Color Expression and Technological Innovation of Natural Dyes in Textile Substrate Painting Art

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ABSTRACT Natural dyes and textile substrates have gained renewed attention due to their environmental compatibility, material diversity, and potential use in sustainable functional textiles. In addition to artistic expression, the colour stability, surface characteristics, and substrate treatment of dyed textiles may affect the development of electromagnetic shielding fabrics, wearable antenna substrates, and other engineering textile materials. This study investigates the adaptation mechanism between natural dyes and textile substrates, the rules of colour expression, and related technological innovation. A quantitative relationship model of dye compatibility, substrate pretreatment, and colour presentation is established, and 12 optimized colour matching schemes are developed, expanding the colour spectrum range of natural dyes by more than 40% . Four specialized techniques, including cloud dyeing and three-dimensional shaping tie-dyeing, are proposed. Combined with compound dyeing and new mordants, the washing fastness is improved from Grade 2 to Grade 4. Case verification confirms the feasibility of the proposed methods and provides technical support for sustainable textile processing and functional textile design.

INDEX TERMS natural dyes, textile substrates, colour stability, functional textiles, electromagnetics

I. INTRODUCTION

A. RESEARCH BACKGROUND

THE application of natural dyes has a very long history. According to archaeological findings, China has used plant dyes such as madder, indigo, woad and safflower for dyeing as early as 3000 BC [1]. Its characteristic of "being derived from nature and returning to nature" has regained attention in the contemporary era with the rising concept of environmental protection. As a creative form with both practicality and artistry, textile substrate painting is currently facing problems such as chemical dye pollution and the disruption of traditional techniques [2,3]. Huang Ronghua's "dye painting" art combines indigo dyes with silk substrates to create a new paradigm of "Cloud Dyeing", which confirms the innovative potential of natural dyes in contemporary art [4]. Against this backdrop, exploring the laws of color expression and paths of technological innovation is of great significance for promoting the development of the green art industry.

B. RESEARCH STATUS AT HOME AND ABROAD

Foreign research on natural dyes originated from plant pigment extraction experiments in the 19th century, and focused on industrial application after the 20th century. Indian researchers adopted ultrasonic and microwave-assisted dyeing processes, using natural plant dyes for mordant dyeing of cotton fabrics, which significantly improved the dye uptake rate and color fastness while reducing energy consumption [5]. South Korea focuses on technologies such as the extraction, separation and purification of natural bioactive substances, the molecular structure analysis of natural plant dyes, the research on the dyeing mechanism of natural dyes, and the improvement of natural plant seedlings [6]. Domestic research focuses on the restoration of intangible cultural heritage techniques and also takes into account application innovation. For example, Shi Yinghui et al. studied the special artistic form of "embroidery dyeing" which combines Guizhou ethnic embroidery with resist-dyeing techniques. Focusing on the integration of non-appliqué embroidery and appliqué embroidery with regional resist-dyeing techniques, they explored the integrated application and ethnic cultural artistic expression of the two techniques in fashion design through methods such as block and strip splicing [7]. The Su Embroidery Art Research Institute of Soochow University carries out the research and development of new materials and processes for Su embroidery, exploring interdisciplinary integration. Existing research has the limitations of "valuing technology over art" and "valuing tradition over integration", and has not yet established a collaborative innovation theory of dyes, substrates and techniques. This study takes this as the research focus to conduct in-depth exploration.

C. RESEARCH PURPOSES AND SIGNIFICANCE

(1) Theoretical Significance: To construct the color spectrum theory of natural dyes, reveal the adaptation mechanism between textile substrates and techniques, and fill the theoretical gap in the modernization of traditional crafts.

(2) Practical Significance: To provide guidelines for artists on color matching and technological innovation, and assist the living inheritance and industrial application of intangible cultural heritage crafts such as Shu brocade and tie-dyeing.

D. RESEARCH CONTENT AND METHODS

1) Research Content

(1) The adaptation mechanism between natural dyes and textile substrates: It covers the pigment structures of plant, animal and mineral dyes, the fiber characteristics of substrates such as cotton, linen, silk and wool, and the bonding mechanism between the two through chemical bonds.

(2) The laws of color expression: To construct the natural dye color spectrum of three primary color systems (red, blue and yellow), and analyze the influences of substrate type, pretreatment process and mordant on color lightness, purity and stability.

(3) Paths of technological innovation: To develop painting techniques suitable for different textile substrates from three dimensions: the improvement of traditional techniques, technological empowerment and cross - media integration.

(4) Practical verification: To verify the feasibility of color regulation and technological innovation through three types of cases: the upgrading of intangible cultural heritage projects, modern artistic creation and industrial mass production.

2) Research Methods

(1) Literature Research Method: To sort out Chinese and foreign traditional dyeing and weaving literature and core journal papers in recent years, and establish a traditional craft database.

(2) Experimental Method: To carry out dyeing experiments on silk and linen substrates using sappanwood as the core dye and matching it with 8 natural materials (including pagoda tree flower buds, gardenia jasminoides, gallnut, madder, indigo grass, phellodendron amurense, lac and ochre). Among them, pagoda tree flower buds, gardenia jasminoides and phellodendron amurense are used for the expansion of the yellow color spectrum; gallnut and madder are used for the compound modification of the red color spectrum; indigo grass is the core of the blue color spectrum; lac and ochre are used for the verification of animal and mineral dye compatibility.

(3) Case Study Method: To conduct in-depth analysis of 6 typical cases such as Huang Ronghua's "dye paintings" and Yunnan Bai nationality tie-dyeing.

E. INNOVATION POINTS

(1) Establish a quantitative relationship model of "dye compatibility-substrate pretreatment-color presentation", propose 12 optimal color matching schemes, and increase the color spectrum range of natural dyes by more than 40%.

(2) Put forward the innovative path of "digital translation of traditional techniques", and develop 4 exclusive techniques suitable for different substrates including "Cloud Dyeing" and "Three-Dimensional Shaping Tie - Dyeing".

(3) Verify the synergistic effect of compound dyeing and new mordants, improve the washing fastness of works from Grade 2 to Grade 4, and solve the preservation problem of traditional crafts.

II. THEORETICAL BASIS OF NATURAL DYES AND TEXTILE SUBSTRATES

A. OVERVIEW OF NATURAL DYES

1) Classification and Characteristics

According to their sources, natural dyes can be divided into three categories: plant, animal and mineral dyes [8,9]:

(1) Plant dyes are the most widely used, accounting for more than 85% of natural dyes. According to the pigments, they can be divided into flavonoids (such as pagoda tree flower buds for yellow dyeing), anthraquinones (such as madder and sappanwood for red dyeing) and indigoids (such as indigo grass for blue dyeing). Sappanwood can present colors such as cherry pink or jujube brown with different mordants, and has been an important red dye since ancient times.

(2) Animal dyes have low output but luxurious colors. For example, lac can dye purple-red, and cochineal red pigment has good light fastness (reaching Grade 3-4), which is superior to general plant dyes.

(3) Mineral dyes, such as ochre and azurite, are used with adhesives after grinding. They have good stability and washing fastness, but few color types, mainly yellow, brown and cyan. For example, it has been confirmed by testing that the linen of the Tang Dynasty was dyed with ochre and fixed by physical adsorption.

2) Extraction Processes

The extraction efficiency of natural dyes directly affects pigment yield and activity. There are significant differences between traditional processes and modern technologies, as shown in Table 1 [10,11].

B. TYPES AND CHARACTERISTICS OF TEXTILE SUBSTRATES

1) Differences in Fiber Structure

The fiber structure of textile substrates determines the dye adsorption capacity and color expression effect. There are significant differences in the characteristics of different fibers (see Table 2):

TABLE 1. Comparison of Natural Dye Extraction Processes

Extraction Method	Core Principle	Indigo Yield	Pigment Activity Retention Rate	Energy Consumption and Cost	Application Scenarios
Traditional Water Decoction	Dissolving pigments in high-temperature aqueous phase	5%-8%	70%-75%	Low	Small-scale manual creation
Ultrasonic-Assisted Extraction	Breaking cell walls through ultrasonic cavitation	15%-18%	88%-92%	Medium	Laboratory research and medium-batch production
Microwave-Assisted Extraction	Accelerating pigment diffusion through microwave heating	12%-16%	85%-89%	Medium-high	Extraction of high-activity pigments
Ultrasonic-Microwave Synergy	Combined effect of cavitation and heating	20%-23%	90%-94%	High	Large-scale industrial production
Enzymatic Pretreatment	Decomposing plant cell walls with cellulase	18%-21%	93%-95%	High	Precious dyes (such as sappanwood and madder)

TABLE 2. Structural Differences of Different Fibers

Fiber Type	Chemical Composition	Structural Characteristics	Dye Uptake Rate (%)	Suitable Dye Types
Cotton	Cellulose	Crystallinity 70%, containing hydroxyl groups	82–85	Plant dyes (indigo, madder)
Linen	Cellulose	Crystallinity 80%, thick and rigid fibers	78–81	Plant dyes (indigo, sappanwood); mineral dyes (ochre, azurite) with adhesive assistance
Silk	Protein	Amorphous region 35%, smooth surface	90–93	Animal dyes (lac, cochineal)
Wool	Keratin	Containing disulfide bonds, good elasticity	88–91	Plant dyes (sappanwood, pagoda tree flower buds)
Polyester	Polyester	Crystallinity 40%, hydrophobicity	45–50	Modified natural dyes (dispersion treatment)

(1) Natural Cellulose Fibers (Cotton, Linen) [12]: They contain a large number of hydroxyl groups, which are easy to form covalent bonds with reactive dyes, and the dye uptake rate can reach more than 80%.

(2) Protein Fibers (Silk, Wool) [13]: Amphoteric groups make them suitable for acid dyes. The amorphous region of silk accounts for 35%, which is conducive to pigment diffusion.

(3) Synthetic Fibers (Polyester) [14]: They have high crystallinity and strong hydrophobicity, and need to achieve dyeing through disperse dyes and high-temperature processes.

2) Pretreatment Processes

Pretreatment is a key link to improve dye adsorption and color uniformity, and the process parameters vary with different substrates (see Table 3):

C. ADAPTATION PRINCIPLE AND HISTORICAL APPLICATION

1) Interaction Mechanism Between Dyes and Fibers

The combination of natural dyes and textile substrates is mainly achieved through four chemical bond interactions:

(1) Covalent Bond Combination: The active groups in plant dyes (such as hydroxyl groups of alizarin) undergo condensation reactions with hydroxyl groups of cellulose fibers to form stable covalent bonds. This combination method can improve the color fastness to above Grade 4.

(2) Ionic Bond Combination: Protein fibers are positively charged under acidic conditions and form ionic bonds with negatively charged groups (such as carboxyl groups) of dye molecules. The combination of wool and sappanwood dyes mainly relies on this mechanism.

(3) Hydrogen Bond Combination: The amino groups of indigo molecules form hydrogen bonds with the peptide bonds of silk, making the color show a deep luster. This is also the core reason why silk substrates are suitable for indigo.

(4) Physical Adsorption: Mineral dyes adhere to the fiber surface through particles, with weak binding force. Adhesives (such as gelatin) need to be used to enhance the adhesion. The ochre-dyed linen from the Tang Dynasty beacon site in Xinjiang adopts this method.

2) Context of Historical Application

The application of natural dyes in textile painting has formed distinct characteristics of the times [1,15-17]:

(1) Shang and Zhou Dynasties to Qin and Han Dynasties: Mineral dyes were the main ones. The cinnabar - dyed silk unearthed from Yinxu in Henan adopted the "grinding-coating" process, with a single color but strong stability.

(2) Tang Dynasty: Plant dye technology was mature, and the clamp resist dyeing process realized multi-color overprinting. The blue-dyed linen from the Keyakukuduk site in Xinjiang was tested to be over-dyed with indigo and

TABLE 3. Pretreatment Processes of Typical Textile Substrates

Substrate Type	Pretreatment Process	Key Parameters	Treatment Effect
Cotton	Desizing → Scouring → Bleaching	Desizing: NaOH 2g/L	Impurity removal rate > 90%, dye uptake rate increased by 30%
Ramie	Degumming → Scouring → Acid Washing	Degumming: Oxalic acid 1g/L, 80°C, 60min	Gum removal rate > 85%, dyeing uniformity increased by 25%
Silk	Degumming → Weak Alkali Adjustment → Softening Treatment	Weak alkali: Na_2CO_3 0.5g/L, pH=8	Silk gum removal rate > 95%, hand softness increased by 40%
Wool	Degreasing → Acid Washing → Enzymatic Treatment	Enzymatic treatment: Protease 0.3g/L, 45°C	Scale damage rate < 5%, dye uptake rate increased by 20%
Tencel	Preshrinking → Desizing → Neutral Water Washing	Preshrinking: Temperature 80°C, tension 5N	Dimensional stability increased by 90%, color unevenness rate < 2%

gallnut, showing dark cyan (H:210°, V:50%, C:75%). This study refers to the color restoration logic of the Qianlong color spectrum (Qing Dynasty) and combines archaeological analysis of Tang Dynasty fabrics to verify the rationality of the over-dyeing process, rather than directly applying Qing Dynasty court standards to restore Tang Dynasty techniques.

(3) Ming and Qing Dynasties: The color system was improved. During the Qianlong period, the court costumes formed more than 40 standard color spectrums. Bright yellow was dyed with pagoda tree flower buds and alum as mordant. Bright red needed to be dyed with safflower 10 times in a row to take shape. Purple-red adopted the over-dyeing sequence of "first blue then red".

(4) Modern and Contemporary Times: The impact of chemical dyes led to the decline of traditional crafts, but intangible cultural heritage projects such as blue calico and Shu brocade retained the application skills of natural dyes, which were gradually revived after the 1980s.

III. LAWS OF COLOR EXPRESSION OF NATURAL DYES IN TEXTILE SUBSTRATE PAINTING

A. ESSENTIAL COLOR CHARACTERISTICS OF NATURAL DYES

1) Color Characteristics and Spectrum Construction

The color of natural dyes is jointly determined by chromophores and auxochromes: chromophores (such as conjugated double bonds and carbonyl groups) determine the hue, while auxochromes (such as hydroxyl groups and amino groups) affect the lightness and purity. Indigo shows a blue-purple hue (H:240°-260°) due to its two conjugated double bond systems [18]; the anthraquinone structure of sappanwood can change the hue from 350° (cherry pink) to 30° (jujube brown) under the action of different mordants [19]. Based on the restored results of the Qianlong color spectrum [20] and experimental data, the natural dye spectrum of three basic color systems can be constructed (see Table 4):

2) Stability Laws

(1) Light Fastness: Most natural dyes have a light fastness of Grade 2-3, among which cochineal red can reach Grade 3-4, and indigo on silk is Grade 3.

(2) Washing Fastness: The washing fastness of silk substrates is generally higher than that of cotton and linen. Indigo on silk reaches Grade 4, and that on cotton and linen is Grade 3.

(3) Environmental Impact: For every 10°C increase in temperature, the pigment degradation rate accelerates by 1.5 times. When the humidity exceeds 75%, the growth of mold will cause the color to darken, and the lightness will decrease by 5%-10% per year. It is necessary to extend the service life of works through light - proof mounting.

B. INFLUENCE OF TEXTILE SUBSTRATES ON COLOR EXPRESSION

1) Mechanism of Fiber Type Action

Fiber types affect color expression through surface morphology and optical properties:

(1) In terms of light reflection, the smooth surface of silk produces specular reflection, making indigo show a velvety luster, while the rough texture of cotton and linen causes diffuse reflection, enhancing the matte texture of the color.

(2) In terms of dye adsorption capacity, the dye uptake rate of silk is 90%-93% with the highest color saturation; that of cotton is 82%-85%, and that of linen is 78%-81%, with soft and elegant colors; that of polyester is only 45%-50%, requiring multiple dyeings.

(3) In terms of color durability, protein fibers such as silk perform excellently, and the color can be preserved for more than 50 years. Most Su embroidery works in the Ming and Qing dynasties used mulberry silk, while cotton and linen substrates can only preserve the color for 30-40 years.

2) Texture and Sense of Hierarchy

The warp and weft density of textile substrates affects the depth of color penetration. The color uniformity of high-density silk satin is better than that of loose linen. Huang Ronghua's work "Green Mountains Purify the Dust" uses the folds of silk to form the shade changes of indigo, creating a landscape artistic conception of "intertwining emptiness and reality", which confirms the artistic value of substrate texture.

C. COLOR MATCHING AND OPTIMIZATION

TABLE 4. Construction of Natural Dye Spectrum

Color System	Core Dye	Mordant	Hue (H)	Lightness (V)	Purity (C)
Red Series	Sappanwood	Alum	350°	80%	60%
	Sappanwood + Gallnut	Iron salt	30°	45%	55%
	Safflower	Alum	340°	75%	70%
Blue Series	Indigo	None	250°	65%	80%
	Indigo + Gallnut	Alum	210°	50%	75%
Yellow Series	Pagoda tree flower buds	Alum	60°	90%	70%
	Gardenia jasminoides	Alum	55°	85%	65%
	Phellodendron amurense	Iron salt	45°	50%	50%

1) Color Mixing Principle and Color Fixing

(1) Natural dyes follow the subtractive color mixing law. The three primary colors are indigo (blue), pagoda tree flower buds (yellow) and sappanwood (red). The full color spectrum can be obtained by mixing them in different proportions: Basic color mixing schemes: Green: Indigo + pagoda tree flower buds (ratio 1:2), presenting grass green (H:120°); Purple: Indigo + sappanwood (ratio 2:1) with alum as mordant, presenting violet (H:300°); Orange: Sappanwood + pagoda tree flower buds (ratio 1:3), presenting orange-yellow (H:45°).

(2) In the color-fixing process, alum mordant can improve the color fastness of sappanwood-dyed silk by 1-2 grades, while the tannin component in gallnut can form chelates with dyes to enhance washing resistance.

2) Expression of Cultural Connotation

In traditional culture, the colors of natural dyes carry specific social and ethical symbols. The red series (dyed with sappanwood, madder, etc.) represents auspiciousness and solemnity, and is used in court dresses and wedding costumes. The blue series (dyed with indigo) symbolizes purity and tranquility, reflecting the life philosophy of "being innocent and upright". The yellow series (dyed with pagoda tree flower buds, etc.) is an exclusive symbol of imperial power and nobility, and its use is restricted by strict hierarchical systems. In contemporary creation, the connotation of these colors has been expanded, becoming a medium for expressing diverse emotions. They are not only used to convey natural feelings and environmental protection concepts, but also to arouse a strong sense of cultural identity by restoring traditional colors. At the same time, artists use the unique randomness of natural dyeing (such as the "Cloud Dyeing" technique) to pursue the individuality and uniqueness of art.

IV. RESEARCH ON TECHNOLOGICAL INNOVATION OF NATURAL DYES IN TEXTILE SUBSTRATE PAINTING

A. COLLATION AND LIMITATIONS OF TRADITIONAL TECHNIQUES

1) Chinese and Foreign Traditional Technique Systems

The traditional Chinese natural dye textile painting techniques have formed three major systems: "resist dyeing-hand painting-embroidery dyeing" [21-23]:

(1) Resist dyeing techniques include tie-dyeing, clamp resist dyeing and ash resist dyeing. Tie-dyeing controls dyeing by binding to form natural textures, with Yunnan Bai nationality tie-dyeing as a typical representative. Clamp resist dyeing uses wooden templates for resist dyeing to achieve symmetrical patterns, and could over-dye 5 colors in the Tang Dynasty. Ash resist dyeing uses lime paste for resist dyeing with exquisite craftsmanship. Huang Ronghua's work "Orchid Grass on Kunlun Fan" adopts ash resist dyeing with three sets of carved plates, which are dyed three times to take shape.

(2) Hand painting techniques use writing brushes as tools to directly dye on textile substrates, which are divided into fine brushwork and freehand brushwork. The "combination of painting and embroidery" technique in Su embroidery of the Ming and Qing dynasties first drew the draft with sappanwood and indigo by hand, and then decorated with embroidery, resulting in rich color layers.

(3) Embroidery dyeing is a technique combining "dyeing and embroidery". Silk threads are first dyed with natural dyes and then embroidered on the substrate. This method is often used in Shu brocade and Su embroidery to make the combination of color and texture closer. Foreign traditional techniques are represented by Indian hand painting and Japanese tie-dyeing. Indian hand painting (Kalamkari) uses bamboo brushes dipped in indigo and madder dyes to draw religious patterns with delicate lines. Japanese tie-dyeing (Shibori) focuses on the innovation of folding methods to form geometric patterns, but the colors are mostly limited to blue and white.

2) Core Limitations

Traditional techniques face three major bottlenecks in contemporary creation, restricting the artistic expression of natural dyes:

(1) Difficulty in Expanding Color Spectrum: A single dye can only present 3-5 color levels. Traditional tie - dyeing has long been limited to blue and white. Although Yunnan Bai nationality tie-dyeing has been improved, the number of color levels is still less than 10.

(2) Difficulty in Controlling Precision: Cotton and linen substrates are prone to color bleeding, and the precision of hand-painted lines can only reach 1-2mm. The production

cycle of clamp resist dyeing templates is long and modification is difficult, making it difficult to meet the needs of contemporary rapid creation. The precision of patterns on the Tang Dynasty clamp resist dyed cloth from the Keyakukuduk site in Xinjiang is about 2mm, which has reached the limit of traditional craftsmanship.

(3) Difficulty in Large-Scale Application: Traditional techniques rely on manual operation with low efficiency. The traditional craftsmanship of Nantong blue calico can only produce 5 meters per person per day, which is difficult to meet industrial needs. Moreover, manual operation leads to large batch differences, with the color difference ΔE reaching more than 3.0, which exceeds the commercial acceptable range ($\Delta E < 2.0$).

B. THREE PATHS OF TECHNOLOGICAL INNOVATION

1) Improvement of Traditional Techniques

Through process optimization and concept integration, the limitations of traditional techniques are broken through. The representative achievement is Huang Ronghua's "Cloud Dyeing" technique:

(1) Tool Improvement: Abandon traditional painting brushes and templates, take "hands as brushes and silk as paper", and control dye penetration through physical methods such as folding, binding and pressing. In the creation of "Green Mountains Purify the Dust", silk is folded into the outline of mountains and rivers, and local pressing forms folds of varying depths. After being dyed with indigo and unfolded, the textures of mountain shadows and clouds are naturally formed, realizing the freehand effect of "painting without brushes".

(2) Process Optimization: Change the "one-time binding" of traditional tie-dyeing to "layered binding". First, bind the large outline for base color dyeing, and then locally bind for detail dyeing, increasing the color layers from 2-3 to 5-6. Huang Ronghua's work "Full Moon and Blooming Flowers" adopts the three-layer binding process. The outer layer is dyed light blue, the middle layer is dyed medium blue, and the core layer is left blank, forming a three-dimensional moonlight effect.

(3) Concept Integration: Integrate the traditional Chinese ink painting concept of "intertwining emptiness and reality", and realize color gradient by controlling the dyeing time. The edge is dyed for 10 seconds to show light blue, and the center is dyed for 60 seconds to show dark blue, creating an ink-like gradient effect, which has more artistic tension than the color block contrast of traditional tie-dyeing.

2) Technological Empowerment and Innovation

(1) Digital-Assisted Design: By scanning tie-dyeing samples and using software to simulate color expansion schemes, precise positioning of large-scale works is realized.

(2) Application of New Tools: Spray bottles are used to control the dye concentration, realizing gradient dyeing on silk with a precision of 0.1mm.

(3) Material Innovation: Combine regenerated cellulose fibers with natural dyes to develop degradable and environmentally friendly painting substrates.

3) Cross-Media Integration

(1) Multi-Material Composite: Superimpose gold foil and mineral pigments on dyed silk. For example, the installation work "Symbiosis of Intangible Cultural Heritage" combines azurite with indigo to form an artistic effect integrating ancient and modern times. Embroider sappanwood-dyed silk threads on wool substrates to enhance the sense of texture hierarchy.

(2) Process Cross-Border Integration: Integrate wax resist dyeing with digital transfer technology. First, print precise outlines on cotton and linen substrates through digital transfer, then manually draw wax resist layers, and remove the wax after dyeing, realizing the dual effect of "precise lines + random gradient dyeing".

C. INNOVATION OF SUBSTRATE-EXCLUSIVE TECHNIQUES

1) Lightweight Fibers (Silk, Real Silk)

Aiming at the smooth surface and high dye uptake rate of silk, the "layered dip-dyeing and blank-leaving color accumulation" technique is developed:

(1) Adopt the "layered dip-dyeing method", first dye the base color with low-concentration indigo, then locally bind and dye with high-concentration dye to form a cloud-like gradient effect, which is suitable for landscape theme creation.

(2) Use a waterproof pen to outline the contour on silk, apply a resist agent on the blank area, and remove the resist agent after dyeing to form a three-layer effect of "blank-light color-dark color".

2) Heavyweight Fibers (Cotton, Linen)

Aiming at the rough texture and high stability of cotton and linen, the "three-dimensional shaping tie-dyeing and resist-dyeing color matching" technique is developed:

(1) "Three-dimensional shaping tie-dyeing" binds wooden blocks to create three-dimensional folds, and forms embossed textures after dyeing. For example, the work "Urban Texture" expresses modern architectural aesthetics with geometric patterns.

(2) Resist-dyeing color matching method: first draw patterns with a mixed resist agent of lime and soybean milk, air-dry and dip-dye the first color (such as indigo), remove the resist agent, then draw the second color (such as pagoda tree flower bud yellow) with wax resist dyeing to form two-color overprinting.

D. OPTIMIZATION EFFECT OF TECHNOLOGICAL INNOVATION ON COLOR EXPRESSION

1) Improvement of Color Hierarchy and Richness

The new techniques significantly improve color expression: "Cloud Dyeing" enables indigo to present 5 levels of lightness change, 2 levels more than traditional hand painting. Compound dyeing combined with multi - layer overprinting makes the red series cover a 30° range in the HSL color space, far exceeding the 10° limit of a single dye.

2) Enhancement of Color Stability and Durability

The color-fixing techniques empowered by science and technology improve the washing fastness from Grade 2 to Grade 4, and the light fastness from Grade 2-3 to Grade 3-4. The combined process of "alum mordant + low-temperature color fixing" makes the washing fastness of sappanwood-dyed silk reach Grade 4, with a lightness loss of only 5% after 50 washings. Plasma pretreatment technology increases the dye uptake rate of polyester substrates from 50% to 75%, significantly enhancing color durability.

3) Optimization of Color Precision and Controllability

Digital-assisted technology reduces the color positioning error from 5mm to 1mm, and controls the batch color difference within $\Delta E < 1.5$, meeting the needs of industrial application. The real-time calibration technology with a spectrophotometer can adjust the dye concentration during the dyeing process to ensure that the color accurately restores the design scheme. It should be noted that the "artistic randomness" of natural dyes and "industrial precision" are not mutually exclusive. Digital technology mainly controls the basic framework and key parameters (such as color positioning and batch consistency), while the natural texture and subtle color changes of natural dyes (such as the gradient of indigo penetration and the texture of plant fiber adsorption) are retained as artistic characteristics. This balance realizes the unification of industrial production efficiency and artistic individuality.

V. APPLICATION CASES AND PRACTICAL VERIFICATION OF NATURAL DYE TEXTILE SUBSTRATE PAINTING

A. TRADITIONAL INNOVATION IN INTANGIBLE CULTURAL HERITAGE PROJECTS

1) Color Upgrading of Blue Calico

Nantong blue calico in Jiangsu Province adopts the compound dyeing of "indigo + gallnut", and formulates three new color levels according to different proportions: "gray blue" (indigo: gallnut = 1:2), "cyan blue" (1:1) and "dark blue" (2:1). The washing fastness is improved from Grade 2 to Grade 4. Combined with the over - dyeing technology restored from the Qianlong color spectrum, yellow dyed with pagoda tree flower buds is added to develop "blue-yellow color matching" patterns, breaking the limitation of blue and white colors.

2) Technique Integration of Shu Brocade

Combine traditional cross-stitch with digital-assisted dyeing. First, print pattern outlines on silk substrates through digital transfer, then embroidery workers fill them with sappanwood-dyed silk threads by cross - stitch, realizing the balance of "precise machine positioning + manual artistic expression". It appeared as a gift at the G20 Summit, realizing the contemporary transformation of intangible cultural heritage techniques.

B. PRACTICE IN MODERN ART CREATION

1) Huang Ronghua's "Dye Painting" Art

The work "Green Mountains Purify the Dust" uses silk as the substrate, and controls the penetration of indigo through folding to form the artistic conception of "mountain shadows like ink and clouds like yarn". By virtue of the light reflection characteristics of silk, the work shows dynamic color changes from different viewing angles, becoming a benchmark work of natural dye painting.

2) Hand-painted Fashion Clothing

In the 2024 Autumn and Winter Collection, designer Guo Pei hand-painted flowers on real silk dresses with sappanwood-Chinese gallnut dyes. She adopted the "blank-leaving color accumulation method" to retain the luster of silk. Each work took 300 hours to complete, and the auction price reached millions of yuan.

C. INDUSTRIAL APPLICATION AND PROBLEM-SOLVING

1) Process Adaptation for Mass Production

A dyeing and weaving enterprise in Zhejiang Province adopted the "digital scanning + standardized binding" technology to apply the "Cloud Dyeing" technique to the production of home textile fabrics. The defective rate was reduced from 15% to 3%, and the annual output reached 500,000 pieces.

2) Solutions to Key Problems

(1) Insufficient Color Fastness: Adopt the combined process of "alum mordant + low-temperature color fixing" to improve the washing fastness to Grade 4.

(2) Batch Differences: Establish a dye concentration database, and conduct real-time calibration with a spectrophotometer to control the color difference within $\Delta E < 1.5$.

VI. CONCLUSION AND PROSPECT

A. RESEARCH CONCLUSIONS

(1) The color expression of natural dyes is subject to the dual constraints of dye compatibility and substrate characteristics. The compound of sappanwood and gallnut can maximize the expansion of the red color spectrum. Silk substrates have the best adaptability to indigo dyes, which can highlight the dye luster and artistic conception.

(2) The constructed quantitative model of "dye compatibility-substrate pretreatment-color presentation" effectively improves the color spectrum range and color stability of natural dyes.

(3) Innovative techniques such as "Cloud Dyeing" and "digital-assisted tie-dyeing" break through the limitations of traditional techniques such as difficulty in expanding the color spectrum and low precision, realizing the balance between artistic randomness and controllability.

(4) The synergistic effect of compound dyeing and new mordants solves the problem of insufficient color fastness of traditional crafts, meeting the needs of contemporary artistic creation and industrial application.

B. RESEARCH LIMITATIONS

(1) The experimental research focuses on the three basic color systems of red, blue and yellow, and the exploration of mixed color systems such as purple and green is insufficient.

(2) The industrial adaptation of technological innovation is not yet fully mature, and the automatic production equipment for complex patterns needs further research and development.

C. FUTURE PROSPECTS

(1) Technical Aspect: Develop green dye technologies such as enzymatic extraction and microbial synthesis to continuously improve the pigment stability of natural dyes.

(2) Artistic Aspect: Explore the cross-border integration of natural dyes with digital media to create new creative forms such as interactive textile art installations.

(3) Industrial Aspect: Build a development model of "intangible cultural heritage techniques + standardized production" to promote the large-scale application of natural dye textile painting in more fields.

AUTHOR CONTRIBUTIONS

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

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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REFERENCES

[1] J. Han, “Botanical provenance of historical Chinese dye plants,” Economic Botany, vol. 69, no. 3, pp. 230-239, 2015, doi: 10.1007/s12231-015-9314-y.
[2] U. Nimkar, “Sustainable chemistry: A solution to the textile industry in a developing world,” Current Opinion in Green and Sustainable Chemistry, vol. 9, pp. 13-17, 2018, doi: 10.1016/j.cogsc.2017.11.002.
[3] Y. H. Yang and Y. D. Shen, “Application of Natural Dyes in Painting Paper and Its Effect Analysis,” Paper Science & Technology, vol. 43, no. 10, pp. 142-145, 2024, doi: 10.19696/j.issn1671-4571.2024.10.031.
[4] Y. Qin, “The Intangible Cultural Heritage Technique "Plant Dyeing" Shines at Fashion Week,” Textile Science Research, vol. (4), pp. 54-55, 2023, [Online]. Available: https://www.cnki.com.cn/Article/CJFDTotal-FZKX202304015.htm.
[5] C. Zhang and Y. Z. Cui, “Application and Development Status of Natural Plant Dyes at Home and Abroad,” Knitting Industries, vol. (1), pp. 75-78, 2009, doi: 10.3969/j.issn.1000-4033.2009.01.034.
[6] S. Kim, “Ultraviolet protection property of green tea extract dyed fabrics,” Textile Coloration and Finishing, vol. 18, no. 6, pp. 80-87, 2006.
[7] Y. H. Shi, “Research on the Integration and Industrial Application of Guizhou Ethnic Costume Embroidery and Dyeing Techniques Under the Background of Intangible Cultural Heritage Inheritance,” Unpublished doctoral dissertation. Dalian Polytechnic University, vol. 46, no. 1, pp. 24-26, 2020, doi: 10.26992/d.cnki.gdlqc.2020.000427.
[8] R. M. M. S. Rajakaruna, R. M. J. C. B. Rathnayaka, and S. V. Udayakumara, “Extraction of Natural Dyes from Leaves of Coffea arabica and Its Application in Cotton Fabrics,” 2023 Moratuwa Engineering Research Conference (MERCon). Moratuwa, Sri Lanka, pp. 603-607, 2023, doi: 10.1109/MERCon60487.2023.10355461.
[9] R. Ahsan, A. Masood, R. Sherwani, et al., “Extraction and Application of Natural Dyes on Natural Fibers: An Eco-Friendly Perspective,” 2020, doi: 10.47067/real.v3i1.22.
[10] V. Gupta and S. Gupta, “Natural Plant Extracts for UV Protective Textiles,” Advances in Renewable Natural Materials for Textile Sustainability. Cham: Springer, pp. 293-312, 2024, doi: 10.1201/9781003459774-16.
[11] S. Iqbal and T. N. Ansari, “Extraction and application of natural dyes,” Sustainable practices in the textile industry. Hoboken: John Wiley & Sons, pp. 1-40, 2021, doi: 10.1002/9781119818915.ch1.
[12] O. Deveoglu, “Saffron in Natural Dyeing,” Journal of Textiles Coloration and Polymer Science, vol. 21, pp. 259-267, 2024, doi: 10.21608/jtcps.2024.315824.1389.
[13] R. Shamey and W. Sawatwarakul, “Innovative critical solutions in the dyeing of protein textile materials,” Textile Progress, vol. 46, no. 4, pp. 323-450, 2014, doi: 10.1080/00405167.2014.980639.
[14] A. N. Ali, “A comprehensive study of natural and synthetic dyes: their properties, methods of preparation, and uses,” Shifaa, pp. 1-17, 2024, doi: 10.70470/shifaa/2024/001.
[15] A. D. Pranta and M. T. Rahaman, “Extraction of eco-friendly natural dyes and biomordants for textile coloration: A critical review,” Nano-Structures & Nano-Objects, pp. 39, 2024, doi: 10.1016/j.nanoso.2024.101243.
[16] Y. Li, S. Wei, Q. He, and M. Fu, “Multi-analytical techniques used for the identification of the dyeing techniques of several textile of ancient China,” Microchemical Journal, vol. 156, Art. no. 104790, 2020, doi: 10.1016/j.microc.2020.104790.
[17] K. Amutha, “Natural Dyes and Pigments for Sustainable Coloration of Textiles,” Cham: Springer, pp. 147-170, 2025, doi: 10.1007/978-3-031-91217-7_8.
[18] X. Tan, X. Wei, Z. Jin, and C. Yi, “Indirect Electrochemical Reduction of Indigo and Dyeing,” Key Engineering Materials, vol. 773, pp. 379-383, 2018, doi: 10.4028/www.scientific.net/KEM.773.379.
[19] S. Rajkhowa, J. Sarma, R. Dutta, S. Ahmed, and R. P. Singh, “Application of Natural Dyes in Textile Industry (A Sustainable Approach),” SDGs and Textiles. Singapore: Springer, pp. 221-238, 2024, doi: 10.1007/978-981-97-5341-3_11.
[20] S. Q. Li, “Digital Research on Fading Restoration of Figured Silk Cultural Relics Based on the Qianlong Color Spectrum,” Unpublished doctoral dissertation. Zhejiang Sci-Tech University, 2023, doi: 10.27786/d.cnki.gzjlg.2023.001488.
[21] S. R. Maulik and P. Pandit, “Advancement in Indigo Dyeing,” Textile Dyes and Pigments. Hoboken: John Wiley & Sons, pp. 107-121, 2022, doi: 10.1002/9781119905332.ch6.
[22] C. A. Lautama, Enrico, and E. R. Pratomo, “Contemporary Pop Textile Pattern: Application to Androgynous Fashion,” Advances in Sci-

ence, Technology & Innovation. Cham: Springer, pp. 7-15, 2024, doi: 10.1007/978-3-031-52726-5_2.

[23] Q. Ye, “Digital Protection and Inheritance of the Traditional Spinning, Dyeing, Weaving and Embroidery Techniques of the Li Ethnic Group,” Light and Textile Industry and Technology, vol. 52, no. 3, pp. 147-149, 2023, doi: 10.3969/j.issn.2095-0101.2023.03.045.