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The Visual Presentation and Cultural Expression of Natural Textiles in the Context of Art Design

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Article

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ABSTRACT

This study examines the visual properties of natural indigo-dyed cotton and seeks to establish a quantitative relationship between traditional dyeing processes, the resulting textile aesthetics, and their role in contemporary cultural expression. Employing a systematic experimental methodology, the research integrates real-time chemical monitoring (Oxidation-Reduction Potential [ORP] and pH) and standardized post-processing (soaping) to ensure chromatic purity. Samples of 100% cotton fabric were subjected to varying numbers of immersion cycles (5, 10, 15, and 20) in a natural indigo vat. Visual outcomes were characterized using spectrophotometry (CIELAB values) and scanning electron microscopy (SEM) to analyze surface texture. The results demonstrate a strong correlation between the number of dyeing cycles and the fabric's visual attributes: increased cycles resulted in greater color depth (L values decreased from 45.3 to 24.3) and enhanced blue saturation (b* values shifted from -24.8 to -36.5). SEM analysis indicated that dye aggregates formed a distinctive particulate layer on the cotton fibers. Through case studies of designers such as Buaisou and Story mfg., the research explores how quantifiable visual attributes—such as color unevenness and unique surface texture—function as physical manifestations of cultural narratives, including craftsmanship, sustainability, and local identity. This study bridges material science and design theory, providing empirical evidence that the visual presentation of natural textiles is an essential medium for cultural expression in contemporary design.*

KEYWORDS

indigo dyeing, natural textiles, visual characterization, cultural expression, surface morphology

INTRODUCTION

In recent decades, the global textile industry has faced increasing scrutiny regarding its environmental impact, prompting a paradigm shift toward sustainability and craftsmanship in both production and consumption [1].

This movement has renewed interest in natural textiles and traditional dyeing techniques, valued not only for their ecological advantages but also for their cultural significance and distinctive aesthetic qualities [2]. Notably, this revival persists despite the significant practical challenges inherent to these traditional methods compared to synthetic alternatives—namely, higher costs, extended processing times, and limited scalability. Among these practices, natural indigo dyeing stands out for its millennia-long history across diverse cultures, including those in Asia, Africa, and the Americas [3–5].

In contemporary art and design, indigo-dyed textiles have evolved from historical artifacts to dynamic mediums for creative expression. Designers are increasingly attracted to the material's unique visual properties: deep, nuanced blue hues, subtle color variations, and a characteristic matte finish with visual depth resulting from the handcrafted process. These visual attributes extend beyond mere decoration, embodying cultural narratives of tradition, authenticity, and a connection to the natural world [6]. Despite extensive research on the history, chemistry, and anthropology of indigo [7,8], there remains a significant gap in the quantitative analysis of its visual characteristics and their direct correlation to reinterpretation in contemporary design. Most existing studies are either purely scientific or broadly cultural, lacking a robust framework that connects the material's physical properties to its expressive potential in design.

The novelty of this research lies not in reaffirming that repeated immersion darkens fabric, but in applying systematic quantification methods—such as L*, a*, b* measurements and scanning electron microscopy (SEM) surface texture analysis—to a controlled *Polygonum tinctorium* dyeing process. This approach establishes an empirical framework that directly links material properties to abstract cultural narratives, including concepts such as *wabi-sabi* and sustainability, as interpreted by designers.

This paper addresses the following research question: How do variations in the traditional indigo dyeing process quantitatively affect the visual properties of cotton fabric, and how are these properties strategically employed by contemporary designers to convey and reinterpret cultural meaning? To answer this, the study adopts a two-fold methodology: a controlled laboratory experiment to characterize visual changes in indigo-dyed cotton as a function of processing parameters, and a case-study analysis of how contemporary designers utilize these visual cues to articulate cultural themes.

By establishing an empirical link between craft processes, quantifiable visual attributes, and cultural expression, this research advances a deeper, evidence-based understanding of natural textiles in art and design. It offers a replicable methodology for future studies and provides valuable insights for designers, material scientists, and cultural theorists interested in the enduring appeal and modern relevance of traditional textile practices.

LITERATURE REVIEW

The Chemistry and Process of Natural Indigo Dyeing

Natural indigo dye is derived from various plant species, most notably from the Indigofera genus and Polygonum tinctorium. The dyeing process is a complex reduction-oxidation (redox) reaction. The precursor compound, indican—a colorless glucoside found in plant leaves—is converted to indoxyl via fermentation or hydrolysis. In an alkaline, oxygen-deprived (reducing) environment, referred to as a 'vat,' indoxyl molecules dimerize to form leuco-indigo, which is water-soluble and yellowish-green [9,10]. Cotton fibers, composed primarily of cellulose, are immersed in this vat. Upon removal and exposure to air, the absorbed leuco-indigo oxidizes, converting back to the water-insoluble blue indigo pigment, which becomes trapped within the fiber matrix [11]. The depth of the blue color is determined not only by the concentration of dye in the vat but primarily by the number of immersion and oxidation cycles. Each cycle deposits an additional layer of indigo pigment, incrementally intensifying the color [12,13]. This layering process is fundamental to the unique visual characteristics of traditionally dyed indigo textiles.

Visual Perception and Measurement in Textiles

The visual perception of textiles is a multifaceted phenomenon influenced by color, luster, and surface texture. To move beyond subjective description, quantitative measurement is essential.

Color: The most widely adopted system for color measurement is the CIE 1976 (Lab*) color space, or CIELAB. This three-dimensional model provides a device-independent representation of color. The value represents lightness (0 for black, 100 for white), a* represents the red/green axis, and b* represents the yellow/blue axis [14]. Spectrophotometers measure the spectral reflectance of a surface and calculate CIELAB values, yielding precise, objective data for textile samples. For indigo, a deep, pure blue is characterized by a low L* value and a strongly negative b* value.

Surface Texture: Texture refers to the fine-scale surface features of a material, perceived visually and tactilely. In textiles, texture is influenced by fiber type, yarn structure, weave, and finishing processes. Pigment deposition during dyeing can significantly modify this texture. SEM is a powerful tool for visualizing material surfaces at high magnification and is used in textile science to examine fiber damage, polymer coatings, and pigment distribution [15]. SEM images reveal how indigo pigment particles adhere to and aggregate on cotton fibers, generating unique surface morphologies that contribute to the final visual and tactile qualities of the fabric.

Cultural Symbolism and Contemporary Reinterpretation

Historically, indigo has held diverse cultural meanings. In Japan, its deep blue (*aizome*) was associated with the samurai class and later became the color of the working class, symbolizing durability and everyday beauty, often linked to the aesthetic concept of *wabi-sabi*—the acceptance of transience and imperfection [16]. In West Africa, indigo textiles symbolized wealth, power, and spiritual connection [17].

Contemporary designers do not merely replicate historical uses; instead, they engage in "cultural reinterpretation." Leveraging indigo's symbolic history, they embed it within modern value systems. Color variations and imperfections, once considered byproducts of manual processes, are now intentionally highlighted as markers of authenticity and wabi-sabi aesthetics, contrasting with the uniformity of industrial synthetic dyes [16,18]. The labor-intensive process itself is frequently central to brand narratives, aligning products with the "slow fashion" movement and ethical consumerism [6]. Thus, the textile's visual presentation becomes a conduit for contemporary cultural narratives.

METHODOLOGY

To investigate the relationship among dyeing processes, visual properties, and cultural expression, a mixed-methods approach was employed, integrating controlled experimentation with qualitative case study analysis.

Research Design

Fabric: All experiments utilized pre-scoured, 100% plain-weave cotton fabric with a weight of 150 g/m², cut into 10 cm × 10 cm samples.

Dye Vat: A natural indigo fermentation vat was prepared using the following concentrations: dried leaves of *Polygonum tinctorium* (50 g/L), sodium carbonate (20 g/L), and fructose (25 g/L) dissolved in deionized water. The vat was maintained at pH 10.5 and 25°C throughout the experiment.

Chemical Stability Verification

To ensure reproducibility and validate the reduction process, the chemical state of the vat was monitored continuously. Oxidation-Reduction Potential (ORP) and pH were measured using a portable meter (Horiba D-72, Horiba Ltd., Kyoto, Japan) throughout the dyeing process. This verification was critical for confirming a stable reducing environment sufficient for leuco-indigo formation, thereby eliminating vat exhaustion or chemical fluctuation as experimental variables.

Experimental Procedure

Cotton samples were divided into four groups, each corresponding to a specific number of dyeing cycles: 5, 10, 15, and 20 dips. An undyed control group was also included. Each dyeing cycle consisted of:

(1) Immersion in the indigo vat for 3 minutes

(2) Removal and exposure to air for 3 minutes (oxidation)

The process was repeated for the designated number of cycles per group. After the final cycle, samples were rinsed in cold water. A soaping step was performed using a neutral detergent solution at 60°C for 15 minutes to remove impurities and unoxidized leuco-indigo, ensuring chromatic purity. Samples were then rinsed again and air-dried in the shade. Three replicates were prepared for each group to ensure reproducibility.

Process Validation

Throughout the experiment, ORP and pH were actively controlled and maintained within strict ranges: pH at 10.5 and ORP between -650 mV and -700 mV. This ensured that observed color variations were attributable solely to dyeing cycle count and pigment layering, not chemical instability.

Characterization and Analysis

Colorimetric Analysis: The Konica Minolta CM-2600d spectrophotometer was calibrated with standard white and black tiles. Color measurements were performed using d/8° geometry, an 8 mm aperture (LAV), SCE (specular component excluded) setting, D65 standard illuminant, and a 10° standard observer. To ensure opacity and consistency, all samples were folded twice (four layers) and measured against the instrument's standard white backing. CIELAB (L*, a*, b*) values were recorded, with measurements taken at ten randomly selected locations across each sample. Reported values of Table 1 represent the mean and standard deviation from three replicates per group.

Table 1. Average CIELAB values for cotton samples at different dyeing cycles

Number of Dips	L* (Lightness)	a* (Red/Green)	b* (Blue/Yellow)
0 (Control)	94.5 ± 0.3	-0.1 ± 0.1	1.5 ± 0.2
5	45.3 ± 1.5	0.2 ± 0.3	-24.8 ± 1.2
10	33.5 ± 1.8	0.4 ± 0.4	-31.5 ± 1.6
15	27.7 ± 2.1	0.6 ± 0.5	-34.2 ± 1.9
20	24.3 ± 2.4	0.8 ± 0.6	-36.5 ± 2.2

Note on Variance: The standard deviation values observed (Table 1) reflect a quantifiable variance exceeding industrial standards. This is not experimental error but a measurable fingerprint of manual craft, corresponding to the visual depth and dynamic quality described in wabi-sabi aesthetics.

Surface Morphology Analysis: Fiber surfaces from each group (including the control) were examined using a JEOL JSM-7600F SEM. Small fabric sections were mounted on aluminum stubs and sputter-coated with a thin gold layer to prevent charging. Images were captured at 2000× magnification to observe dye coverage and micro-scale pigment distribution on cotton fibers.

Analytical Framework

Two contemporary design entities were selected as case studies based on the following criteria: (1) exclusive use of natural indigo dye, (2) international recognition, and (3) an explicit design philosophy linking material choices to cultural values.

Case Study 1: Buaisou (Japan) – A collective of indigo farmers and dyers in Tokushima Prefecture, Japan, renowned for mastering traditional *aizome* techniques and applying them to modern products.

Case Study 2: Story mfg. (UK) – A fashion brand prioritizing sustainability and ethics, utilizing natural dyes such as indigo to create collections that champion a “slow fashion” ethos.

Qualitative analysis was conducted using product documentation, public statements, official websites, and interviews. The focus was on how specific visual characteristics of indigo textiles (e.g., color depth, texture, hand-processing marks) are framed and utilized to communicate core cultural and philosophical messages.

RESULTS

Process Stability (Vat Chemistry)

Continuous monitoring confirmed a stable chemical environment throughout the experiment. The pH remained constant at 10.5 ± 0.2, and ORP fluctuated narrowly between -680 mV and -700 mV. These values indicate a strong reduction potential, ensuring that progressive color changes in the fabric resulted exclusively from immersion cycles and pigment layering, not from chemical degradation of the dye bath.

Quantitative Visual Characterization

The experimental analysis provides a quantitative foundation for understanding the visual evolution of cotton fabric during indigo dyeing.

Colorimetric Properties (CIELAB)

CIELAB values, presented in Table 1, demonstrate a systematic trend: as the number of dyeing cycles increases, lightness (L*) decreases, from 45.3 for 5 dips to 24.3 for 20 dips, confirming that the fabric becomes significantly darker. The inclusion of the soaping step effectively removed yellow impurities, preventing the greenish cast often associated with insufficient post-processing and yielding a pure indigo hue.

Notably, the b* value becomes increasingly negative, shifting from -24.8 (5 dips) to -36.5 (20 dips). A more negative b* value represents a stronger, more saturated blue. The most significant increase in blue saturation occurs between 10 and 15 dips, with diminishing returns thereafter—suggesting that the fiber surface approaches pigment saturation. These quantified values replace subjective descriptors such as “light blue” or “dark blue” with precise data, revealing that indigo “depth” is a measurable decrease in L* and a simultaneous increase in negative b*.

Surface Morphology

The macroscopic color evolution of the dyed fabrics is shown in Figure 1, where progressive darkening and saturation can be observed with increasing numbers of dipping cycles. Although the visual changes become less pronounced at higher dipping numbers, subtle differences in surface appearance and light scattering remain evident.

SEM images (Figure 2) provide microstructural evidence of how dyeing physically alters textile surfaces.

(A) Control Sample (0 Dips): Untreated cotton fibers exhibit a relatively smooth surface with characteristic natural convolutions.

(B) 5 Dips: Fine particulate deposits of indigo pigment are visible on the fiber surfaces, with sparse and uneven distribution.

(C) 15 Dips: The particulate coverage becomes considerably denser; indigo particles form larger aggregates, partially filling surface grooves and creating a rougher, more textured surface. The cotton fiber structure remains discernible, although it is increasingly covered by pigment aggregates.

SEM analysis reveals that indigo dyeing does not merely stain the fiber; instead, it leads to progressive particulate deposition and aggregation on the fiber surface. This heterogeneous pigment coverage creates a complex micro-topography that interacts with light, promoting diffuse reflection and resulting in the deep, matte visual appearance observed at the macroscopic scale. This surface-induced optical effect contributes to the characteristic visual depth of traditionally indigo-dyed fabrics, whereas in many synthetic dyeing processes, dye molecules tend to penetrate the fiber more uniformly, leaving the surface morphology comparatively unchanged.

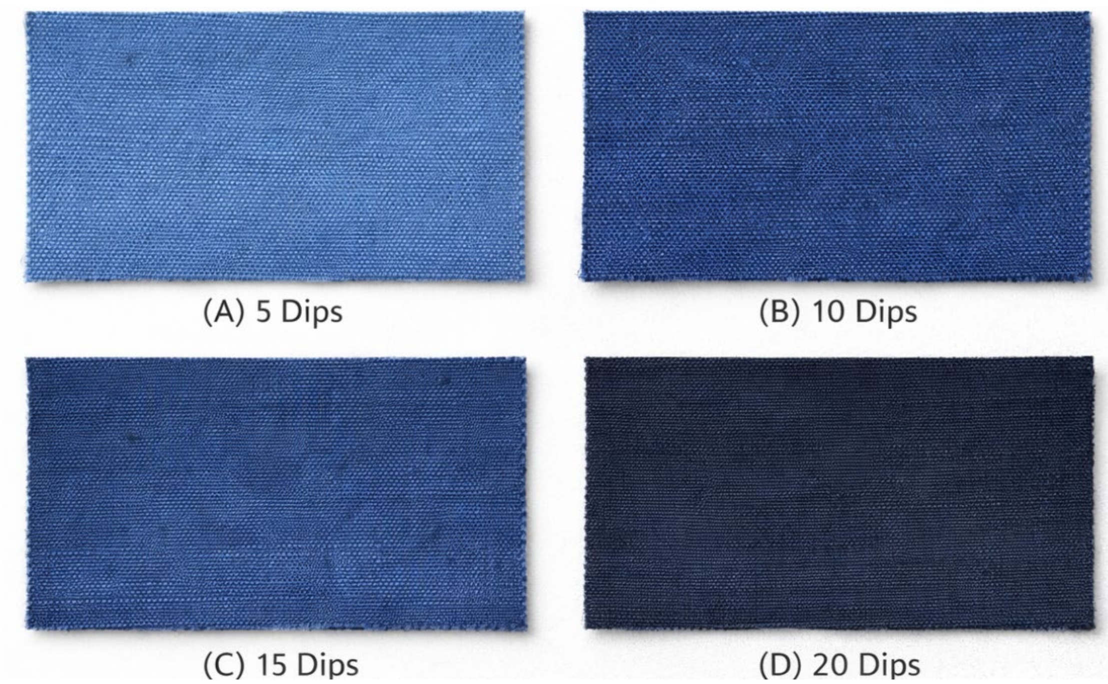

Figure 1. Visual appearance of cotton fabrics after repeated indigo dyeing cycles

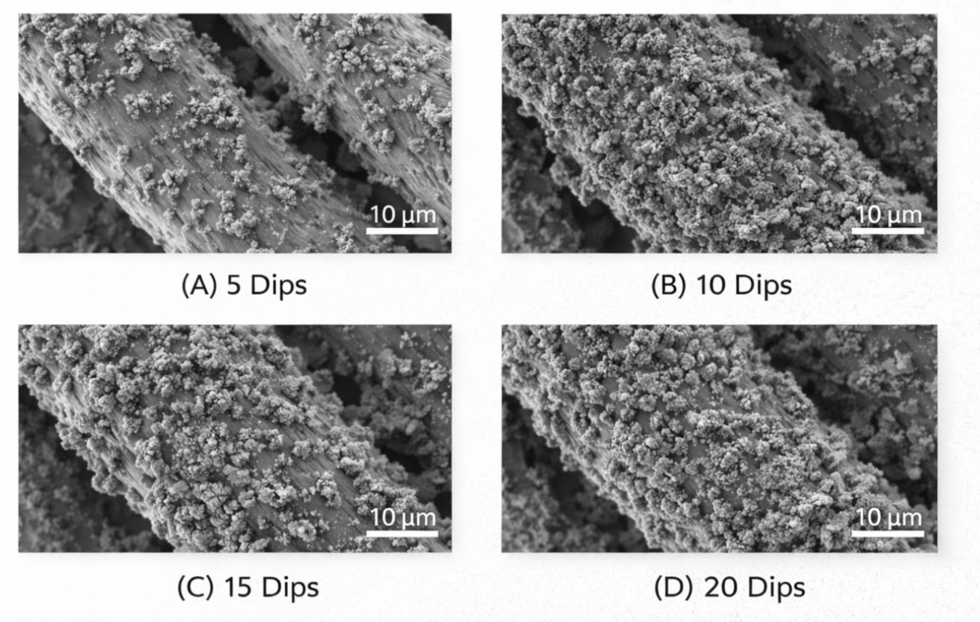

Figure 2. SEM micrographs of cotton fibers after repeated indigo dyeing cycles

Cultural Reinterpretation in Contemporary Design: Case Studies

The case studies of Buaisou and Story mfg. demonstrate how the quantified visual properties identified above are strategically manipulated and narratively framed to express cultural values. The quantitative data from laboratory samples serve as a reference framework for interpreting these commercial examples, rather than as direct measurements of the brands' products.

Case Study 1: Buaisou (Japan)

Buaisou's work exemplifies the pursuit of deep, saturated color. Their products frequently feature the darkest shades of indigo, corresponding to experimental samples with 15–20 dips (low L*, highly negative b*). Their narrative explicitly celebrates the meticulous, time-consuming process of repeated dipping required to achieve this depth. Subtle color variations and the rich, matte appearance resulting from heavy pigment aggregation (as observed in SEM analysis) are not regarded as defects, but as evidence of hand craftsmanship, embodying the Japanese aesthetic of *wabi-sabi* [19,20]. The "living" quality of the color, which evolves with wear and washing, is central to their brand identity, linking the physical instability of surface-bound pigment to a cultural appreciation for impermanence and authenticity. Thus, the visual presentation—deep, textured, and imperfect—becomes a direct expression of a specific cultural philosophy.

Case Study 2: Story mfg. (UK)

Story mfg. operates within a Western “slow fashion” context. While employing traditional methods, their design language often embraces a broader spectrum of blue shades, including the lighter blues observed in 5-dip samples. They emphasize the “natural” and “raw” qualities of their textiles, with visible texture and imperfect color uniformity serving as primary indicators of core brand values: sustainability and transparency [21,22]. The visible evidence of natural dye processes—uneven pigment distribution and particulate texture—provides a guarantee against industrial homogeneity. For their consumers, garments exhibiting these visual characteristics represent ecological awareness and a rejection of fast fashion. In this context, visual presentation communicates a modern, ethical narrative, rather than a traditional Japanese aesthetic. The same material properties are reframed to express different cultural values.

DISCUSSION

This research demonstrates that the cultural expression of indigo-dyed textiles is intrinsically linked to measurable physical and visual properties. The discussion can be synthesized into two core points:

From Process to Perception: The traditional multi-cycle dyeing process generates unique visual markers: a deep, saturated color (quantified by low L* and highly negative b* values) and a distinct surface texture (quantified by SEM imaging). The manual nature of the process imparts non-uniformity and inherent variance, which are culturally valued—even though this variance was not directly captured by a methodology focused on average color values. These outcomes result systematically from the interaction between natural pigment and fiber. Chemical stability, confirmed via real-time vat monitoring, supports the conclusion that the craft of layering is a controllable, parametric process rather than a random one. This methodological rigor ensures chromatic purity, allowing designers reliable access to the authentic “Japan Blue,” while the artisanal process introduces quantifiable textural variance—demonstrating that the contemporary *wabi-sabi* aesthetic emerges from a sophisticated balance between chemical precision and procedural humanity.

From Perception to Meaning: Contemporary designers act as interpreters, grounding cultural narratives (e.g., *wabi-sabi*, sustainability) in the material’s specific visual properties. While designers may not select specific L* or b* values, these attributes—quantified by laboratory data—provide tangible evidence that makes cultural narratives authentic and resonant. Buaisou leverages color depth and nuance to express *wabi-sabi* and craftsmanship; Story mfg. utilizes rawness and variation to convey sustainability and authenticity. In both cases, quantified visual characteristics are the essential medium through which abstract cultural ideas are made tangible and communicated to consumers. The “story” of the textile is not only narrated but visually and physically encoded in its color and texture.

CONCLUSION

This study aimed to establish an empirical link between production processes, visual characteristics, and cultural expression in natural indigo-dyed cotton textiles. Employing controlled laboratory experiments and qualitative case study analysis, several key findings emerged:

Visual properties of indigo-dyed cotton can be effectively quantified. Colorimetric data reveal a predictable, non-linear relationship between the number of immersion cycles and resulting color depth and saturation. SEM analysis demonstrates that dyeing fundamentally alters surface texture by depositing pigment aggregates.

These specific, measurable visual properties—nuanced color unattainable through industrial uniformity and distinctive matte texture—serve as significant vehicles for cultural expression in contemporary design. Designers choose not only colors but also visual characteristics imbued with meaning. While designer intent regarding particular L* values cannot be proven, these quantifiable attributes—color depth, process-inherent non-uniformity, and micro-granular surface morphology—are the necessary physical evidence validating cultural narratives of heritage, craftsmanship, and sustainability.

The primary contribution of this paper is its methodology, which bridges materials science and design studies. By grounding analyses of cultural expression in objective measurements of visual properties, this work provides a more rigorous and nuanced understanding of how natural materials function in art and design.

Limitations include the use of a single cotton fabric type and one indigo vat recipe. Future research could expand this methodology to other natural fibers (e.g., silk, hemp), weave structures, and dyes. Additional studies might incorporate psychophysical analysis to explore how users perceive quantified visual differences and what emotional or cognitive responses they elicit. While this study focused on visual implications of surface morphology (matte finish, color depth), SEM results suggest potential haptic consequences. The observed micro-topography likely influences tactile experience, though this was not quantified here. Future research could integrate tribological testing (e.g., surface friction analysis) to determine whether quantified visual textures correspond to measurable tactile properties. Ultimately, this research affirms that, in natural textiles, visual presentation is not a superficial layer but a necessary physical substrate that validates and materializes cultural narratives of heritage, craftsmanship, and sustainability.

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

Zhengbin Huang and Xuejun Zhu designed the study; all authors conducted the study; Xuejun Zhu and Zhengbin Huang collected and analyzed the data. Xuejun Zhu and Zhengbin Huang participated in drafting the manuscript, and all authors contributed to critical revision of the manuscript for important intellectual content. All authors gave final approval of the version to be published. All authors 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 completeness of any part of the work were appropriately investigated and resolved.

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Conflict of Interest

The authors declare no conflict of interest.

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