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Quanmiao Lu

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Art and Intelligent Textile Design: The Integration of Art and Technology

Quanmiao LU

Experimental Art Academy, Sichuan Fine Arts Institute, Chongqing 400053, China

LQM00320@163.com

Article

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ABSTRACT

This study presents the development and optimization of a screen-printing process for thermochromic smart textiles that integrate functionality with aesthetic design. Four common substrates—poplin, polyester, flannel, and linen—were printed using a blue thermochromic microcapsule pigment paste. Critical process parameters, including binder concentration, crosslinking agent dosage, curing temperature, and curing time, were systematically investigated through single-factor experiments. Flannel was identified as the optimal substrate. The finalized process—30% binder, 1.0% crosslinker, curing at 130 °C for 4 minutes—produced textiles with superior durability, achieving grade 4–5 in rubbing and washing fastness. A distinct reversible thermochromic response was observed over 36 °C–58 °C. The optimized technique was further demonstrated in a Chinese Lion Dance-themed smart textile, underscoring its potential for effectively uniting artistic design with functional smart textile technology.

KEYWORDS

screen printing, temperature-sensitive color-changing material, intelligent textiles, flannelette

INTRODUCTION

With the continuous advancement of science and technology, the demand for improved quality of life has driven an increasing need for textiles with higher added value. Smart textiles have emerged as a promising solution, partially meeting these evolving demands [1,2]. These textiles are not merely intelligent outputs of manufacturing lines but also perceptible, interactive products that engage users directly. Broadly, smart textiles can be classified into two categories. The first category comprises products made from intelligent fibers and advanced textile/weaving technologies [3]. A typical example is thermochromic color-changing materials, also known as smart textile materials, which represent one essential aspect of the “intelligence” in such products [4]. The second category involves the integration of conventional textiles with functional smart materials, resulting in inherently interdisciplinary research outcomes [5,6]. As a widely used smart textile material, thermochromic pigments exhibit color transitions in response to temperature fluctuations [7]. Due to their versatility and high safety, incorporating these materials into textiles is not only feasible but has become a focal point of contemporary academic research.

Recent studies have reported substantial progress in applying thermochromic materials to textile products. Mao et al. [8] employed white polyester-spandex plain weave fabrics as substrates, analyzing the influence of binder and crosslinker concentrations to integrate thermochromic microcapsules into printing pastes and optimizing process conditions to produce high-performance smart textiles. Wu et al. [9] investigated printed cotton fabrics prepared with thermochromic microcapsule pastes, focusing on the effects of binder and microcapsule dosages on washing fastness, reversible thermochromism, and color depth. Karpagam et al. [10], inspired by the principles of chameleonic camouflage, blended thermochromic pigments with other dyes for cotton military uniforms and introduced graphite to mimic pronounced color shifts from jungle to desert environments. Hung-Jen Chen et al. [11] integrated thermochromic pigments with stainless steel conductive yarns into textile structures, developing thermochromic household devices by altering the weave of the conductive yarns.

Despite these advances, systematic optimization of screen-printing processes for specific substrates (such as flannelette, characterized by short pile and uneven surfaces) remains scarce. Such fabrics pose unique challenges for pigment adhesion, uniform curing, and maintaining a soft hand feel. Moreover, comprehensive case studies directly linking process parameter optimization with both functional and artistic requirements of the final product are relatively limited. Addressing this gap, the present study aims to: (1) conduct systematic single-factor experiments to investigate the effects of binder concentration, crosslinker dosage, curing temperature, and curing time on the thermochromic performance of printed textiles, thereby establishing optimized parameters that balance color fastness with tactile softness on flannelette; and (2) apply the optimized process to a design project incorporating traditional Chinese Lion Dance cultural elements, delivering a full-cycle development from material treatment to functional end-product, and providing an empirical model for integrating artistic design with advanced smart textile technology.

EXPERIMENTAL DESIGN

Materials and Equipment

The base fabrics used in this study were four common household textiles: poplin, polyester, flannelette, and linen. The thermochromic material used was a blue temperature-sensitive color-changing microcapsule pigment paste (color change onset at 36 °C) supplied by Shenzhen Qiansebian New Material Technology Co., Ltd. The binder (PRITOS RSM-28), cross-linking agent (FINFOCE NX), and thickener (PRITOS RHT) were all sourced from Jiangsu Xinruibei Technology Co., Ltd.

The primary equipment utilized included:

Curing Oven: RC-LDX Setting and Curing Oven (Jiangsu Jingjiang Huaxia Technology Co., Ltd.)

Color Fastness to Rubbing Tester: YS71A Type (Zhejiang Wenzhou Textile Instrument Factory)

Color Fastness to Soaping Tester: SW-12G Type (Wenzhou Darong Textile Instrument Co., Ltd.)

Computerized Color Measurement and Matching System: MINOLTA CM-3600D (ORINTEX Dyeing Technology Co., Ltd., Italy)

Differential Scanning Calorimeter (DSC): 1 STARE system DSC (Mettler-Toledo, Switzerland)

Printing Paste Formulation and Process Optimization

A series of single-factor experiments was designed to systematically optimize the screen-printing process. For each experiment, one parameter was varied while all other parameters were held at a constant, predetermined level. The base formulation for the printing paste is shown in Table 1, and all fabric samples (35 cm × 20 cm) were printed with rectangular patterns.

Table 1. Base formulation for thermochromic printing paste

Component	Dosage (Based on Total Weight)
Thermochromic Microcapsule Powder	5.00%
Noveon Acrylate Binder	Variable (2.2.1)
Cross-linking Agent	Variable (2.2.2)
Thickener	q.s. (to achieve proper viscosity)
Distilled Water	Remainder to 100%

Optimization of Binder Dosage

To investigate the effect of the binder on performance, the mass fraction of the Noveon acrylate binder was varied across five levels: 15%, 20%, 25%, 30%, and 35%. During these trials, the cross-linking agent was held constant at 1.0%, and all printed samples were cured at 130 °C for 4 minutes.

Optimization of Cross-Linking Agent Dosage

Based on the optimal binder dosage determined in the previous step (30%), the effect of the cross-linking agent was examined. The mass fraction of the cross-linking agent was varied across six levels: 0.00%, 0.50%, 1.00%, 1.50%, 2.00%, and 2.50%. All samples were cured at 130°C for 4 minutes.

Optimization of Curing Temperature

Using the optimized binder (30%) and cross-linking agent (1.0%) dosages, the curing temperature was varied to determine its impact on fixation. The five temperature levels tested were 100 °C, 110 °C, 120 °C, 130 °C, and 140 °C. The curing time was held constant at 4 minutes.

Optimization of Curing Time

Finally, with the optimal binder (30%), cross-linking agent (1.0%), and curing temperature (130°C) established, the curing time was varied across four levels: 2, 3, 4, and 5 minutes.

Performance Characterization

Color Fastness Testing

The durability of the printed fabrics was evaluated using standardized methods:
Color Fastness to Rubbing: Both dry and wet rubbing fastness were tested in accordance with the ISO 105-E04:2013, "Textiles - Tests for Color Fastness - Color Fastness to Rubbing" standard [12].
Color Fastness to Soaping: Washing fastness (both color change of the sample and staining of adjacent fabrics) was evaluated according to the ISO 105-C10:2006 "Textiles - Tests for Color Fastness - Color Fastness to Soaping" standard [13].

Colorimetric Analysis (K/S Value)

The apparent color depth of the printed samples was quantified using the MINOLTA CM-3600D computerized color measurement system. The Kubelka–Munk value (K/S) was calculated from the spectral reflectance of the samples. Measurements were taken at both room temperature (~25°C, colored state) and an elevated temperature (~65°C, colorless state) to assess the color development and fading characteristics.

RESULTS AND DISCUSSION

Analysis and Selection of Fabric Substrates

To evaluate the suitability of different substrates, the optimized printing process (30% binder, 1.0% crosslinker, curing at 130 °C for 4 minutes) was applied to four commonly used household fabrics. The resulting color fastness performance is summarized in Table 2. All four fabrics exhibited excellent fastness, with ratings reaching or exceeding grade 4, fully meeting the standards for household textiles. Beyond quantitative performance, each substrate possesses distinct physical characteristics. Comprehensive evaluation identified flannel as the optimal substrate, not only for its superior color fastness but also for its desirable physical properties: a soft hand feel, good thermal insulation, and a unique napped structure that enhances the three-dimensional appearance of printed patterns [14].

Table 2. Color fastness performance on different fabric substrates

Fabric Type	Dry Rubbing Fastness (Grade)	Wet Rubbing Fastness (Grade)	Soaping Fastness (Color Change, Grade)	Soaping Fastness (Staining, Grade)
Poplin	4-5	4-5	4-5	4-5
Linen	4-5	4	4-5	4-5
Polyester	4-5	4-5	4-5	5
Flannelette	4-5	4-5	4-5	5

Effect of Binder Content on Performance

The binder plays a pivotal role by forming a polymeric film that anchors thermochromic microcapsules to the textile fibers [15,16]. As shown in Table 3, binder concentration significantly affects color fastness. Increasing the binder content from 15% to 30% markedly improved both dry and wet rubbing fastness from a poor grade of 1–2 to an excellent grade of 4–5. This improvement results from the formation of a stronger and more continuous polymer film on the fiber surface, effectively encapsulating the microcapsules. However, binder concentrations beyond 30% offered no further enhancement in fastness while causing noticeable stiffening of the fabric, compromising comfort. Analysis of K/S values (color depth) revealed that binder content had minimal influence on apparent chroma. As shown in Figure 1, K/S curves remained relatively stable across the entire temperature range. Thus, 30% binder was determined as optimal, balancing superior color fastness with an acceptable hand feel.

Table 3. Effect of binder dosage on color fastness of printed flannelette

Binder Dosage	Dry Rubbing (Grade)	Wet Rubbing (Grade)	Soaping (Color Change, Grade)	Soaping (Staining, Grade)	Fabric Hand Feel
15%	2	1-2	3	4	Soft
20%	3	3	4	4-5	Slightly Stiff
25%	3-4	3-4	4	4-5	Stiff
30%	4-5	4-5	4-5	5	Acceptably Stiff
35%	4-5	4-5	4-5	5	Excessively Stiff

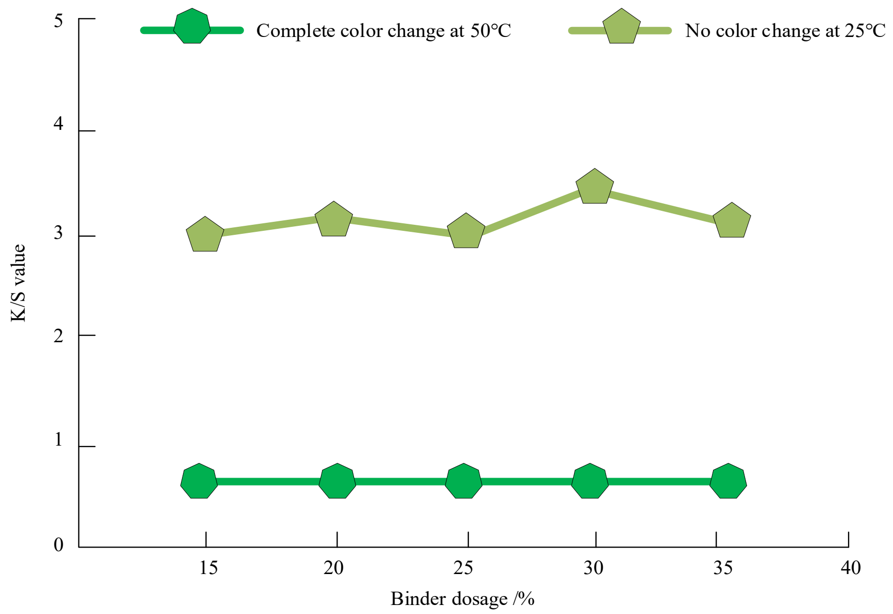

Figure 1. Effect of binder dosage on the K/S value of printed fabric

Effect of Crosslinker Content on Performance

Crosslinkers enhance the mechanical strength and adhesion of the binder film by forming a three-dimensional network [17]. In the absence of a crosslinker, color fastness was suboptimal (< grade 3, Table 4). Increasing the dosage to 1.00% significantly improved all fastness parameters to acceptable levels, while further increases yielded negligible benefits. However, K/S values exhibited a decreasing trend with increasing crosslinker content, primarily due to the inherent milky-white appearance of the crosslinker diluting the blue thermochromic system, thereby reducing color saturation (Figure 2). Consequently, 1.00% was identified as the optimal dosage, ensuring high color fastness while maintaining vivid chromatic performance.

Table 4. Effect of cross-linking agent dosage on color fastness of printed flannelette

Cross-linking Agent Dosage	Dry Rubbing (Grade)	Wet Rubbing (Grade)	Soaping (Color Change, Grade)	Soaping (Staining, Grade)	K/S Value (Relative)
0.00%	2-3	2	3	3	100%
0.50%	3	2-3	4-5	4-5	92%
1.00%	4	4-5	4-5	4-5	85%
1.50%	4	3-4	4-5	4-5	78%
2.00%	4	3-4	5	5	71%
2.50%	4-5	4	5	5	65%

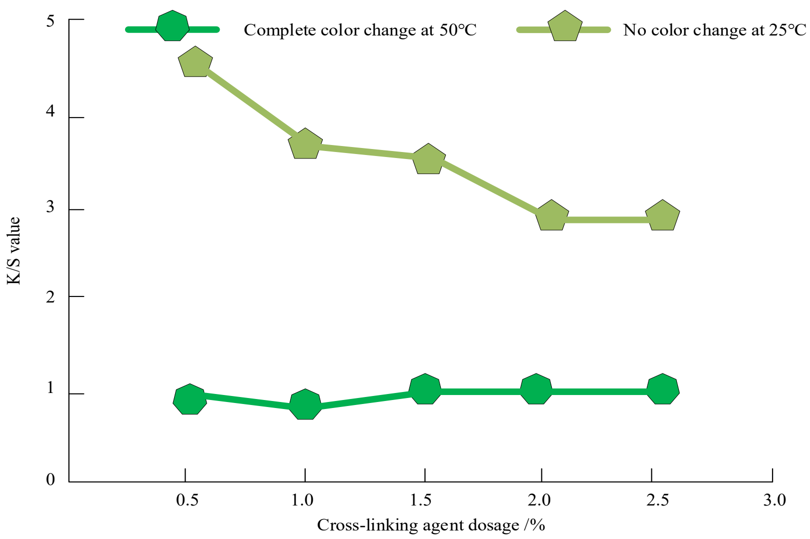

Figure 2. Effect of cross-linking agent dosage on the k/s value of printed fabric

Effect of Curing Temperature on Performance

Curing temperature is critical for polymerization and crosslinking of the binder [18]. Increasing the temperature from 100 °C to 130 °C led to steady and pronounced improvements in all fastness parameters. At 130 °C, fastness ratings met or exceeded the performance standards for household textiles (rubbing fastness grades 4–5, washing fastness grade 4–5, Table 5). Although a further increase to 140 °C yielded marginal improvements, exceeding this threshold risks thermal damage to the microcapsule structure, potentially causing irreversible loss of thermochromic function. Thus, 130 °C was determined as the optimal curing temperature to ensure both high performance and functional integrity.

Table 5. Effect of Curing Temperature on Color Fastness of Printed Flannelette

Curing Temperature	Dry Rubbing (Grade)	Wet Rubbing (Grade)	Soaping (Color Change, Grade)	Soaping (Staining, Grade)
100 °C	2-3	1-2	2-3	3-4
110 °C	3	2	3-4	4
120 °C	3	2-3	3-4	4
130 °C	4	4-5	4-5	4-5
140 °C	4-5	4	4-5	4-5

Effect of Curing Time on Performance

Adequate curing time is essential for complete film formation and crosslinking [19]. As shown in Table 6, extending the curing time from 2 min to 4 min significantly improved all fastness properties. At 4 min, the reaction reached completion, forming a dense, stable, and strongly adherent film on the fiber surface, resulting in outstanding fastness ratings of ≥ grade 4–5. Prolonging the curing time to 5 min offered no further benefits. From both efficiency and performance perspectives, 4 min was therefore selected as the optimal curing time.

Table 6. Effect of curing time on color fastness of printed flannelette

Curing Time (min)	Dry Rubbing (Grade)	Wet Rubbing (Grade)	Soaping (Color Change, Grade)	Soaping (Staining, Grade)
2	2-3	3	3-4	4
3	3-4	3-4	3-4	4
4	4-5	4-5	5	5
5	4-5	4-5	4-5	4-5

Performance and Design Application of the Optimized Smart Textile

Based on systematic optimization experiments, the final process parameters were established. The performance and design applications of the finished smart textile are summarized in Table 7. Thermochromic behavior was evaluated on a temperature-controlled platform. A noticeable fading of color began at 36 °C, and as the temperature increased, the blue coloration gradually disappeared, becoming completely colorless at 58 °C (Figure 3). This thermoresponsive range is highly suitable for direct-contact applications, offering a visually intuitive indication of temperature within a comfortable and safe range. In the final design application, the optimized process was employed to create a series of smart textile products (hand-warmer covers), as shown in Figure 4. Inspired by the art of the Chinese Lion Dance, the design utilized thermochromic microcapsules to produce patterns that not only indicate temperature changes through color shifts but also provide an engaging and interactive visual experience, effectively merging artistic design with advanced textile technology.

Table 7. Summary of optimized process and final product performance

Parameter / Metric	Optimal Value / Result
Optimized Process	
Fabric Substrate	Flannelette
Binder Dosage	30%
Cross-linking Agent	1.00%
Curing Temperature	130°C

Curing Time	4 minutes
Final Performance	
Dry / Wet Rubbing Fastness	Grade 4-5
Soaping Fastness	Grade 4-5 or higher
Color Change Onset Temp.	36°C
Color Disappearance Temp.	58°C

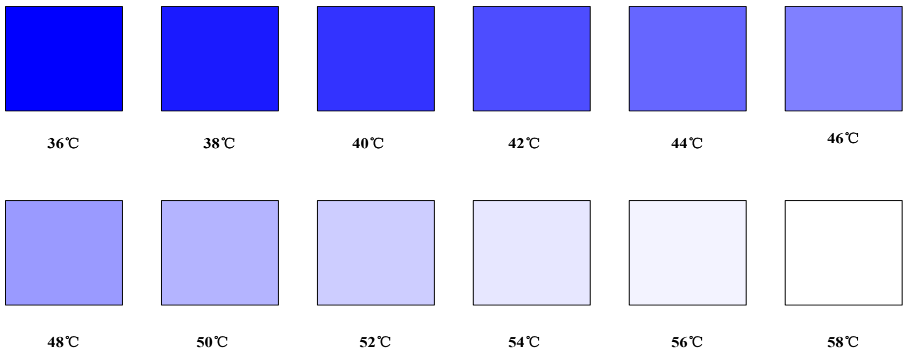

Figure 3. Color change of blue printed fabric

Figure 4. Images of the finished smart textile product

CONCLUSIONS

This study aimed to integrate thermochromic smart materials with textile design through optimized process parameters, successfully developing a smart textile that embodies functional and aesthetic attributes. A series of systematic single-factor experiments were conducted to establish the optimal screen-printing conditions for flannelette substrates: a binder concentration of 30%, a crosslinker dosage of 1.0%, and curing at 130 °C for 4 minutes. The optimized process yielded thermochromic printed textiles with excellent performance, achieving dry and wet rubbing fastness as well as washing fastness ratings of grade 4–5, fully meeting textile industry standards [20]. The products exhibited stable and desirable thermochromic behavior, with reversible color changes occurring over a temperature range of 36 °C to 58 °C. By merging technology and art, this research extended beyond technical development, successfully applying the optimized process to practical design. Drawing inspiration from the traditional Chinese Lion Dance, a thermochromic smart hand-warmer cover was created, featuring patterns that dynamically change color with temperature, providing a vivid demonstration of the organic integration of technology and artistic design.

Despite achieving the expected outcomes, the study highlights areas for future exploration. While the single-factor experimental approach effectively identified key parameters, it did not account for potential interactions among variables. Future studies may employ comprehensive experimental designs, such as response surface methodology (RSM), to determine globally optimized process combinations. Furthermore, to assess the commercialization potential of the developed textiles, systematic long-term durability evaluations are recommended, including quantitative analyses of performance degradation after repeated washing cycles and prolonged ultraviolet exposure. Such in-depth investigations will provide valuable data to support the industrial development of thermochromic smart textiles.

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

Quanmiao Lu designed, collected and analyzed the data, and drafted the manuscript. Quanmiao Lu conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Quanmiao Lu 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.

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Conflict of Interest

The author declares no conflict of interest.

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