing decisions increasingly influence textile demand [39]. For producers, natural dyes can therefore function not only as an environmentally preferable input, but also as a product differentiation mechanism.

A strategic implication is that sustainability claims require credible implementation. Manufacturers may improve market outcomes by strengthening traceability, ensuring product consistency, and adopting transparent communication of environmental attributes. These actions support brand credibility in markets where sustainability certification and product integrity influence purchase decisions.

5.6 Technological Innovation and Scalability

A key contribution of this study is the evidence that technology can reduce process barriers commonly associated with natural dyeing. The use of modern dyeing equipment improved operational efficiency and reduced resource requirements. In particular, the Gama Warni system reduced labor and energy inputs, indicating that natural dyes can be applied more efficiently than suggested by earlier studies emphasizing high cost and low scalability [40].

These findings suggest that small and medium-sized enterprises may be able to scale natural dye production more effectively when appropriate equipment and standardized protocols are adopted. Scalability is further supported when dye plant supply chains are localized, as this can reduce input costs and improve raw material consistency.

5.7 Technological Innovation and Cost Efficiency

This study demonstrates that modern dyeing technology improved cost efficiency in natural dyeing. The Gama Warni system enhanced process control over temperature, pH, and liquor circulation. These controls increased dye uptake and reduced variability in color yield. They also reduced resource consumption, particularly energy and water, which lowered operational costs.

Table 12 compares production cost components between conventional natural dyeing and Gama Warni-assisted dyeing. The data indicate reductions in energy, labor, raw material use, and waste treatment. Total cost decreased from 60,000 IDR/m^2 to 46,000 IDR/m^2. Profit margin increased from 60,000 IDR/m^2 to 64,000 IDR/m^2.

Table 12. Production costs and profit margins for conventional and Gama Warni-assisted natural dyeing

Parameter	Conventional Natural Dyeing (IDR/m^2)	Gama Warni-Assisted Dyeing (IDR/m^2)
Energy cost	10,000	8,000
Labor cost	20,000	15,000
Raw material cost	25,000	20,000
Waste treatment	5,000	3,000
Total cost	60,000	46,000
Profit margin	60,000	64,000

The cost reductions are consistent with process improvements observed during implementation, including shorter processing time, improved dye exhaustion, and reduced wastewater volume. These outcomes indicate that natural dyeing is not inherently cost-prohibitive when modern equipment and controlled protocols are used.

5.8 Implications for Industry

The results indicate that natural dyeing can be viable for manufacturers when supported by process optimization and appropriate technology. A practical implication is that investment in controlled dyeing infrastructure may improve both product quality and cost performance. This may be especially relevant for export-oriented producers and Small and Medium-sized Enterprises (SMEs) targeting sustainability-driven markets.

5.8.1 Limitations and generalizability

Several limitations should be noted. First, the experiments were conducted under controlled laboratory conditions. Full industrial implementation may introduce variability due to batch size, water composition, and operator-dependent practices. Second, natural dyes differed in performance. Dyes dominated by anthocyanin- and flavonoid-based components exhibited higher ΔE values after repeated washing. In some cases, ΔE values approached 5, exceeding a commonly cited perceptibility threshold (ΔE = 3). This may be a concern for applications requiring strict color fidelity, such as luxury textiles [41]. Continued development of fixation and stabilization techniques is therefore necessary to improve consistency across a broader range of natural dyes.

5.8.2 Summary and theoretical contribution

The findings support Sustainability-Oriented Innovation and the Natural Resource-Based View by demonstrating that renewable inputs, when combined with technological upgrading, can generate both environmental and economic value. The results provide a direct response to the study's central question: natural dyes can be competitive with synthetic dyes when performance is optimized through controlled processing conditions and modern equipment. The statistical evidence ($p < 0.05$) strengthens the validity of these conclusions.

5.9 Regional Market Insights and Adoption Barriers

Market demand differed substantially across regions. Demand in Europe and Japan was higher than domestic demand. These patterns may be linked to stronger eco-label awareness, greater purchasing power, and supportive institutional frameworks in developed markets [42]. Domestic demand was moderate, indicating that sustainability is an emerging but not dominant purchasing criterion.

Adoption barriers in developing markets include limited access to modern equipment, high initial investment cost, inconsistent raw material supply, and limited technical training. In addition, small producers may lack connections to export buyers, which reduces the economic incentive to adopt higher-cost sustainable processes.

5.9.1 Actionable recommendations for industry

Manufacturers can improve adoption outcomes through targeted strategies. Export-oriented product lines can focus on markets where eco-premiums are well established. For domestic markets, cost-reduction strategies and simplified protocols may improve affordability. Collaboration with research institutions can also support locally optimized dyeing procedures and improved fixation methods. In addition, product traceability systems can strengthen consumer trust, especially in premium segments.

5.9.2 Recommendations for policymakers

Policy measures can reduce adoption barriers. Financial support for efficient dyeing equipment can lower entry costs for SMEs. National eco-labeling frameworks can standardize sustainability claims and support export qualification. Farmer-dyer partnerships can strengthen raw material consistency and traceability. Public procurement programs can also create baseline demand for certified sustainable textiles.

5.9.3 Broader implications

If these barriers are addressed, natural dyes can contribute to sustainable industrial transitions in both developed and developing economies. Regions with strong biodiversity and existing traditional knowledge can benefit from opportunities for green industrialization while preserving cultural heritage [43].

5.10 Practical Implications and Stakeholder Guidance

The findings provide operational guidance for stakeholders involved in textile production and policy development. For manufacturers, the results support investment in modern dyeing systems, workforce training, and structured product segmentation for premium markets. For policymakers, the evidence supports targeted subsidies, eco-labeling frameworks, and incentives for sustainable procurement. For researchers, priorities include improving fixation methods, optimizing extraction efficiency, and expanding durability and lifecycle studies across a wider set of natural dyes.

5.11 Remaining Constraints and Future Work

This study evaluated a limited set of natural dyes, and additional dye sources may exhibit different durability profiles. Future research should test broader dye categories and investigate stabilization techniques that can improve performance consistency. In addition, the economic feasibility of large-scale deployment should be examined through industrial pilot studies incorporating real-world operational variability [44]. Finally, policy and market analyses should be expanded to clarify how regulatory change and sustainability incentives may accelerate adoption.

6 Conclusions

This study compared natural and synthetic dyes in textile applications by evaluating color stability, UV resistance, production costs, and market competitiveness. The results showed that natural dyes generally achieved stronger UV resistance and better color retention under optimized dyeing conditions. Although natural dyeing involved higher production costs, naturally dyed textiles obtained higher selling prices and profit margins, particularly in export-oriented markets where sustainability attributes influence purchasing decisions. These findings indicate that natural dyes can function as technically viable and commercially competitive alternatives to synthetic dyes when appropriate process controls and efficient dyeing technologies are applied.

The study also contributes to sustainability-oriented perspectives in textile production by demonstrating that renewable dye sources, combined with process innovation, can generate both environmental and economic value. From a practical standpoint, the findings support manufacturers in adopting natural dyeing for premium product segments and provide evidence for policymakers to strengthen incentives, eco-labeling frameworks, and capacity-building programs that facilitate sustainable dye adoption.

Future research should expand the analysis to a wider range of natural dyes and fiber types and should validate the reported performance under industrial-scale conditions. Further work is also needed to assess long-term durability, supply chain consistency of dye plant materials, and cost optimization strategies to support broader adoption of sustainable dyeing practices.

Author Contributions

Conceptualization, J.W.; methodology, J.W.; validation, C.; formal analysis, J.W.; investigation, F.I.D.; data curation, J.W.; writing—original draft preparation, J.W.; writing—review and editing, C.; visualization, F.I.D.; supervision, C.; project administration, C. All authors have read and agreed to the published version of the manuscript.

Data Availability

Not applicable.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this research.

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