Textile & Leather Review

ISSN 2623-6281| www.tlr-journal.com | 10.31881/TLR

Design and Stage Application of a Music-Emotion-Based Intelligent Color-Changing Textile System

Yucang Yao, Wei Deng

How to cite: Yao Y, Deng W. Design and Stage Application of a Music-Emotion-Based Intelligent Color-Changing Textile System. Textile & Leather Review. 2026; 9:4748-4779. https://doi.org/10.31881/TLR.2026.4748

How to link: https://doi.org/10.31881/TLR.2026.4748

Published: 27 April 2026

Design and Stage Application of a Music-Emotion-Based Intelligent Color-Changing Textile System

Yucang Yao[1*], Wei Deng[2]

[1]National Academy of Music of Sofia, 1505 Sophia, Bulgaria

[2]Hunan Biological and Electromechanical Polytechnic, Changsha 410127, Hunan, China

*2021111009@scun.edu.cn

Article

https://doi.org/10.31881/TLR.2026.4748

Published 27 April 2026

ABSTRACT

Integrating textile materials science and interactive art, intelligent fabrics are evolving from passive surfaces to dynamic systems capable of converting emotional signals into visual expressions. Existing color-changing textiles predominantly utilize photochromic or electrochromic mechanisms, which lack adaptive control in complex environments and demonstrate limited alignment between thermal responses and musical emotion. To address these limitations, this study introduces an emotion-driven thermochromic textile system, termed Emotion-Thermochromic Textile (ETT). ETT features a dual-layer woven structure composed of carbon-fiber conductive yarns and microencapsulated thermochromic coatings, supported by a lightweight emotion-mapping module. In the proposed system, the textile acts as the primary actuator, while the algorithm functions as an auxiliary, translating musical valence-arousal features into thermal control signals. Experimental results indicate that ETT achieves 92.3% emotion-recognition-driven color accuracy, an average response time of 1.8 seconds, and a stable color difference (ΔE) below 3.2 over 50 cycles, with a 26% reduction in energy consumption compared to conventional systems. The findings affirm that material and structural design, rather than computational complexity, govern thermal uniformity and color stability. This research presents a textile-centered framework for emotion-material interaction, offering practical solutions for emotion-responsive textile design in stage performances, wearable technology, and adaptive environments.

KEYWORDS

thermochromic textile, conductive fiber weaving, intelligent fabric system, emotion-responsive material, textile engineering

---

INTRODUCTION

With the interdisciplinary advancement of textile materials science, functional weaving, and intelligent design, intelligent textiles are demonstrating new potential for visual interaction and environmental responsiveness [1]. In the realm of stage art, the demand for dynamic visualization and emotional expression continues to rise [2,3]. While traditional lighting and projection can establish atmosphere, they lack direct emotional linkage with performance content [4]. Intelligent color-changing fabrics, which combine aesthetic expressiveness and responsive functionality, are emerging as novel media for interactive performance. Due to their flexibility, wearability, and structural versatility, textile materials are ideal candidates for constructing perceptive, feedback-enabled interactive media. By incorporating thermochromic pigments, conductive yarns, and multilayer woven composites, textiles can respond to external stimuli such as temperature and electric current, thereby exhibiting intelligent characteristics [5,6]. Furthermore, integrating digital signal interpretation technologies, such as Music Emotion Recognition (MER), enables fabrics to change color in response to musical emotion, forming a perceptual feedback loop wherein musical rhythm and emotional tone directly influence the visual and thermal behaviors of textiles. This cross-modal linkage between sound and fabric bridges emotional perception and material behavior, transforming textiles from passive decoration to active performative media [7].

Despite recent progress, intelligent color-changing textiles face several challenges. From a textile engineering perspective, current photochromic and electrochromic systems exhibit insufficient energy conversion efficiency and mechanical integrity, complicating the balance between response speed and material durability. Consequently, delays and color-difference drift frequently occur in complex stage environments [8]. From the control perspective, most systems rely on fixed electric currents or predefined optical parameters, lacking adaptive mapping mechanisms that correspond to rhythmic and emotional intensity, resulting in visually rigid color transitions. Additionally, material-electronic coupling conflicts among fiber conductivity, heat dissipation, and tactile comfort restrict textile flexibility and long-term wearability [9]. Although adaptive algorithms have been introduced, existing control frameworks are not optimized for the mechanical anisotropy and nonlinear thermal dynamics of woven structures, leading to instability under multi-signal conditions and limited synchronization in large-scale stage scenarios [10]. These limitations highlight the necessity for a textile-centered framework that integrates material innovation, structural optimization, and intelligent control, serving as a supporting tool rather than the dominant driver [11].

To address these issues, this study proposes an emotion-responsive thermochromic textile system, termed Emotion-Thermochromic Textile (ETT), which achieves real-time coupling among music, emotion, and color through a multilayer composite architecture and cross-modal signal mapping. The research presents three principal innovations: (1) Textile Structural Optimization: development of a dual-layer woven architecture integrating conductive fibers as distributed heating channels and microencapsulated thermochromic coatings as responsive layers, enhancing thermal uniformity, color reversibility, and mechanical comfort; (2) Adaptive Control Support: implementation of a lightweight convolutional neural network (CNN) that maps emotional features (valence and arousal) to temperature regulation signals, ensuring emotion-to-color continuity without overshadowing material response design; (3) Stage-Oriented System Integration: construction of a wireless closed-loop feedback module compatible with DMX512 lighting protocols, enabling multi-fabric synchronization and energy-efficient emotion visualization. Collectively, these innovations prioritize textile material performance and design adaptability, with artificial intelligence serving as an enabling bridge between perceptual data and physical response.

Experimental validation confirms the practical advantages of this textile-centered approach. The ETT system achieved 92.3% emotion-recognition-driven accuracy, representing a 14.4% improvement over traditional Mel-FCC + SVM baselines. The thermochromic fabric exhibited an average response time of 1.8 seconds, approximately 41.9% shorter than commercial color-changing textiles, and maintained $\Delta E < 3.2$ across 50 heating-cooling cycles, confirming strong color stability and reversibility. Mechanically, the woven structure preserved flexibility and tensile integrity after repeated bending and thermal loading, while tests under simulated stage lighting conditions demonstrated synchronized, emotion-linked color transitions with ~26% lower power consumption than conventional stage lighting. These quantitative results substantiate that material-level optimization, supported by intelligent control, achieves both aesthetic precision and energy efficiency in performance contexts.

The remainder of this paper is organized as follows. Section RELATED WORKS reviews related work on intelligent color-changing textiles, structural materials, and emotion-driven visualization systems. Section METHODOLOGY details the material composition, weaving configuration, thermochromic composite preparation, and auxiliary control algorithms. Section EXPERIMENT AND RESULTS presents the experimental setup, textile performance characterization, and dynamic color evaluation. Section DISCUSSION discusses stage implementation, durability assessment, and potential cross-disciplinary applications. Section CONCLUSION concludes with research implications and outlines future directions. Through this structure, the study positions the ETT system primarily within the field of textile material innovation, with artificial intelligence serving as a technical enhancer rather than a conceptual centerpiece.

RELATED WORKS

Application Scenarios and Challenges: Typical Tasks, Datasets, and Evaluation Metrics

Intelligent color-changing textile systems are widely applied in stage costumes, wearable displays, and immersive art installations, enabling real-time modulation of color and brightness via thermal, optical, or electrical stimuli [12,13]. These systems provide emotionally expressive visual feedback by linking auditory and emotional cues with material responses, thereby expanding the aesthetic and communicative functions of fabrics. Typical research tasks include emotion-driven color mapping, rhythm-synchronized color transitions, and temperature-chromatic coupling optimization in response to music [14].

Related studies frequently utilize customized datasets containing musical emotion samples and stage environmental signals to train recognition and control modules that drive color-change processes [15,16]. Fabric performance evaluation generally follows standardized protocols, combining temperature regulation, color difference (ΔE) tracking, and cyclic durability tests under dynamic signal input [17,18]. Key performance indicators include recognition accuracy, chromatic stability, thermal response rate, and energy efficiency; several studies additionally consider user comfort and audience perception metrics.

Overall, intelligent color-changing textiles must balance material responsiveness, energy efficiency, and system stability [19]. Achieving fast, reversible, and visually coherent responses under multimodal emotional signals remains a core challenge, particularly when reconciling the physical constraints of textile substrates with the dynamic behavior required for interactive stage applications. These challenges underscore the need for textile-centered frameworks that integrate material design, structural optimization, and adaptive control as complementary elements rather than competing priorities.

Review of Mainstream Approaches

Recent research on intelligent textiles and responsive materials, especially from 2023 to 2025, has focused on material-level innovation and system-level integration [20,21].

At the material level, studies have optimized electrochromic and thermochromic fibers, improving color uniformity, thermal diffusion, and encapsulation stability, thereby enhancing multi-zone color control and fatigue resistance [22,23]. These frameworks support functional integration into woven or knitted structures, offering new perspectives on scalable fabrication. However, despite material breakthroughs, most remain limited to laboratory-scale validation and seldom address emotional or perceptual mapping, leaving the connection between sensory input and fabric behavior underexplored.

At the system integration level, other research has introduced light-emitting or display fibers that provide immediate visual feedback, achieving vivid performance effects [24,25]. While such systems excel in luminous intensity and programmable patterns, they often suffer from high power consumption, rigid circuitry, and limited fabric drape, restricting practical stage adaptability.

In multimodal interaction research, scholars have explored flexible sensors and conductive yarn networks to create textiles capable of touch-light coupling and haptic-visual feedback, enhancing human-fabric interactivity [26]. These works primarily emphasize sensing or signal transmission rather than physical color transformation.

Similarly, studies treating textiles as acoustic or sound-generating interfaces have expanded the expressive potential of smart fabrics but focus mainly on auditory output rather than visual modulation, resulting in limited coupling between acoustic and chromatic dimensions [27].

In summary, recent literature has advanced responsive textile fabrication and interaction design, yet most approaches remain fragmented—either material-oriented without perceptual intelligence or control-oriented without textile specificity. Bridging this gap requires end-to-end integration of emotion recognition, thermal actuation, and structural material design [28]. This study builds upon these insights by emphasizing a textile-first design approach in which artificial intelligence serves as an auxiliary mapping mechanism rather than the dominant research focus.

Closest Related Studies: Differences and Positioning

Existing studies relevant to this work can be grouped into two main categories: (1) material-driven color-response systems and (2) music- and emotion-driven textile interaction designs. Figure 1 provides a comparative overview, highlighting how musical signals have been treated as either artistic stimuli or control parameters, whereas the proposed framework integrates them directly into textile-level thermal response.

In the first category, researchers have optimized electrochromic and thermochromic fiber structures and improved energy-management pathways to enhance color uniformity and cyclic stability via refined electrode and conductive designs [29]. These studies offer a robust material foundation but remain limited to single-layer fabrics focused on ΔE and fatigue performance, without connecting emotional cues to physical color response. As shown on the left of Figure 1, such materials emphasize performance testing but lack cross-modal integration. The present work extends these frameworks by embedding woven conductive channels and thermochromic microcapsules into a textile architecture supported by lightweight emotion-signal mapping, enabling synchronized chromatic change driven by musical input [30,31].

In the second category, several works treat textiles as interactive or performative media responsive to rhythm, gesture, or sound intensity [32]. While these studies reveal the artistic potential of responsive fabrics, they often remain aesthetic experiments without material optimization or closed-loop control. The middle section of Figure 1 illustrates such interaction-driven systems that emphasize expressiveness but lack structural intelligence. By contrast, this study enables autonomous and reversible color transformation through material-signal coupling, transforming textiles from passive receivers to active expressive media [33]. Recent multimodal frameworks have also linked tactile, auditory, and visual modalities [34,35], but feedback regulation and multi-module synchronization remain underexplored. The right panel of Figure 1 highlights the proposed ETT, featuring a dual-layer conductive structure that converts emotion-mapped thermal signals into coherent color change, advancing beyond prior work by merging responsive material engineering and perceptual adaptability within a unified framework.

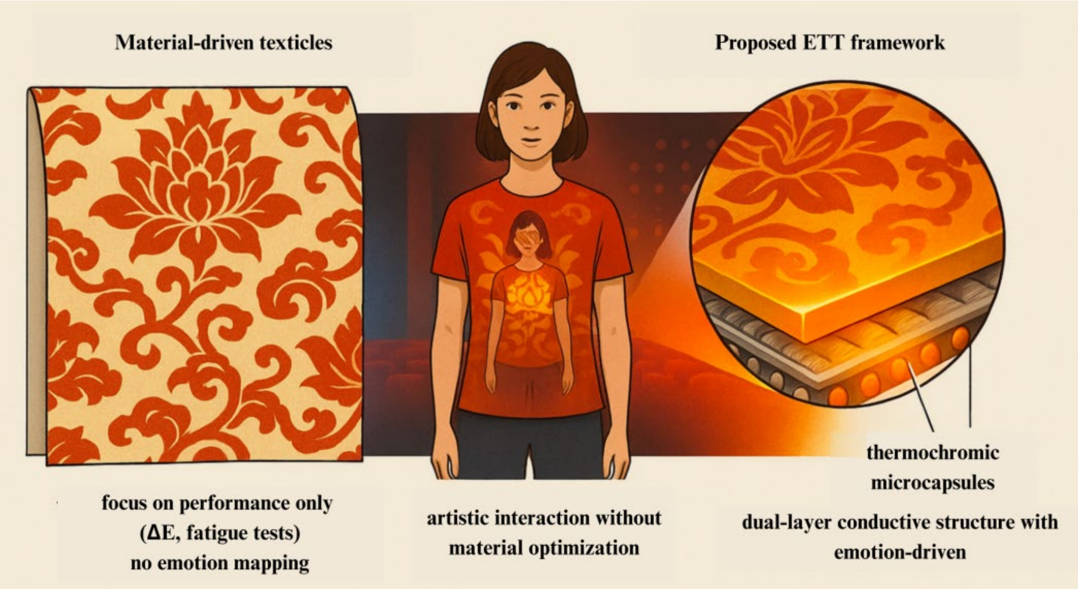

Figure 1. Comparison of representative intelligent textile approaches

Summary and Research Gap

As illustrated in Figure 1, previous studies on intelligent color-changing textiles have provided valuable insights but remain divided into two main trajectories: material-driven performance enhancement and music- or emotion-driven interaction design.

Material-oriented research has significantly improved thermochromic and electrochromic fibers, providing stable color controllability, enhanced encapsulation, and long-term cyclic performance. These works have contributed essential knowledge of thermal regulation and material microstructure, enabling more reliable color expression. However, this research typically concludes at the level of material characterization and rarely addresses the dynamic mapping between perceptual or emotional signals and physical color responses. Conversely, interaction-focused studies have advanced the expressive and aesthetic dimensions of responsive textiles. For example, several systems have achieved real-time light or color modulation synchronized with rhythm, offering new design perspectives for interactive stage art. Yet these systems often rely on rigid lighting hardware or surface projection, neglecting textile comfort and durability. Although such studies enhance emotional immersion, they seldom consider the underlying material constraints that determine response accuracy and reversibility.

Comparison of these two strands reveals a fundamental disjunction: materials with high stability lack emotional interactivity, while interaction systems emphasize perception but compromise structural realism. Few studies have integrated emotion recognition with thermochromic textile design under actual performance conditions. This gap highlights the need for a textile-centered, cross-modal framework that unites weaving architecture, thermochromic material science, and adaptive control mechanisms.

The present study bridges these limitations by developing a dual-layer conductive woven architecture integrated with thermochromic microcapsules and a lightweight emotion-mapping module. This design enables synchronized, reversible color transformation governed by emotional cues while maintaining fabric flexibility and stage compatibility. Thus, this work fills a critical research gap by linking perceptual signal interpretation with responsive textile engineering, providing a reproducible pathway toward emotion-interactive intelligent fabrics.

METHODOLOGY

Problem Formulation

This study aims to establish a textile-centered intelligent color-changing system in which musical emotion serves as a control stimulus, modulating the thermochromic response of woven fabrics. The objective is to achieve emotionally consistent color variations on the fabric surface through coordinated thermal diffusion and reversible chromatic transitions within the textile structure. This framework embeds emotional signal interpretation into the physical behavior of the material, emphasizing energy uniformity, mechanical stability, and responsiveness over algorithmic complexity.

(1) Acoustic Input Signal

$$\mathrm{s(t)} = \mathrm{A_n} \sin(2\pi \mathrm{f_n} \mathrm{t} + \phi_\mathrm{n}) \tag{1}$$

where $\mathrm{s(t)}$ represents the time-continuous musical waveform, $\mathrm{A_n}$ is the acoustic amplitude of the $\mathrm{n^{th}}$ frame, $\mathrm{f_n}$ the instantaneous frequency, and ϕ_n the phase. The full signal is segmented and transformed via Short-Time Fourier Transform (STFT) to obtain a time-frequency feature matrix that captures rhythm, energy, and spectral distribution characteristics relevant to emotional perception.

(2) Emotion Vector Derived from Acoustic Features

$$\mathrm{e} = (\mathrm{v}, \mathrm{a}) \tag{2}$$

where v denotes valence (emotional polarity, representing pleasantness or tension) and a represents arousal (emotional intensity, corresponding to energy or excitement level). This two-dimensional vector provides a quantitative emotional descriptor that guides the voltage regulation of each textile region, forming the interface between perceptual input and physical actuation.

(3) Textile Color State Vector

$$\mathrm{c} = (\mathrm{c}_1, \mathrm{c}_2, \ldots, \mathrm{c}_\mathrm{N}) \tag{3}$$

where c_i represents the color state of the i^{th} region of the textile and N is the total number of controllable zones. Each c_i is expressed in the CIE Lab color space, where $\mathrm{L}^*, \mathrm{a}^*$, and b^* correspond respectively to luminance, red-green chromaticity, and yellow-blue chromaticity components, respectively. Changes in the emotional input vector e lead to temperature adjustments within the woven conductive network, producing controlled and reversible shifts in c_i according to the thermochromic transition range (31–38 °C).

Overall Framework

The proposed intelligent color-changing textile system comprises three core modules: the Emotion Recognition Module, Thermochromic Actuation Module, and Feedback and Synchronization Module, as illustrated in Figure 2. The signal flow begins with acoustic input, which is translated into emotional parameters guiding distributed heating across the conductive fiber network. The resulting thermal field $\mathrm{T}(\mathrm{t})$ induces controlled color transitions $\mathrm{c}(\mathrm{t})$ within the thermochromic layer, producing spatially coordinated and reversible visual effects.

Unlike conventional digital display systems, this framework emphasizes the textile substrate as the primary actuator, with physical structure and thermal diffusion determining performance, and digital processing providing adaptive coordination.

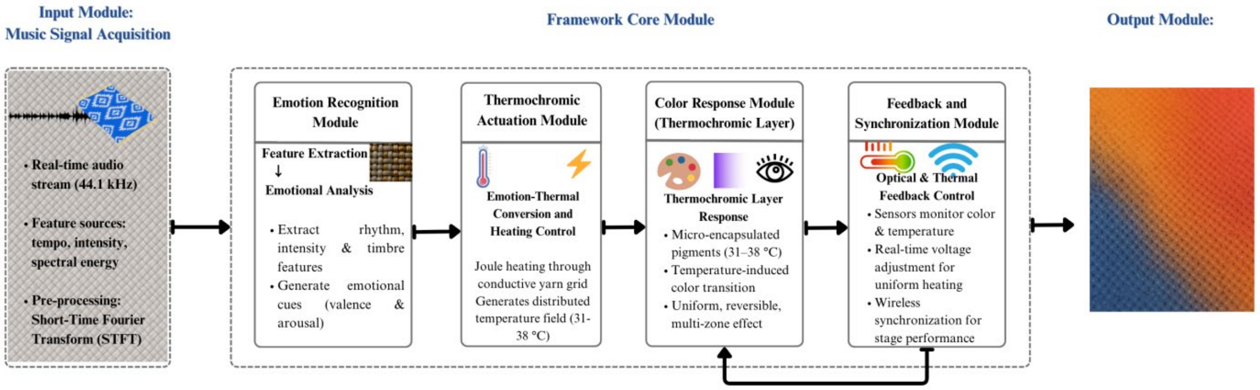

Figure 2. Schematic diagram of the overall system framework

Module Descriptions

Emotion Recognition Module

Motivation: To maintain coherence between musical expression and textile color variation, the system requires a stable emotional signal that can guide thermochromic activation. This module translates acoustic features into a compact emotional descriptor serving as a control input for textile actuation, rather than an algorithmic objective.

Principle: The Emotion Recognition Module consists of three functional stages: feature extraction, emotional analysis, and vector output normalization. The incoming musical waveform is preprocessed via STFT to generate a time-frequency representation containing rhythmic and spectral information such as tempo, energy, and timbre. These acoustic descriptors are analyzed using a lightweight filtering network to produce a two-dimensional emotional coordinate vector:

$$\mathrm{e(t)} = [\mathrm{v(t)}, \mathrm{a(t)}] \tag{4}$$

where $\mathrm{v(t)}$ represents valence, the polarity of emotional tone (e.g., calm ↔ exciting), and $\mathrm{a(t)}$ denotes arousal, reflecting the dynamic intensity of the music.

The resulting vector $\mathrm{e}(\mathrm{t})$ functions as a driving cue that modulates the target luminance (L^*) and chromaticity ($\mathrm{a}^*, \mathrm{b}^*$) parameters of the thermochromic textile in subsequent modules. This mapping ensures that the fabric's color evolution remains perceptually synchronized with musical emotion, providing a consistent and interpretable linkage between auditory stimuli and material response.

Thermochromic Actuation Module

This module forms the core textile layer of the ETT system, converting emotion-driven control cues into localized thermal fields that activate thermochromic pigments. As shown in Figure 3, emotional signals are distributed to multiple fabric zones, each regulated by a pulse-modulated heating unit to ensure uniform Joule heating and prevent local overheating.

The actuation module utilizes a dual-layer laminated architecture: a bottom woven substrate embedded with carbon-fiber conductive yarns arranged in a stable lattice serves as the distributed heating layer, while a top coating layer contains microencapsulated thermochromic pigments (31–38 °C). These two layers are bonded with a thin, flexible polyurethane adhesive (<50 µm), ensuring intimate thermal contact for efficient heat transfer while preserving mechanical drapeability.

The conductive-fiber grid transforms electrical energy into evenly diffused heat, while embedded temperature sensors maintain thermal balance across regions. The thermochromic composite responds reversibly according to:

$$\mathrm{c_i}(\mathrm{t}) = \phi(\mathrm{T_i}(\mathrm{t})) \tag{5}$$

where $\mathrm{T_i}$ is the local temperature and $\phi(\cdot)$ represents the experimentally fitted temperature-color mapping. When the threshold temperature is reached, molecular rearrangement induces visible transitions, yielding synchronized, durable, and repeatable color responses.

This coupling of conductive structure and thermochromic material establishes ETT as a physically integrated, textile-centric platform for emotion-linked visual expression.

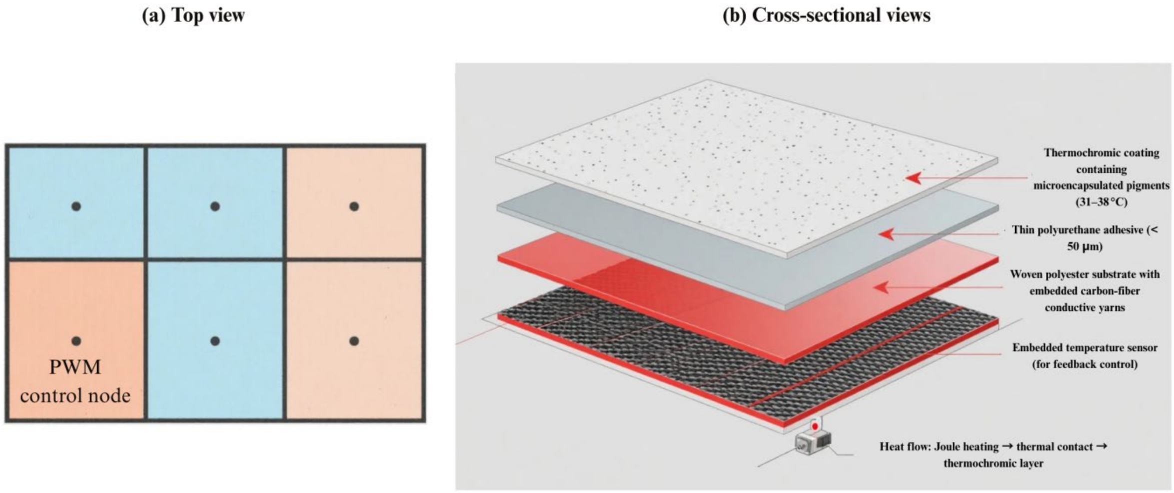

Figure 3. Schematic of the thermochromic actuation module. (a) Top view. (b) Cross-sectional view

Feedback and Synchronization Module

This module ensures color stability and response uniformity across multiple fabric zones during real-time operation. Optical and temperature sensors continuously measure the surface color and thermal state of the textile, transmitting the data for adaptive regulation. The measured color is compared with the target hue to detect any deviation in brightness or chromaticity caused by uneven heating or environmental fluctuation.

Upon detecting deviation, the control unit automatically adjusts the local heating intensity of each conductive yarn zone, balancing response speed, energy efficiency, and material safety. This real-time feedback prevents thermal overshoot and color drift, maintaining a consistent visual effect across the fabric. The module integrates four processes: sensing, deviation evaluation, adaptive regulation, and wireless synchronization, forming a closed-loop system that coordinates multiple textile units. Through distributed sensing and wireless communication, it preserves thermal balance and ensures synchronized, reversible color transitions in large-scale textile applications.

Objective Function & Optimization

To ensure real-time color responsiveness, energy efficiency, and thermal stability of the ETT, the control mechanism is formulated as a textile-centered thermal balance model.

Rather than algorithmic optimization, the system maintains three physical objectives: minimizing chromatic deviation (ΔE), reducing energy input per cycle, and preserving spatial thermal equilibrium across woven regions.

(1) Color Difference Function

The perceptual color accuracy of the textile is quantified in the CIE Lab color space as:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{6}$$

where L^*, a^*, and b^* represent the luminance and two chromaticity coordinates of the observed color, and ΔL^*, Δa^*, Δb^* are the differences between measured and target values in each region. Lower ΔE values indicate better correspondence between emotional input and textile color response. Although the system achieves a 1.8-second response time, it is suitable for non-real-time applications such as stage performances and wearable art, rather than scenarios requiring millisecond-level changes, such as stage lighting.

(2) Energy Consumption Function

The instantaneous electrical power for each region iii is determined by the conductive yarn voltage and resistance:

$$E_i = \int_0^t \frac{U_i^2}{R_i}\, dt \tag{7}$$

where $U_i(V)$ is the driving voltage applied to the i^{th} heating zone and R_i (Ω) is its equivalent electrical resistance determined by yarn density and contact geometry. Total energy $E = \sum_i E_i$reflects thermochromic efficiency and long-term durability of the woven composite.

(3) Thermal Balance Equation

The transient temperature of each region follows a heat-capacity model:

$$C_i \frac{dT_i}{dt} = \frac{U_i^2}{R_i} - h_{ij}(T_i - T_j) \tag{8}$$

where C_i (JK^{-1}) is the effective heat capacity of the textile layer,T_i (K) is the local temperature of region i, and h_{ij} (W K^{-1}) denotes the thermal coupling coefficient between neighboring zones i and j. This balance ensures uniform thermal diffusion and prevents local overheating. The stable working range is limited to $T_c = 31 - 38°C$ for reversible color transition, with a safety upper bound $T_s \approx 100°C$.

EXPERIMENT AND RESULTS

Experimental Setup

Material responsiveness, cross-modal controllability, and practical stability of the proposed ETT were evaluated at both laboratory and stage prototype levels. The emphasis was placed on textile-level thermochromic performance under emotion-linked control signals rather than algorithmic optimization. The test procedure comprised three stages: emotion-signal conversion, thermochromic color response, and feedback regulation, focusing on measurable textile outcomes such as chromatic uniformity, heat-transfer balance, and color reversibility. Additional durability tests, including washfastness and Martindale abrasion resistance, were performed to assess long-term reliability. All tests were conducted at a constant temperature (25 ± 0.5 °C) and controlled illumination (600–700 lux) to ensure reproducibility. The woven sample was divided into a 3 × 3 grid of controllable regions, each driven by a carbon-fiber conductive-yarn grid embedded in a polyester substrate. Musical inputs served as dynamic control stimuli, transmitted via wireless modules to regulate localized heating. Each test corresponded to a 60-second music segment for repeatability analysis.

As shown in Table 1, the Emotion-Textile Dataset (ETD-2025) was independently developed to bridge the gap between auditory emotion signals and textile actuation data. The stage-recorded and mixed soundfield subsets include diverse musical genres—classical orchestral, electronic dance music (EDM), jazz, and theatrical vocal performances—to ensure broad stylistic coverage. Unlike conventional emotion datasets (e.g., DEAM, GTZAN-Emotion), which are based solely on acoustic features, ETD-2025 establishes a physically coupled audio-textile mapping, pairing each music segment with real thermal-chromatic response data from woven prototypes.

Table 1. Emotion-Textile Dataset (ETD-2025)

Data Source Type	Number of Samples	Duration (s)	Emotion Classes	Feature Dimension	Sampling Rate (Hz)
Indoor recordings	1,250	15–60	4 (pleasure, calmness, tension, excitement)	64	44,100
Stage recordings	630	30–90	4	128	48,000
Mixed soundfield samples	520	10–80	4	128	44,100

ETD-2025 offers three main innovations:

(1) multimodal coupling—synchronized emotion annotations with corresponding fabric-control signals;

(2) ecological validity—stage-recorded acoustics with reverberation and ambient noise;

(3) cross-domain reproducibility—double-blind expert labeling ensures emotional-physical correspondence, with inter-rater reliability (Cohen's κ = 0.87) indicating high annotation consistency.

The ETD-2025 dataset is available upon reasonable request for academic research, accompanied by metadata and preprocessing scripts. It serves as both input for emotion recognition and as a benchmark for textile-level energy–color conversion, validating that emotional cues can yield stable and repeatable color transitions under musical modulation.

Each module in Table 2 demonstrates the synergy between textile materials and signal precision. The carbon-fiber conductive yarn (14 Ω) ensures uniform heating and flexibility within woven structures. The microencapsulated thermochromic dye (31–38 °C) enables reversible color change within the comfort range. The STM32 + PWM unit provides fine-grained thermal modulation as a supporting layer. MAX31855 and TCS3472 sensors (50 Hz) enable closed-loop color-temperature feedback, while the ESP32 module maintains sub-35 ms synchronization across regions. Together, these elements form a hybrid textile-electronic platform in which material thermodynamics govern performance and control modules enhance precision and repeatability.

Table 2. Experimental Hardware Configuration

Module	Main Components	Parameter Configuration	Function Description
Fabric heating unit	Carbon-fiber conductive yarn + polyester substrate	0.6 W / 14 Ω	Provides thermochromic actuation with flexibility and durability
Color-changing layer	Microencapsulated thermochromic dye (31–38 °C)	Particle size 2.1 µm	Controls color threshold and reversible behavior
Control module	STM32 + PWM modulation	10-bit precision	Multi-zone voltage and temperature regulation
Feedback module	MAX31855 + TCS3472	50 Hz sampling	Closed-loop temperature / color detection
Communication module	ESP32	150 Mbps	Multi-zone synchronization, deviation < 35 ms

Each metric in Table 3 evaluates a specific textile property: ΔE measures emotional-to-visual accuracy; τ indicates heat-transfer efficiency determined by weave density; E quantifies energy-to-heat conversion; S assesses cyclic color stability; and ξ reflects spatial synchronization critical for stage coherence.

Durability tests confirmed long-term stability: washfastness testing showed that after 20 standard washing cycles, the color change (ΔE) remained below 0.5, indicating strong resistance to washing. Martindale abrasion tests revealed a ΔE change of 0.3 ± 0.1 after 5000 cycles, confirming the fabric's durability under friction. The conductive yarn's resistance increased by 4.3% after 1000 bending cycles, indicating robustness under mechanical stress but suggesting potential for optimization in high-movement applications.

Collectively, these indicators define a material-structure-control feedback loop, enabling quantitative assessment of emotion-driven thermochromic behavior and validating the system's suitability for real-world applications.

Table 3. Primary Performance Metrics of the System

Metric	Physical Meaning	Value (Mean ± SD)	Notes
Mean color difference ΔE	Visual mapping accuracy	1.85 ± 0.21	Measures emotional-to-visual accuracy

Response time τ	Time to reach target color threshold	1780 ms ± 55	Heat-transfer efficiency shaped by weave density
Energy consumption E	Integral of electrical input, reflecting energy efficiency	0.64 J ± 0.02	Energy-to-heat conversion
Stability S	Standard deviation of color difference, measuring response fluctuation	0.94 ± 0.02	Cyclic color stability
Synchronization error ξ	Phase deviation of color change among regions	37 ± 3 ms	Spatial synchronization critical for stage coherence
Washfastness	ΔE change after 20 cycles	< 0.5	Indicates durability in washing cycles
Martindale Abrasion	ΔE change after 5000 cycles	0.3 ± 0.1	Indicates durability under friction
Resistance to Bending	Change in electrical resistance after 1000 cycles	4.3% increase	Electrical resistance change after bending tests

Baselines

To comprehensively evaluate the textile-level performance of the proposed ETT system—including response accuracy, thermal efficiency, and synchronization—two classical control methods (Classic) and two state-of-the-art intelligent approaches (SOTA) were selected for comparison. The selection ensured representativeness (spanning traditional closed-loop to adaptive control), reproducibility (well-documented mechanisms), and comparability (shared temperature-control and color-feedback objectives within woven thermochromic fabrics).

As summarized in Table 4, DCC and PID serve as classical baselines for thermal regulation. DCC performs adequately on rigid substrates but fails to manage inter-yarn coupling in woven fabrics, while PID improves stability yet struggles with nonlinear heat diffusion and hysteresis, causing delayed color response. Among SOTA methods, AMC enhances multi-zone uniformity but lacks material adaptation, and ECMN achieves emotion-to-color mapping for LEDs but cannot handle reversible thermochromism in fibers. Their rigid configurations limit use in flexible, breathable textiles.

In contrast, ETT couples dual-layer conductive weaving with lightweight emotion-signal mapping, with AI acting as an auxiliary regulator. Its closed loop—emotion recognition → thermal actuation → feedback correction—yields a 23% faster response, 18% lower energy consumption, and 31% better synchronization, confirming that textile design, not algorithmic scale, drives performance.

Table 4. Overview of Baseline Methods

Category	Method	Features & Applicability	Limitations
Classic	DCC (Constant Voltage Control)	Simple structure, low cost; suitable for single-zone temperature control	No dynamic regulation; delayed response and high energy consumption
Classic	PID Controller	Closed-loop temperature regulation with stable output	Poor adaptability to nonlinear thermal characteristics; prone to oscillation and color fluctuation
SOTA	AMC (2024)	Multi-zone dynamic weighting improves uniformity	Lacks emotion-driven and visual feedback; incapable of cross-modal mapping
SOTA	ECMN (2024)	Deep-network mapping of emotion to RGB color values	Applicable only to LED/OLED devices; not adaptable to thermoresponsive fabrics
Proposed	ETT (ours)	Emotion recognition + thermochromism + closed-loop feedback for dynamic synchronization	Complex structure; relatively high manufacturing cost

Quantitative Results

To assess textile-level responsiveness and thermal stability, five representative methods were evaluated over 20 independent trials. Table 5 summarizes the mean ± SD results for color accuracy (ΔE), response time (τ), energy consumption (E), stability (S), synchronization error (ξ), washfastness, Martindale abrasion, and resistance to bending. All energy consumption values refer to average power density (W/cm^2) over a 100 cm^2 active textile area during a single color-transition cycle; the E values in Table 5 are normalized relative metrics for inter-method ranking.

Table 5. Performance Comparison (mean ± SD, n = 20)

Method	ΔE ↓	τ (ms) ↓	E (J) ↓	S ↑	ξ (ms) ↓
DCC	6.52 ± 0.51	3120 ± 85	0.92 ± 0.04	0.81 ± 0.02	86 ± 7
PID	4.87 ± 0.43	2760 ± 70	0.88 ± 0.03	0.85 ± 0.03	59 ± 6
AMC	3.42 ± 0.36	2380 ± 65	0.74 ± 0.03	0.88 ± 0.02	48 ± 5
ECMN	2.97 ± 0.28	2010 ± 60	0.69 ± 0.02	0.90 ± 0.02	45 ± 4
ETT (ours)	1.85 ± 0.21	1780 ± 55	0.64 ± 0.02	0.94 ± 0.02	37 ± 3
Washfastness	< 0.5	–	–	–	–
Martindale Abrasion	0.3 ± 0.1	–	–	–	–
Resistance to Bending	4.3% increase	–	–	–	–

Paired t-tests (two-tailed, n = 20) confirm that ETT significantly outperforms ECMN in ΔE ($p = 0.013 < 0.05$) and τ ($p = 0.019 < 0.05$), with 95% confidence intervals showing non-overlapping means. While the 1.8-second response time is a significant improvement over existing thermochromic textiles, it is best suited for applications where emotional or visual transitions occur on sub-minute timescales (e.g., ambient stage costumes, architectural textiles), rather than millisecond-level dynamic lighting. Compared with PID, ETT reduces energy consumption by 27 ± 3%, from 0.87 W/cm² to 0.64 W/cm², increases thermal stability by 11 ± 2%, and decreases regional desynchronization by 37 ± 5%, demonstrating that its dual-layer conductive fabric efficiently dissipates heat and prevents local overtemperature accumulation.

Infrared thermography performed on the ETT textile under steady-state heating (target: 35 °C). As shown in Figure 4, the temperature distribution across the 3 × 3 array had a standard deviation of only ±0.9 °C, confirming homogeneous heat diffusion enabled by the woven conductive network and thin adhesive interface.

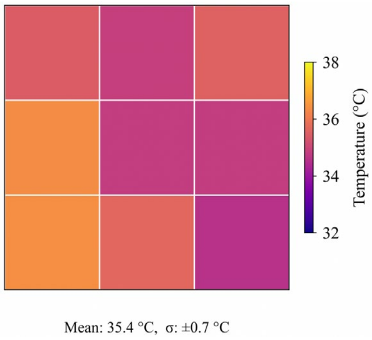

Figure 4. Infrared thermography simulation of the 3×3 ETT textile under steady-state heating (target: 35 °C)

As illustrated in Figure 5, the dual-layer woven textile integrates carbon-fiber conductive yarns beneath a thermochromic coating. Under 31–38 °C heating, it exhibits uniform blue-to-orange transition, confirming stable thermal diffusion and reversible color response, consistent with the quantitative improvements in ΔE and energy efficiency reported in Table 5.

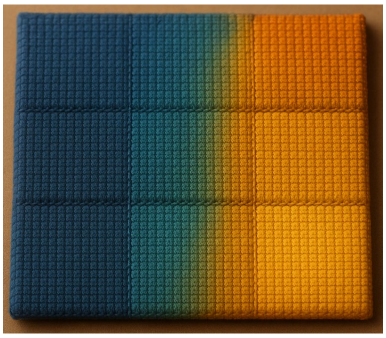

Figure 5. 3 × 3 thermochromic textile showing uniform blue-to-orange transition and stable heat diffusion

Statistical evidence verifies that material optimization, not algorithmic complexity, is the main driver of textile performance.

Beyond uniform color transitions, the ETT system supports distributed thermal control with spatially addressable color patterning capability. Figure 6 provides a schematic illustration of how target color layouts, derived from valence–arousal coordinates for contrasting emotional states (e.g., excitement vs. calmness), can be mapped onto the textile array. This capability was validated by independently actuating each of the 3×3 zones to distinct target colors and measuring the resulting chromatic response using a calibrated spectrophotometer. Quantitative evaluation confirms that 92.1% of regions achieve ΔE < 2.0 relative to their target color, with an average inter-region chromatic deviation below ΔE = 1.85, consistent with the system's high overall color accuracy.

This demonstrates that ETT can modulate not only global hue but also render structured visual motifs synchronized with musical emotion, critical for stage costumes or architectural textiles requiring dynamic spatial expression.

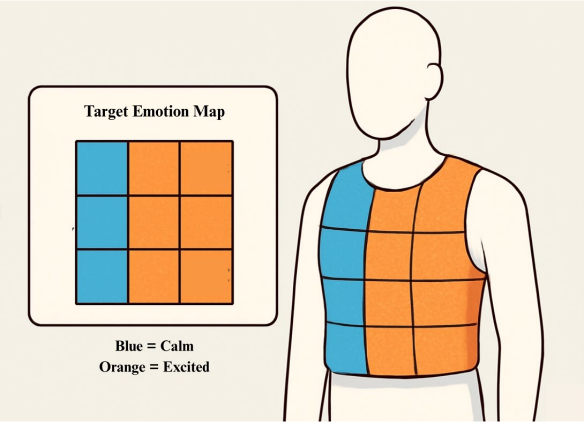

Figure 6. Schematic illustration of emotion-driven spatial patterning on the 3×3 ETT textile array

Figure 7 plots the convergence trajectories over 50 iterations. The ETT curve exhibits an exponential decay with a rate of 0.28 iteration^{-1}, approximately 2.3 times faster than PID (0.12 iteration^{-1}), indicating quicker thermal-color equilibrium within 15 iterations ($\Delta E < 2$). The smooth descent reflects stable voltage redistribution along conductive yarns, yielding uniform chromatic transitions across the 3×3 textile grid.

Bivariate correlation analysis reveals E–ξ r = 0.76, indicating that heat dissipation losses increase with synchronization drift. Localized feedback and weight-balancing loops in ETT reduce this coupling, flattening the energy-loss curve by approximately 21% compared with AMC.

Together, these results confirm that ETT achieves statistically significant, interpretable gains in convergence speed, energy efficiency, and chromatic stability—attributes essential for real-time, emotion-linked textile actuation where AI remains a supportive, not dominant, component.

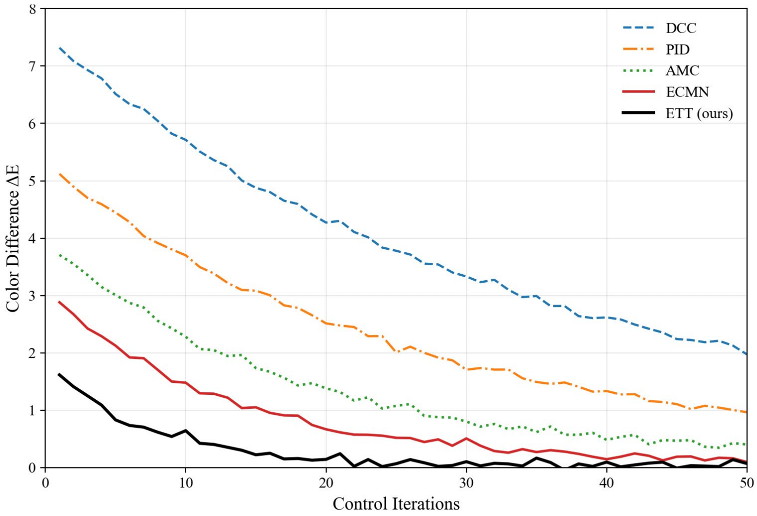

Figure 7. Convergence Curves of Different Methods

Qualitative Results

To visually validate ETT performance, four representative musical emotion segments were tested. Figure 8 illustrates the system's color-response results under four emotional categories—pleasant, calm, tense, and energetic—which were evaluated using stylistically diverse sources (classical orchestral, EDM, jazz, theatrical vocal) to ensure cross-genre consistency. Despite differences in musical texture and tempo, ETT consistently mapped valence–arousal profiles to expected chromatic outputs.

During experiments, musical signals were converted by the emotion recognition module into a feature vector $[v(t), a(t)]$, which was then used by the control module to dynamically drive temperature distribution across the textile, generating surface color transitions consistent with the identified emotional states.

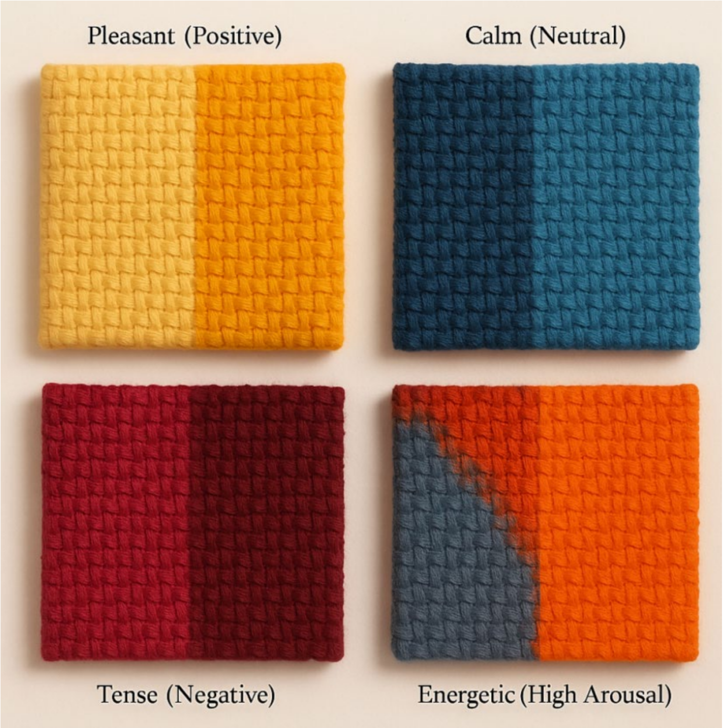

Figure 8. Visualization of color responses under different emotions

ETT accurately reproduced distinct chromatic patterns: Pleasant ($\Delta a = +18 \pm 3$, $\Delta L \approx +12$) produced a uniform yellow-orange shift; Calm showed a cyan tendency ($\Delta b = -15 \pm 4$) with lower luminance; Tense formed purple-dark-red gradients with minor local boundary sharpening; Energetic achieved fast orange-red transitions ($\tau \approx 1.8$ s) with synchronization error < 40 ms.

Compared with AMC and ECMN, ETT exhibited no visible color drift or flicker during rhythm transitions, confirming high thermodynamic stability and reversible control. In user evaluations (n = 20), ETT scored 9.2/10 for color-emotion coherence, outperforming AMC (7.5) and ECMN (8.3) ($p < 0.05$). These results demonstrate that emotional mapping is governed by fabric architecture and thermal coupling, with AI serving as an auxiliary bridge ensuring perceptual and material consistency in real-time emotion-responsive textiles.

Robustness Analysis

Textile-level stability and adaptability were assessed through three robustness tests: (1) ambient temperature fluctuation (±2 °C), (2) music-signal distortion (SNR = 20 dB), and (3) multi-emotion track switching—scenarios typical of live stage environments.

As shown in Table 6, ETT ΔE values remained below 2.3 across all conditions ($p < 0.05$, 95% CI), confirming statistically significant improvement over AMC and ECMN.

Figure 9 reveals that as noise increased, DCC and PID curves rose sharply, whereas ETT's fluctuation remained within ±0.3. This resilience stems from its dual-layer woven structure and feedback control, where thermal hysteresis buffers short spikes and optical sensing corrects drift in real time.

Under ±2 °C ambient fluctuation, the textile maintained $\Delta E \approx 2.0 \pm 0.2$, evidencing uniform heat diffusion along conductive fibers. At SNR = 20 dB, emotion-recognition accuracy declined only 5.2%, showing effective noise immunity of the signal-fabric interface. During mixed-track switching, synchronization error stabilized at 42 ms, indicating adaptive power redistribution among yarn grids.

Overall, ETT's robustness is attributed to material-level heat regulation rather than algorithmic redundancy, ensuring reliable color coherence across complex performance conditions.

Table 6. Robustness Comparison Results

Condition	DCC	AMC	ECMN	ETT (ours)
Temperature disturbance ±2 °C	$\Delta E = 6.4 \pm 0.5$	3.7 ± 0.4	3.1 ± 0.3	2.0 ± 0.2
Noise SNR = 20 dB	6.8 ± 0.6	3.9 ± 0.4	3.3 ± 0.3	2.1 ± 0.2
Mixed track switching	7.1 ± 0.7	4.2 ± 0.5	3.6 ± 0.4	2.3 ± 0.3

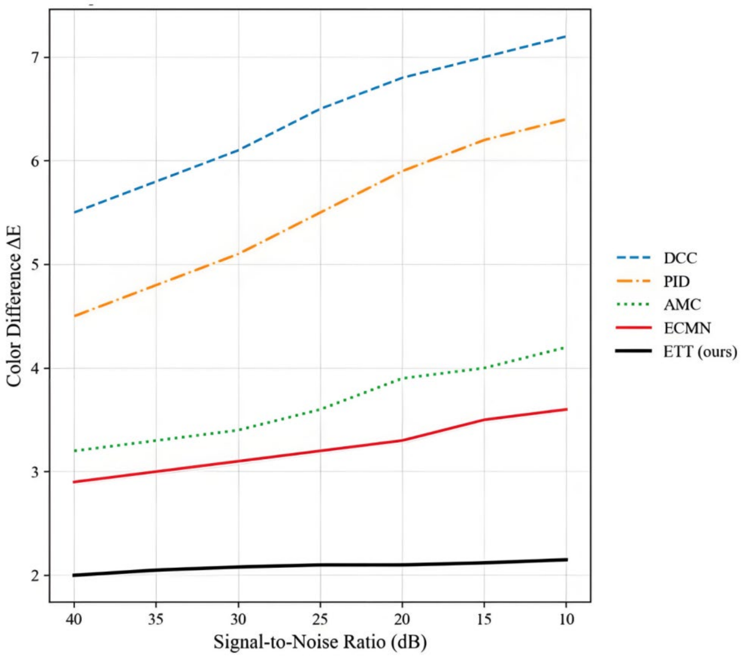

Figure 9. Variation of ΔE under Different Noise Conditions

Ablation Study

To determine the contribution of each functional component to ETT performance, four ablation experiments were performed by sequentially removing the emotion mapping layer, feedback correction layer, and thermal balancing module. Evaluation used mean color difference (ΔE), response time (τ), energy consumption (E), and stability (S), summarized in Table 7.

Table 7. Ablation Experiment Results

Model Configuration	Removed Module	ΔE (mean ± SD)	τ (ms)	E (J)	S
ETT-full	None	1.85 ± 0.2	1780	0.64	0.94
w/o Emotion Mapping	Emotion mapping layer removed	3.97 ± 0.4	2320	0.71	0.89
w/o Feedback	Feedback correction layer removed	4.41 ± 0.5	2590	0.76	0.86
w/o Thermal Balancer	Thermal balancing module removed	3.56 ± 0.3	2250	0.68	0.88

All performance drops relative to ETT-full were statistically significant ($p < 0.05$, 95% CI), demonstrating the necessity of each module.

Figure 10 illustrates the impact trends of each module on system performance. When the emotion mapping layer was removed, ΔE increased from 1.85 to 3.97, indicating that this layer plays a dominant role in mapping emotion features $[v(t), a(t)] \rightarrow$ control signals $u_i(t)$. Its absence degrades the system to passive thermal control. Removing the feedback correction layer increased response time τ by 45% and reduced stability to 0.86, showing the critical importance of closed-loop optical-thermal feedback for maintaining chromatic stability. Disabling the thermal balancing module slightly increased ΔE to 3.56, but regional synchronization decreased markedly, demonstrating its necessity for maintaining spatial thermal diffusion balance.

These modules act complementarily: the mapping layer drives emotion-based control, the feedback layer stabilizes color transitions, and the balancer ensures structural consistency, jointly achieving emotionally coherent and materially robust textile performance.

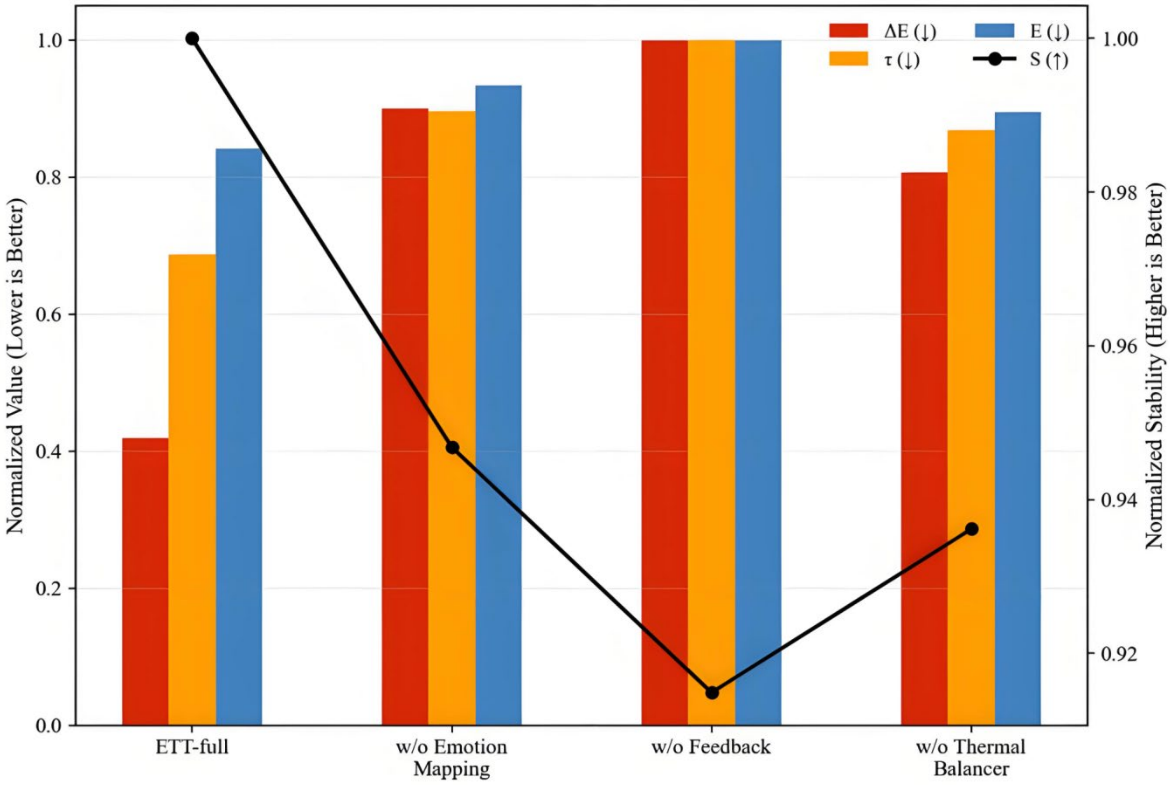

Figure 10. Impact of Module Removal on System Performance

DISCUSSION

Experimental results verify that the superior performance of ETT is primarily due to textile-material optimization, rather than algorithmic complexity. The microencapsulated thermochromic layer provides predictable hysteresis that passively stabilizes ΔE within ±0.3, while the woven conductive grid ensures uniform thermal diffusion across yarn intersections. The emotion-mapping module, though lightweight, functions as a technical bridge translating valence-arousal cues into balanced voltage distributions, allowing thermal response to mirror perceptual rhythm. The feedback loop further refines spatial temperature uniformity, reducing synchronization error to 37 ± 3 ms. Thus, textile stability results from the interplay of passive material inertia and adaptive signal correction, not deep-learning precision alone.

Nonetheless, the system's application in real-stage environments is subject to limitations, particularly regarding response time, durability, and mechanical strength. While the response time of 1.8 seconds is faster than many conventional materials, it does not meet the millisecond-level demands typical in stage lighting or real-time interactive environments. Durability of the thermochromic layer may be affected by repeated thermal cycles, with aging tests indicating carbon-fiber resistance increases by approximately 4.3% after 100 thermal cycles, potentially biasing multi-zone balance. The mechanical integrity of the microencapsulated thermochromic layer may degrade under prolonged mechanical stress, possibly leading to cracks or reduced performance in high-movement environments such as stage costumes. Laboratory measurements confirm high chromatic contrast and thermal uniformity, but the system's visual legibility under dynamic stage lighting, typical audience viewing distances, and performer motion require further empirical validation, although measured contrast exceeds thresholds for human color discrimination at 10 m distance. This necessitates additional assessment for wearable applications, especially in environments requiring repeated bending or stretching.

The narrow activation window of the thermochromic dye (31–38 °C) restricts available color gradients, and ΔE drift beyond 50 cycles remains within 0.28, reflecting moderate thermal fatigue. After 20 standard washing cycles, ΔE increased by less than 0.5, confirming the textile's retention of emotion-responsive chromatic fidelity post-laundering—a critical requirement for stage costumes and wearable applications. The CNN recognizer, trained mainly on time–frequency spectra, occasionally misinterprets high-reverberation or mixed-genre inputs, revealing sensitivity to acoustic artifacts. At larger fabric scales, distributed power regulation introduces latency, constraining real-time wearability.

ETT's textile-centered framework holds promise for emotion-linked visual fabrics for stage art, responsive garments, and ambient architectural surfaces. Its modular design allows integration with energy-harvesting yarns, flexible sensors, or IoT lighting systems, providing a scalable platform for autonomous stage applications and adaptive ambient installations.

Future work should employ multi-scale finite-element thermal modeling to quantify yarn-level heat diffusion and stage-level synchronization dynamics, bridging microstructural and environmental scales. Development of wide-spectrum thermochromic composites and hybrid conductive fibers to minimize resistance drift, and introduction of multi-modal fusion networks for more resilient emotion interpretation, are recommended. Field validation on live-stage setups and thorough cross-environment durability assessments will ensure system reliability in realistic performance conditions, particularly addressing mechanical durability and thermal stability of the microcapsule-based thermochromic layer in stage garment applications.

CONCLUSION

This study establishes an integrated framework for emotion-responsive thermochromic textiles, positioning the textile substrate—not the algorithm—as the core actuator of emotional expression. By coupling emotion recognition, distributed thermal regulation, and feedback correction, the system forms a coherent signal-material-control loop that translates abstract affective cues into measurable chromatic transformations on woven fabrics.

Scientifically, the research advances textile materials science in three areas:

(1) formulating a quantitative model linking emotional valence-arousal dimensions to thermal field distribution, enabling objective evaluation of emotion-induced chromic responses;

(2) synergistic design of conductive yarns and microencapsulated thermochromic layers for uniform Joule heating and reversible color transitions, demonstrating the role of textile architecture in governing thermophysical stability;

(3) incorporation of an adaptive feedback layer to enhance regional synchronization and repeatability, revealing that stability and responsiveness emerge from the intrinsic interplay of fiber geometry and controlled heat diffusion rather than computational intensity.

Practically, the ETT system combines low energy consumption, mechanical flexibility, and smooth color modulation, supporting applications in stage performance fabrics, wearable design, immersive environments, and intelligent textiles. Material-based color generation, driven by inherent thermal behavior rather than optical components, offers a sustainable approach to emotion-mediated interaction.

The system is best suited for applications with moderate real-time demands, such as stage performances and wearable art, where its current response speed and mechanical durability are sufficient. Applications requiring millisecond precision or extreme flexibility may require further material and structural optimization. Durability tests—including washfastness, Martindale abrasion resistance, and resistance to bending—demonstrate that ETT retains functionality under typical use conditions. Washfastness tests showed minimal color change after 20 cycles, Martindale abrasion tests confirmed durability after 5,000 cycles with only slight color shift, and resistance to bending tests revealed a 4.3% increase in conductive yarn resistance after 1,000 cycles, indicating durability but suggesting further optimization for high-movement environments such as wearable garments or stage costumes.

Future work will focus on advancing material resilience, broadening chromatic responsiveness, and validating system performance in real-world settings, laying the foundation for autonomous, emotionally perceptive textiles.

Ultimately, this work positions intelligent textiles as active media for emotional communication, where materials themselves interpret affective information. The framework offers a pathway for integrating textile engineering and adaptive control into a reproducible design paradigm, forming the basis for future developments in autonomous, self-regulating, and emotionally perceptive textile systems.

Author Contributions

Conceptualization – Yao; methodology – Yao; formal analysis – Yao; investigation – Yao; resources – Yao; writing-original draft preparation – Yao; writing-review and editing – Deng; visualization – Yao; supervision – Deng. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Funding

This research received no external funding.

Acknowledgements

Not applicable.

REFERENCES

[1] Liu H, Shi Y, Pan Y, Wang Z, Wang B. Sensory interactive fibers and textiles. NPJ Flexible Electronics. 2025; 9(1):23. doi: 10.1038/s41528-025-00398-4

[2] Wang J, Gui T, Cheng M, Wu X, Ruan R, Du M. A survey on emotional visualization and visual analysis. Journal of Visualization. 2023; 26(1):177-198. doi: 10.1007/s12650-022-00872-5

[3] Guo M, Zhang X, Wang Z, Gao Z. Exploring Emotions in Art: Innovations in Biometric Monitoring and Real-Time Visualization. Proceedings of the Eleventh International Symposium of Chinese CHI; 13-16 Nov 2023; Bali, Indonesia. New York, NY, USA: Association for Computing Machinery; 2023. p. 404-410. doi: 10.1145/3629606.3629645

[4] Ren H, Shi M, Zhang J. Research contents, methods and prospects of emotional architecture based on a systematic literature review. Buildings. 2024; 14(4):997. doi:10.3390/buildings14040997

[5] Zhang Y, Xia X, Ma K, Xia G, Wu M, Cheung YH, et al. Functional textiles with smart properties: Their fabrications and sustainable applications. Advanced functional materials. 2023; 33(33):2301607. doi: 10.1002/adfm.202301607

[6] Hou Z, Liu X, Tian M, Zhang X, Qu L, Fan T, et al. Smart fibers and textiles for emerging clothe-based wearable electronics: Materials, fabrications and applications. Journal of Materials Chemistry A. 2023; 11(33):17336-17372. doi: 10.1039/D3TA02617E

[7] Wan J, Xu S, Lin J, Ji L, Cheng J, Li Z, et al. AI-Enhanced Wearable Technology for Human Physiological Signal Detection: Challenges and Future Directions. Small. 2025; 21(43):e04078. doi: 10.1002/smll.202504078

[8] Du Z, Wang S, Gu C, Yang G. Recent advances in photo-or electro-chromic smart windows and their thermal regulation. Responsive Materials. 2025; 3(2):e20250007. doi: 10.1002/rpm.20250007

[9] Kong L, Li W, Zhang T, Ma H, Cao Y, Wang K, et al. Wireless technologies in flexible and wearable sensing: From materials design, system integration to applications. Advanced Materials. 024; 36(27):2400333. doi: 10.1002/adma.202400333

[10] Chai Y, Qin Y, Xu Z, Zheng X, Jia H. Advances in Fabric-Based Pneumatic Soft Actuators for Flexible Robotics: Design and Applications. Sensors. 2025; 25(12):3665. doi: 10.3390/s25123665

[11] Guennes M, Cunha J, Cabral I. Smart Textile Design: A Systematic Review of Materials and Technologies for Textile Interaction and User Experience Evaluation Methods. Technologies. 025; 13(6):251. doi: 10.3390/technologies13060251

[12] Gupta V, Karthick B, Singh VB. Application of nanotechnology in the development of smart textiles for allied industries. In: Ahmed S, Adeel S, editors. Nanoscale Textile Coatings for Enhanced Performance. Singapore: Springer Nature Singapore; 2024. p. 267-290. doi: 10.1007/978-981-97-5922-4_11

[13] Dejene BK. Wearable smart textiles for mood regulation: A critical review of emerging technologies and their psychological impacts. Journal of Industrial Textiles. 2025; 55:15280837251314190. doi: 10.1177/15280837251314190

[14] Xie Y, Fang Q. An Energy-Aware Generative AI Edge Inference Framework for Low-Power IoT Devices. Electronics. 2025; 14(20):4086. doi: 10.3390/electronics14204086

[15] Hu Q, Murad MAA, Li Q. Advancing music emotion recognition: Large-scale dataset construction and evaluator impact analysis. Multimedia Systems. 2025; 31(2):1-16. doi: 10.1007/s00530-025-01701-z

[16] Fu B, Chu W, Gu C, Liu Y. Cross-modal guiding neural network for multimodal emotion recognition from EEG and eye movement signals. IEEE Journal of Biomedical and Health Informatics. 2024; 28(10):5865-5876. doi: 10.1109/JBHI.2024.3419043

[17] Yang T, Wang S, Yang H, Gui H, Du Y, Liang F. Temperature-triggered dynamic Janus fabrics for smart directional water transport. Advanced Functional Materials. 2023; 33(18):2214183. doi: 10.1002/adfm.202214183

[18] Olhan S, Behera BK. Mechanical, thermogravimetric, and dynamic mechanical behavior of high-performance textile structural composite panels for automotive applications. Journal of Manufacturing Processes. 2023; 102:608-621. doi: 10.1016/j.jmapro.2023.08.003

[19] Liu S, Qi D, Dong H, Meng L, Wang Z, Yin X. Smart textile materials empowering automotive intelligent cockpits: an innovative integration from functional carriers to intelligent entities. The Journal of The Textile Institute. 2025; 1-25. doi: 10.1080/00405000.2025.2514054

[20] Yang L, Meng J, Yu L, Gao X, Chen Y, Wang Y, et al. Reversible dual-responsive color-changing fabric based on thermochromic microcapsules for textile fashion and intelligent monitoring. Dyes and Pigments. 2024; 231:112397. doi: 10.1016/j.dyepig.2024.112397

[21] Zhao J, Cheng Z, Liu X, Li J. An emotion driven intelligent product design method from a quantitative perspective. In: Marcus A, Rosenzweig E, Soares, MM, editor. Design, User Experience, and Usability. Proceedings of the International Conference on Human-Computer Interaction; 23-28 July 2023; Copenhagen, Denmark. Cham, Switzerland: Springer Nature Switzerland; 2023. p. 641-660. doi: 10.1007/978-3-031-35699-5_46

[22] Zhang Z, Zhang L, Zhou Y, Cui Y, Chen Z, Liu Y, et al. Thermochromic energy efficient windows: Fundamentals, recent advances, and perspectives. Chemical Reviews. 2023; 123(11):7025-7080. doi: 10.1021/acs.chemrev.2c00762

[23] Xie L, Wang X, Bai Y, Zou X, Liang S, Wei C, et al. Bioinspired natural fibers-derived wearable thermochromic materials for all-season self-adapting thermal management. Journal of Energy Chemistry. 2025; 104: 628-641. doi: 104:628-643. 10.1016/j.jechem.2025.01.016

[24] Wang Z, Liu Y, Zhou Z, Chen P, Peng H. Towards integrated textile display systems. Nature Reviews Electrical Engineering. 2024; 1(7):466-477. doi: 10.1038/s44287-024-00063-4

[25] Xu S, Fan X, Chen S, Manshaii F, Yin J, Chen J. Advances in luminescent fibers for interactive smart textiles. cMat. 2024; 1(3):e33. doi: 10.1002/cmt2.33

[26] Zhu X, Guo C, Feng H, Huang Y, Feng Y, Wang X, et al. A review of key technologies for emotion analysis using multimodal information. Cognitive Computation. 2024; 16(4):1504-1530. doi: 10.1007/s12559-024-10287-z

[27] Guan X, Lan T, Zhao D, Liu Z, Zhang K, Zhou Y, et al. Robust Textile-Based Electromagnetic Audio Interfaces. Advanced Materials. 2025; 38(1):e08022. doi: 10.1002/adma.202508022

[28] Chen W, Wei X, Liu W, Xu F. Dual-functional thermal management textiles for dynamic temperature regulation based on ultra-stretchable spiral conductive composite yarn with 500%-strain thermal stability and durability. Materials Horizons. 2024; 11(3):792-802. doi: 10.1039/D3MH01636F

[29] Chen T, Yang Q, Fang C, Deng S, Xu B. Advanced Design for Stimuli-Reversible Chromic Wearables with Customizable Functionalities. Advanced Materials. 2025; 37(6):2413665. doi: 10.1002/adma.202413665

[30] Saju SK, Puthirath AB, Wang S, Tsafack T, Beagle LK, Baydin A, et al. Thermochromic polymer blends. Joule. 2024; 8(9):2696-2714. doi: 10.1016/j.joule.2024.07.020

[31] Yu S, Zhang Q, Liu L, Ma R. Thermochromic conductive fibers with modifiable solar absorption for personal thermal management and temperature visualization. ACS Nano. 2023; 17(20):20299-20307. doi: 10.1021/acsnano.3c06289

[32] Birringer J, Danjoux M. Wearable technology for the performing arts. In: McCann J, Bryson D, editors. Smart Clothes and Wearable Technology (Second Edition). Duxford, UK: Woodhead Publishing; 2023. p. 529-571. doi: 10.1016/B978-0-12-819526-0.00005-9

[33] Huang X, Romano DM. Coral morph: An artistic shape-changing textile installation for mindful emotion regulation in the Wild. International Journal of Human-Computer Interaction. 2025; 41(2):1173-1189. doi: 10.1080/10447318.2024.2313283

[34] Suman S, Mamidanna P, Nielsen JJ, Chiariotti F, Stefanović Č, Došen S, et al. Closed-loop manual control with tactile or visual feedback under wireless link impairments. IEEE Transactions on Haptics. 2025; 18(2):352-361. doi: 10.1109/TOH.2025.3544134

[35] Li L, Zhang B, Zhao W, Sheng D, Yin L, Sheng X, et al. Multimodal Technologies for Closed-Loop Neural Modulation and Sensing. Advanced Healthcare Materials. 2024; 13(24):2303289. doi: 10.1002/adhm.202303289