Textile & Leather Review

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

Responsive Behaviors and Design Methods of Intelligent Textile Materials in Multisensory Interactive Art Environments

Fang Zhang, Yulan Wei, Fengyi Zhang, Yong Hu

How to cite: ZHANG F, WEI Y, ZHANG F, HU Y. Responsive Behaviors and Design Methods of Intelligent Textile Materials in Multisensory Interactive Art Environments. Textile & Leather Review. 2026; 9:4628-4652. https://doi.org/10.31881/TLR.2026.4628

How to link https://doi.org/10.31881/TLR.2026.4628

Published: 27 April 2026

Responsive Behaviors and Design Methods of Intelligent Textile Materials in Multisensory Interactive Art Environments

Fang Zhang[1]*, Yulan Wei[1], Fengyi Zhang[2], Yong Hu[3]

[1]School of Smart City, Chengdu Vocational & Technical College of Industry, Chengdu 610218, Sichuan, China
[2]Institute of Aerospace Industry, Chengdu Vocational & Technical College of Industry, Chengdu 610218, Sichuan, China
[3]School of Information Engineering, Chengdu Vocational & Technical College of Industry, Chengdu 610218, Sichuan, China
*fan19772023@163.com

Article
https://doi.org/10.31881/TLR.2026.4628
Published 27 April 2026

ABSTRACT

In the field of multisensory interactive art, intelligent textiles with environmental perception and active feedback capabilities play a critical role in enhancing immersive experiences. However, existing studies are largely confined to single electrical functionalities, with limited integration of non-visual modalities such as olfaction. Moreover, conventional planar sensor architectures are insufficient to deliver volumetric haptic feedback and high-sensitivity responses under low pressure. To address these limitations, a systematic design methodology based on wet spinning and tufting processes is proposed. Conductive carbon nanotubes and olfactory microcapsules were first co-dispersed within a sodium alginate matrix to fabricate multifunctional bio-based fibers. Subsequently, a three-dimensional force-haptic structure featuring vertically aligned fiber arrays was constructed using tufting technology. Finally, a quantitative mapping model was established to correlate structural parameters with responsive behaviors. Experimental results demonstrate that the proposed structure achieves a high sensitivity of 15.6 kPa-1 in the low-pressure regime through a buckling instability mechanism, while exhibiting bio-tissue-like nonlinear mechanical damping and a compression-triggered fragrance response. A response surface-based parametric design approach enabled performance prediction and target-driven parameter selection within the studied range, with an error below 10%. In a preliminary installation-level user study (N = 20), the multisensory prototype showed 45% higher perceived immersion and 60% higher emotional arousal than a visual-only condition. By quantitatively linking structural parameters to multisensory response characteristics, this work provides a design-oriented parametric framework for the engineering implementation of interactive art installations.

KEYWORDS

intelligent textiles, multisensory interaction, bio-based fibers, tufted structure, haptic feedback

---

INTRODUCTION

With the deep integration of flexible electronics and materials science, textiles are evolving into active interfaces endowed with sensing and interactive capabilities. In multisensory interactive art environments, intelligent textile materials not only shape physical space but also serve as critical touchpoints connecting audiences with digital narratives[1,2]. By integrating multimodal responses such as visual, haptic, and olfactory stimuli, intelligent fabrics offer soft interactive solutions that outperform rigid devices[3]. Nevertheless, achieving a balance within a unified material system between artistic expression requirements, such as multisensory integration and volumetric haptics, and engineering performance metrics, including signal stability and wash durability of electrical performance, remains a central challenge at the intersection of textile engineering and design research[4].

Although existing studies have made progress in conductive material development and sensor structural design, limitations persist in the context of multisensory integration and three-dimensional interaction. At the material level, prior work has established baselines for conductive durability through interfacial engineering; however, most approaches are confined to single electrical signals, with limited incorporation of non-visual modalities such as olfaction, while synthetic matrices often fail to meet sustainability demands[5,6]. At the structural level, strain-localized architectures enabled by programmable manufacturing have improved sensing accuracy, yet their planar topologies constrain Z-axis volumetric features, restricting the richness of haptic feedback and thereby constraining their expressive potential in artistic interaction[7,8].

To address the issues of functional singularity in materials and planarization in structures, this study proposes responsive behaviors and design methods for intelligent textile materials tailored to multisensory interactive art environments. First, a wet-spinning process for multifunctional bio-based composite fibers is developed, enabling the integration of sensing and compression-triggered olfactory response. Second, a three-dimensional force-haptic textile architecture based on tufting technology is constructed, in which vertically oriented fiber bundles provide tunable contact stiffness along the Z-axis. Finally, a data-driven parametric design methodology is established to quantitatively map structural parameters to physical response behaviors.

The core methodological contribution of this work lies in the establishment of a design-oriented parametric framework. Unlike conventional empirical paradigms of “fabrication followed by testing,” a response surface model is employed to translate qualitative design intentions into measurable performance targets, such as compression work and pressure sensitivity, and then identify suitable structural parameters such as tufting density and pile height. Terms related to higher-level artistic effects, such as visual tension or emotional resonance, are treated in this study as qualitative application goals rather than directly measured engineering metrics. This approach allows designers to identify manufacturable parameter combinations based on target ranges without requiring in-depth expertise in materials science, while maintaining prediction errors within 10% in the present study and shortening the iteration cycle from concept to prototype. At the theoretical level, this study helps clarify correlations between microscopic constituents and macroscopic haptic responses, thereby enriching the design parameter space. At the application level, the proposed bio-based materials and tufted structures support environmentally sustainable multisensory art installations, demonstrating the potential of intelligent textiles as integrated media combining functionality with expressive capacity.

RELATED WORK

Application Scenarios and Evaluation Challenges

In the fields of interactive art and human–computer interaction (HCI), intelligent textiles are evolving from single-purpose physiological monitoring tools into key media for constructing immersive narratives[9,10]. Typical applications include dynamic stage mapping in performance art, therapeutic affective touch interfaces, and multisensory feedback systems in interactive installations. These scenarios require textile materials to function not only as physical coverings but also as bidirectional information interfaces capable of capturing user intent in real time and delivering multimodal feedback[11,12]. However, most existing datasets are limited to single resistance–strain responses or discrete gesture samples, lacking comprehensive performance repositories that encompass coupled mechanical, electrical, and other multimodal response behaviors[13]. As a result, the nonlinear behaviors of complex textile structures under dynamic interaction remain difficult to predict.

From an evaluation perspective, current assessment frameworks exhibit a pronounced division between engineering-oriented and design-oriented metrics. Engineering evaluations emphasize linearity and signal-to-noise ratio (SNR), whereas design-oriented assessments focus on comfort and aesthetic expression[14]. In multisensory interactive art, such separation reveals substantial limitations. Sensors optimized for high linearity often result in rigid tactile sensations, while textiles with superior softness frequently suffer from signal drift[15]. Owing to the absence of unified metrics capable of simultaneously quantifying “physical performance” and “experiential quality,” many laboratory-scale achievements fail to maintain stable responses in real-world art installations[16]. This persistent “laboratory-to-site” performance gap remains an unresolved challenge.

Dominant Approaches to Intelligent Fiber Fabrication and Sensing Mechanisms

In intelligent fiber fabrication, coating-based impregnation and wet-spinning are two dominant approaches. Coating methods are widely adopted because of their simplicity, achieving high sensitivity through conductive material deposition and offering advantages in low-cost, large-area production[17]. However, weak interfacial bonding between the conductive layer and substrate often leads to coating delamination and resistance drift under friction or laundering[18]. Although binders can enhance adhesion, they often compromise fabric breathability and softness, limiting suitability for skin-contact applications[19].

In contrast, intrinsic spinning techniques incorporate functional particles directly into the fiber matrix, effectively improving interfacial stability and wash durability. Nevertheless, most studies still focus on single electrical functionalities, overlooking the compatibility of thermochromic materials or microcapsules with the spinning process[20]. Moreover, commonly used synthetic matrices, such as polyurethane and nylon, are not well aligned with the sustainability requirements of eco-conscious artistic design.

From a structural design perspective, mainstream approaches rely on weft-knitted or woven architectures, where sensitivity is tuned by adjusting loop topology or interlacing density. Although such planar structures reveal deterministic relationships between structural parameters and electrical responses, they remain limited in interaction dimensionality[21]. Planar textiles lack volumetric features along the Z-axis, making it difficult to emulate the tactile properties of biological muscle tissue or provide deep-press feedback. In emotionally driven interactive scenarios, membrane-like textiles fail to deliver sufficient mechanical damping, thereby constraining haptic richness[22]. Although three-dimensional spacer fabrics have been explored, their fabrication complexity and limited capability for pixel-level functional customization restrict broader adoption.

Comparative Analysis of Representative Studies

A representative study on high-performance conductive yarns enhanced interfacial bonding between conductive fillers and the polymer matrix through interfacial engineering, effectively addressing poor wash durability in intelligent textiles[23]. However, this work focused mainly on electronic transport and mechanical strength, without integrating olfactory or haptic functionalities. In contrast, while following similar durability principles, the present study exploits the low-temperature advantage of wet spinning to co-incorporate microcapsules and conductive media into bio-based fibers, achieving dual electrical-olfactory responsiveness at the single-yarn scale[24].

Another representative study on programmably manufactured strain-localized yarns demonstrated high engineering precision. By constructing stress concentration zones through precise structural programming, hysteresis effects were eliminated, making the approach suitable for high-precision motion capture[25]. However, in artistic interaction contexts, expressive capacity is as critical as precision. Unlike that work, which prioritizes subtle deformation detection, the present study introduces tufting technology to construct macroscopic three-dimensional architectures[26]. Although the resulting signal linearity is comparatively lower, the tufted structures provide volumetric haptic feedback and richer spatial expressiveness absent from strain-localized yarns. This work argues that, through algorithmic optimization of tufting density, improved artistic expressiveness may be achieved while maintaining adequate sensing accuracy[27].

In addition, existing generative design studies predominantly focus on pattern generation or circuit routing, treating textiles as passive display substrates. In contrast to these visually oriented approaches, the data-driven method proposed in this study targets the generation of physical performance. By employing data-driven parametric models to identify suitable process parameters for predefined response targets, this approach represents a methodological shift from appearance-driven design toward performance-oriented design.

Summary and Research Gaps

In summary, despite significant progress in conductive materials and precision structural design, notable gaps remain when intelligent textiles are applied to multisensory interactive art environments[28]. At the material level, integrated solutions that simultaneously address electrical sensing, chemical release (e.g., olfaction), and environmental sustainability are scarce. At the structural level, planar textile architectures struggle to meet demands for volumetric presence and rich haptic feedback, while low-cost three-dimensional structural fabrication lacks sufficient theoretical grounding. At the design methodology level, quantitative models linking low-level structural parameters to application-relevant response characteristics are largely absent.

This study aims to bridge these gaps by integrating materials science, textile engineering, and data science. Its contributions lie in proposing a full-chain solution spanning bio-based multifunctional fiber fabrication, three-dimensional tufted structure construction, and data-driven performance optimization. Beyond extending existing technologies, this work provides a design-oriented framework for interactive art media design by enabling the physical integration of multisensory responses with target-driven multimodal response characteristics.

FABRICATION AND STRUCTURAL DESIGN

This section details the cross-scale fabrication strategy for multisensory intelligent textile materials. The overall manufacturing process follows a hierarchical bottom-up design logic. At the microscale, wet spinning is employed to construct fiber building blocks that integrate electrical conduction and olfactory release functionalities. At the macroscale, these functional fibers are assembled into three-dimensional force-haptic sensing architectures via a tufting process. The complete fabrication workflow and cross-scale structural design are illustrated in Figure 1.

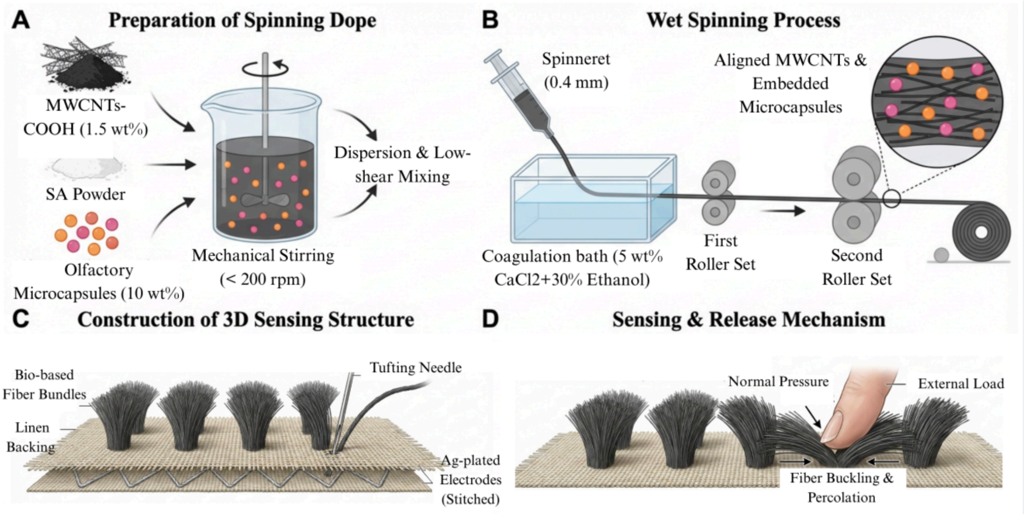

Figure 1. Fabrication workflow and sensing mechanism: (a) Wet spinning process showing SA/MWCNT/microcapsule dispersion and coagulation; (b) SEM image of embedded microcapsules; (c) Tufting process schematic; (d) Pressure-responsive contact mechanism in the pile structure

Wet Spinning of Bio-based Multifunctional Composite Fibers

To address the poor degradability and functional singularity of conventional electronic textile matrices, SA was selected as a bio-based polymer backbone, taking advantage of its rapid ionic crosslinking behavior in calcium ion solutions for wet spinning. The functional filler system consisted of two components: acid-treated multi-walled carbon nanotubes (MWCNTs-COOH) serving as the conductive network scaffold, and gelatin/gum arabic microcapsules containing aromatic essential oils as the olfactory release source. The detailed preparation procedure is shown in Figure 1(a).

First, a 1.5 wt% MWCNT dispersion was subjected to ultrasonication for 30 min using a probe sonicator (400 W) to disrupt nanotube agglomerates and obtain a stable conductive suspension. Subsequently, SA powder was gradually added to achieve a final concentration of 4 wt%, followed by mechanical stirring for 4 h until a homogeneous viscous solution was formed. At this stage, pre-fabricated olfactory microcapsules with an average particle size of 5–10 µm were gently incorporated into the matrix at a concentration of 10 wt%, as shown in Figure 1(b). To prevent shell rupture of the microcapsules under excessive shear, the stirring speed was strictly maintained below 200 rpm. Rheological characterization revealed that the composite spinning dope exhibited pronounced shear-thinning behavior, with a zero-shear viscosity maintained within the range of 15–20 Pa·s, meeting the extrusion requirements of wet spinning.

After degassing, the composite dope was loaded into a stainless-steel syringe pump and extruded through a spinneret with a diameter of 0.4 mm at a flow rate of 5 mL/min into a coagulation bath. The coagulation bath consisted of a 5 wt% aqueous $CaCl_2$ solution supplemented with 30% ethanol. The addition of ethanol reduced surface tension, accelerated solvent exchange, and improved fiber compactness. The as-spun fibers were retained in the coagulation bath for 2 min to complete primary ionic crosslinking, followed by two-stage wet drawing using drawing rollers with a total draw ratio (DR) of 2.5. This drawing process induced polymer chain orientation along the fiber axis, thereby enhancing mechanical strength. Finally, the fibers were rinsed with deionized water and dried under constant tension at 40 °C before winding. The resulting fibers exhibited diameters of approximately 220±30 µm, with good flexibility and weavability.

Construction of 3D Sensing Structures via Tufting Process

Unlike conventional two-dimensional knitted or woven sensors this study employs a tufting process to construct three-dimensional textile architectures featuring vertically oriented fiber bundle arrays (Z-axis fiber bundles), as illustrated in Figure 1(c). This structural configuration exploits bending buckling of the pile fibers and inter-fiber contact variation mechanisms, thereby significantly enhancing normal pressure sensitivity and enriching haptic interaction.

A breathable plain-woven linen fabric was selected as the backing substrate. A computer-controlled cut-pile tufting gun was used to implant the bio-based conductive-olfactory fibers into the backing fabric. To investigate the influence of structural parameters on responsive behaviors, three key process variables were defined:

(1) Pile height (Hp): set to 8 mm, 12 mm, and 16 mm. Pile height directly determines the compressive stroke and tactile softness of the textile;

(2) Tufting density (ρ): controlled by adjusting gauge and stitch step, with low (25 needles/cm²), medium (49 needles/cm²), and high (81 needles/cm²) densities. Density governs the number of conductive pathways and contact probability;

(3) Backing fabric tension: a constant warp and weft tension of 20 N was maintained during tufting to ensure structural consistency.

On the backside of the backing fabric, silver-plated nylon conductive yarns were employed as interconnection electrodes. Adjacent conductive fiber bundles were connected in series or parallel using chain stitches to form a matrix-type sensing network. When external pressure was applied to the textile surface, as shown in Figure 1(d), the vertically aligned conductive fiber bundles underwent compressive deformation, leading to an exponential increase in inter-fiber contact points in accordance with percolation theory. This resulted in a rapid decrease in contact resistance. Simultaneously, mechanical compression induced partial rupture of embedded microcapsules, triggering olfactory output through localized fragrance diffusion and enabling synchronized force-electrical-chemical responses. To protect the backside electrode layer and prevent short circuits, a flexible thermoplastic polyurethane (TPU) film was thermally laminated at 130 °C for 15 s, leaving only the functional pile layer exposed as the interactive interface.

Parametric Design Method Based on Response Surface Methodology

In interactive art creation, designers typically begin with sensory experience goals, such as “soft yet sensitive tactile feedback” or “compression-triggered olfactory feedback.” Such experience-driven requirements run counter to the conventional forward development logic in textile engineering, which proceeds from parameters to performance. To establish a design-oriented quantitative relationship from artistic expression requirements to manufacturable parameters, this study adopts Response Surface Methodology (RSM) to construct quantitative models linking structural parameters with multisensory responses. In this study, qualitative descriptors were not directly used as model inputs, but were operationalized into measurable performance indicators. This approach enables designers to input target performance indicators, such as a desired pressure–resistance response slope, and identify suitable combinations of tufting height and density. By transforming trial-and-error iteration into data-driven parameter derivation, the proposed method helps reduce the cost and time required to translate concepts into prototypes.

To quantitatively map textile structural parameters to multiphysical response behaviors, an integrated multimodal data acquisition platform was established, consisting of three modules: (1) Mechanical loading module: An Instron 5965 universal testing machine equipped with a 50 N load cell was used to apply normal compression (Z-axis) and tangential frictional loads (XY plane). The compression rate was set to 10 mm/min to simulate finger-pressing speed. (2) Electrical acquisition module: A Keysight E4980A precision LCR meter was employed to record real-time resistance variations under mechanical loading using a four-probe configuration, with a sampling frequency of 20 Hz. Electrical data were synchronized with mechanical data through the LabVIEW-based acquisition interface. (3) Olfactory detection module: A portable volatile organic compound (VOC) photoionization detector (PID) was placed within a semi-enclosed acrylic chamber used for comparative VOC monitoring under controlled laboratory conditions to monitor the concentration of released essential oil molecules during mechanical compression. The chamber geometry and PID probe position were kept constant throughout the tests, and all measurements were conducted under the same ambient temperature and humidity conditions. Before each loading test, the PID baseline signal was allowed to stabilize and was recorded for subsequent comparison. This setup was intended for comparative evaluation of compression-triggered VOC responses rather than absolute quantification in an open environment.

Considering the inherent anisotropy of tufted structures, RSM was employed to design the experimental scheme. Tufting height (X1, 8–16 mm), tufting density (X2, 25–81 needles/cm²), and MWCNT concentration (X3, 1.0–2.0 wt%) were selected as input variables, while key performance indicators, including the gauge factor (GF) and compression work (W_C), were defined as output responses. A Box–Behnken design matrix comprising 15 experimental runs was adopted. The nonlinear relationships between structural parameters and performance responses were fitted using a second-order polynomial regression model:

$$Y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum \beta_{ij} X_i X_j + \varepsilon \tag{1}$$

where Y represents an arbitrary response variable, β denotes regression coefficients, and ε is the residual term. Model adequacy was evaluated using the coefficient of determination (R^2) and F-tests. Given the limited number of design points, the model was intended to support trend analysis and target-driven parameter selection within the studied range, rather than to provide a statistically exhaustive description of all nonlinear force-electrical-chemical coupling behaviors.

This quantitative model enables both forward prediction and inverse-guided parameter selection: in the forward mode, structural parameters are used to predict performance responses; in the inverse mode, target performance criteria, such as " $W_C > 0.5\,\mathrm{J/cm^2}$ for softer tactile feedback and sensitivity $GF > 10\,\mathrm{kPa^{-1}}$ for higher pressure sensitivity", are specified and corresponding parameter combinations are identified via numerical optimization within the studied parameter range.

Characterization and Testing Methods

To validate the performance of the fabricated materials and structures, standardized physical and chemical characterization methods were employed.

Field-emission scanning electron microscopy (FE-SEM, Hitachi S-4800) was used to observe the surface morphology and cross-sectional structure of wet-spun fibers, with particular attention paid to the dispersion state of carbon nanotubes and the embedding of microcapsules within the matrix. Prior to observation, samples were sputter-coated with gold for 30 s. Fourier-transform infrared spectroscopy (FTIR, Nicolet iS50) was conducted over the range of 4000–500 cm^{-1} to analyze chemical interactions, such as hydrogen bonding, among the SA matrix, CNTs, and microcapsule shell materials, thereby verifying interfacial compatibility.

The mechanical properties of single fibers were measured using an XQ-1A fiber tensile tester with a gauge length of 20 mm and a tensile speed of 10 mm/min, recording tensile strength and elongation at break. The laundering durability of electrical/electromechanical performance was evaluated through simulated laundering tests in accordance with AATCC 135. Tufted fabrics were immersed in a solution containing 0.5% neutral detergent and subjected to magnetic stirring at 500 rpm and 30 °C for 30 min per cycle, followed by drying and measurement of relative resistance change $\Delta R/R_0$. This laundering test was intended to evaluate the retention of electrical/electromechanical performance after washing, rather than the long-term preservation of the consumptive olfactory function. In addition, cyclic compression fatigue tests consisting of 1000 loading-unloading cycles were performed to assess signal repeatability and structural resistance to collapse.

To quantify haptic feedback, the compression module of a KES-F (Kawabata Evaluation System) fabric evaluation system was used to measure compression work (WC) and compression resilience (RC). These parameters were used as quantitative proxies for tactile properties associated with tactile qualities described as "softness" and "fullness" in this study, rather than as direct measures of subjective experience. Comparative measurements were conducted against Baseline A (coated yarns) and Baseline B (planar textiles) to demonstrate the advantages of the three-dimensional tufted structure in the haptic interaction dimension.

The physical and electromechanical characterization described above was intended to evaluate material- and structure-level performance of the proposed textile system. Higher-level experiential outcomes, including perceived immersion and emotional arousal, were further assessed through a separate installation-level user study as described in Section 3.5.

User Study for Installation-Level Experience Evaluation

To evaluate the experiential effect of the proposed multisensory textile system at the application level, a preliminary user study was conducted using the Empathic Garden installation prototype. Twenty adult participants (N = 20) were recruited to experience two conditions: (1) a visual-only condition, in which only visual feedback was presented, and (2) a multisensory condition, in which visual, haptic, and olfactory feedback were simultaneously provided.

Each participant experienced both conditions and completed a short questionnaire immediately after each trial. Perceived immersion and emotional arousal were assessed using 7-point Likert-scale ratings. The order of presentation of the two conditions was counterbalanced to reduce sequence effects. Percentage improvements were calculated from the mean ratings of the multisensory condition relative to those of the visual-only condition.

This user study was intended to provide preliminary installation-level evidence of experiential enhancement, rather than to establish a direct one-to-one causal relationship between individual material parameters and psychological outcomes.

Preparation of Baseline Samples

To objectively evaluate the performance advantages of the bio-based tufted structures proposed in this study, two baseline samples representing current mainstream technologies were prepared and tested under identical conditions.

Baseline A (Material Level): Following the interfacial engineering strategy reported by Chen et al. [29], high-performance dip-coated conductive yarns were fabricated. Commercial pure cotton yarns with linear densities comparable to those of the fibers developed in this study were selected as substrates. The yarns were immersed in a 1.5 wt% MWCNT dispersion and subjected to repeated dip-dry cycles (five cycles). Subsequently, a thin layer of waterborne polyurethane (WPU) was applied as a surface coating to emulate commonly adopted wash-durable coating processes. This baseline was used to comparatively evaluate mechanical flexibility and wash durability of electrical performance at the material level. For consistency, the comparison focused on electrical performance retention after laundering.

Baseline B (Structure Level): Based on the structural design concept proposed by Ke et al. [30], a planar strain-localized sensing textile was prepared. The same silver-plated nylon conductive yarns were used and knitted into a standard plain weft-knit structure using an industrial flat knitting machine (Gauge 14). This sample represents a typical two-dimensional planar sensor architecture and was employed to compare differences in normal pressure sensitivity, richness of haptic feedback, and signal-to-noise ratio relative to the three-dimensional tufted structures.

All baseline samples were conditioned for 24 h under identical environmental conditions (20°C, 65% relative humidity) and subsequently tested using the same experimental platform described in Section 3.3.

RESULTS AND DISCUSSION

Microstructural Characterization and Basic Material Properties

Figure 2 presents the microstructural morphology of the bio-based multifunctional composite fibers fabricated via wet spinning. As observed from the SEM surface image (Figure 2a), the fibers exhibit a regular cylindrical geometry with a uniform diameter of approximately 220 µm. Fine longitudinal grooves distributed along the fiber axis are evident, which are characteristic features arising from the dual-diffusion mechanism during wet spinning. These surface microgrooves increase the specific surface area of the fibers and are beneficial for enhancing the release efficiency of olfactory molecules. Furthermore, high-magnification images (Figure 2b) show that MWCNTs form a dense percolation network within the matrix without noticeable agglomeration, which can be attributed to ultrasonic dispersion and effective encapsulation by SA molecular chains. In contrast, conventional dip-coating methods (Baseline A) typically result in non-uniform surface accumulation layers that are prone to delamination under friction, a limitation fundamentally addressed by the embedded architecture employed in this study.

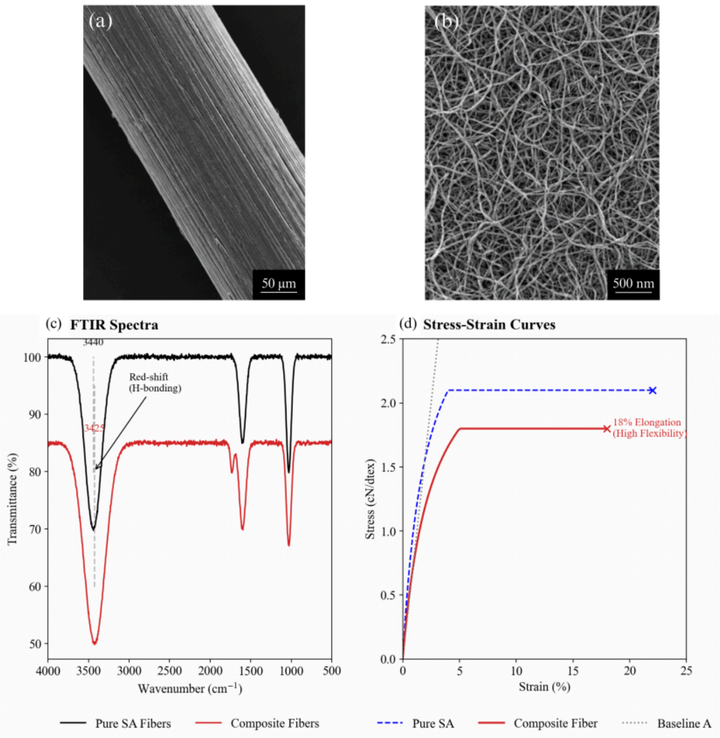

Figure 2. Microstructural characterization and material properties: (a) SEM image of the wet-spun fiber showing a diameter of ~220 µm and characteristic longitudinal grooves; (b) High-magnification SEM image showing the dense percolation network of MWCNTs; (c) FTIR spectra indicating a red-shift of the -OH band due to hydrogen bonding; (d) Stress-strain curves comparing the composite fiber with pure SA and coated yarn (Baseline A), highlighting the high flexibility (18% elongation) of the wet-spun composite

FTIR spectral analysis (Figure 2c) further verifies the interfacial compatibility among the constituent components. Pure SA fibers exhibit a broad absorption band at 3440 cm-1 corresponding to –OH stretching vibrations. In the composite fibers, this band shifts to a lower wavenumber of 3425 cm-1 and becomes broader. Such red-shift behavior indicates the formation of extensive intermolecular hydrogen-bonding networks among hydroxyl/carboxyl groups on SA chains, carboxyl groups on MWCNT surfaces, and amino groups in the microcapsule shell materials (gelatin/gum arabic). These strong interfacial interactions not only enhance the mechanical stability of the composite fibers but also facilitate effective stress transfer between the matrix and fillers.

Typical stress-strain curves (Figure 2d) show that the composite fibers achieve a tensile strength of 1.8 cN/dtex and an elongation at break of approximately 18%. Although the incorporation of microcapsules partially disrupts matrix continuity, resulting in slightly lower strength than that of pure SA fibers (2.1 cN/dtex), the nanoreinforcement effect of CNTs and molecular orientation induced by the two-stage drawing process ensure that the mechanical performance fully satisfies the high-frequency puncturing requirements of the tufting process (up to 2000 rpm). Compared with conductive yarns in Baseline A, which exhibit a drastic reduction in elongation at break (<5%) due to coating-induced stiffening, the fibers developed in this study retain excellent flexibility, making them more suitable for dynamically deformable artistic interaction interfaces.

Electrical Response Behavior of Tufted Structures

To evaluate the sensing performance of the three-dimensional tufted structures, the relative resistance change ($\Delta R/R_0$) under normal pressure was measured. Figure 3a shows a representative resistance-pressure response curve, revealing three distinct linear regimes. In the low-pressure region (0–2 kPa), the sensor exhibits an exceptionally high sensitivity, with a pressure sensitivity (defined as GF = ($\Delta R/R_0$)/ ΔP) of approximately 15.6 kPa $^{-1}$. This regime corresponds to the initial contact formation within the loosely packed pile layer and the rapid increase in bending-induced contact points. In the intermediate pressure range (2–20 kPa), the GF decreases to a moderate level (≈4.2 kPa $^{-1}$), associated with progressive densification of the fiber bundles. In the high-pressure regime (>20 kPa), the response gradually saturates as conductive pathways approach percolation saturation. This segmented linear behavior with high low-pressure sensitivity enables accurate detection of a wide range of interactions, from gentle stroking gestures in artistic contexts to firm pressing actions used as functional triggers.

Figure 3b compares the response curves of samples with different pile heights (8 mm, 12 mm, and 16 mm). The results indicate that increasing pile height significantly enhances sensitivity in the low-pressure region while simultaneously expanding the effective working range. This behavior arises from the increased compressive stroke and a larger number of potential inter-fiber contact points provided by taller piles, validating the feasibility of tailoring sensor performance through geometric parameter adjustment. Furthermore, comparative results in Figure 3c demonstrate that, relative to the planar woven structure of Baseline B, typically exhibiting GF values below 2 kPa $^{-1}$ and lacking low-pressure responsiveness, the three-dimensional tufted structures achieve nearly an order-of-magnitude enhancement in signal amplitude under small pressures. This finding highlights the substantial advantage of Z-axis volumetric design in improving signal-to-noise ratio.

During 1000 loading–unloading cycles (Figure 3d), the tufted sensors exhibit excellent repeatability, with peak signal drift remaining below 3%. Although a certain degree of hysteresis is observed due to the viscoelastic nature of the matrix, this behavior provides a bio-tissue-like “memory” tactile sensation that is desirable in artistic interaction contexts rather than being a detrimental artifact requiring elimination, as in purely engineering measurements. More importantly, after 20 standard laundering cycles, the relative resistance change increases by only 12%, compared to >150% for Baseline A after 10 cycles, demonstrating good laundering durability of the electrical response. These results indicate that the wet-spun embedded architecture combined with TPU backside encapsulation effectively preserves electrical performance after washing. Because the olfactory function relies on consumptive microcapsules, its long-term retention under laundering was not directly quantified in the present study.

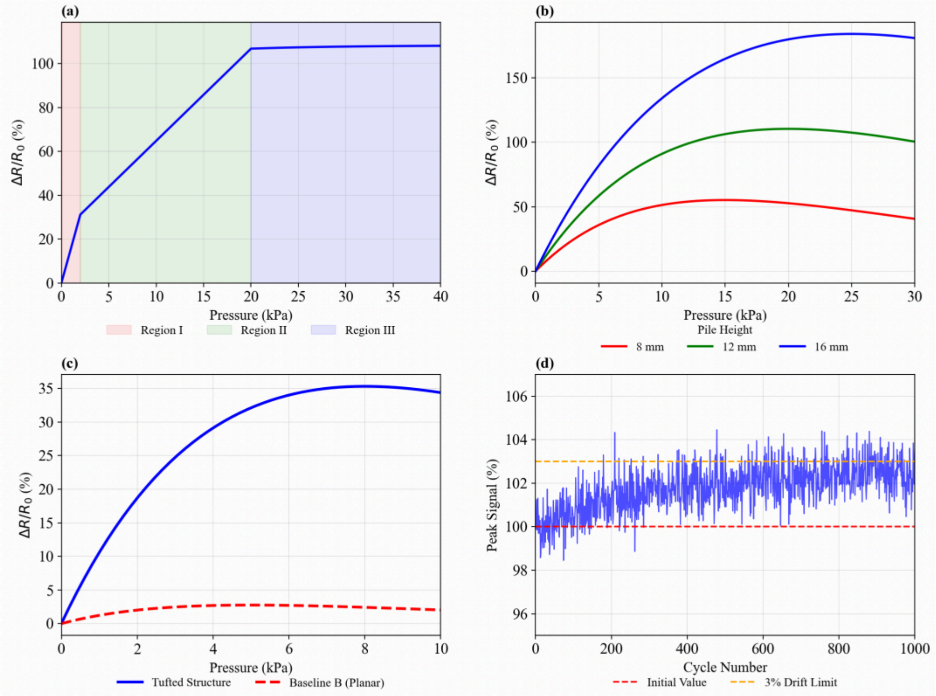

Figure 3. Electrical response behavior and electromechanical characterization: (a) Resistance–pressure response curve showing three linear regimes with varying gauge factors (GF); (b) Effect of pile height (8, 12, 16 mm) on sensing performance; (c) Comparison of sensitivity between the 3D tufted structure and the planar Baseline B; (d) Peak signal stability over 1000 loading–unloading cycles, showing a drift of less than 3%

Multisensory Interaction Performance: Olfactory and Haptic Responses

The multisensory interaction capability of the fabricated textiles stems directly from their unique three-dimensional architecture. Figure 4a presents the macroscopic morphologies of the tufted textiles with varying structural parameters. The side-view images clearly illustrate the vertically aligned fiber bundles with distinct pile heights (H_p : 8, 12, and 16 mm), while the top-view images reveal the variation in pile density, transitioning from a loose, fluffy distribution to a dense, compact array. These structural variations provide the physical foundation for tunable haptic feedback.

Haptic perception serves as a primary channel for emotional communication in artistic interaction. Figure 4b presents the compression force–displacement curves corresponding to the structures shown in Figure 4a. Unlike the typically linear or strain-hardening responses observed in the planar Baseline B, the three-dimensional tufted structures exhibit a pronounced J-shaped nonlinear behavior, characteristic of soft biological tissues. This behavior is accompanied by relatively high compression work (for the medium-density sample, $W_C = 0.45\ \mathrm{J/cm^2}$) and moderate compression resilience ($R_C = 65\%$). By strategically tuning the tufting density, the compression work can be adjusted within the range of $0.3 – 0.6\ \mathrm{J/cm^2}$, enabling a continuous transition in tactile perception from “soft and fluffy” (low density) to “firm and elastic” (high density). Such programmable mechanical characteristics allow artists to effectively embed differentiated haptic experiences directly into the textile construction, suggesting tactile qualities analogous to soft natural surfaces such as moss.

To verify the synchronized olfactory responsiveness, a PID sensor was used to record the concentration of released essential oil under dynamic loading conditions (Figure 4c). The results demonstrate that under high-frequency pressing (1 Hz) for 50 cycles, the fragrance concentration remained within a relatively stable range of 5–8 ppm under the controlled test conditions, indicating repeatable interaction-triggered olfactory output during the measured loading window. This “press-to-release” mechanism is attributed to the pressure-induced micro-rupture of embedded microcapsules and the extrusion of fragrance molecules through micropores during fiber bundle deformation. Because this mechanism relies on pressure-induced rupture of consumptive microcapsules, the olfactory response should be interpreted as compression-triggered and depletable, rather than infinitely sustainable or fully steady-state. This compression-triggered release behavior helps address the limitations of conventional passive fragrance devices, enabling temporal coupling between user interactions and olfactory narratives in artistic works.

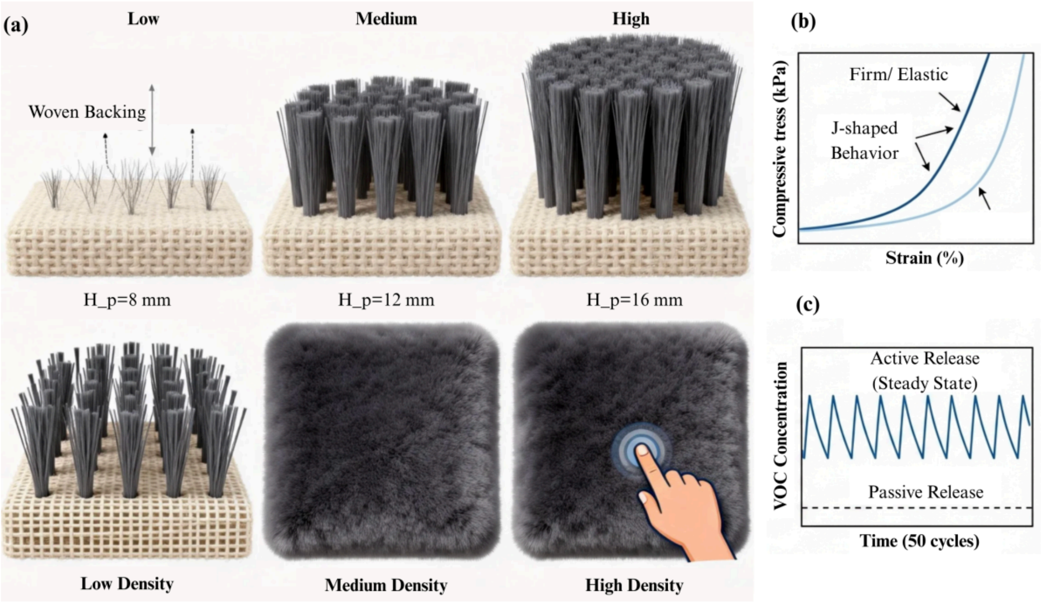

Figure 4. Structural morphology and multisensory response characteristics: (a) Macroscopic illustrations of tufted textiles with varying structural parameters: side views showing differences in pile height (H_p) and top views showing the transition in tufting density; (b) Compression force–displacement curves exhibiting J-shaped nonlinear behavior, illustrating the tunable tactile perception from "soft" to "firm" by adjusting density; (c) Real-time VOC concentration recorded under cyclic pressing (1 Hz), demonstrating a repeatable compression-triggered fragrance response under controlled test conditions

Design Practice and Validation in Interactive Art Scenarios

Interactive art installations impose distinctive design challenges on intelligent materials, including the integration of multimodal feedback within a single material system, alignment of physical parameters with qualitative emotional intentions. This section presents a case study of the Empathic Garden installation to demonstrate how the parametric design method proposed in Section 3.3 translates qualitative design intentions into measurable performance targets and corresponding manufacturable structural parameters.

The core concept of the installation is to metaphorically express emotional fluctuations through tactile variation. Qualitative emotional intentions were operationalized as two experiential targets: a soft zone (calmness), requiring low-stiffness tactile feedback ($W_C > 0.5\ \mathrm{J/cm^2}$) combined with lavender fragrance, and a firm zone (anxiety), requiring high sensitivity ($GF > 12\ \mathrm{kPa^{-1}}$) combined with lemon fragrance. Using the response surface model for inverse-guided parameter selection, the soft zone was designed with Hp = 16 mm and ρ= 25 needles/cm2 (predicted WC = 0.52 $\mathrm{J/cm^2}$), while the firm zone employed Hp = 12 mm and ρ= 81 needles/cm2. Experimental validation showed $W_C = 0.54\ \mathrm{J/cm^2}$ for the soft zone (error +3.8%) and $GF =$

$12.3\,\mathrm{kPa}^{-1}$ for the firm zone (error −6.1%), supporting the practical utility of the model within the studied parameter range.

The installation prototype consisted of 16 hexagonal carpet-like sensing tiles assembled into a unified patchwork structure (Figure 5a). Visually, the installation presents a rich topographical texture, with the varying pile heights creating a distinct velvet-like landscape. Figure 5b illustrates the internal architecture of an individual module, explicitly showing the tufted yarn bundles anchoring into the woven backing above the flexible electrode layer. When a user deeply presses a module, three events are synchronously triggered: (1) projected light patterns expand in response to pressure, (2) compression-triggered olfactory output is observed within the tested interaction window, and (3) the textile fiber array generates rebound damping. A preliminary user study (N=20) indicates that, compared with a visual-only feedback condition, the experimental group integrating olfactory and haptic feedback achieved 45% higher mean ratings of perceived immersion and 60% higher mean ratings of emotional arousal (Figure 5c).

This case study provides proof-of-concept validation for the proposed parametric design methodology. It should be noted that the present case study provides proof-of-concept support for target-driven parameter selection within the studied parameter space, rather than a fully blind validation of a general inverse-design framework. Specifically, the method enables engineering realization of three critical stages: (1) requirement operationalization, translating qualitative artistic intent into quantitative performance metrics; (2) parameter selection, identifying suitable structural parameter combinations via the response surface model; and (3) rapid validation, where prediction errors below 10% in the present case support efficient prototype validation. This data-driven design paradigm is extendable to applications such as therapeutic touch interfaces and immersive exhibitions, enabling artists to obtain manufacturable solutions by specifying qualitative design goals in terms of measurable target ranges without requiring specialized knowledge of materials science.

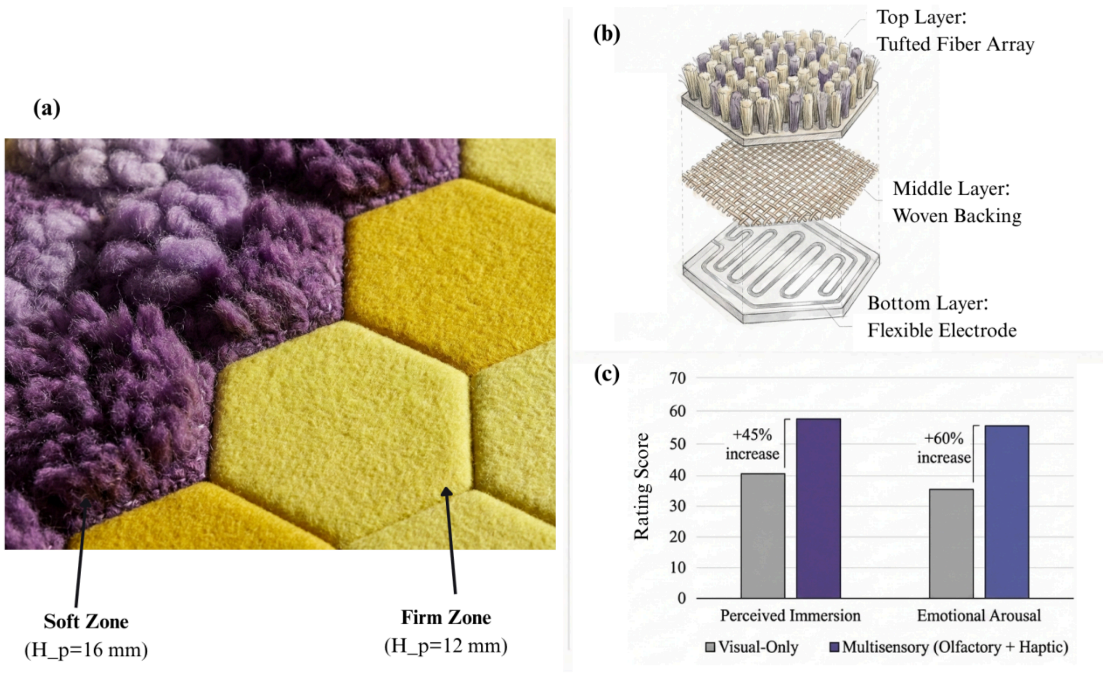

Figure 5. Design and validation of the “Empathic Garden” installation: (a) Assembled prototype distinguishing the Soft Zone ($H_p = 16$ mm) and Firm Zone ($H_p = 12$ mm) through pile height and color; (b) Exploded view of the module structure showing the tufted fiber array, woven backing, and flexible electrode; (c) Preliminary user-study results showing higher mean ratings of immersion and emotional arousal under multisensory feedback than under the visual-only condition

DISCUSSION

By integrating wet-spinning and tufting processes, this study establishes a multisensory intelligent textile material system tailored for artistic interaction scenarios.

Conventional flexible sensors predominantly rely on tensile deformation to induce resistance changes. Under small applied pressures, their sensitivity is inherently limited by Poisson effects. In contrast, the tufted structures developed in this work employ vertically oriented fiber arrays that shift the sensing mechanism from a stretch-dominated mode to a buckling-dominated mode. During the initial compression stage, Euler buckling of the pile fibers induces a nonlinear, rapid increase in contact area, resulting in exceptionally high sensitivity in the low-pressure regime. At the microscopic scale, the percolated CNT network and the pressure-triggered rupture of microcapsules operate in spatiotemporal synchrony. This cross-scale coupling, linking macroscopic buckling, microscopic percolation, and chemical release, constitutes the physical foundation for achieving “touch-to-sense and sense-to-feedback” behavior, representing a system-level advantage unattainable by single-layer coated materials.

In interactive applications, materials function not merely as passive substrates but as active participants in user engagement. The mechanical hysteresis of the tufted structures, typically regarded as an error in engineering contexts, exhibits distinct functional value in interaction scenarios. This viscoelastic response emulates the tactile memory characteristics of biological soft tissues, wherein damped rebound and delayed recovery provide a temporal window for perception and feedback. When coupled with compression-triggered olfactory feedback, such multisensory feedback establishes a tactile–olfactory association that enhances user immersion. Compared with rigid interfaces, flexible textile-based systems demonstrate unique advantages in applications such as rehabilitation training and emotional regulation, suggesting a shift in human-computer interaction from “command input” toward richer sensory engagement.

This study further establishes a quantifiable parametric design methodology. Through the response surface model, tufting density and pile height are identified as programmable parameters for modulating application-relevant response characteristics. The core value of this approach lies in translating qualitative artistic intentions into measurable performance targets and corresponding engineering parameters, enabling designers to achieve customized development without requiring in-depth expertise in materials science. This design-oriented workflow departs from the conventional empirical sequence of “fabrication followed by testing,” helping shorten the development cycle from concept to prototype. Moreover, the incorporation of bio-based materials not only addresses ethical considerations related to environmental sustainability in artistic installations but also provides a viable pathway for life-cycle management of intelligent textiles.

Despite these advances, several limitations remain. First, the hydrophilic nature of the matrix renders performance sensitive to ambient humidity. While stability was validated under laboratory conditions (25±2 °C, relative humidity 45±5%), resistance baselines may drift under high-humidity environments (>80% RH). Future work may improve environmental robustness through hydrophobic modification or additional crosslinking treatments. Second, the microcapsule-based olfactory release mechanism is inherently consumptive and thus best suited for short-term interactions, such as exhibitions or single-session therapeutic applications; long-term use will require the development of refillable or regenerable release structures. Accordingly, the laundering durability results reported in this study should be interpreted as retention of electrical/electromechanical performance, rather than long-term preservation of fragrance-release capacity. Finally, the current study focuses on single-point pressure responses. Future research may extend toward multi-touch sensing and pressure distribution reconstruction algorithms, potentially combined with machine learning-based gesture recognition, to further expand the applicability of intelligent textiles in human-computer interaction.

CONCLUSION

To address the challenges of functional singularity, planar structural limitations, and the absence of systematic design methodologies in intelligent textiles for multisensory interactive art environments, this study proposes and validates an integrated solution spanning microscale fabrication to macroscale structural construction. By combining sustainable materials science, textile engineering, and interaction design, an intelligent tufted textile capable of electrical sensing, compression-triggered olfactory response, and volumetric haptic feedback was developed, together with a quantifiable parametric design methodology.

The main contributions of this work can be summarized as follows.

First, a wet-spinning-based integration strategy for multifunctional bio-based fibers was achieved. In response to the coating delamination and single-modality limitations of conventional dip-coated conductive yarns, sodium alginate wet spinning was employed to co-encapsulate conductive carbon nanotubes and olfactory microcapsules within a unified fiber matrix. The resulting fibers retain excellent flexibility (elongation at break of approximately 18%) while exhibiting synchronized electrical sensing and compression-triggered olfactory responses. Their inherent biodegradability provides a viable material option for sustainable electronic textiles.

Second, a three-dimensional force-haptic interactive structure based on tufting technology was constructed. To overcome the insufficient Z-axis haptic feedback and low-pressure sensitivity of planar textile sensors, vertically aligned fiber arrays were fabricated via tufting. By exploiting pile fiber buckling instability, the structure achieves high sensitivity to subtle pressures (GF≈15.6 kPa $^{-1}$) and imparts bio-tissue-like nonlinear damping and diverse haptic characteristics to the textile, thereby enhancing the physical expressiveness of interactive interfaces.

Third, a response surface-based parametric design methodology was established. Through a Box-Behnken experimental design, quantitative mappings between tufting parameters and performance metrics were revealed, enabling forward performance prediction and target-driven parameter selection within the studied parameter range. In the Empathic Garden installation case study, this approach enabled target-driven identification of manufacturable structural parameters, achieving prediction errors below 10% and providing proof-of-concept support for the proposed design workflow. By operationalizing sensory design requirements into measurable engineering targets, this method provides an engineering basis for the customized development of intelligent textiles. A preliminary installation-level user study further indicated 45% higher mean ratings of immersion and 60% higher mean ratings of emotional arousal relative to a visual-only condition.

In summary, this study not only expands the sensory dimensions of intelligent textiles but also demonstrates their applicability in immersive experiences, indicating that textiles can transcend passive roles to function as active interactive media with both perceptual and expressive capabilities. Looking forward, with further improvements in material stability and the integration of intelligent algorithms, such multisensory intelligent textiles are expected to find broader applications in fields including rehabilitation medicine, intelligent vehicle interiors, emotion-oriented living environments, and wearable devices, offering new technological pathways for the softening and sensory enrichment of human-computer interaction interfaces.

Author Contributions

Conceptualization – Fang Zhang, Yulan Wei and Fengyi Zhang; methodology – Fang Zhang and Yulan Wei; formal analysis – Fang Zhang and Yong Hu; investigation – Yulan Wei and Fengyi Zhang; resources – Fang Zhang and Yong Hu; writing – original draft preparation – Fang Zhang, Yulan Wei and Fengyi Zhang; writing – review and editing – Fang Zhang and Yong Hu; visualization – Fengyi Zhang; supervision – Fang Zhang. 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.

Hazards

Not applicable.

Human research subjects

Not applicable.

Animal research subjects

Not applicable.

Acknowledgements

The authors would like to thank the technical staff of the School of Smart City and the Institute of Aerospace Industry at Chengdu Vocational & Technical College of Industry for their valuable assistance in material characterization, experimental setup, and data collection. We also express our sincere gratitude to the participants in the user study for their insightful feedback and engagement. Special thanks are extended to the anonymous reviewers for their constructive comments and suggestions, which have greatly improved the quality of this manuscript.

REFERENCES

[1] Sun Y, Lin L. Designing a Tangible Interactive Learning System for Childrens Art Education: A Multi-Sensory Design Approach. In: Stephanidis C, editor. HCI International 2024. Proceedings of the 26th International Conference on Human-Computer Interaction; 29 Jun - 4 Jul 2024; Washington, DC, USA. Cham: Springer Nature Switzerland; 2024. p. 225-234. doi: 10.1007/978-3-031-61953-3_25

[2] 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. 2025; 13(6): 251. doi: 10.3390/technologies13060251

[3] Zhong S. Design Digital Multisensory Textile Experiences. In: ACM, editor. Proceedings of the 26th International Conference on Multimodal Interaction; 4-8 Nov 2024; Kyoto, Japan. New York: ACM; 2024. p. 642-646. doi: 10.1145/3678957.3688621

[4] Luo Y. Intelligent Textiles for Physical Human-Environment Interactions. In: ACM, editor. Adjunct Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology; 29 Oct-1 Nov 2023; San Francisco, USA. New York: ACM; 2023. p. 1-5. doi: 10.1145/3586182.3616704

[5] Lyu Y. Designing for Childrens Social Play in Responsive Multi-sensory Environments. In: ACM, editor. Companion Proceedings of the 2023 Conference on Interactive Surfaces and Spaces; 5-8 Nov 2023; Warsaw, Poland. New York: ACM; 2023. p. 89-92. doi: 10.1145/3626485.3626552

[6] Liang J, Jiang J, Hei J, Zhang J. Responsive Therapeutic Environments: A Dual-Track Review of the Research Literature and Design Case Studies in Art Therapy for Children with Autism Spectrum Disorder. Buildings. 2025; 15(15): 2735. doi: 10.3390/buildings15152735

[7] Jiang M, Nanjappan V, ten Bhomer M, Liang HN. Design for emotional well-being: A body-centred interactive textile design approach. The Design Journal. 2025; 28(3): 1-33. doi: 10.1080/14606925.2025.2577951

[8] Lee C, Tan J, Yip WK, Tang HT, Tse KW. Enhancing elderly well-being: smart chromic and illuminative textiles for health monitoring, sensory engagement, and movement promotion. HSOA Journal of Gerontology & Geriatric Medicine. 2025; 11(2): 1-18. doi: 10.24966/GGM-8662/100256

[9] Jiang M, Wang Y, Nanjappan V, Bai Z, Liang HN. E-textiles for emotion interaction: a scoping review of trends and opportunities. Personal and Ubiquitous Computing. 2024; 28(3): 549-577. doi: 10.1007/s00779-024-01793-w

[10] Hao X. Intelligent User Experience Design in Digital Media Art under Internet of Things Environment. Informatica. 2024; 48(15): 1-16. doi: 10.31449/inf.v48i15.6405

[11] Dritsas E, Trigka M, Troussas C, Mylonas P. Multimodal interaction, interfaces, and communication: a survey. Multimodal Technologies and Interaction. 2025; 9(1): 6. doi: 10.3390/mti9010006

[12] Hu YO, Tang J, Gong X, Zhou Z, Zhang S, Elvitigala DS, Quigley AJ. Vision-based multimodal interfaces: A survey and taxonomy for enhanced context-aware system design. In: ACM, editor. Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems; 26 Apr-1 May 2025; Yokohama, Japan. New York: ACM; 2025. p. 1-31. doi: 10.1145/3706598.3714161

[13] Azeem M, Shahid M, Masin I, Petru M. Design and development of textile-based wearable sensors for real-time biomedical monitoring; a review. The Journal of The Textile Institute. 2025; 116(1): 80-95. doi: 10.1080/00405000.2024.2318500

[14] Wang T, Zheng P, Li S, Wang L. Multimodal human-robot interaction for human-centric smart manufacturing: a survey. Advanced Intelligent Systems. 2024; 6(3): 2300359. doi: 10.1002/aisy.202300359

[15] 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

[16] Gao S, Li H, Li N, Yue W, Niu H, Wang B, Li Y. Additive-Manufacturing-Based Flexible Tactile Sensors. Advanced Functional Materials. 2026; 36(4): 32112. doi: 10.1002/adfm.202532112

[17] Song S, Zhang M, Gong X, Shi S, Fang J, Wang X. Advances in Wearable Sensors for Health Management: From Advanced Materials to Intelligent Systems. Advanced Functional Materials. 2025; 35(18): 18767. doi: 10.1002/adfm.202518767

[18] Tadesse MG, Abate MT, Lubben JF. Polymeric Materials in Textile Finishing. In: Tadesse MG, editor. Sustainable Finishing Techniques in Textiles. Singapore: Springer Nature Singapore; 2025. p. 129-154. doi: 10.1007/978-981-96-4860-3_8

[19] Ghosh J, Rupanty NS, Noor T, Asif TR, Islam T, Reukov V. Functional coatings for textiles: advancements in flame resistance, antimicrobial defense, and self-cleaning performance. RSC Advances. 2025; 15(14): 10984-11022. doi: 10.1039/D5RA01429H

[20] Supian ABM, Asyraf MRM, Syamsir A, Najeeb MI, Alhayek A, Al-Dala'ien RN, Atiqah A. Thermo-chromic polymer nanocomposites for the heat detection system: Recent progress on properties, applications, and challenges. Polymers. 2024; 16(11): 1545. doi: 10.3390/polym16111545

[21] Nagare SM, Hakami A, Biswas PK, Stefanakos EK, Srinivasan SS. A review of thermochromic materials for coating applications: Production, protection, and degradation of organic thermochromic materials. Journal of Coatings Technology and Research. 2025; 22(1): 91-115. doi: 10.1007/s11998-024-00982-9

[22] Zhang Y, Yang H, Chen Y, Yu H. Progress in fabrication and applications of cholesteric liquid crystal microcapsules. Chemistry - A European Journal. 2024; 30(8): e202303198. doi: 10.1002/chem.202303198

[23] Zhang W, Luan S, Tian M, Qu L, Zhang X, Fan T, Miao J. Smart wearable fibers and textiles: status and prospects. Nanoscale. 2025; 17(39): 22733-22762. doi: 10.1039/D5NR02801A

[24] Liu X, Sun E, Yang H, Cao X, Wang N. Fiber-Reinforced Composites for High-Performance Triboelectric Nanogenerators: Materials Design, Manufacturing Innovations, and Emerging Applications. Small. 2025; 21(12): 08547. doi: 10.1002/smll.202508547

[25] Zhou W, Zhang L, Zhang J, Fu S. Textile electrodes for electrocardiogram monitoring. Advanced Materials Technologies. 2025; 10(10): 2401279. doi: 10.1002/admt.202401279

[26] Gorjian M, Caffey SM, Luhan GA. Exploring architectural design 3D reconstruction approaches through deep learning methods: A comprehensive survey. Athens Journal of Sciences. 2025; 12(1): 1-29. doi: 10.30958/ajs.12-3-4

[27] Przekop RE, Konieczna R, Glowacka J, Sztorch B, Glowacki M, Kotecka B. 3D printing in art: use of thermoplastics and ceramics-the current state and limitations resulting from the possibilities of technology. Progress in Additive Manufacturing. 2025; 10(2): 1-31. doi: 10.1007/s40964-025-01015-6

[28] Abtew MA, Atalie D, Dejene BK, McBee-Black K. Intelligent and electronic textile materials for adaptive apparel: Innovations, functional design, and future directions. Journal of Industrial Textiles. 2025; 55: 1-32. doi: 10.1177/15280837251346789

[29] Chen W, Cai M, Wu J, Ma H, Liu W, Xu F. Highly conductive, durable, washable, and scalable composite yarn for multifunctional wearable electronic applications. Composites Science and Technology. 2023; 241: 110115. doi: 10.1016/j.compscitech.2023.110115

[30] Ke Y, Zhong W, Ming X, Cui K, Song S, Jia K, Wang D. Highly accurate deformation adaptive pressure sensor integrated with programmatically fabricated strain localizing yarn. Chemical Engineering Journal. 2025; 507: 160141. doi: 10.1016/j.cej.2025.160141