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# Research on Sustainable Textile Green Printing Design Incorporating Calligraphy Culture

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**Article**

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**ABSTRACT**

*This research addresses the high pollution and cultural disconnection in the traditional textile industry by proposing a sustainable green printing design that incorporates Chinese calligraphy. The method utilizes the natural plant dyes gardenia yellow and indigo with digital inkjet printing technology on silk and cotton/linen fabrics. The process involved the digital deconstruction and reconstruction of calligraphic elements to create unique textile patterns. In this study, the natural dyeing process was optimized, using different mordants to expand the color spectrum. The resulting eco-friendly inks were physically stable and suitable for digital printing. Performance tests confirmed the success of this approach. The printed fabrics exhibited satisfactory color fastness properties; specifically, washing fastness on silk reached grade 4 and dry friction fastness reached grades 4–5, demonstrating significant potential for commercial apparel applications. A Scanning Electron Microscope (SEM) analysis showed that dye particles attached evenly to the fibers, preserving the fabric's original texture and breathability. Most significantly, the process demonstrated substantial environmental benefits. Compared to traditional screen printing, it reduces water consumption by up to 90% (eliminating screen washing) and reduces Chemical Oxygen Demand (COD) emissions by more than 85%. Although post-treatment requires energy for heat fixation, the overall process offers a vast improvement in environmental performance. This study successfully merges intangible cultural heritage with green manufacturing, providing a viable technical path for developing high-value-added, environmentally friendly textiles with distinct cultural appeal.*

**KEYWORDS**

*sustainable design, green dyeing, natural dyes, calligraphy culture, digital inkjet dyeing*

## INTRODUCTION

The dyeing process of the textile industry, a global basic manufacturing sector, is typically resource- and pollution-intensive. Traditional dyeing techniques consume large amounts of water, energy, and chemical auxiliaries, and the resulting wastewater has complex components, high color intensity, and a high Chemical Oxygen Demand (COD) value, posing a serious threat to the environment [1,2]. With the growing global emphasis on sustainable development and heightened consumer environmental awareness, "green textiles" have become a mainstream market trend. Therefore, developing environmentally friendly dyeing technologies to reduce the ecological footprint of production has become an urgent priority and a research hotspot for the industry's transformation [3].

Natural dyes, which are derived from plants, animals, or minerals, possess advantages such as biodegradability, good environmental compatibility, and unique color aesthetics [4]. Consequently, they show great potential in the development of green textiles [5]. However, natural dyes also present technical bottlenecks, including an incomplete color range, low color fastness, and poor color reproducibility, which limit their industrial application [6]. In recent years, the performance of natural dyes has been significantly improved by combining modern analytical techniques, optimizing dyeing agents, and controlling dyeing processes [7,8].

Simultaneously, digital inkjet dyeing technology, as a "waterless" or "low-water" dyeing method, offers advantages such as on-demand inkjet printing, no need for plate making, high precision, and suitability for small-batch production and fast response times. Its production process greatly reduces water consumption and pollutant emissions and is thus regarded as a revolutionary technology in the dyeing industry [9,10]. Combining natural dyes with digital inkjet technology is expected to solve the environmental problems of dyeing at both the source and process levels.

Furthermore, contemporary textile design increasingly emphasizes the incorporation of cultural attributes and emotional value. The competitiveness of high-value-added textiles lies not only in their physical and environmental properties but also in the cultural connotations and aesthetic appeal they carry [11,12]. Chinese calligraphy, as a core representative of Eastern aesthetics and an intangible cultural heritage, contains rich philosophical concepts and visual art principles. The force of its lines, the rhythm of its ink, and its spatial composition provide an inexhaustible source of inspiration for modern design [13]. Currently, the application of calligraphy in textile design mostly remains at the level of simple pattern appropriation, failing to deeply explore its artistic essence and rarely combining it systematically with green manufacturing processes.

Therefore, this study aims to explore a sustainable textile design path that integrates calligraphy culture and green manufacturing. We used typical natural plant dyes (gardenia yellow and indigo) as coloring agents and natural fiber fabrics (silk and cotton-linen) as carriers. A complete green dyeing design system was constructed through research at the following three levels. First, at the process level, we investigated the extraction and dyeing processes of natural dyes, examining their performance with various mordants and their feasibility for use in digital inkjet dyeing to prepare eco-friendly ink. Second, at the design level, we analyzed the formal aesthetic principles of calligraphy, deconstructing and digitally reconstructing its brushstrokes, structure, and composition to create unique textile patterns suitable for inkjet dyeing. Finally, at the performance and evaluation level, we conducted standardized tests on the color performance and physical properties (e.g., color fastness) of the final products and established a preliminary style evaluation model to verify the scheme's effectiveness. This research is significant because it integrates traditional cultural aesthetics with cutting-edge green technologies. It not only provides specific technical solutions for environmental issues in the textile industry but also opens new design avenues for enhancing the cultural value and market competitiveness of textile products.

## MATERIALS AND METHODS

### Experimental Materials

**Fabrics:** 16-millimeter silk double crepe (Hangzhou, Zhejiang, China) and 120 g/m$^2$ cotton-linen blended plain weave fabric (Qingdao, Shandong, China) were used. All fabrics were pre-cleaned with a 0.5% (w/v) non-ionic surfactant at 60°C for 30 minutes to remove sizing and impurities, then rinsed with deionized water, dried, and stored for use.

**Dyes:** Dried fruits of *Gardenia jasminoides* Ellis (Yulin, Guangxi, China) and powder of *Indigofera tinctoria* (Dali, Yunnan, China) were used.

**Chemical Reagents:** Anhydrous ethanol, citric acid, ferrous sulfate ($FeSO_4 \cdot 7H_2O$), alum ($KAl(SO_4)_2 \cdot 12H_2O$), sodium carbonate ($Na_2CO_3$), sodium alginate, urea, and glycerol were used. All chemical reagents were of analytical grade.

### Extraction of Natural Dyes and Preparation of Ink

**Extraction of Gardenia Yellow Dye:** Dried gardenia fruits were crushed and mixed with deionized water at a 1:20 solid-to-liquid ratio at pH 7. The mixture was extracted for 2 hours in a constant-temperature water bath at 80°C. After filtration, the filtrate was concentrated by rotary evaporation to 1/10 of its original volume to obtain the gardenia yellow dye solution.

**Indigo Dye Reduction:** The sodium hydrosulfite–soda ash method was used. Weighed indigo powder was added to deionized water, followed by the successive addition of soda ash and sodium hydrosulfite. The solution was stirred in a 50°C water bath until it turned into a yellow-green semi-transparent state, which was the leuco-indigo mother solution.

**Preparation of Eco-Friendly Ink:** The dye concentrate was refined to meet inkjet printing requirements. Taking gardenia yellow as an example, urea (10%), glycerol (15%), sodium alginate (1.5%), and a small amount of non-ionic surfactant were added to the concentrate. For the indigo ink, an additional 0.5% (w/v) of sodium hydrosulfite was incorporated as an oxygen scavenger to prevent premature oxidation in the cartridge. The solution was mixed evenly by high-speed stirring, followed by ultrasonic treatment (40 kHz, 200 W) for 30 minutes to disrupt macromolecular aggregates and ensure uniform dispersion. Subsequently, the ink was filtered through a 0.22μm microfiltration membrane to strictly remove any residual insoluble impurities and ensure the particle size requirement for smooth jetting. Finally, the pH, viscosity, and surface tension of the ink were tested to ensure they were within the operational range of the inkjet printhead. Crucially, the pH of the indigo ink was adjusted to and maintained at 11.5 using a carbonate/hydroxide buffer system. This high alkalinity is strictly required to ensure the leuco-indigo remains in its soluble ionic state and to prevent premature oxidation or clogging during the jetting process.

### Fabric Pretreatment and Mordanting

To ensure optimal inkjet receptivity and dye fixation, a dual-stage pretreatment was employed. First, to enhance the dye uptake and expand the color gamut of gardenia yellow, the corresponding fabrics underwent mordanting using the immersion method. In contrast, the indigo samples were prepared without metallic mordants. The mordant solutions were prepared using ferrous sulfate and alum with a dosage of 2% (o.w.f.). Subsequently, all fabrics intended for digital printing were padded with a cationic pretreatment solution. This solution, containing 30 g/L of a commercial cationic surface modifier (quaternary ammonium type) and 10 g/L of sodium alginate (as a migration inhibitor), forms a positive charge layer on the fiber surface to bond with anionic dye molecules. Excess liquid was removed by a roller (retention rate of 70–80%), and the fabrics were dried at room temperature before use.

**Digital Design of Calligraphy Elements**

**Element Collection:** Classic calligraphy works, such as Wang Xizhi's "Preface to the Orchid Pavilion" and Huai Su's "Autobiography," were selected. The morphological characteristics of their basic strokes (e.g., "dots," "horizontals," "verticals") and ink effects (e.g., *fei bai* or "flying white" and "expanding ink") were analyzed.

**Decomposition and Reconstruction:** Calligraphy works were digitized using a high-resolution scanner. In vector graphics software, a morphological analysis based on calligraphic principles was conducted, which went beyond simple contour extraction. Primary strokes carrying the most dynamic energy (*势, shi*) and secondary, connective strokes were identified. The objective was to preserve the integrity and vitality of individual strokes, such as the nuanced effects of 'flying white' that reveal the brush's speed and pressure.

**Reconstruction Guided by Calligraphic Aesthetics:** The reconstruction of patterns was guided by a deliberate fusion of calligraphic aesthetics with modern design principles, governed by the following considerations:

**Rhythm and Flow:** To emulate calligraphic rhythm, stroke elements were arranged in a varied, non-uniform sequence, altering their scale, angle, and spacing to create a visual flow that mimics the cadence of cursive script, ensuring a dynamic character.

**Composition and Negative Space:** A core principle was the thoughtful management of density and space, inspired by the calligraphic concept of *liú bái* (*留白, leaving white*). The pattern's composition was balanced between areas of dense stroke interplay and open, "breathing" room to create a sophisticated spatial harmony.

This method produced continuous patterns that were not merely collections of strokes but thoughtfully recomposed visual textures carrying foundational aesthetic principles into a modern textile context.

**Color Setting:** Based on the color spectrum produced by combinations of gardenia yellow, indigo, and different mordants (e.g., yellow, blue, green, gray, brown), CIE L*a*b* color values were assigned to the digital pattern to simulate the final effect. This color assignment was planned to translate the calligraphic principle of 'the five colors of ink' (*墨分五色*) into the natural dye palette. By assigning different color values—such as deep indigo, grayish-brown from ferrous sulfate, and vibrant gardenia yellow—to different stroke elements, we simulated the tonal variations of 'dark, light, dry, and wet' ink effects. This added a layer of depth and visual complexity to the textile surface inspired by the rich tonality of traditional ink wash art. The final design draft was saved in TIFF format.

### Digital Inkjet Printing and Post-Treatment

An EPSON SureColor series flatbed inkjet printer was used. The pre-treated fabric was placed flat on the printing platform. The prepared natural dye ink was injected into the printer cartridge. The printing resolution (720 dpi) and ink droplet size were set via the printer driver, and the TIFF pattern was printed onto the fabric. For color fixation, the printed fabric was dried in an oven at 102 ± 2°C for 5 minutes, followed by high-temperature steam fixation (102 °C, 10 min) to ensure a thorough reaction between the dye and fibers. Subsequently, the fabrics were exposed to air to allow for the full oxidation of the leuco-indigo back to its insoluble blue form. Finally, the fabric was washed with 2 g/L of non-ionic detergent at 50°C for 15 min to remove any residual unfixed dye, then rinsed with cold water and dried.

### Performance Testing and Evaluation

**Color Performance:** A Datacolor SF600X colorimeter was used to measure the apparent color depth (K/S value) and CIE L*a*b* chromaticity values of the printed fabric under a D65 light source and a 10° viewing angle. The K/S value was calculated using the Kubelka-Munk equation: $K/S = (1 - R)^2/2R$, where R is the surface reflectance of the fabric. All colorimetric measurements were performed in triplicate (n = 3) at random positions on each sample, and the average values were recorded to ensure data reliability.

**Color Fastness Tests:**

Washing fastness was tested according to ISO 105-C06:2010 to evaluate color fading and staining.

Rubbing fastness was tested according to ISO 105-X12:2016 to measure color fading after dry and wet rubbing. Each fastness test was repeated three times (n = 3) using independent samples. The results reported in this study represent the consensus grades derived from these repeated trials.

**SEM Morphological Observation:** The distribution of dye particles on the fiber surface was observed using a scanning electron microscope (SEM, JEOL JSM-6390LV).

**Style and Image Evaluation:** A Semantic Differential questionnaire was used, featuring 10 pairs of adjectives (e.g., "traditional–modern," "plain–ornate"). Thirty evaluators with design backgrounds rated the samples using a 5-point Likert scale. Factor analysis was employed to extract the main style elements. Evaluators with design backgrounds were chosen to obtain a professional assessment of the design's stylistic attributes, providing a foundational expert critique.

**Environmental Impact Assessment:** The water-saving rate and COD reduction rate per unit area of printed fabric were estimated and compared with the traditional screen printing process.

## RESULTS AND DISCUSSION

### Physical Properties of Natural Dye Inks

The physical properties of the inks are crucial for ensuring the stability and quality of the digital inkjet printing process. Key parameters, including viscosity, surface tension, and pH, were measured for the gardenia yellow and indigo inks to confirm their suitability for the EPSON SureColor series printhead. The results are presented in Table 1. For the piezoelectric printheads used, the optimal range for viscosity is 3–10 mPa·s and for surface tension is 25–40 mN/m. Regarding pH, while standard aqueous inks typically operate at neutral pH, the reduced indigo ink necessitates an alkaline environment (pH > 11). Therefore, we utilized a corrosion-resistant piezoelectric printhead (compatible with reactive/alkaline inks) and optimized the cleaning protocol to prevent nozzle damage. As shown in Table 1, the rheological properties were well-controlled, ensuring stable droplet formation.

Optimization of Ink pH and Stability The solubility of leuco-indigo is strictly pH-dependent. To determine the optimal pH for inkjet stability, we evaluated the dispersion state of the ink at pH levels of 8.0, 10.0, and 11.5. As expected, at pH 8.0 and 10.0, the leuco-indigo underwent partial oxidation and acid precipitation, resulting in visible turbidity and particle agglomertion (particle size > 500 nm), which poses a severe risk of nozzle clogging. In contrast, at pH 11.5, the ink maintained a stable, transparent yellow-green state with an average particle size below 200 nm, indicating the formation of stable disodium leuco-indigo salts. Crucially, the excess sodium hydrosulfite acted as an antioxidant buffer, neutralizing dissolved oxygen within the inkjet system to strictly prevent the formation of insoluble indigo particles that could cause nozzle clogging. This formulation ensured stability for at least 48 hours, providing a sufficient temporal window for the printing process. Therefore, pH 11.5 was selected as the critical operational parameter for the indigo ink.

Table 1. Physical Properties of Prepared Natural Dye Inks

| Ink Type | Viscosity (mPa·s at 25°C) | Surface Tension (mN/m) | pH Value | Particle Size (nm) | Stability (24h) |
|---|---|---|---|---|---|
| Gardenia Yellow Ink | 5 | 37 | 7.2 | < 150 | Stable |
| Indigo Ink | 6 | 32 | 11.5 | < 180 | Stable |

Jetting Reliability Although the high alkalinity of the indigo ink exceeds the standard range for conventional aqueous inks, the jetting reliability was verified. We conducted a continuous printing test for 60 minutes. The nozzle check patterns before and after the test showed no missing lines or deflection, confirming that the leuco-indigo solution at pH 11.5 possesses sufficient latency and stability for the digital printing process adopted in this study.

**Optimization of Natural Dyeing and Color Representation**

Different mordants had a significant impact on the dyeing effects of gardenia yellow and indigo on silk and cotton-linen fabrics (Table 2). Without a mordant, gardenia yellow appeared as a bright yellow on silk. When alum was used as a mordant, the color's vividness and K/S value were enhanced. This is because $Al^{3+}$ forms stable coordination complexes with the dye molecules and the fiber's hydroxyl groups, acting as a "bridge" [14]. The ferrous sulfate mordant acted as a coordination center, shifting the gardenia yellow to a deep, dark grayish-brown. These mordant effects, when combined with the potential for digital color mixing, greatly expand the design possibilities achievable with limited natural dye sources. Indigo, a vat dye, does not rely on mordants for dyeing; its K/S value on silk was higher than on cotton-linen, indicating a better affinity for protein fibers. Through the use of alum and ferrous sulfate mordants, and the digital superposition of gardenia yellow and indigo inks to create secondary colors (e.g., green), we successfully constructed a complete calligraphy color palette containing yellow, green, blue, brown, and gray hues with a natural and harmonious aesthetic.

Table 2. Influence of Different Mordants on the Color Value (CIE Lab*) and K/S Value of Natural Dyed Fabrics

| Dye | Fabric | Mordant | L* | a* | b* | K/S value | Color description |
|---|---|---|---|---|---|---|---|
| Gardenia yellow | Silk | - | 85.2 | -2.1 | 75.8 | 12.5 | Bright yellow |
| Gardenia yellow | Silk | Alum | 84.5 | -1.5 | 78.2 | 14.1 | Lemon Yellow |
| Gardenia yellow | Silk | $FeSO_4$ | 55.8 | 2.5 | 35.1 | 18.2 | Grayish brown |
| Gardenia yellow | Cotton and linen | Alum | 78.9 | 1.2 | 65.4 | 10.3 | Turmeric |
| Indigo | Silk | - | 30.1 | -5.6 | -28.9 | 22.5 | Deep Blue |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Indigo | Cotton and linen | - | 35.4 | -4.8 | -25.1 | 19.8 | Cowboy Blue |

**Digital Inkjet Printing Effect of Calligraphy Patterns**

Figure 1 shows the effect of digital inkjet printing on silk fabric using patterns derived from the deconstructed brushstroke elements of cursive script.


Figure 1. Digital design of calligraphy elements and inkjet printing effect. (a) Detail from the original calligraphy work; (b) Deconstruction of brushstrokes into a digital pattern; (c) Final printed silk fabric; (d) Magnified detail of the printed fabric

As seen in Figure 1c and 1d, the digital inkjet technology reproduced the design patterns with high fidelity. The fine ink dot control allowed for the creation of complex textures that approached the 'flying white' effect.

The pattern edges are sharp, with no obvious smudging, which is likely due to the pre-treatment agent. In digital textile printing, such agents form a functional layer on the fiber surface that helps control ink absorption and limit lateral bleeding, thereby ensuring sharp pattern definition. Direct characterization of this layer was beyond the scope of this study; however, its apparent effect was crucial for achieving high-fidelity printing. By adjusting the ink concentration and printing parameters, the "dark, light, dry, and wet" ink color variations inspired by the 'five-color ink gradation' principle were also achieved within the same pattern.

SEM observation further revealed the microscopic state of the dye on the fibers (Figure 2).

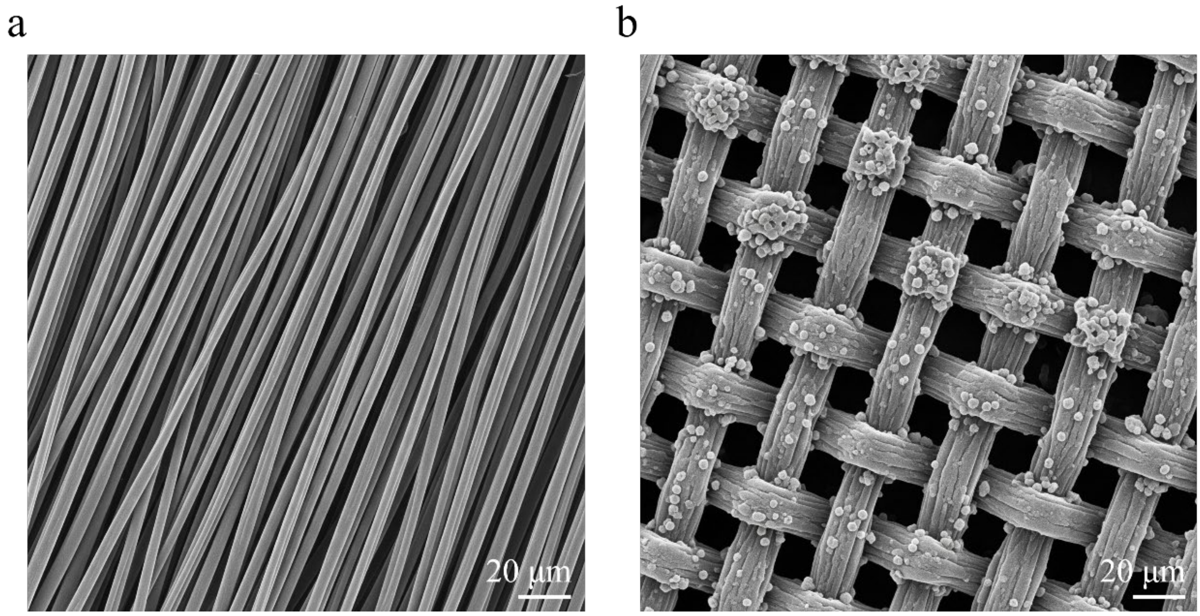


Figure 2. SEM morphology of silk fiber surfaces. (a) Unprinted silk fibers; (b) Silk fibers after inkjet printing. Magnification: 400×

As observed in Figure 2b, the silk fibers maintained their natural surface morphology. Unlike pigment printing which forms a continuous binder film, the surface exhibits only discrete granular structures. This morphology suggests that the leuco-indigo solution permeated the fiber structure rather than accumulating solely on the surface. The discrete particles are attributed to surface-oxidized indigo micro-aggregates. This penetration-based mechanism is further corroborated by the high wash fastness (Grade 4) reported in Table 3. This robust fixation is likely achieved through a dual mechanism: the physical entrapment of oxidized indigo within the fiber's amorphous regions and the electrostatic interaction with the cationic pretreatment agent.

Furthermore, despite the high alkalinity of the indigo ink (pH 11.5), the precise micro-dosage of the digital jetting process limited the total alkali exposure. Coupled with the moderate fixation temperature (102°C), this prevented the excessive hydrolysis of silk fibroin, thereby ensuring the preservation of the fabric's mechanical strength and original soft feel. Finally, the SEM analysis confirms that the interfiber gaps remain unobstructed and no rigid film connects individual fibers, providing structural evidence that the fabric's original drape and air permeability are likely maintained.

**Performance Analysis of Printed Fabrics**

*Color Fastness*

Fastness is a key indicator of quality for printed textiles. Table 3 lists the color fastness test results.

Table 3. Color Fastness Test Results of Printed Fabrics (Grades)

| Fabric | Dyes/Mordants | Wash fastness (color fading) | Wash fastness (color set) | Dry rubbing fastness | Wet rubbing fastness |
|---|---|---|---|---|---|
| Silk | Gardenia Yellow / Alum | 4 | 4 | 4–5 | 3 |
| Silk | Indigo / - | 4 | 4 | 4 | 2–3 |
| Cotton and linen | Gardenia Yellow / Alum | 3–4 | 3–4 | 4 | 2–3 |
| Cotton and linen | Indigo / - | 4 | 4 | 4 | 3 |

The results show that after process optimization, key indicators such as washing fastness on silk reached a level of Grade 4. Typically, the wash fastness of direct-dyeing gardenia yellow is relatively poor (Grade 2-3) due to its high water solubility. However, the Grade 4 result achieved in this study is attributed to the critical role of the cationic pretreatment agent. The cationic groups on the fiber surface form strong ionic bonds with the anionic gardenia yellow molecules, creating insoluble complexes that significantly prevent dye desorption during washing. This demonstrates that the digital printing pretreatment effectively overcomes the inherent fastness limitations of natural dyes. However, the wet rubbing fastness of indigo on silk was Grade 2–3. This is a known technical challenge associated with indigo dyeing [15]. While showing some improvement, this result does not meet the stringent requirements for all high-end apparel, which often demand a grade of 3–4 or above for all fastness properties. Therefore, the claim of suitability for 'high-end clothing' must be qualified. While the excellent wash and dry fastness make the products suitable for many applications, the use of indigo-dyed silk would require careful consideration of this limitation, for example, by designing garments less susceptible to wet abrasion. The color fastness on cotton-linen fabric was slightly lower than that on silk, which is related to fiber structure and dye affinity. The relatively low wet rubbing fastness of indigo is an inherent characteristic; however, it was improved to some extent through sufficient post-treatment washing and fixation [16,17]. Overall, the textiles prepared by the proposed green dyeing process have good practical performance.

*Style and Imagery Analysis*

Factor analysis of the questionnaire data from 30 evaluators extracted two main factors, named "Cultured Elegance" and "Modern Vitality" (Figure 3).

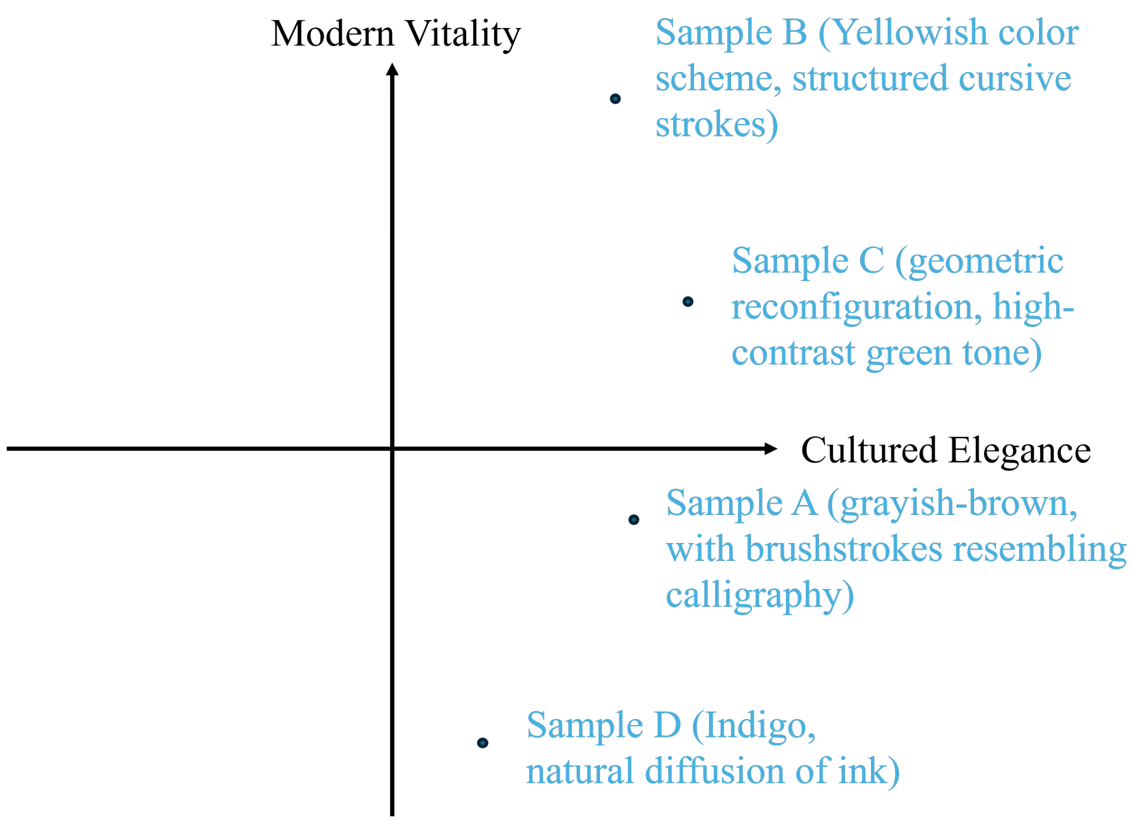


Figure 3. Perceptual map of sample style imagery

The analysis reveals that design samples incorporating cursive script elements with lower color saturation (e.g., grayish-brown and indigo) scored higher in the "Cultured Elegance" factor, evoking feelings of "serenity," "authenticity," and "subtlety." Conversely, design samples featuring geometrically reorganized calligraphic strokes and bright gardenia yellow scored higher in the "Modern Vitality" factor, embodying "fashionable," "orderly," and "dynamic" characteristics. This indicates that through systematic design, the final style of the textiles can be effectively controlled to elicit predictable aesthetic responses within an expert group. It is important to acknowledge that the subjectivity of aesthetic evaluation, along with the small and specialized sample group, limits the generalizability of these findings. However, the results provide valuable initial validation of the design concept, confirming that specific design choices can evoke intended perceptions. Assessing broader market acceptance among diverse consumer segments remains a crucial direction for future research.

**Environmental Impact Assessment**

A comparative assessment reveals that the digital inkjet process adopted in this study has significant advantages over traditional flat-screen printing, particularly concerning water consumption and effluent pollution. Traditional printing requires multiple water-intensive steps, including screen preparation, printing, and screen washing. In contrast, the digital printing process itself consumes almost no water; water is only needed for fabric pre-treatment and post-treatment scouring. Preliminary calculations show that, compared to traditional screen printing (especially in small-batch production where screen washing consumes excessive water), the comprehensive water-saving rate of this digital process can exceed 90%. Although post-print washing is still required, the elimination of color paste preparation and screen cleaning dramatically lowers the water footprint. Furthermore, due to on-demand ink spraying, the dye utilization rate is as high as 95%, significantly reducing dye waste. Since the wastewater from screen washing and residual ink in traditional printing is the main source of COD, this scheme avoids this pollution at its source. Compared with the traditional process, COD emissions are estimated to be reduced by more than 85%, primarily due to the elimination of leftover color paste and the highly polluting screen cleaning wastewater. Although the washing off of ink additives (e.g., glycerol, urea) contributes to the effluent load, it is significantly lower than the cumulative chemical discharge of the conventional screen printing workflow, which involves massive wastage of colorants and auxiliaries.

It is acknowledged that the post-treatment steps—specifically high-temperature drying (102°C) and steam fixation (102°C)—are energy-intensive. However, these steps are essential for ensuring robust dye-fiber bonding, which is critical for achieving the high-grade color fastness required for durable textiles. From a holistic sustainability perspective, product longevity is a key factor. When viewed in its entirety, the profound reduction in water consumption and pollutant load far outweighs the energy expenditure of the final fixation stage, which is also a common step in many conventional dyeing processes. Therefore, the proposed system represents a substantial net improvement in environmental performance.

These findings must be positioned within a broader context. This comparison is not a comprehensive Life Cycle Assessment (LCA), which is the standard methodology for a truly holistic evaluation. A full LCA would quantify the footprint of upstream processes, including the cultivation of plants for dyes and the inputs required for ink preparation. Furthermore, the energy-intensive post-treatment steps contribute to the overall environmental profile. However, given that massive water consumption and high-COD effluent are arguably the most severe environmental challenges in the conventional textile printing industry, the demonstrated water savings of over 90% and COD reduction exceeding 85% represent a highly meaningful improvement at the manufacturing stage. While future work should aim for a more holistic LCA, this study validates the potential of the proposed technology to mitigate critical environmental hotspots in textile production.

**Limitations and Future Directions**

A key limitation of the present study for industrial application is the issue of batch-to-batch color reproducibility. As noted, the color of natural dyes can vary significantly due to factors such as plant origin, harvest time, and extraction methods. Overcoming this is crucial for industrial-scale production. However, the digital workflow presented here offers a potential framework to address this issue. Secondly, the performance evaluation in this study was conducted based on standard laboratory protocols using newly prepared samples. While the results meet current industrial standards for apparel, the long-term durability of the printed textiles—specifically regarding color retention after repeated washing cycles (e.g., 20 or more cycles) and resistance to aging factors such as prolonged UV exposure—was not within the scope of this investigation. Since natural dyes are generally more susceptible to oxidation and photo-degradation than synthetic counterparts, future work should involve comprehensive lifecycle testing to further validate the commercial longevity of these eco-friendly products. Another technical challenge lies in the long-term storage of leuco-indigo ink. Although the addition of excess reducing agents and pH control ensured stability during the printing process (48 hours), the ink remains sensitive to oxygen over extended periods. Achieving a commercial-grade shelf life (e.g., several months) would likely require advanced packaging solutions, such as vacuum-sealed cartridges or dual-component jetting systems where reduction occurs immediately prior to printing.

A future fully-integrated system would necessitate a robust quality control and color management strategy. This would involve: (1) standardizing the extraction process to minimize initial variability; (2) implementing colorimetric quality control for each batch of ink using a spectrophotometer to quantify exact CIE L*a*b* values; and (3) creating batch-specific ICC profiles for the digital printer. Based on the colorimetric data of a new ink batch, a unique color profile could be generated that allows the printing system to adjust ink output dynamically, thereby compensating for the inherent variability of the natural dye. Future research should focus on integrating such a color management system to ensure the color consistency required for market-ready textiles.

## CONCLUSION

This research successfully demonstrated a sustainable design system that fuses Chinese calligraphy with green textile manufacturing. By optimizing the use of natural dyes like gardenia yellow and indigo and converting them into eco-friendly digital inks, this system achieved high-fidelity reproduction of calligraphic aesthetics on fabric. Furthermore, the products exhibited good color fastness (grades 3–4 or higher), meeting the standard requirements for apparel. Most importantly, this solution offers significant environmental benefits, with a water-saving rate exceeding 90% and a COD emission reduction of more than 85% compared to traditional processes. While acknowledging the energy consumption in the necessary heat-fixation stage, the overall process constitutes a significant advancement toward cleaner textile production.

Therefore, this research verified a technically feasible and performance-reliable green dyeing path for translating intangible cultural heritage into high-end sustainable textiles. Although achieving industrial-scale color reproducibility requires further development in color management, this study establishes a crucial proof-of-concept. It charts a clear direction for future work in creating high-value, sustainable textile products with distinct cultural appeal.

*Availability of Data and Materials*

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

*Author Contributions*

Pengyue Zhang designed, collected and analyzed the data, and drafted the manuscript. Pengyue Zhang conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Pengyue Zhang participated fully in the work, took 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.

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*Conflict of Interest*

The author declares no conflict of interest.

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