

Smart and Functional Fabrics: A Review of Wearable Technology Integration in Fabric Design

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Article Info	ABSTRACT
Article type: Review Article	The convergence of material science, textile engineering, and design has given rise to a new generation of intelligent and functional fabrics that extend far beyond the traditional roles of clothing. This review paper, framed from a textile design perspective, provides a comprehensive overview of smart and functional fabrics, with particular emphasis on their mechanisms, literature, and applications in fabric design. The paper first introduces smart fabrics (e-textiles) that integrate electronic components for sensing, responding, and communicating, alongside wearable fabrics and functional fabrics that offer performance-enhancing properties without necessarily incorporating electronics. The discussion then examines four key functional fabric categories in detail: UV-blocking fabrics that protect against solar radiation through nanoparticle coatings and fiber engineering; antibacterial fabrics that inhibit microbial growth using silver, zinc oxide, chitosan, and other biocidal agents; self-cleaning fabrics inspired by the lotus effect, operating via superhydrophobic or photocatalytic mechanisms; and photochromic/thermochromic fabrics that reversibly change color in response to UV light or temperature fluctuations, enabled by microencapsulated dyes. For each category, the review synthesizes foundational and recent literature, identifies persistent challenges including durability, washability, environmental impact, and safety, and explores applications across fashion, sportswear, medical textiles, home furnishings, military apparel, and protective clothing. The findings indicate that while these technologies have matured significantly, issues of longevity, cost, and scalability remain barriers to widespread adoption. From a design standpoint, successful integration requires balancing advanced functionality with aesthetic qualities, comfort, breathability, and hand feel. This review concludes that the future of textile design lies in multifunctional, sustainable, and user-centered solutions that seamlessly embed performance into everyday fabrics.
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Introduction

Smart fabrics, also known as e-textiles or intelligent textiles, represent a paradigm shift in traditional fabric design by integrating electronic components, sensors, and conductive materials directly into textile structures. Unlike conventional fabrics that serve primarily aesthetic or protective functions, smart fabrics are capable of sensing environmental conditions, responding to stimuli, and communicating data to the user or connected devices. These materials are generally classified into three categories: passive smart fabrics (which only sense environmental changes), active smart fabrics (which both sense and respond, e.g., shape memory polymers or thermochromic dyes), and very smart fabrics (which incorporate artificial intelligence or adaptive learning). The integration of wearable technology into fabric design has opened new frontiers in health monitoring, athletic performance tracking, military applications, and interactive fashion, where garments can monitor heart rate, regulate body temperature, or even change color based on mood or external conditions. This convergence of textile engineering, material science, and electronics has redefined the boundaries of clothing, transforming it from a passive covering into an active interface between the human body and the digital environment (Jeyranzadeh et al., 2025; Zohoori et al., 2025; Zohoori et al., 2024; Davodiroknabadi et al., 2024).

The academic literature on smart fabrics has grown rapidly over the past two decades, with early foundational work focusing on the development of conductive yarns and flexible circuitry. Researchers pioneered the concept of "e-broidery," where conductive threads were embroidered onto fabrics to create wearable computers, while others provided comprehensive reviews of smart textile architectures, emphasizing the challenges of integrating rigid electronic components into flexible textile substrates. More recent studies have shifted toward energy harvesting and storage solutions, including textile-based solar cells, piezoelectric fabrics that generate electricity from body movement, and supercapacitor-integrated yarns. In the biomedical domain, several clinical trials have validated the accuracy of smart garments for continuous ECG monitoring, respiration rate detection, and temperature sensing. However, the literature also identifies persistent challenges, including washability, durability, power supply limitations, and user comfort. Despite these hurdles, emerging research on nanofiber-based sensors, self-healing conductive polymers, and wireless power transfer suggests that next-generation smart fabrics will be increasingly robust, unobtrusive, and commercially viable paving the way for seamless wearable technology embedded into everyday clothing (Naddafiun et al., 2024; Ghiasi, Davodiroknabadi, and Zohoori, 2021; Zohoori et al., 2022).

Wearable fabrics, often referred to as e-textiles or garment-integrated electronics, are textiles specifically engineered to incorporate electronic components such as sensors, actuators, microcontrollers, and communication modules directly into the fabric structure, enabling the garment to collect, process, and transmit physiological or environmental data. Unlike external

wearable devices (e.g., smartwatches or chest straps), wearable fabrics offer seamless integration, allowing the technology to become almost invisible and highly comfortable for long-term use. Despite these advances, the literature consistently identifies major challenges in power supply (battery rigidity and capacity), washability (waterproofing electronic components), and data security, which remain active areas of investigation (Asakereh et al., 2022; Zohoori, Davodiroknabadi, and Dadmarz, 2017; Zohoori, and Sakeniyandehkordi, 2025).

Functional fabrics, while often overlapping with wearable fabrics, represent a broader category of textiles that are engineered to exhibit specific performance-enhancing properties beyond basic aesthetics or protection, without necessarily incorporating electronic components. These properties may include moisture management, thermal regulation, antimicrobial activity, UV protection, flame resistance, water repellency, or self-cleaning capabilities. Unlike wearable fabrics that actively sense and respond to digital inputs, functional fabrics typically rely on advanced material chemistry, fiber engineering, or surface finishing techniques to achieve desired behaviors. The literature on functional fabrics is extensive and multidisciplinary. For example, research by Zohoori et. al. reviewed various chemical finishing methods for imparting antimicrobial properties using silver nanoparticles, chitosan, or triclosan, particularly for medical and sportswear applications. In thermal regulation, researchers investigated phase-change materials (PCMs) encapsulated within microcapsules and embedded into fabric coatings, enabling textiles to absorb, store, and release latent heat for adaptive body temperature control. More recent studies by them explored the use of graphene oxide coatings to produce flame-retardant functional fabrics with enhanced mechanical strength. Additionally, superhydrophobic or self-cleaning fabrics have been achieved through biomimetic approaches inspired by the lotus leaf, using fluorinated compounds or silica nanoparticles to create ultra-water-repellent surfaces. The literature also highlights growing concerns about the environmental impact of functional finishes, leading to a new wave of research into bio-based, non-toxic, and durable functional treatments that align with circular economy principles (Zohoori, and Sakeniyandehkordi, 2025; Kooshamoghdam et al., 2022; Bekrani, Zohoori, and Davodiroknabadi, 2020; Mohamadiyan, Zohoori, and Davodiroknabadi, 2020; Dadkhah Tirani, Davodiroknabadi, and Zohoori, 2018).

Discussion

UV-Blocking Fabrics

Ultraviolet (UV) radiation, particularly UVA (320–400 nm) and UVB (280–320 nm) wavelengths, poses significant risks to human skin, including sunburn, premature aging, and an increased incidence of skin cancers. In response to growing public awareness of photodamage, UV-blocking fabrics have emerged as a critical category of functional textiles designed to provide effective personal sun protection. Unlike conventional fabrics that offer incidental and inconsistent UV shielding, UV-blocking fabrics are specifically engineered (through fiber

selection, fabric construction, chemical treatments, or nanoparticle integration) to achieve high ultraviolet protection factor (UPF) ratings, typically UPF 30 to 50+. These fabrics are increasingly applied in everyday clothing, outdoor sportswear, swimwear, children's apparel, and even medical garments for photosensitive patients. Their integration into fabric design represents a convergence of textile physics, material chemistry, and consumer-driven functional aesthetics.

The academic literature on UV-blocking textiles has grown substantially since the introduction of the UPF rating system by the Australian/New Zealand Standard AS/NZS 4399 in 1996, which was later adapted by AATCC and ASTM internationally. Early studies systematically examined the effects of laundering, wear, and fabric wetness on UV transmission, demonstrating that cotton fabrics lose significant UV protection when wet, while polyester retains performance. Subsequent research evaluated commercial summer clothing and found that many light-colored, lightweight garments offered inadequate protection (UPF < 15), highlighting the need for engineered UV-blocking designs.

More recent literature has focused on nanotechnology-based solutions. For instance, Zohoori et al. synthesized TiO₂ and ZnO nanoparticles and applied them to cotton fabrics via pad-dry-cure methods, achieving UPF values exceeding 50 while maintaining breathability and softness. Similarly, researchers investigated the use of sol-gel coatings incorporating nanosilica and TiO₂, which provided durable UV protection even after multiple laundering cycles. In a comparative study, researchers reviewed various nanofinishing techniques (including plasma pretreatment, microencapsulation, and layer-by-layer assembly) concluding that nanoparticle-based finishes offer superior durability and performance compared to conventional organic UV absorbers.

Beyond protection efficiency, recent literature has addressed the challenge of balancing UV-blocking performance with other fabric design priorities. For example, some researches demonstrated that high UPF values can be achieved without compromising thermal comfort by using hybrid woven-knit structures or by applying TiO₂ coatings only to the outer fabric surface, leaving the inner layer untreated for moisture management. Additionally, researchers explored the use of natural UV-blocking agents, such as lignin, tannic acid, and plant-based dyes (e.g., indigo, madder, and turmeric), as sustainable alternatives to synthetic UV absorbers. These natural products offer dual functionality (providing both color and protection) while aligning with eco-friendly design principles.

Applications in Fabric Design

In contemporary fabric design, UV-blocking technology has moved beyond niche sun-protective garments to become a standard feature in many apparel categories. For outdoor and activewear, brands incorporate permanent UV-blocking finishes or use inherently protective fibers (e.g., polyester or nylon with TiO₂ embedded during extrusion) in hiking shirts, leggings,

and hats. In swimwear, UV-blocking fabrics with UPF 50+ are now common, often combined with chlorine resistance and stretch recovery. For children's clothing, given their greater skin sensitivity and longer sun exposure, many designers prioritize UV-blocking properties alongside softness and bright, appealing prints. Medical textiles for patients with xeroderma pigmentosum or lupus erythematosus—conditions requiring strict sun avoidance—represent another specialized application, where garments must offer maximum protection (UPF 50+) while being lightweight and non-irritating. Even in fashion-forward daily wear, summer dresses, cardigans, and scarves are increasingly marketed with UV-blocking claims, often finished with odorless, colorless nanoparticle coatings that do not alter hand feel or drape. From a design perspective, the challenge lies in integrating UV protection without sacrificing aesthetics, breathability, or moisture transport, which has driven innovations in gradient coatings, perforated structures, and dual-layer fabrics (Zohoori et al., 2017; Avazpour, Karimi, and Zohoori, 2017; Zohoori, Karimi, and Ayazi Yazdi, 2014; Karimi, Zohoori, and Amini, 2014).

Antibacterial Fabrics

Antibacterial fabrics represent a vital category of functional textiles engineered to inhibit the growth of bacteria, fungi, and other microorganisms on fabric surfaces. In everyday life, textiles provide an ideal environment for microbial proliferation due to their large surface area, moisture retention, and prolonged contact with human skin, which supplies organic nutrients such as sweat, sebum, and shed skin cells. This microbial colonization can lead to unpleasant odors, fabric discoloration, staining, mechanical degradation, and, more critically, an increased risk of skin infections and cross-contamination in healthcare settings. Antibacterial fabrics address these issues by incorporating biocidal or biostatic agents that either kill microorganisms or suppress their reproduction. The growing consumer awareness of hygiene, particularly in the post-pandemic era, has significantly accelerated the demand for antibacterial clothing, sportswear, underwear, medical textiles, home furnishings, and children's apparel. From a fabric design perspective, integrating antibacterial functionality requires careful consideration of efficacy, durability, safety to human skin, environmental impact, and compatibility with other design features such as color, softness, and breathability.

Applications in Fabric Design

The integration of antibacterial functionality into fabric design spans a wide range of product categories, each with distinct performance requirements. In medical textiles, including surgical gowns, drapes, wound dressings, and hospital linens, antibacterial fabrics play a critical role in reducing healthcare-associated infections (HAIs). For these applications, designers prioritize high efficacy against pathogens such as *S. aureus*, *Escherichia coli*, *Pseudomonas aeruginosa*, and *Candida albicans*, combined with biocompatibility and resistance to sterilization processes.

Nonwoven fabrics with embedded silver or copper are commonly used for disposable medical textiles, while reusable cotton or polyester fabrics require durable finishes that withstand repeated high-temperature laundering.

In sportswear and activewear, antibacterial fabrics address the problem of odor formation caused by bacterial metabolism of sweat components, particularly underarm, foot, and groin areas. Designers of athletic apparel incorporate antibacterial finishes into moisture-wicking fabrics, often combining them with odor-absorbing materials such as activated carbon or cyclodextrins. For example, many branded sportswear lines use silver-based or zinc-based antibacterial treatments in socks, undershirts, yoga pants, and base layers, ensuring that garments remain fresh throughout prolonged physical activity. Importantly, these finishes must not compromise stretch recovery, breathability, or moisture transport.

Underwear and intimate apparel represent another major application category, where bacterial overgrowth can lead to discomfort, infections and unpleasant odors. Antibacterial fabrics in this category typically employ mild, skin-friendly agents such as chitosan, bamboo-derived charcoal, or low-concentration silver. Design considerations include softness, hypoallergenicity, and wash durability, as these garments undergo frequent laundering. Similarly, children's clothing benefits from antibacterial finishes to reduce the risk of skin infections and dermatitis, though safety standards require extremely low toxicity and minimal leaching potential.

Beyond apparel, antibacterial fabrics are increasingly used in home textiles, including bed sheets, pillowcases, towels, bathmats, and upholstery. These items are prone to bacterial and fungal growth due to retained moisture from sweat or bathing. Antibacterial bedding has shown particular promise for individuals with acne or eczema, as it reduces microbial load on skin-contact surfaces. In public and hospitality settings, antibacterial curtain fabrics, carpeting, and seat covers help maintain hygiene in hotels, hospitals, and transportation systems (Zohoori, Karimi, and Ayaziyazdi, 2014; Karimi, Zohoori, and Amini, 2014; Zohoori, and Karimi, 2013; Dastyar, Nayebyzadeh, and Zohoori, 2022; Dehbozorgi et al., 2020; Azaditehrani, Karimi, and Zohoori, 2017).

Self-Cleaning Fabrics

Self-cleaning fabrics represent one of the most innovative and technologically advanced categories of functional textiles, designed to degrade or repel dirt, stains, oils, and microbial contaminants without conventional laundering. The concept of self-cleaning surfaces is inspired by natural phenomena, most famously the "lotus effect," where water droplets roll off the hydrophobic leaves of the lotus plant, carrying dust and dirt particles with them. In textile applications, self-cleaning functionality is achieved through two distinct mechanisms: superhydrophobic (water-repellent) surfaces that cause liquid-borne dirt to bead and roll off, and

photocatalytic surfaces that chemically break down organic stains and pollutants when exposed to light. The development of self-cleaning fabrics addresses several pressing concerns in modern society: reducing water and energy consumption associated with frequent laundry, extending garment lifespan by minimizing mechanical and chemical stress from washing, and providing convenience for consumers in situations where regular laundering is impractical, such as outdoor activities, travel, or military operations. From a fabric design perspective, self-cleaning textiles must balance extraordinary surface properties with wear comfort, breathability, flexibility, and durability against abrasion and laundering, presenting both significant scientific challenges and exciting creative opportunities.

Applications in Fabric Design

Self-cleaning fabrics have found applications across a diverse range of product categories, each with distinct performance requirements and design constraints. In outdoor and performance apparel, including hiking gear, rain jackets, and camping equipment, self-cleaning properties offer significant practical advantages. Hikers and campers often lack access to laundry facilities, and outdoor garments are prone to mud, plant stains, and food spills. Superhydrophobic finishes on nylon or polyester shell fabrics cause water and mud to bead and roll off, while photocatalytic coatings gradually degrade organic stains during daylight exposure. Major outdoor brands have commercialized such technologies, with fabrics that require only a quick shake or wipe to remain clean throughout multi-day expeditions. Design considerations for this category include maintaining breathability and moisture vapor transmission, ensuring that the self-cleaning finish does not interfere with waterproof membranes (e.g., Gore-Tex), and achieving sufficient abrasion resistance for contact with rocks, branches, and backpack straps.

In formal and everyday clothing, self-cleaning fabrics appeal to consumers seeking convenience and reduced laundry frequency. White shirts, blouses, and dresses (highly susceptible to visible stains from food, beverages, and body oils) are particularly promising candidates for photocatalytic self-cleaning treatments. Designers must ensure that TiO_2 or ZnO coatings do not alter the fabric's color, whiteness, or soft hand feel, as these attributes are critical for formal wear. Nanoscale coating thickness (typically 20–100 nm) allows optical transparency while providing functionality. Additionally, the photocatalytic mechanism requires light exposure; therefore, garments may be designed with photocatalytic coatings on outer surfaces (exposed to sunlight) while maintaining uncoated, comfortable inner layers.

Workwear and uniforms represent another substantial application area. Chefs' aprons, laboratory coats, medical scrubs, restaurant server uniforms, and industrial workwear are subjected to frequent staining from food, chemicals, blood, and oils. Self-cleaning fabrics can reduce the number of laundering cycles required, lowering operational costs and extending

garment life. For medical applications, the combination of self-cleaning (stain degradation) with antibacterial properties is particularly valuable, as it reduces the bioburden on fabric surfaces and minimizes cross-contamination risks. However, healthcare regulations require rigorous safety testing to ensure that photocatalytic nanoparticles do not leach or generate cytotoxic ROS concentrations harmful to patients or staff.

In home textiles, self-cleaning finishes are being applied to curtains, upholstery fabrics, carpets, and table linens. Curtains and upholstery are difficult and expensive to clean using traditional methods; self-cleaning fabrics that decompose airborne pollutants and stains from accidental spills offer significant convenience. Photocatalytic TiO₂-coated curtain fabrics have been shown to degrade volatile organic compounds (VOCs) and nitrogen oxides from indoor air, providing passive air purification alongside stain resistance. For tablecloths and napkins, superhydrophobic finishes cause spilled liquids (wine, coffee, sauces) to form beads that can be wiped away before they penetrate and stain the fabric, dramatically simplifying post-meal cleanup.

Military and tactical apparel represents a specialized but important application domain. Soldiers on extended missions have limited laundry access, and visibility-reducing stains can compromise camouflage effectiveness. Self-cleaning fabrics that repel mud and degrade organic stains under sunlight improve operational hygiene, reduce logistical burden, and maintain camouflage performance. Additionally, self-cleaning technologies have been explored for chemical and biological protective clothing, where photocatalytic surfaces could degrade chemical warfare agents and biological toxins upon exposure.

Photochromic and Thermochromic Fabrics

Photochromic and thermochromic fabrics represent a fascinating category of chromic or "color-changing" textiles that respond dynamically to environmental stimuli—specifically, ultraviolet (UV) light exposure and temperature changes, respectively. Unlike conventional fabrics with static colors, chromic textiles possess the remarkable ability to reversibly alter their color appearance when triggered by external energy inputs. Photochromic fabrics change color when exposed to sunlight or UV radiation, reverting to their original color when the light source is removed. Thermochromic fabrics change color in response to temperature fluctuations, transitioning between different hues at specific threshold temperatures. These intelligent materials have transitioned from scientific curiosities to commercially viable textile products, driven by advances in microencapsulation technology, organic dye chemistry, and textile finishing techniques. The integration of photochromic and thermochromic functionality into fabric design opens extraordinary creative possibilities for fashion designers, product developers, and technical textile engineers. Applications range from novelty garments that change color outdoors and UV-indicating sportswear that warns of excessive sun exposure, to

thermoregulation-indicating fabrics, interactive fashion, smart packaging textiles, and even medical monitoring garments. From a fabric design perspective, chromic textiles must balance color change performance (reversibility, response speed, color intensity, and cycle life) with practical textile properties such as wash fastness, light fastness, abrasion resistance, comfort, and compatibility with conventional dyeing and printing processes.

Applications in Fabric Design

Photochromic and thermochromic fabrics have found diverse applications across fashion, functional sportswear, safety equipment, medical textiles, and home furnishings, each with distinct design requirements.

In fashion and apparel, chromic textiles enable unprecedented levels of interactivity and personal expression. Photochromic fashion garments appear one color indoors and transform into entirely different patterns or hues when worn outdoors in sunlight. Designers have used screen-printed photochromic patterns to create "invisible" designs (floral patterns, logos, or abstract graphics) that only reveal themselves under UV illumination. Thermochromic fashion allows garments to respond to body heat, environmental temperature, or wearer activity. For example, a thermochromic dress may appear black at room temperature but reveal red patterns where body heat warms the fabric—under arms, along the spine, or at the chest. Some high-fashion collections have featured thermochromic fabrics that change color when touched, creating garments that reflect social interactions. For designers, key considerations include maintaining desired color aesthetics in both activated and deactivated states, ensuring that chromic materials do not compromise fabric drape or breathability, and communicating realistic performance expectations to consumers (e.g., that color change is reversible but may diminish after many washes).

In sportswear and outdoor apparel, photochromic fabrics offer functional benefits beyond aesthetics. Photochromic sports garments can serve as UV exposure indicators; the depth or area of color change correlates with UV intensity, alerting wearers to apply sunscreen or seek shade. Several outdoor brands have launched photochromic performance wear that changes from colorless to deep blue or purple under high UV conditions, combining sun safety awareness with aesthetic appeal. Additionally, photochromic fabrics used in accessories such as hats, arm sleeves, and neck gaiters provide sun protection while indicating when protection is most needed. Thermochromic sportswear, while primarily aesthetic, can provide visual feedback on body heating zones, helping athletes and coaches identify areas requiring improved ventilation or cooling.

In safety and protective clothing, chromic textiles serve critical warning functions. Thermochromic safety labels and patches applied to protective clothing can change color when

the garment has been exposed to excessive heat, indicating potential degradation of protective properties or warning of burn hazards. For example, firefighter turnout gear with thermochromic indicators reveals when outer shells have exceeded safe temperature limits. Similarly, photochromic indicators on high-visibility safety vests provide primitive light sensors, though this application remains developmental.

In medical textiles, thermochromic fabrics offer non-invasive temperature monitoring capabilities. Thermochromic bandages and wound dressings change color when localized skin temperature rises above normal ranges, potentially indicating infection or inflammation. For infant care, thermochromic bedding and clothing can alert caregivers to fever without repeated thermometer measurements. While these applications show promise, medical adoption requires rigorous validation, calibration, and regulatory approval to ensure that thermochromic responses correlate reliably with clinically significant temperature thresholds.

In home textiles and interior design, chromic materials create interactive and mood-responsive environments. Thermochromic upholstery fabrics change color where people sit, creating living impressions of occupancy and movement. Photochromic curtains and blinds reveal patterns when sunlight streams through windows, providing constantly changing decorative effects throughout the day. Thermochromic bath mats show footprints after showering, and thermochromic mugs change color when filled with hot beverages—applications that leverage consumer novelty interest for commercial products. Designers working with interior chromic textiles must consider that indoor light levels may be insufficient for photochromic activation (requiring supplement with UV-emitting light sources) and that thermochromic response temperatures must be matched to typical indoor and surface contact conditions (Avazpour, Karimi, and Zohoori, 2017; Zohoori, Karimi, and Ayaziyazdi, 2014; Karimi, Zohoori, and Amini, 2014; Zohoori, and Karimi, 2013; Dastyar, Nayebyzadeh, and Zohoori, 2022; Dehbozorgi et al., 2020; Azaditehrani, Karimi, and Zohoori, 2017; Zohoori, Payvandy, and Bekrani, 2021; Yamin, Naddafion, and Zohoori, 2022; Derakhshan et al., 2018).

Conclusion

This review paper has provided a systematic examination of smart and functional fabrics from a textile design perspective, covering four major categories: UV-blocking fabrics, antibacterial fabrics, self-cleaning fabrics, and photochromic/thermochromic fabrics. Collectively, the literature and applications discussed reveal several overarching conclusions that inform both current practice and future development.

First, functional fabric technologies have matured considerably over the past two decades, moving from laboratory curiosities to commercially viable products. The introduction of nanotechnology, particularly the use of TiO₂, ZnO, and silver nanoparticles, has significantly

enhanced the performance of UV-blocking, antibacterial, and self-cleaning fabrics, achieving UPF ratings exceeding 50, bacterial reduction rates of over 99%, and effective stain degradation under UV or visible light. Similarly, microencapsulation has enabled the successful application of photochromic and thermochromic dyes to textiles, creating reversible color-change effects that respond to sunlight and temperature. These advances have translated into real-world applications across fashion, sportswear, medical textiles, home furnishings, military apparel, and protective clothing, demonstrating that functional textiles are no longer niche products but increasingly expected features in everyday garments.

Second, despite significant progress, persistent challenges remain that limit widespread adoption and long-term performance. Durability, particularly resistance to repeated laundering, mechanical abrasion, and prolonged environmental exposure, is the most commonly cited limitation across all fabric categories. Microcapsules rupture, nanoparticle coatings delaminate, and functional finishes degrade, typically losing 50–80% of their initial activity after 20–50 wash cycles. For smart and wearable fabrics, additional challenges include power supply (battery rigidity, capacity, and recharging), washability of electronic components, and data security. For chromic fabrics, slow response speed, limited color intensity, and poor fatigue resistance under prolonged UV exposure remain unresolved. These durability and performance gaps represent critical barriers to consumer acceptance, as users expect functional benefits to persist throughout the garment's natural lifespan.

Third, the environmental and health implications of functional fabric technologies have emerged as major concerns requiring urgent attention. Fluorinated compounds used in superhydrophobic self-cleaning finishes (e.g., PFOA and PFOS) are persistent environmental pollutants associated with bioaccumulation and toxicity, leading to regulatory restrictions and a push toward fluorine-free alternatives. Metal nanoparticles (silver, copper, zinc oxide) released during laundering enter wastewater streams, raising ecotoxicological risks to aquatic organisms. The long-term dermal and inhalation safety of nanoparticle-coated fabrics for manufacturing workers and end-users remains incompletely characterized. In response, the literature demonstrates a clear shift toward bio-based, non-toxic, and biodegradable alternatives, including chitosan, plant-derived extracts (neem, curcumin, tea tree oil), lignin, tannic acid, and natural photochromic compounds. This transition aligns with circular economy principles and growing consumer demand for sustainable textiles, though bio-based alternatives generally offer lower durability and efficacy compared to synthetic counterparts, indicating a need for continued research.

Fourth, from a textile design perspective, successful integration of functional properties requires holistic consideration of the entire garment lifecycle and user experience. The literature consistently emphasizes that functionality cannot come at the expense of aesthetic and tactile

qualities. UV-blocking finishes must not alter fabric color, softness, or breathability; antibacterial agents must be skin-safe, hypoallergenic, and compatible with moisture-wicking structures; self-cleaning coatings must preserve drape and flexibility; and chromic dyes must maintain pattern definition and color vibrancy in both activated and deactivated states. Designers must also consider that functional mechanisms have inherent limitations—photocatalytic self-cleaning requires light exposure, superhydrophobic surfaces are ineffective against oils, thermochromic fabrics require specific temperature thresholds, and photochromic fabrics need UV radiation. Effective design therefore involves matching material capabilities to specific use contexts (e.g., outdoor versus indoor, medical versus fashion), managing consumer expectations through clear communication, and often adopting hybrid approaches where functional finishes are applied selectively to accent areas rather than entire garments.

Finally, the future directions identified in this review point toward several promising trajectories. Multifunctional fabrics that combine two or more properties (e.g., UV-blocking with antibacterial activity, or self-cleaning with thermochromic color change) offer synergistic benefits and reduced processing costs. Visible-light-active photocatalysts (nitrogen-doped TiO₂, graphene oxide composites) and fluorine-free superhydrophobic coatings address environmental and functional limitations of current technologies. Durable chromic fibers produced by melt-spinning or wet-spinning, rather than surface coating, could dramatically improve wash fastness. Self-healing polymers and covalent bonding strategies for nanoparticle coatings offer pathways to extended functional lifetimes. Additionally, the integration of chromic indicators with smartphone-based color analysis enables quantitative UV dosimetry and temperature monitoring, bridging chromic textiles with digital health applications. For textile designers, researchers, and manufacturers, the challenge lies in scaling these advanced materials from laboratory demonstrations to cost-effective, durable, and sustainable commercial products. As consumer expectations for intelligent, hygienic, and environmentally responsible clothing continue to rise, the successful integration of functional and smart properties into fabric design will define the next generation of textile innovation.

Author Contributions

The author has contributed to the conceptualization of the article and writing of the original and subsequent drafts.

Data Availability Statement

Data available on request from the author.

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Ethical considerations

The author avoided data fabrication, falsification, plagiarism, and misconduct.

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Conflict of interest

The author declares no conflict of interest.

References

- Asakereh, M., Zohoori, S., Mohammadisaghand, F., Sabzali, M., Mohammadisaghand, R., & Soltani, B. (2022). Extracting hazelnut green shell cellulose and electrospinning nanofibers doped with gelatin/nano silver. *Journal of Natural Fibers*, 19(17), 15552-15562.
- Avazpour, S., Karimi, L., & Zohoori, S. (2017). Simultaneous coloration and functional finishing of cotton fabric using Ag/ZnO nanocomposite. *Coloration Technology*, 133(5), 423-430.
- Azaditehrani, F., Karimi, L., & Zohoori, S. (2017). Tie Design using Electrical Conductive Fabrics. *International Journal of Applied Arts Studies (IJAPAS)*, 2(2). Retrieved from <http://www.ijapas.ir/index.php/ijapas/article/view/134>
- Bekrani, M., Zohoori, S., & Davodiroknabadi, A. (2020). Producing multifunctional cotton fabrics using nano CeO₂ doped with nano TiO₂ and ZnO. *Autex Research Journal*, 20(1), 78-84.
- Davodiroknabadi, A., Zohoori, S., Talebikatieklahijany, R., Mohammadisaghand, F., Shahsavari, S., Mohammadisaghand, R., & Zangeneh, P. (2024). Fabrication of multifunctional nanocomposite fiber extracted from *Sambucus nigra*: anti-nociceptive, anti-inflammatory, self-cleaning, and UV blocking. *Applied Biochemistry and Biotechnology*, 196(11), 8058-8069. <https://doi.org/10.1007/s12010-024-04967-7>
- Dadkhah Tirani, A., Davodiroknabadi, A., & Zohoori, S. (2018). Combining Traditional and Modern Art to make Fabric using Poly Vinyl Alcohol Material. *International Journal of Applied Arts Studies (IJAPAS)*, 2(4). Retrieved from <http://www.ijapas.ir/index.php/ijapas/article/view/111>
- Dastyar, Z., Nayeibzadeh, S., & Zohoori, S. (2022). Designing Doll Costume Inspired by “Simorgh” and using the Properties of Harmel and Nano Zinc Oxide. *International Journal of Applied Arts Studies (IJAPAS)*, 6(3), 39-46. Retrieved from <http://www.ijapas.ir/index.php/ijapas/article/view/368>
- Dehbozorgi, E., Zohoori, S., Davodiroknabadi, A., Derakhshan, S., & Sakenyandehkordi, M. (2020). Designing Costume for Circus Performers Considering the Special Capabilities of the Cloth. *International Journal of Applied Arts Studies (IJAPAS)*, 4(3), 67-74. Retrieved from <http://www.ijapas.ir/index.php/ijapas/article/view/268>
- Derakhshan, S. J., Karimi, L., Zohoori, S., Davodiroknabadi, A., & Lessani, L. (2018). Antibacterial and self-cleaning properties of cotton fabric treated with TiO₂/Pt. *Indian Journal of Fibre & Textile Research*, 43(3).
- Ghiasi, Y., Davodiroknabadi, A., & Zohoori, S. (2021). Electrospinning of wheat bran cellulose/TiO₂/ZnO nanofibre and investigating the UV blocking and bactericidal properties. *Bulletin of Materials Science*, 44(2), 89.
- Jeyranzadeh, R., Zohoori, S., Davodiroknabadi, A., & Jahangard, A. (2025). Investigating the Integration of Nanotechnology and Fabric Art in the Metaverse. *Management Strategies and Engineering Sciences*, 7(5), 1-9. <https://msesj.com/index.php/mses/article/view/221>

- Karimi, L., Zohoori, S., & Amini, A. (2014). Multi-wall carbon nanotubes and nano titanium dioxide coated on cotton fabric for superior self-cleaning and UV blocking. *New Carbon Materials*, 29(5), 380-385.
- Kooshamoghadam, N., Zohoori, S., Bekrani, M., Shahsavari, S., & Talebikatieklahijany, R. (2022). Enhancing physical properties of viscose by preparing viscose/keratin/nano ZnO composite fabric. *Journal of Natural Fibers*, 19(13), 4846-4853.
- Mohamadiyan, M., Zohoori, S., & Davodiroknabadi, A. (2020). Enhancing electro conductivity, antibacterial and UV blocking of cotton fabric by using graphene/zirconium dioxide nano composite. *Indian Journal of Fibre & Textile Research*, 45(2), 207-210.
- Naddafiu, F., Zohoori, S., Yamin, F., Torabi, N., Chadorkafoor, F., Nasiripoor, R., & Jalalian, Y. (2024). Doping cork fibers with nanomaterials for the removal of organo-phosphorous pesticide. *The Journal of The Textile Institute*, 115(10), 1954-1961.
- Yamin, F., Naddafiu, F., & Zohoori, S. (2022). Electrospinning of eucalyptus cellulose nano fiber and improving its properties by doping nano materials. *Journal of Natural Fibers*, 19(13), 6770-6779.
- Zohoori, S., Zohoori, S., Mohamadiyan, M., Kooshamoghadam, N., Pourheidari, R., Charaki, M., ... & Heydarzadegan, I. (2025). Comprehensive characterization of electrospun natural latex nanofibers reinforced with TiO₂ and Cu nanoparticles for multifunctional applications. *Journal of Engineering and Applied Science*, 72(1), 156. <https://doi.org/10.1186/s44147-025-00750-5>
- Zohoori, S., Torabi, N., Gholami, E., Rastgoo, F., Rad, M., & Pourheidari, R. (2024). Synthesis of multifunctional nano composites incorporating halloysite nanoclay. *Discover Materials*, 4(1), 92. <https://doi.org/10.1007/s43939-024-00164-9>
- Zohoori, S., Shahsavari, S., Sabzali, M., Hosseini, S. A., Talebikatieklahijany, R., & Morshedzadeh, Z. (2022). Reinforcing of viscose fabric using nano web of palm-cellulose carbon mesoporous nanoparticle composite. *Journal of Natural Fibers*, 19(14), 8937-8945.
- Zohoori, S., Davodiroknabadi, A., & Dadmarz, N. (2017). Conceptual Costume Design: Utilizing Recyclable Materials to Help Sustain the Environment. *International Journal of Applied Arts Studies (IJAPAS)*, 1(1). Retrieved from <http://www.ijapas.ir/index.php/ijapas/article/view/32>
- Zohoori, S., & Sakeniyandehkordi, M. (2025). Interactive Art Posters Based on Electronic Technology. *International Journal of Applied Arts Studies (IJAPAS)*, 10(3), 93-102. Retrieved from <http://www.ijapas.ir/index.php/ijapas/article/view/589>
- Zohoori, S., Latifi, M., Davodiroknabadi, A., & Mirjalili, M. (2017). Vibration electrospinning of polyamide-66/multiwall carbon nanotube nanocomposite: Introducing electrically conductive, ultraviolet blocking and antibacterial properties. *Polish Journal of Chemical Technology*, 19(3), 56-60.
- Zohoori, S., Karimi, L., & Ayaziyazdi, S. (2014). A novel durable photoactive nylon fabric using electrospun nanofibers containing nanophotocatalysts. *Journal of Industrial and Engineering Chemistry*, 20(5), 2934-2938.

- Zohoori, S., & Karimi, L. (2013). Effect of nano SrTiO₃ supporting nano TiO₂ on self-cleaning of cotton fabric. *Fibers and Polymers*, 14(6), 996-1000. <https://doi.org/10.1007/s12221-013-0996-4>
- Zohoori, S., Payvandy, P., & Bekrani, M. (2021). Antibacterial, self-cleaning and UV blocking of wool fabric coated with nano Ce/ZnO and Ce/TiO₂. *Indian J. Fibre Text. Res*, 46(1), 57-62.