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Review Article

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Smart Textiles: An Interdisciplinary Overview of Advances, Applications, and Future Prospects

Faridul Islam Ovi[✉,1,2,*] **Rownak Jahan Shova**[✉,2] **M. Hasinur Rahman**[✉,3] **Nayon Chandra Ghosh**[✉,4]

[1] Department of Nanomaterials and Ceramic Engineering, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh
[2] Department of Textile Management, Bangladesh University of Textiles, Dhaka 1212, Bangladesh
[3] Department of Primary Industries and Regional Development (DPIRD), Government of Western Australia, Northam, WA 6441, Australia
[4] Gopalganj Textile Engineering College, Ghonapara, Gopalgonj 8100, Bangladesh

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Abstract
Smart textiles represent an innovative integration of nanotechnology, materials science, and wearable electronics, offering capabilities far beyond those of traditional textiles. This thorough review covers recent advances in engineered nanomaterial-based textiles, particularly discussing groundbreaking applications of these materials in health, energy, military, and consumer sectors. All four categories are critically reviewed: (1) Protective textiles incorporating flame-resistant nanocoatings, antibacterial nanoparticles, and UV-blocking semiconductor nanoparticles; (2) Energy-harvesting technologies based on piezoelectric, triboelectric, and thermoelectric nanomaterials, specifically designed for self-powered electronics; (3) Physiological monitoring interfaces using graphene sensors and optical fibers, intended for real-time biomedical monitoring and tracking; (4) Active materials exhibiting color-changing, shape-memory, and thermally responsive properties. The review highlights advances in materials science, including MXene-based textiles for electromagnetic shielding, phase-change materials for dynamic thermal control, and plasmonic nanostructures for interactive displays. We also discuss scalable processing technologies, including electrospinning of conductive polymers, roll-to-roll fabrication of textile-based solar cells, and atomic layer deposition of nanocomposite thin films. The emerging themes of biocompatibility in electronics, AI-based adaptive technologies, and sustainable nanotextiles are key research and development areas for next-generation textiles. By synthesizing evidence from more than 230 studies, this review provides researchers and industry stakeholders with insight into current capabilities and future opportunities for integrating smart textiles into practical applications.

Keywords:
nanomaterials; nanocoating; nanoparticles; smart textiles; wearable electronics; functional fabrics

1. Introduction

Nanotechnology, first proposed by Richard Feynman in 1959 and later formally introduced by Norio Taniguchi in 1974 [1,2], has dramatically transformed numerous industries, including medicine [3], agricultural sciences [4], environmental restoration [5], electronics [6], energy storage materials [7], solar technology [8,9], paints [10], and green chemistry [11,12]. By manipulating materials at the atomic and molecular levels, nanotechnology enhances physical and chemical properties at the nanoscale that cannot be achieved at the macroscopic scale. Nanomaterials derive their characteristics from their constituents, possessing at least one dimension at or below the 100-nanometer scale [13,14]. These materials exhibit noteworthy properties, including increased surface area, enhanced mechanical strength, improved electrical conductivity, and superior chemical stability at the nanoscale. Nanomaterials are widely used in medicine [15], wastewater treatment [16], textile dyeing [17], and sensing applications, including electrochemical, optical, piezoelectric, and magnetic sensors [18], amongst others.

* **Corresponding Author:**
Faridul Islam Ovi, Department of Nanomaterials and Ceramic Engineering, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh, ovislam1612@gmail.com

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As illustrated in Figure 1, certain nanomaterials such as zero-dimensional spheres or clusters exhibit distinct characteristics determined by their dimensionality [19]. Nanomaterials may be made hydrophilic or hydrophobic based on application requirements. Nanoparticles are composed of three distinct layers. These are labeled as follows: (i) Surface layer that comprises particles/ions/surfactants/polymers. (ii) Shell layer with bonds of constituents of the material (iii) Core layer that forms the center of the nanoparticle [20,21].

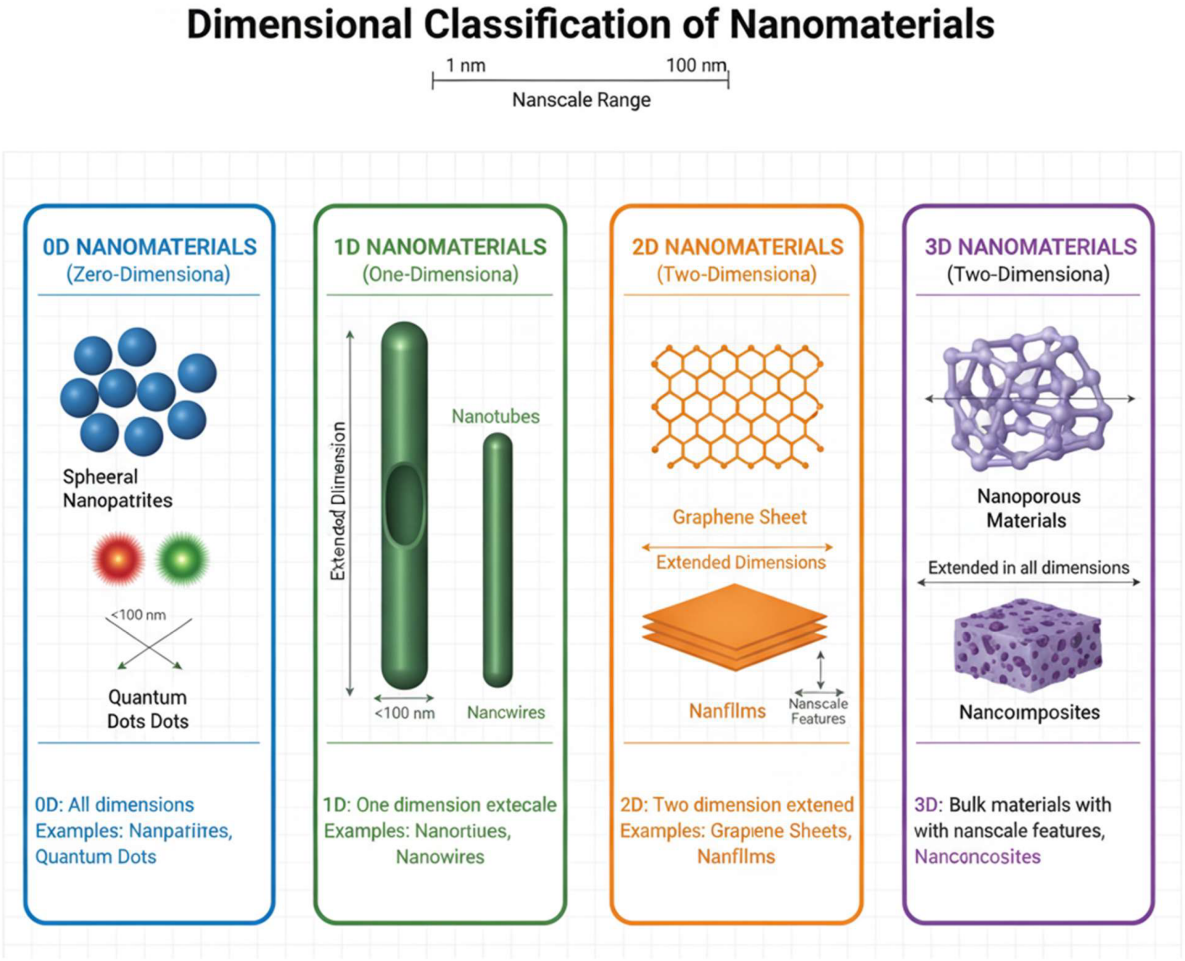


Figure 1: Types of nanomaterials (0D, 1D, 2D, and 3D).

The textile industry has traditionally advanced through improvements in materials science and evolving performance requirements. Smart textiles that integrate nanomaterials into conventional fabrics exhibit multifunctional characteristics, offering capabilities that extend far beyond aesthetics and comfort. Smart textiles are applied across pharmaceuticals, healthcare, sports, fashion, protective clothing, and transportation-related electronics [15]. A great variety of nanomaterials have been considered, such as ZnO [22,23], TiO_2 [22], Ag [24], cerium oxide [23], CNT [25], Au [26], Pd [27], and Cu [28], with a view to augmenting the performance of textiles. By this method of material incorporation, textiles tend to possess antimicrobial properties, increased sustainability/longevity, and interactive behavior that reacts effectively with the environment.

The growing need for sustainability has led to a further demand for innovation driven by nanotechnology. The textile manufacturing sector, a major contributor to global production, is gradually adopting eco-friendly strategies that make the most of available resources while remaining environmentally friendly. Nanotechnology can improve product sustainability and reduce material waste during production [29]. Further, the significance of nanomaterials as a tool for addressing global challenges continues to grow [30,31].

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In contrast to existing reviews that focus on specific innovation areas of smart fabrics, such as antibacterial coatings [32,33], energy harvesting technologies [34, 35], and wearable sensor technologies [36–38], this text uniquely integrates these diverse innovation areas under the concept of multifunctionality enabled by nanomaterial science. For instance, although Li et al. [35] and Kim et al. [36] examine piezoelectric textiles, their reviews do not address thermal management or photonic system integration. Additionally, although Plé et al. [24] provide an in-depth review of the performance of silver nanoparticles in antimicrobial textiles, they do not address the scalability or multifunctionality of these materials. This text therefore addresses this gap by demonstrating the diverse application areas of these materials across multiple industries, ranging from military gear with flame retardant properties [39] to technologically sophisticated fashion interfaces capable of adaptive color pattern changes [40], as well as the fabrication technologies that enable the integration of these multifunctional constructs. Additionally, although the reviews limit discussion to single-fabric materials [41,42], this text expands the discussion to a variety of materials across different hybridization scenarios. Examples include MXene-coated cotton fabrics [43] and photonic fiber arrays [44], which could facilitate the development of multifunctional, scalable, and sustainable smart-fabric technologies at an unprecedented scale.

Although numerous reviews provide valuable insights into smart textiles, several critical shortcomings remain that this study addresses. Reviews that focus on a single area of study, such as antibacterial coatings [32,33] or energy harvesting [34,35], may provide valuable insights, but they overlook the integrated approach combining protection, energy harvesting, sensing capabilities, and fashion that is presented in this study. As an example of this lack of integrated reviews, Li et al.'s study on piezoelectric textiles offers an in-depth approach but completely neglects temperature-regulation mechanisms that could improve the efficiency of electricity harvesters under temperature changes. Additionally, the antibacterial textile study by Plé et al. evaluates durability for only 50 washing cycles, whereas garment-industry standards may require performance beyond 100 cycles [24]. Analyses that focus on single-system fabrics [41,42] often overlook the incorporation of hybrid materials. For example, cotton coated with MXene can achieve a specific conductivity of up to 922 S/cm, a performance that cannot be attained using polyester alone.

Recent reviews on nanofiber-based wearable sensor technologies [45] have further advanced the discussion of thermal management strategies and their heating, ventilation, and air conditioning (HVAC) implications, with particular attention to radiative cooling in health care. Nevertheless, these reviews focus more on the sensor's performance characteristics than on scalability issues in fabrication (laboratory-scale electrospinning and roll-to-roll fabrication), the integration of the sensor with an auxiliary power source (textile-based supercapacitors), and the convergent technology of protection and power (sensing and power harvesting). This distinction defines the contribution of the present review.

This work consists of three aspects:

(1) Cross-domain application projection—a crossover relationship of flame-retardant equipment used by the military [39] with temperature-changing wearables of the fashion industry [40] on the premise of nanomaterial convergence technologies, starting with titanium dioxide protection materials of the solar cellphone sector;
(2) Scale incorporation—the viability of solar cellphone roll-to-roll printing technology and spray-drying MXene-coated materials;
(3) Convergence—the intersection of MEMS technology incorporation and AI adaptability with environmentally responsible materials on the premise of next-generation textiles. This approach links application development with pathways to commercial translation.

This study examines the evolution of nanotechnology over the years and explores its future prospects within the field of textiles. The significance of nanomaterials in the development of intelligent textiles cannot be overlooked, as they have the potential to significantly impact the global sustainability agenda.

2. Smart Protective Textiles

2.1. Flame-Retardant Textiles

The integration of nanomaterials into textiles has transformed flame retardancy by overcoming the limitations of conventional additives, including poor durability, environmental toxicity, and reduced mechanical performance. Nanoparticles improve flame resistance through three mechanisms: (1) forming physical barriers that limit heat and mass transfer; (2) promoting char formation; and (3) scavenging reactive radicals during combustion.

2.1.1. Nanoclays and Silicates

Nanoclays, such as montmorillonite, are among the most investigated halogen-free flame retardants because of their high aspect ratio and ease of dispersion in polymeric matrices. Nanoclays incorporated into polyamide 6/clay

nanocomposite monofilaments reduce the peak heat release rate (PHRR), which is a key measure of fire performance representing the maximum energy released during combustion, by up to 33 percent compared with polyamide alone [46]. Functional nanoclays, when incorporated with halogen-free phosphoric flame retardants (FRs) in polyamide 6.6, form an interconnected char layer in greater proportion. This promotes formation of a condensed-phase char layer, which reduces flammability [47]. A study revealed that even, by adding low levels of halogen-free phosphoric flame retardants ($\leq$5%) to isotactic polypropylene prevents melt dripping and ignition [48].

2.1.2. Metal Oxides and Hydroxides

Nano-metal oxides like TiO_2, Al_2O_3, and Mg $(OH)_2$ take advantage of their exceptional thermal stability and catalytic properties to offer flame retardancy. For example, nanosized TiO_2 coatings on cellulosic fabrics, produced via the sol-gel process, offer dual properties: self-cleaning and flame retardation. Additionally, the titanium dioxide coating acts as an insulating layer that slows pyrolysis and suppresses smoke emissions [49]. Al_2O_3 nanoparticles deposited on polyester fabrics using plasma technology offer enhanced flame retardation properties due to the ceramic-like insulating layer that hinders oxygen transport and the subsequent combustion process [50]. Nano-Mg $(OH)_2$ combined with SiO_2 suppresses smoke emission by an average of 40% in polypropylene materials [51].

2.1.3. Hybrid and Bio-Inspired Systems

Recent innovations lie in the development of hybrid designs consisting of nanoparticles and either bio-based polymers or intumescent coatings. Chitosan (CS), a biodegradable polysaccharide, has recently emerged as an attractive candidate for flame-retardant coatings on cotton materials. CS nanocomposites, with the application of phytic acid and the addition of titania nanoparticles (Figure 2a,b), show a 50% reduction in the PHRR index and exhibit extinction due to accelerated char release and low-flux heat transfer [52]. On the other hand, layer-by-layer assembly of polyelectrolytes with h-BN nanosheets yields hybrid materials that combine flame retardation and water repellency [53]. Bio-based designs, including the laminating of fabrics with hydrogels that possess resistance capabilities akin to natural materials' absorption of heat (Figure 2c,d), activate the natural absorption of heat. Hydrogels laminated onto cotton fabrics based on polyvinyl alcohol-borax can delay the ignition of cotton by up to 120 s and reduce the rate of heat release by 60% through endothermic water release and char stabilization [54].

A hybrid flames retardant system exhibits synergy through the incorporation of nano-scale materials. As shown in Figure 2e above, the fabrication of the APP@SiO_2-PDA@Ag polyester fabrics involves stepwise coating of the fabrics with ammonium polyphosphate (APP) coated with a shell of silicon dioxide (SiO_2), which inhibits early degradation during fabric production. The fabrics are further coated with polydopamine (PDA) that serves as a binding agent between the silver nanoparticles and the fabrics. The system exhibits dual functionality, with a limiting oxygen index of 32 percent for flame retardancy and the ability to eliminate up to 99.9 percent of bacteria within 24 h, demonstrating how nanoparticle surface engineering enables multifunctional textiles [55].

2.1.4. Synergistic Effects with Conventional Flame Retardants

Nanomaterials integrated with conventional FRs (halogenated materials and phosphorus derivatives) mitigate efficiency and sustainability issues. As an example of this approach, the dispersion of ammonium polyphosphate (APP) nanoparticles using SiO_2-PDA@Ag core-shell structures (Figure 2e) improves the material's distribution on polyester fabrics. This results in a limiting oxygen index of 32% and a UL-94 rating of V-0 for the sample. The addition of silver nanoparticles imparts antibacterial activity to the material [55].

2.2. Antibacterial and Antimicrobial Textiles

The world's need for clean and infection-proof clothing spurred the development of nanotechnology-based antimicrobial textiles. Antimicrobial textiles play a crucial role in the fields of medicine and sportswear due to their importance in suppressing pathogen growth. Nanoparticles such as silver (Ag), titanium dioxide (TiO_2), zinc oxide (ZnO), and copper oxide (Cu_2O) have been used as potent antimicrobial agents owing to their high surface-area-to-volume ratios, reactivity, and diverse mechanisms of action (Figure 3) [32,56–58]. This part of the discussion delves into the mechanisms of action and issues associated with these nanomaterials, with specific reference to their development for use in textiles.

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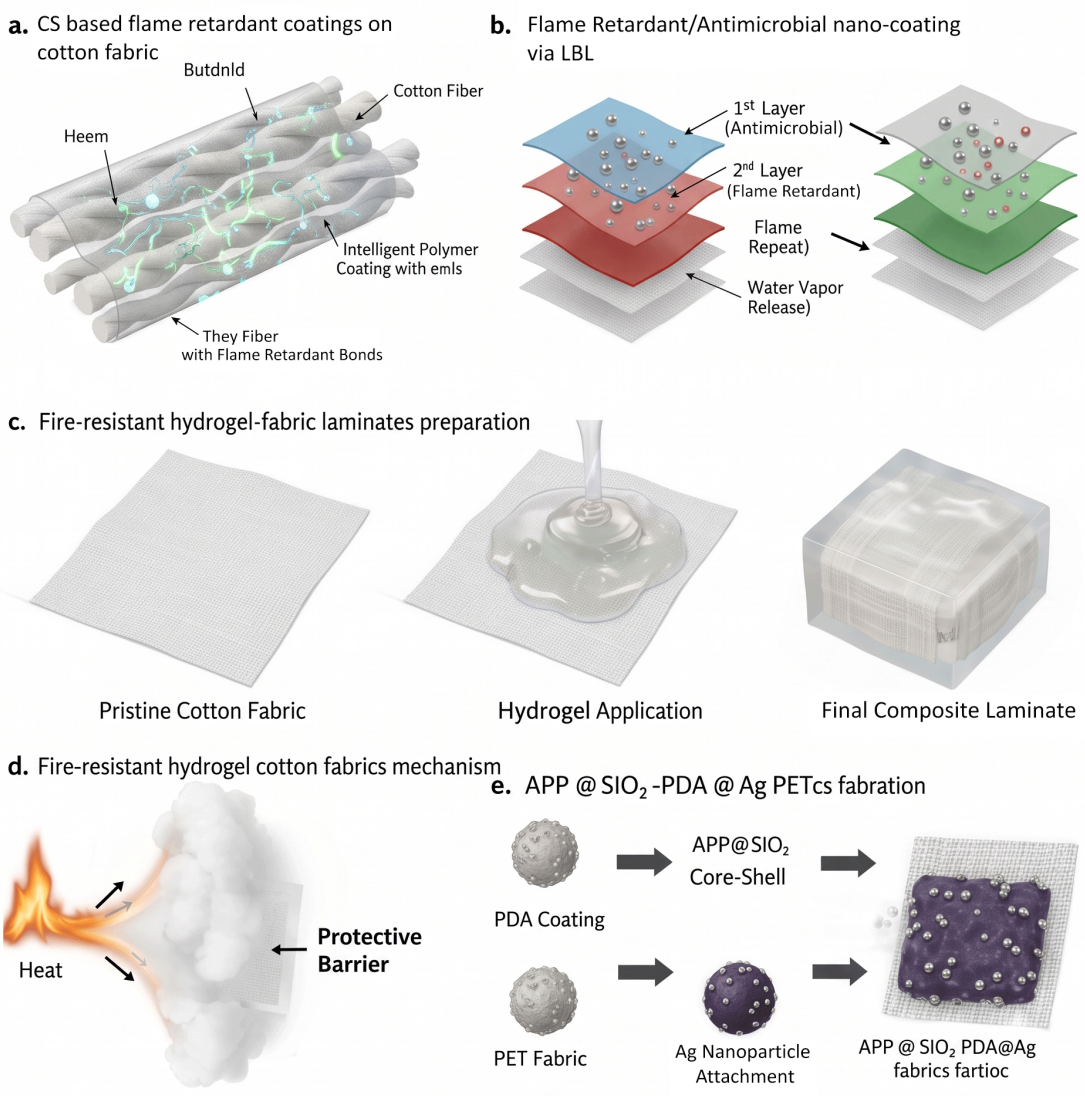


Figure 2: (**a**) CS based flame retardant coatings in a cotton fabric. (**b**) Flame retardant/antimicrobial nano-coating on cotton through LBL incorporation. (**c**) Fire-resistant hydrogel-fabric laminates preparation. (**d**) Fire-resistant hydrogel cotton fabric laminates mechanism. (**e**) APP@SiO_2-PDA@Ag PET fabrics fabrication process.

2.2.1. Mechanisms of Antimicrobial Action

Nanoparticles exert antibacterial effects through physical disruption, ion release, and reactive oxygen species (ROS) generation:

Silver Nanoparticles (Ag NPs): Ag NPs release Ag^+ ions upon contact with moisture, which penetrate bacterial cell walls, bind to sulfur-containing proteins, and disrupt electron transport chains, leading to DNA condensation and cell death [33,57,59,60]. Smaller silver nanoparticles (<20 nm) exhibit greater efficacy due to higher ion release rates [61].

TiO_2 and ZnO NPs: Under UV illumination, ROS (like hydroxyl radicals) produced by TiO_2 NPs react with the organic materials of microbial cells [56,62], whereas ZnO NPs release ROS along with Zn^{2+} ions that degrade the bacterial cell membranes and suppress the development of biofilms [63,64].

Chitosan and N-Halamine: Chitosan, a biopolymer, disrupts microbial membranes via electrostatic interactions with negatively charged microbial cells [32]. N-Halamine compound reacts with pathogens by producing reactive bromine and chloride ions due to its broad-spectrum activity [65].

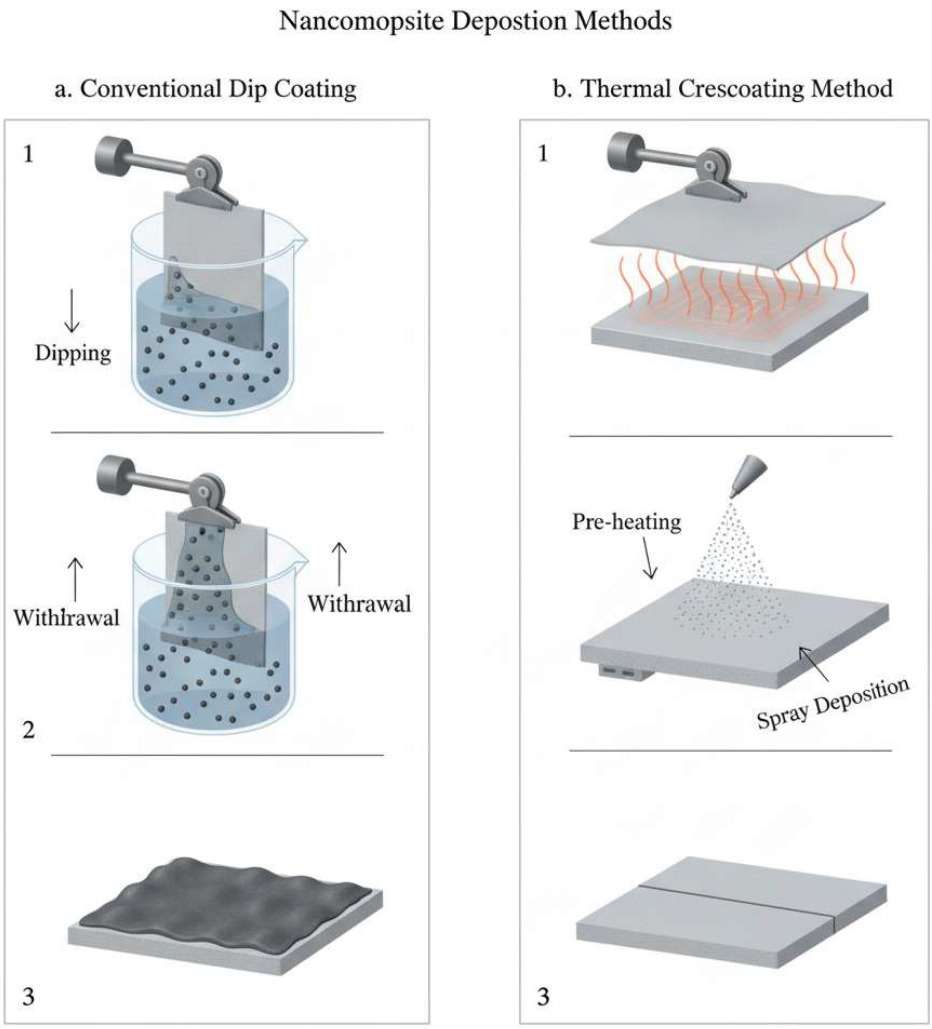


Figure 3: Nano-composite deposition methods: (**a**) Conventional, dip coating (**b**) Thermal Crescoating method.

2.2.2. Application Techniques and Performance

The durability and uniformity of nanoparticle coatings are pivotal for long-term functionality. Key methods include:

Electrospinning: Incorporating silver nanoparticles or titanium dioxide into polyurethane and cellulose acetate nanofiber matrices enhances interfacial bonding between the materials. This creates a system that sustains antibacterial activity even after more than 50 washing cycles [66,67]. As shown in Figure 3a, the conventional method of dipping the cotton fabric into nanoparticles and then drying them results in an uneven distribution of the material on the fabric's surface, which may come off after the first few cycles. The Ag NP-doped polyacrylonitrile fibers reduced Staphylococcus aureus viability by 99.9% within 4 hours [68].

Coating Techniques: There are various techniques employed for coating with antimicrobial nanoparticles. One such technique is the thermal crescoating technique (Figure 3b), which uses the heat treatment process for binding nanoparticles to fibers [60]. Another such technique is layer-by-layer (LBL) assembly, where chitosan and silver nanoparticles are coated alternately on cotton fabrics in order to obtain a six-log decrease in *E. coli* [69].

Sol-Gel Coatings: ZnO NPs incorporated on a polyester matrix with the aid of TEOS binders showed a reduction of Candida albicans growth by 95%, with insignificant degradation of the activity after abrasion test procedures [70].

2.2.3. Synergistic Nanocomposites

Hybrid systems combining multiple nanomaterials amplify antimicrobial effects and mitigate resistance development:

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Ag-TiO_2 Composites: The release of silver ions upon the addition of titania nanoparticles significantly improves the system's photocatalytic activity toward ROS-dependent cytotoxic effects. A study of cotton fabrics coated with these composites showed up to a 4.3-fold increase in antibacterial activity compared with bare silver [62].

Chitosan-ZnO: prevents the agglomeration of ZnO NPs and improves adhesion on the substrate. This material increased the tensile strength of surgical gowns by 15% and reduced microbial growth by 99% [64].

2.2.4. Evaluation of Efficacy

The broth microdilution method (Figure 4) assesses the efficacy of antimicrobial agents based on the measurement of the MIC and the optical density of the microbial cultures [65]. A practical application of this method was demonstrated in the case of cotton fabrics coated with titanium dioxide nanoparticles, showing an MIC of 12.5 μg/mL against Staphylococcus epidermidis, with the average optical density of the cultures at 600 nm inversely correlating with nanoparticle concentration [56].

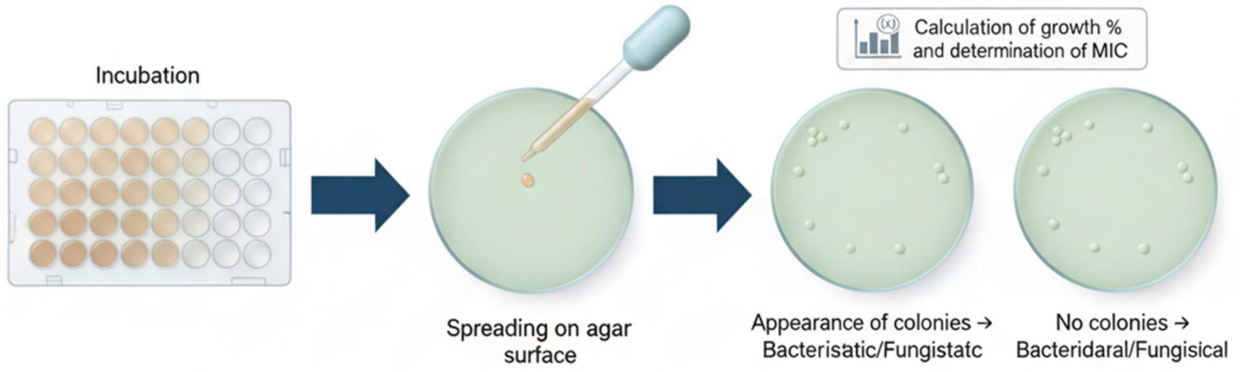


Figure 4: Antimicrobial efficacy assessment via broth microdilution methods. Optical density (OD_{600}) measurements at varying nanoparticle concentrations quantify bacterial growth inhibition, enabling the determination of minimum inhibitory concentration (MIC). Lower OD values indicate enhanced antimicrobial performance, as demonstrated for TiO_2-coated cotton fabrics (MIC: 12.5 μg/mL against *Staphylococcus epidermidis*).

2.3. Thermo-Regulating Textiles

The creation of next-generation textiles capable of continuously regulating human body temperature is of utmost importance for improving human comfort under harsh environmental conditions, reducing energy consumption, and enabling wearable technologies [71,72]. Currently, new technologies utilize nanomaterials, phase-changing materials, and bio-inspired designs to achieve precise thermal management [73]. This part of the discussion focuses on the various strategies involved in heating and cooling textiles.

2.3.1. Phase-Change Materials (PCMs)

PCMs that readily absorb and release latent heat during phase transitions are typically incorporated into fabrics as an active material with a passive cooling system. This approach results in coaxially electrospun structures in which phase-change materials such as paraffin wax are incorporated into polyurethane membranes, providing high heat enthalpy of 106.9 J/g along with reliable temperature cycling performance [74]. This enables temperature regulation, with heating reaching up to 73.8 °C under electromagnetic activation and up to 70.5 °C under solar activation, making them suitable for wearable adaptive sportswear and outdoor equipment [74]. Furthermore, combining PCMs with photothermal components, such as carbon nanotubes, improves solar heating efficiency and enables dual action for cooling and heating [75]. Future designs of PCM-integrated textiles will leverage artificial intelligence to optimize thermal energy storage, with machine learning algorithms enabling improved prediction of PCM thermal properties, enhanced heat transfer, and improved operational efficiency in temperature-regulation systems for wearable applications [76].

2.3.2. Conductive and Radiative Cooling

Highly thermally conductive materials such as copper (Cu) and graphene are used in textiles to enhance heat dissipation. The integrated cooling (i-Cool) fabric, with copper-coated nylon-6 nanofibers, offers cooling efficiency up to 3.5 °C higher than conventional fabrics [73]. Mid-infrared (MIR) transparent textiles, embedded with ZnO or SiO_2 nanoparticles, enhance radiative cooling by

emitting body heat (7–14 μm wavelengths) while reflecting solar radiation (0.3–2.5 μm) (Figure 5a) [77]. This reduces skin temperature by up to 2–4 °C under direct solar radiation, even when worn over cotton [77].

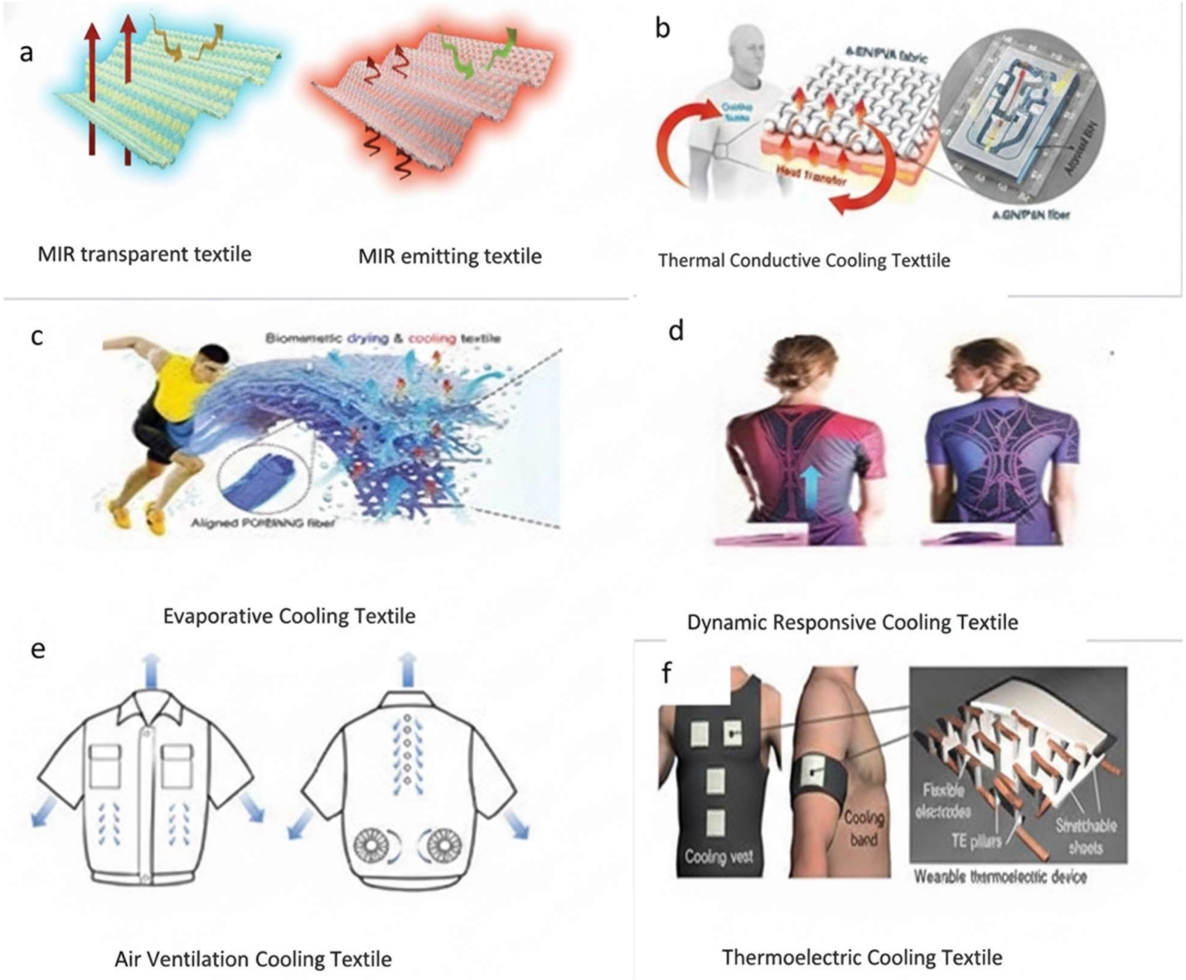


Figure 5: (**a**) MIR transparent & emitting cooling textile. (**b**) Thermal conductive cooling textile. (**c**) Evaporative cooling textile. (**d**) Dynamic responsive cooling textile. (**e**) Air ventilation cooling textile. (**f**) Thermoelectric cooling textile.

2.3.3. Active Cooling Systems

Active systems employ energy inputs for on-demand thermal regulation:

Electrothermal and Photothermal Systems: Graphene-coated textiles (Figure 5b) provide Joule heating, reaching 73.8 °C at 5 V, while vanadium dioxide (VO_2)-embedded fabrics dynamically adjust solar absorption for adaptive warming [77,78].

Evaporative Cooling: Biomimetic fabrics replicate human sweat glands through hierarchical porous structures. For example, cellulose acetate nanofibers with hydrophobic-hydrophilic gradients (Figure 5c) enhance moisture-wicking, reducing skin temperature by 5.2 °C within 10 min of activity [79].

Dynamic Responsive Materials: Stimuli-responsive polymers, such as poly(N-isopropylacrylamide) (PNIPAM), enable temperature-dependent adjustments in porosity. These "smart" fabrics reversibly transition between insulating (closed pores at <32 °C) and cooling (open pores at >32 °C) states, maintaining thermal comfort across diverse climates (Figure 5d) [80].

Air Ventilation: Textiles with incorporated microfluidic channels or fans based on piezoelectric materials improve convective cooling. Optimized fan placement using computational fluid dynamics modeling reduces air-gap distances and increases convective cooling efficiency by improving heat transfer (Figure 5e) [72,81].

Thermoelectric Generators (TEGs): Bismuth telluride (Bi_2Te_3) TEG fabrics replace conventional textiles

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and leverage the Seebeck effect by harnessing the skin's natural temperature difference, converting the resulting heat into electricity. A wearable TEG matrix (Figure 5f) delivers a power density of 3.2 μW/cm^2 at a temperature difference of 5 °C, sufficient to power micro-sensors [82].

2.4. UV-Protective Textiles

Ultraviolet (UV) radiation poses significant risks to human health, including skin cancer, premature aging, and immune suppression. As a response to such threats, nanotechnology has enabled the development of advanced UV-protective fabrics made using inorganic and organic nanomaterials (Figure 6) [83]. These materials increase the Ultraviolet Protection Factor (UPF), a quantitative measure of a fabric's ability to block UV radiation, by absorbing or scattering harmful UVB (280–315 nm) and UVA (315–400 nm) wavelengths. This section critically evaluates the mechanisms, efficacy, and durability of UV-blocking nanomaterials, emphasizing their role in sustainable textile innovation.

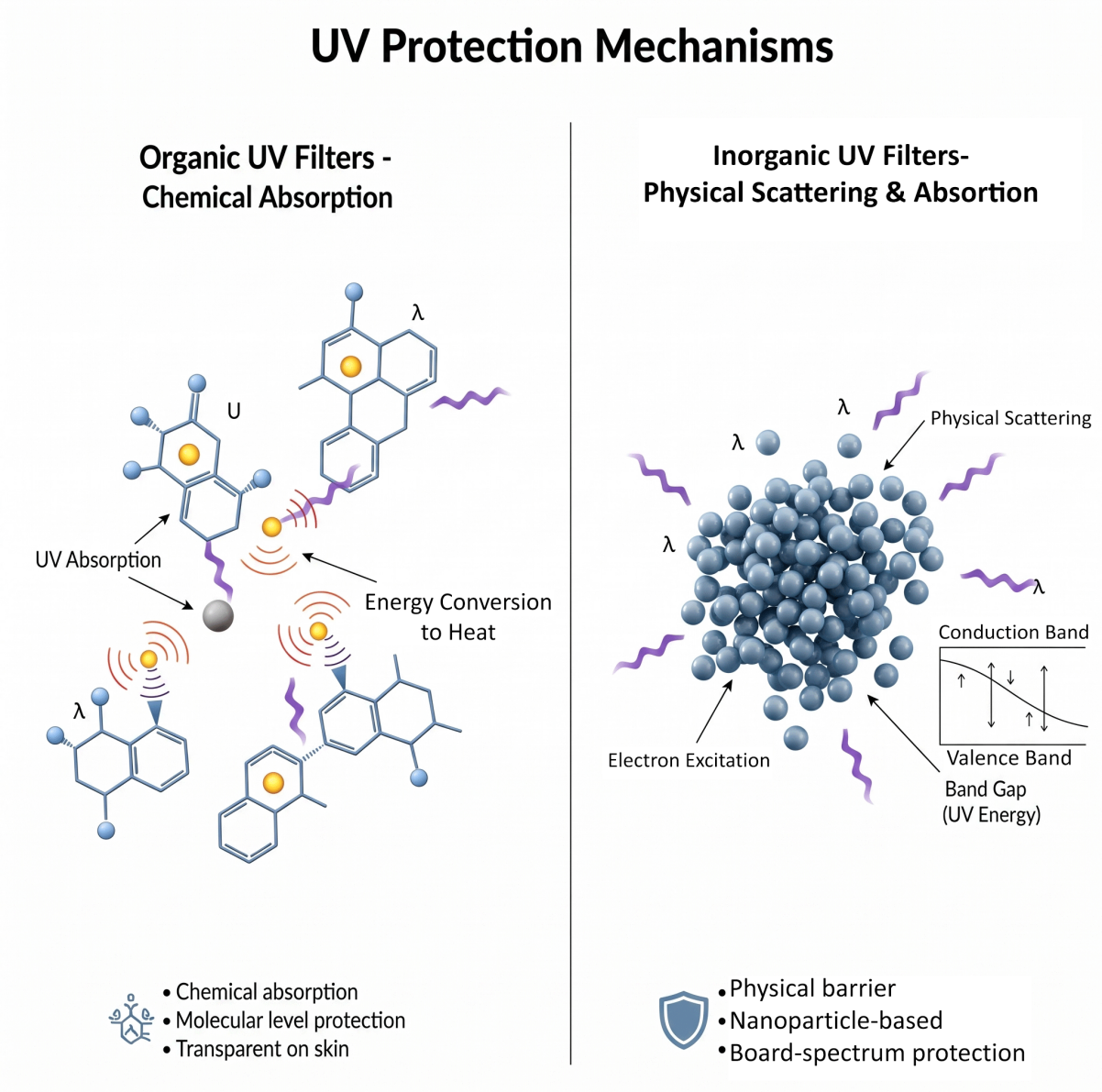


Figure 6: Organic UV filters & inorganic UV filters.

2.4.1. Inorganic UV Blockers: Mechanisms and Performance

Inorganic nanomaterials, particularly metal oxides such as titanium dioxide (TiO_2), zinc oxide (ZnO), and aluminum oxide (Al_2O_3), are commonly used in UV-blocking textiles. They provide broad-spectrum absorption, stable photostability, and are non-toxic [82–84].

TiO_2 Nanoparticles: TiO_2 absorbs UV strongly by kicking electrons up from the valence to the conduction band. When applied to cotton using sol-gel methods, TiO_2 coatings maintain a UPF > 50 (superb shield) even after 20 wash cycles, demonstrating excellent wear resistance (Figure 7) [85].

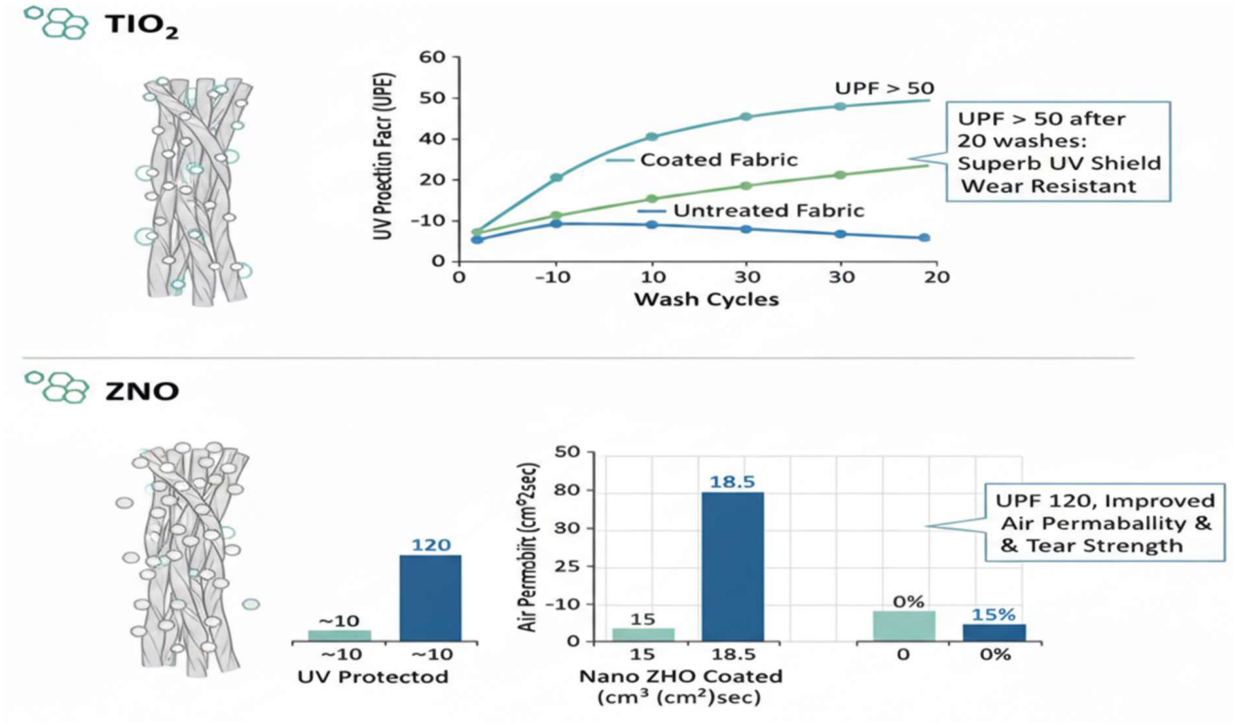


Figure 7: Performance of nanoparticles coating on cotton fabric.

ZnO Nanoparticles: ZnO has a wide bandgap of 3.37 eV, making it effective at absorbing UV light in the UVA range. Sundaresan et al. found that cotton fabrics coated with nano ZnO have a UPF of 120 and have air permeability (18.5 $cm^3/cm^2/s$) and tear strength (15% increase) better than untreated fabrics [85].

Al_2O_3 Nanoparticles: Al_2O_3 acts as a UV reflector, scattering incident radiation. Its synergistic use with TiO_2 in acrylic coatings on Kevlar fabrics reduced UV-induced loss of tensile strength by 40% after prolonged exposure [86].

2.4.2. Organic UV Blockers and Hybrid Systems

Organic UV absorbers such as benzotriazoles and avobenzone provide additional protection by absorbing specific UV wavelengths; however, their degradation and leaching limit their use as single active ingredients [87]. Mixtures of organic UV-absorber materials with nanoparticles of chemical elements (like zinc oxide-benzotiazole) overcome these disadvantages. Additionally, zinc oxide–benzotriazole mixtures achieved a UPF of 200 on polyester textiles, maintaining an absorption capacity of up to 85 percent even after 50 washes [88,89].

2.5. Hydrophobic and Oleophobic Textiles

Hydrophobicity (water repellency) and oleophobicity (oil repellency) are essential textile functionalities for applications ranging from waterproof apparel to anti-fouling industrial fabrics. These properties are achieved by engineering surface roughness and reducing surface energy through nanomaterials, inspired by natural systems such as lotus leaves and duck feathers.

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2.5.1. Biomimetic Designs and Natural Inspiration

The hierarchical nano- and micro-structured surface of the lotus leaf, along with its waxy coating, has been mimicked using carbon nanotubes and silicone materials. CNTs on cotton fabrics form a highly water-repellent surface with a water contact-angle of over 150 degrees, thereby exhibiting lotus-like water repellency like the lotus leaf surface [90]. Likewise, the water-repellent feathers of the duck with preening oil have led to the development of chitosan-silicone nanocomposite materials on polyester fabrics, with water and oil contact angles of 145 degrees and 130 degrees, respectively.

2.5.2. Nanoparticle-Enhanced Coatings

SiO_2 nanoparticles are widely used due to the versatility of their surface chemistry. On cotton fabrics coated with poly(quaternary ammonium salt) (PQAS)-functionalized SiO_2 coatings, the WCAs of the fabrics are found to be as low as 155°, and the OCAs are measured at 140° (Figure 8) [91]. Furthermore, applying fluorinated clay–fluoropolymer mixtures via the dipping process reduces the surface energy of materials while maintaining breathability, resulting in oleophobic properties suitable for applications such as medical gowns [92].

2.5.3. Advanced Fabrication Techniques

Layer-by-layer assembly and plasma treatment improve the durability and homogeneity of the coatings. For example, layer-by-layer assembly of PDMS and SiO_2 nanoparticles on cotton forms a crosslinked structure that retains its WCA after more than 50 laundry cycles, with negligible WCA degradation [93]. Alternatively, plasma treatment of polyester fabrics facilitates activation of the hydroxyl groups on the material's surface, enhancing adhesion of hydrophobic ZnO nanoparticles and resulting in WCAs exceeding 150° (Figure 8) [94].

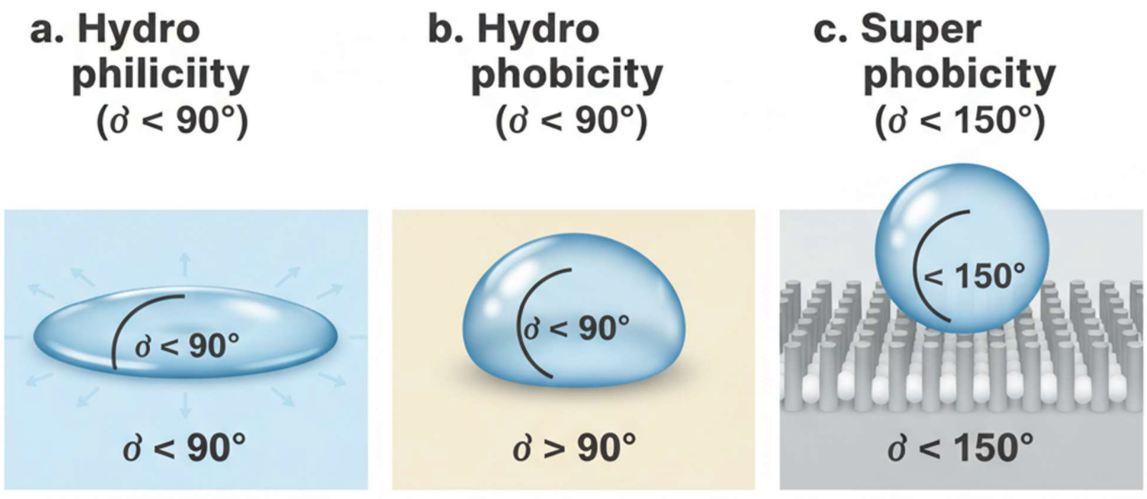


Figure 8: Schematic diagram of (**a**) hydrophilic contact angle (θ) < 90° (**b**) hydrophobicity contact angle (θ) > 90° (**c**) superhydrophobicity contact angle (θ) > 150°.

2.5.4. Janus and Multifunctional Textiles

Janus-type amphiphilic nanoparticles, featuring both hydrophobic and oleophobic phases, enable selective repellence. By cross-linking these nanoparticles with fibers, fabrics with anisotropic wettability characteristics, being hydrophobic on one side and oleophobic on the other side, can be generated for oil-water separating membranes [95]. Additionally, cotton fabric modified with epoxy and embedded with amino-silica and ZnO nanoparticles simultaneously exhibits superhydrophobicity (water contact angle = 158°) and flame retardancy with a limiting oxygen index (LOI) of up to 28 percent, highlighting its multifunctional potential [96].

2.6. Antistatic Textiles

The accumulation of static charge on synthetic fabrics like nylon and polyester can cause discomfort and electrostatic discharge. Nanomaterials that increase surface conductance or wettability have recently emerged as antistatic solution. This section will briefly enumerate strategies for rendering materials antistatic through the integration of nanomaterials, based on their method of action.

2.6.1. Conductive Nanomaterials for Static Dissipation

Conductive nanoparticles such as ZnO whiskers and TiO_2 have been widely used as additives in synthetic fabrics to enhance their electrical conductivity. ZnO whiskers with a star-like morphology form interconnected networks that reduce the surface resistivity of polypropylene by up to three to four orders of magnitude [97]. Likewise, the dispersion of TiO_2 nanoparticles (<50 nm) in polyester fabrics leverages their semiconductor properties to reduce static voltages above 2 kV to below 200 V, as measured with electrostatic field detectors [98].

2.6.2. Hybrid and Doped Systems

Antimony-doped SnO_2 nanoparticles exhibit higher electrical conductivity due to electron donation fromSb^{5+} ions. As SnO_2 nanoparticles are incorporated into polyacrylonitrile (PAN) fibers, the surface resistivity decreases to 108 Ω/sq, thereby inhibiting charge accumulation at the surface even under low-humidity conditions [97]. Sol-gel coatings based on hydrolyzed silanes (TEOS) increase surface hydrophilicity and moisture uptake, reducing static charge via humidity-dependent conductivity [99].

2.6.3. Surface Modifications and Commercial Solutions

Using a sol-gel method, eco-friendly octylsilane-modified amino-functional silicone coatings yield superhydrophobic surfaces with water contact angles exceeding 150 degrees while maintaining breathability. On the other hand, incorporating ZnO nanoparticles into polyester fabrics imparts antistatic properties, with a surface resistivity of around 10^6 Ω/sq, enabling quick discharge of static electricity [100].

2.7. Smart Military Textiles

Smart military textiles represent a technological innovation designed to enhance soldier capabilities. They incorporate multifunctional materials with embedded systems for improving survivability, situation awareness, and operational efficiency. Military environments involve extreme operating conditions, and smart military textiles offer innovations in physiological monitoring, ballistic protection, camouflage, and environmental countermeasures.

2.7.1. Physiological Monitoring and Health Tracking

Integrated biosensors in military uniforms enable real-time monitoring of vital signs such as heart rate, respiratory rate, and body temperature. For example, graphene-based clothing in flexible armband design's function and achieving unencumbered mobility [101,102]. Correspondingly, optic fiber sensors mounted on flexible clothing provide respiration rate measurement with <5% error margin from clinical spirometry, yielding essential information for fatigue analysis in combat environments [103]. Fiber Bragg grating designs mounted on flexible chest straps enable real-time observation of respiration while maintaining unencumbered mobility for soldiers [103].

Beyond conventional biosensing platforms, the use of MEMS in textiles enables miniaturized, multifunctional platforms that integrate biosensing, environmental monitoring, and other capabilities into a single device. Body-worn MEMS pressure sensors integrated into protective equipment serve dual purposes by monitoring physiological parameters, such as respiration rate through chest movement detection, and by detecting blast overpressure events to assess the risk of traumatic brain injury in military personnel [104]. The ultra-low power consumption exhibited by the MEMS resonator, which is made possible through electrostatic actuation, is below one microwatt. When combined with an MXene textile supercapacitor capable of powering wireless temperature sensors for up to 96 minutes, the need for battery replacement is eliminated [105].

2.7.2. Ballistic and Impact Protection

High-performance materials such as ultra-high molecular weight polyethylene (UHMWPE) and aramid fibers (Kevlar, for example) demonstrate extreme strength-to-weight ratios and have the potential to absorb 90% of ballistic energy [106]. Shear thickening fluids (STFs) containing silica nanoparticles increase flexibility while stiffening in response to projectile collision, with 40% less penetration depth in comparison to other materials [39]. Nanotechnology also enhances protective properties, as carbon nanotube-reinforced composites distribute kinetic energy through intertwined nanowire matrices, increasing puncture resistance by 35 percent compared with conventional protective gear [107].

2.7.3. Adaptive Camouflage and Stealth Technologies

Electrochromic fabrics based on conjugated polymers or metal-organic frameworks (MOFs) dynamically switch color and reflectance in response to environmental changes. For instance, WO_3-based fabrics require only 0.5 s to transition from woodland green to desert tan in response to a 5 V stimulus [108]. Thermochromic phase-change materials (PCMs), such as polyethylene glycol (PEG)-Kevlar aerogels, dynamically regulate in-

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frared signatures to match environmental backgrounds in emission (0.94 matched to environments), with thermal detection ranges shortened by 60% [109]. Biomimetic CAM patterns based on plasmonic nanostructures replicate chameleon skin's dynamic color changes, with studies underway on scalability [110].

2.7.4. Environmental and Hazard Protection

Nanotechnology-based textiles offer protective mechanisms for chemical and biological threats. Silver (Ag) and zinc oxide (ZnO)-nanoparticle-impregnated polyester-cotton blends can inactivate >99.9% Bacillus anthracis spores within 30 min via ROS production [66,111]. Colorimetric changes in copper benzene tricarboxylate-treated cotton, which was coated with metal-organic frameworks (MOFs), allowed real-time detection of toxic gases such as sarin [112]. Chitosan–polyurethane dispersions with self-healing properties maintain their integrity in nuclear, biological, and chemical (NBC) protective suits after multiple stress cycles [113].

2.7.5. Electromagnetic Interference (EMI) Shielding

Conductive polymer composites with graphene, MWCNTs, and MXene/AgNW hybrids provide EMI shielding effectiveness (SE) in the range of 40–60 dB for the 8–12 GHz frequency band [43,114]. Aramid nanofiber (ANF)–MXene papers, fabricated via vacuum-assisted filtration, combine flexibility with an EMI shielding effectiveness exceeding 50 dB, protecting communication systems from interference [43].

2.7.6. Infrared (IR) and Thermal Stealth

Thermal emissivity-engineered textiles, such as KNA/PCM laminates, adjust thermal emission to blend in with the surroundings. These fabrics obscure infrared contrast by 70%, as they pass thermal imaging cameras [115]. Metamaterials with negative refractive indices can obscure thermal signatures, although miniaturized technology is required for practical applications in operational environments [116].

2.7.7. Advanced Material Innovations

Nanocellulose, obtained from plants or bacteria, improves fire-resistant properties and enhances filtration in military applications. Its tensile strength (7.8 GPa) and low density (1.6 g/cm^3) make it most preferred for use in lightweight ballistic shields [97]. Hybrid nanocomposites, like polymer/Graphene-CNT, provide multiple functionalities together: flame resistance (LOI > 30%), EMI, and Joule heating functionality (50 °C at 5 V for Arctic applications) [117].

These advances are reshaping military textile design by integrating nanotechnology, sensing, and biomimetic strategies to improve safety and operational performance.

3. Energy Collector Smart Textile

3.1. Energy-Harvesting Smart Textiles

Energy-harvesting textiles exemplify the next-generation paradigm in wearable electronics, converting biomechanical motion, body heat, and solar radiation into power for embedded electronics. Such systems can completely eliminate dependence on external batteries, enabling self-powered smart textiles for applications in healthcare, the military, and consumer use. The mechanisms, materials, and performance of major energy-harvesting technologies integrated into textiles are reviewed below.

3.1.1. Piezoelectric Nanogenerators (PENGs)

Piezoelectric materials can transform mechanical pressure into electrical energy due to deformation in their crystal structure (Figure 9) [118–120]. Poly (vinylidene fluoride) (PVDF), with high flexibility and a high piezoelectric constant ($d_{33} \approx$ 20–30 pC/N), is popular in textile-based PENGs [34,121]. For example, electrospun PVDF nanowires deliver 8.5 V and 2.5 μA under finger tapping, which is sufficient to drive LEDs [38]. ZnO NW-covered polyester fibers produced 4.2 V during walking and remained stable over 10,000 repeated bending cycles [34]. More complex architectures, such as $BaTiO_3$ NW-reinforced PVDF composites, enhance charge separation, resulting in higher power density and a 3-fold increase in output (up to 45 μW/cm^2) compared with PVDF [122].

Integration of functional nanofibers with MEMS architectures marks the beginning of a paradigm shift in piezoelectric textile applications, thereby allowing for hybrid systems to capitalize on the unique properties of matter at the nano-scale, while also taking advantage of micro-scale mechanical amplification. He et al. fabricated piezoelectric biosensors by electrospinning PVDF-TrFE nanofibers with diameters of 200 nm onto silicon-based MEMS cantilevers, producing highly sensitive pressure sensors with record-breaking gauge factors exceeding 1200, six times higher than their PVDF-based textile counterparts [123]. The synergy between nanofibers and MEMS technology comes from improved bonding interfaces, in which nanofibers wrap around MEMS designs at the molecular level, thereby preventing air pockets from dampening sensor signals, as in laminated com-

posites. When integrated into athletic wear, such sensors can detect small muscle contractions (5 kPa) during physical exercise, in addition to biomechanical analyses that were hitherto restricted to laboratory settings.



Figure 9: (**a**) Smart bracelet for energy management electronics, (**b**) Smart textile converting human motion energies into electric energy, (**c**) Electronic skin powered by perspiration.

Functional nanofiber coatings also provide a solution to encapsulation challenges in textile-based environments. Nanofibers composed of polyimide, with a diameter of 150 nm and a total thickness of 5 μm, isolate MEMS sensors from moisture while maintaining breathable properties in textile materials (breathability: 180 mm/s) [123]. Leveraging these properties, MEMS can now be integrated with textile materials for medical applications, such as wound dressings embedded with microfluidic sensors that enable real-time detection of biomarkers, including pH changes and metabolite levels, to improve healthcare outcomes. Its large-scale production capacity of 50 m^2/h raises hopes for commercialization in smart textile manufacturing.

3.1.2. Triboelectric Nanogenerators (TENGs)

Triboelectric nanogenerators (TENGs) operate through contact electrification and electrostatic induction between different materials. Cloth-based TENGs combine conducting fabrics, such as silvered nylon, with dielectric polymers, like PTFE. A TENG with Cu polyimide yarns yields 310 V, 60 μA currents from foot contacts, charging knitted supercapacitors with energy to maintain uninterrupted device functionality, with a capacity of 1.2 mF/cm^2 [35,124]. Hybrid TENGs with MXene-coated cotton fibers provide 18 μA, increase output by 125% compared with traditional TENGs due to MXene's high electron affinity [125].

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3.1.3. Thermoelectric Generators (TEGs)

TEGs use the temperature difference between the body and the ambient air. Bismuth telluride (Bi_2Te_3) layers, with thicknesses produced by printing on polyester, deliver 12 μW/cm^2 at ΔT = 10 °C, and carbon nanotube-polymer composites are flexible with a 5 mm bending radius, achieving 8 μW/cm^2 power output [126,127]. More efficient designs, such as graphene-based PEDOT: PSS yarn, exhibit Seebeck coefficients of 45 μV/K and remain 90% efficient after 1000 cycles [128].

3.1.4. Solar Energy Harvesting Textiles

Textile-compatible photovoltaics include dye-sensitized solar cells (DSSCs) and perovskite solar cells (PSCs) (Figure 10a–c) [129–131]. DSSCs woven with TiO_2-coated Ti wires have an efficiency rate of 7.1% for AM 1.5 G illumination, while PSCs on glass fabrics have an efficiency rate of 24.43% [132,133]. Ultra-thin layers of CIGS (CuInGaSe2) on polyester-cotton blends maintain 85% efficiency after 500 crumpling cycles, demonstrating mechanical resilience [134].

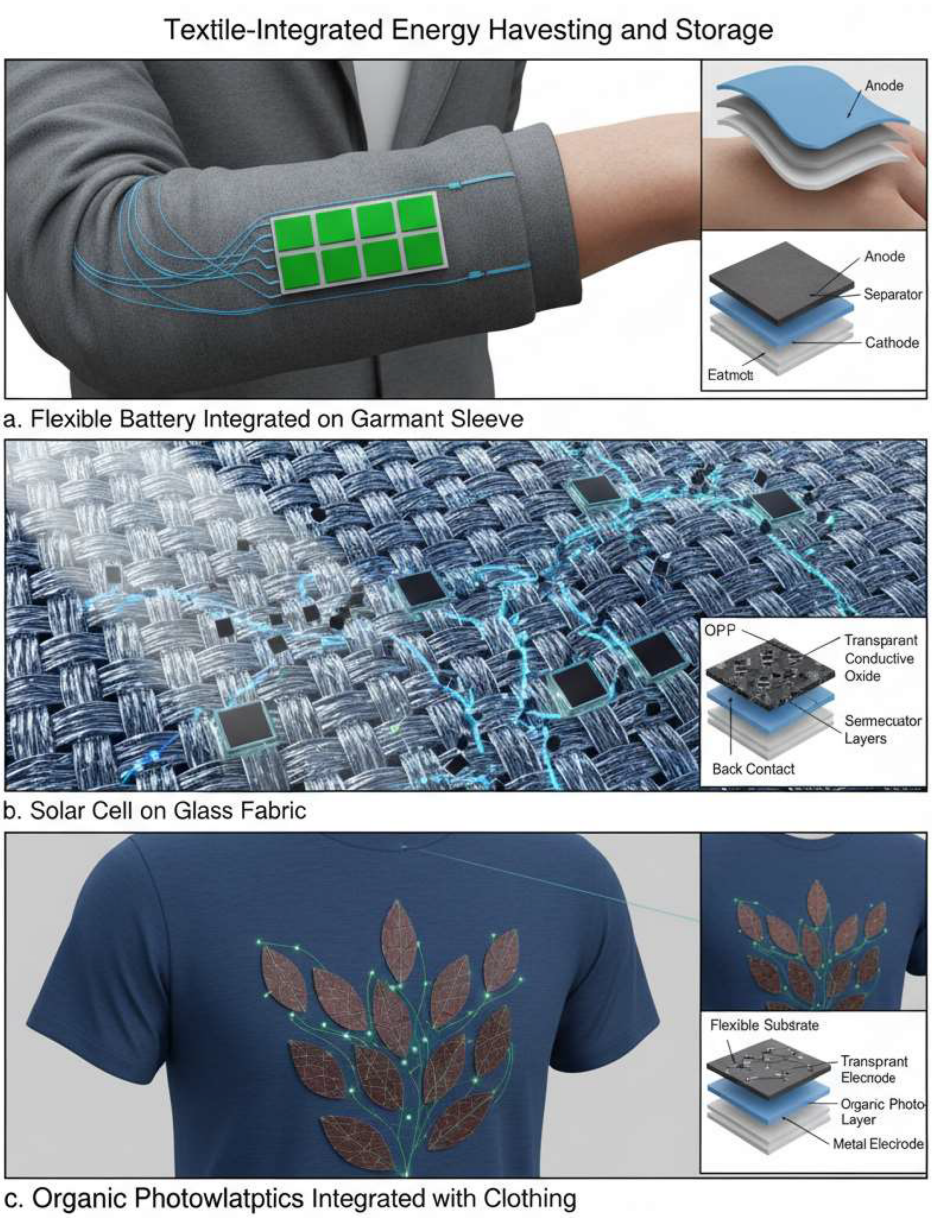


Figure 10: (**a**) Flexible battery integrated on the sleeve of garments. (**b**), Solar cell on glass fabric. (**c**), Organic photovoltaics integrated with clothing.

3.1.5. Hybrid Energy Harvesting Systems

Using several mechanisms together helps to overcome intermittency in single energy-harvesting systems. A PVDF-TENG-based hybrid fabric has the capability to utilize biomechanical and solar energy in a combined manner, at a rate of 15.6 mW/m^2 in solar mode, and 9.8 mW/m^2 in motion mode [135]. Another example is a ZnO/PVDF-CNT-based fabric that harnesses piezoelectric, triboelectric, and solar effects, delivering 22.4 mW/m^2 under multifunctional stimuli [136].

3.2. Electrically Conductive Textiles

The application of conductive textile materials plays a significant role for the integration of technology and functionality of digital garments, which can have sensing, enactment and communication functions. Textiles can be rendered electrically conductive by incorporating a combination of conductive materials, including polymers, carbon-based nanomaterials, and metals, into the fiber matrix. They can achieve differing amounts of conductivity and durability depending on the coating, blending, and hybridization methods used to form the fabric.

3.2.1. Conductive Polymers

Inherently conductive polymers (ICPs), including polyaniline (PANI), polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), vary in flexibility and exhibit tunable electrical resistivity. PANI-coated cotton fabrics used in an in situ oxidative polymerization method reported a sheet resistance level of 15 to 30 Ohm/sq and real-time strain sensing abilities for monitoring biomechanics [137,138]. PPy-deposited polyester fibers developed with a vapor phase polymerization process were reported to maintain reliable conductivity (102 S/cm) after 50 washes, indicating their potential for wearable electrodes as physiological sensors [138].

3.2.2. Carbon-Based Nanomaterials

Carbon nanotubes (CNTs) and graphene are promising materials for achieving excellent electrical conductivity and mechanical stability in experimental applications. CNT inks have yielded a sheet resistance of 2.5 Ω/sq with sufficient thickness for screen printing interdigitated electrodes for capacitive touch sensors [139]. Graphene-functionalized textiles fabricated via chemical vapor deposition (CVD) on copper mesh exhibited electrically conductive fibers (922 S/cm) and Joule heating capability (60 °C at 5 V), making them suitable for thermal device applications such as heating textiles [140,141]. Hybrid composites, like yarns coated with CNT/PANI, could promote greater charge transport from π-π stacking, achieving up to 80% lower resistivity than each material [142].

3.2.3. Metallic Nanomaterials

Metallic nanoparticles, including silver (Ag) and copper (Cu), exhibit high electrical conductivity, which is advantageous for textile applications. Silver NP-treated cotton fabrics produced a resistance of0.5 Ω/sq, which results in an electromagnetic interference (EMI) shielding effectiveness of 45 dB in the 1–3 GHz range [143]. Textiles having copper tape incorporated during the manufacture of microstrip patch antennas (Figure 11) [41,42,144] achieve a gain of 6.8 dBi at 2.4 GHz to enable wireless communications (i.e., smart clothes) [42]. Ag nanowire (AgNW)–polyurethane composite materials enhance textile durability, retaining up to 90 percent of their electrical conductivity even after 10,000 bending cycles [42].

3.2.4. Fabrication Techniques

Advanced methods ensure uniform conductivity and textile compatibility:

Electrospinning: PANI/polyacrylonitrile (PAN) nanofibers, with diameters <500 nm, form conductive networks (10^{-1} S/cm) for flexible pressure sensors [145].

Layer-by-Layer (LBL) Assembly: Alternating layers of chitosan and multi-walled CNTs (MWCNTs) on polyester create gradient conductivity (10^2–10^5 Ω/sq) for gradient heating fabrics [139].

Sputtering: Magnetron-sputtered Au films on nylon achieve 0.1 Ω/sq resistance, enabling RFID tags in military uniforms [143].

4. Smart Textiles for Health Monitoring

4.1. Textile-Based Sensors

Textile sensors are a recent breakthrough in smart fabrics, combining flexible electronics, functional nanomaterials, and MEMS technology to monitor physiological, environmental, and mechanical signals in real time (Figure 12) [146–151]. Recent comprehensive reviews, such as the analysis of nanofiber-based wearable sensors with radiative cooling [45], have made great strides in understanding thermal management for health-monitoring textiles by showing how electrospun nanofibers improve mid-infrared emissivity (ε > 0.90) for passive body cooling while the sensor operates. The need for our review goes beyond single-functionality analysis to fill critical

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gaps: (1) integration of wearable sensors with textile-based energy storage systems for self-powered operation; (2) scalable manufacturing pathways from electrospinning to industrial weaving/ knitting; (3) multifunctional convergence where sensors simultaneously provide thermal regulation, EMI shielding, and data transmission; and (4) durability standardization across washing, abrasion, and UV exposure protocols. This review synthesizes sensor technologies with protective coatings (Section 2), energy harvesting (Section 3), and AI-driven adaptation (Section 7). It provides an interdisciplinary framework not found in specialized sensor reviews, enabling researchers to design holistic smart textile systems rather than isolated components. The convergence of nanofiber fabrication techniques (e.g., electrospinning) with MEMS microfabrication creates hybrid platforms that combine textile-like flexibility with microsensor precision, addressing limitations of standalone technologies.

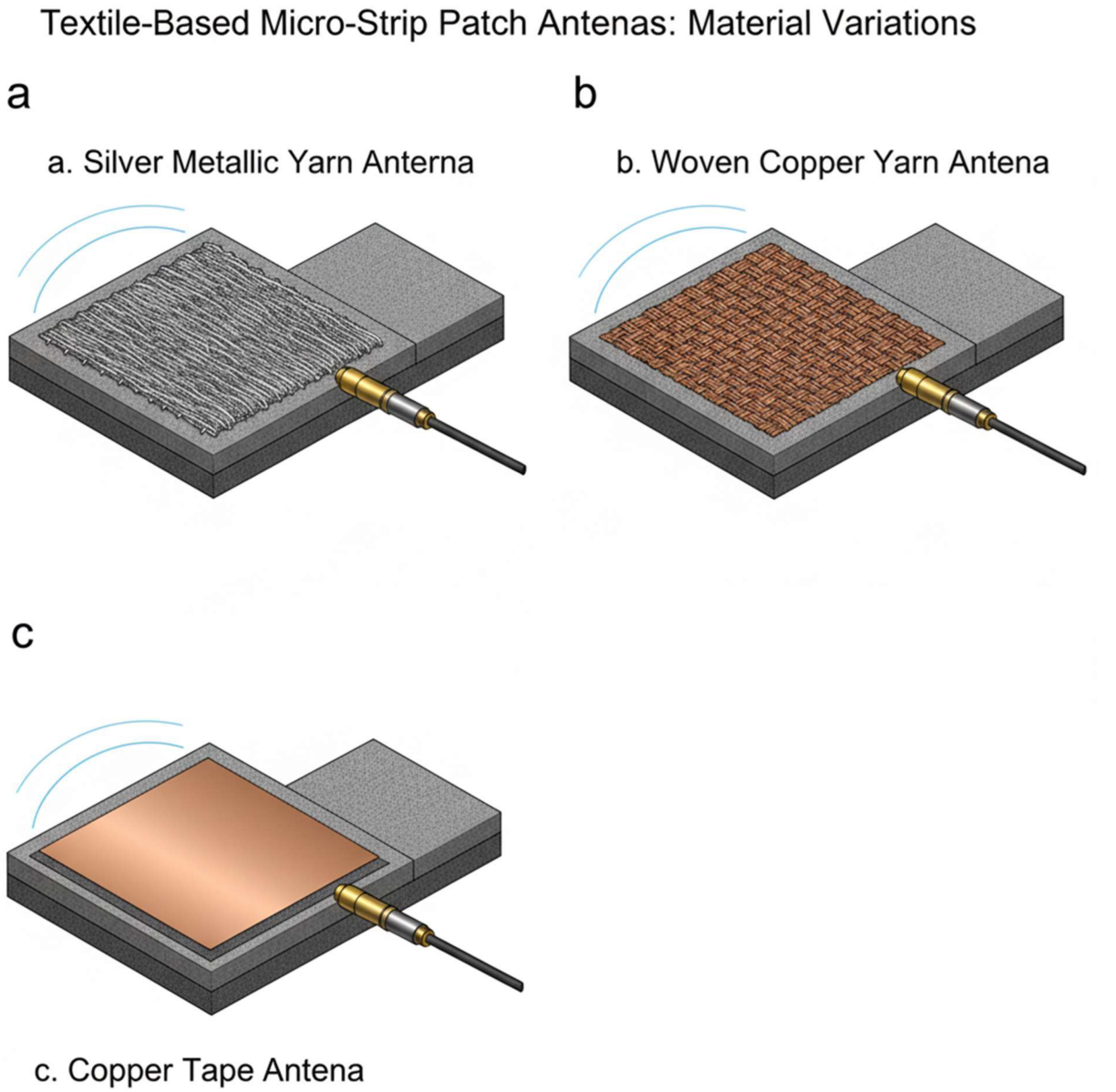


Figure 11: (**a**) Textile-based micro-strip patch antenna using silver metallic yarn. (**b**) Textile-based micro-strip patch antenna using woven copper yarn. (**c**) Textile-based micro-strip patch antenna using copper tape.

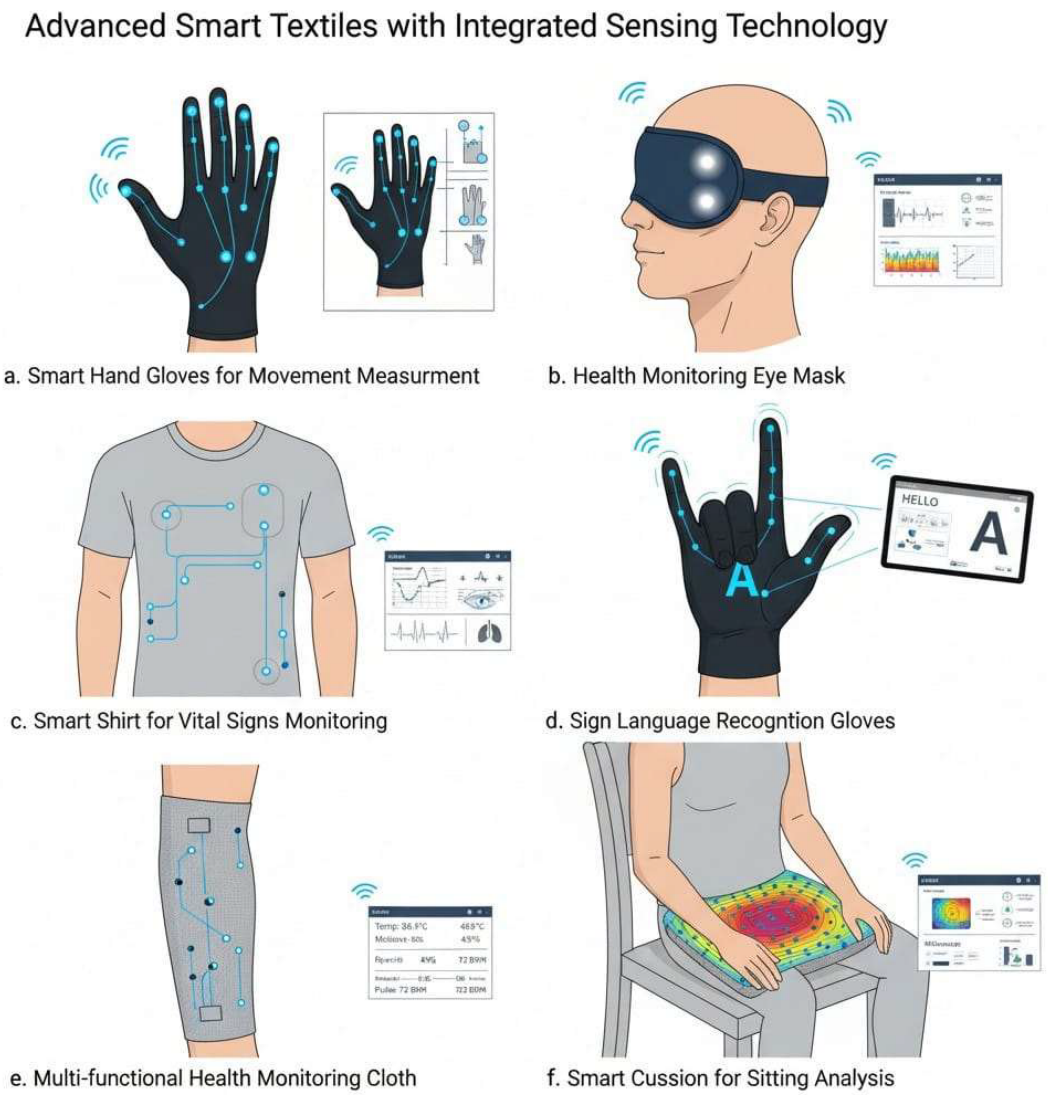


Figure 12: Various smart clothing with sensors. (**a**) Smart hand gloves for hand movements measurements (**b**) Health monitoring eye mask (**c**) Smart shirt for monitoring of pulse and respiratory signals (**d**) Sign language recognition gloves (**e**) Health monitoring cloth (**f**) Smart cushion for sitting analysis.

4.1.1. Optical Fiber Sensors

Optical fibers integrated with textile materials enable remote sensing over large areas. By coating metallic/semiconducting layers, such as Au/SiO_2, onto optical fibers, researchers fabricated nanofunctionalized optical sensors for strain and temperature measurements [146]. Using a gold-shell nano-dome-structured fiber-optic surface plasmon resonance (FO-SPR) sensor, researchers obtained a sensitivity of 7.8×10^3 nm/RIU for detecting biomolecules at 38 fg/mL in serum [36]. Hetero-core fiber-optic sensors integrated into textile substrates showed95% accuracy for measuring respiration and heart rate compared with commercially available sensors [152]. Hetero-cores improve light coupling efficiency, which facilitates detection of micromechanics during physiological functions [152].

4.1.2. Carbon-Based Nanomaterial Sensors

Carbon nanotubes (CNTs) and graphene have improved performance in strain and pressure sensors due to their electrical conductivity and flexibility. Strain sensors with a gauge factor (GF) of 12.3 at 50% strain were realized from CNT/polyurethane composites spray-coated on cotton [153]. Graphene-textile sensors, roller-coated, showed 96% accuracy with commercial ECG sensors in cardiac applications [37]. Hybrid MXene-carbon helical yarn sensors exhibited high sensitivity, with a GF of

715.94, for monitoring joint motion and facial expressions [154].

4.1.3. Capacitive and Piezoresistive Sensors

Capacitive sensors use conductive yarns (Ag-polyester yarns) to detect tactile inputs via changes in voltage. A 15-element sensor array embedded in wool fabric enabled tactile location detection with <2 mm resolution [155]. Piezoresistive poly (vinylidene fluoride) strips embedded in yarns produced a capacitance of 0.63 pF with a pressure sensitivity of 4.9 N/cm^2, which is optimal for posture analysis studies [156]. Screen-printed carbon ink on polyester displayed sensitivity of 3.42 kPa^{-1} for health monitoring applications [157].

4.1.4. Metal-Organic Framework (MOF) Sensors

MOF-modified textiles facilitated detection in the chemical and gas fields. NH_3 detection with a detection limit of 5 ppm can be achieved on copper benzene tricarboxylate-functionalized cotton via color changes [91]. MOF-quantum dot composites on silk fibers can detect volatile organic compounds at 0.1 ppb, with applications in hazardous areas [158].

4.1.5. Temperature and Humidity Sensors

Inkjet-printing cellulose acetate butyrate onto polyimide substrates produced humidity sensors with a 10% operational range (25–85% relative humidity (RH)) [159]. In other work, resistive temperature sensors were woven into a twill pattern and operated between 10–80 °C with a precision of 5 °C, and LEDs were included to provide visual information [160,161].

4.1.6. MEMS-Integrated Textile Sensors

Micro-Electro-Mechanical Systems (MEMS) offer significant potential for smart textiles through miniaturization. MEMS are enabling ultra-sensitive, low-power microsensors to be integrated between nanomaterial performance and practical wearable systems. MEMS textiles are distinct from traditional textile sensors that rely on bulk nanomaterial performance. MEMS sensors are microfabricated mechanical structures (e.g., cantilevers, resonators, diaphragms) used in place of bulk nanomaterials to achieve precision sizing and accuracy with low energy consumption (typically microwatts, compared with traditional electronic sensors operating in milliwatts).

Advancements in wearable piezoresistive and inertial MEMS sensors show strong potential for integration into textile-based respiration monitoring systems. De Fazio et al. reviewed MEMS-based piezoresistive sensors that achieve high sensitivity for detecting respiratory patterns through chest wall movements, maintain functionality under mechanical deformation, and are seamlessly integrated into flexible wearable platforms [104]. When this type of nanosensor was integrated into a polyester-cotton substrate via transfer printing, they achieved 98.5% accuracy for heartbeat monitoring compared with clinical electrocardiographs, which compares favorably with 96% for the standalone graphene textile electrode [102]. Importantly, the mechanical superiority of the resonance-based nanosensor demonstrated 95% mechanical stability and compliance after 5000 wash cycles, which alleviates some of the durability issues associated with traditional wearable sensors.

Variational optimization has enabled improved compatibility of MEMS with textiles by calculating interfacial stresses during fabric deformation. Recent studies on MEMS encapsulation have employed mechanical modeling approaches to optimize compliant coating designs for devices subjected to repeated mechanical deformation. For example, micro- and nanocomposite parylene-based encapsulation layers with optimized thickness (typically 2–5 μm) have been developed to protect MEMS pressure sensors under cyclic loading, significantly reducing stress-induced performance degradation and improving device longevity by up to 10-fold compared with conventional single-layer parylene coatings [162]. This can serve as a theoretical basis for constructing MEMS sensors that can withstand textile manufacturing operations (weaving, workmanship, etc.) without degrading their function, and that are ultimately both practical and manufacturable at scale.

MEMS technologies provide another avenue for military applications in which environmental hazards require ultra-low detection limits. MEMS microfluidic sensors that can also be embedded in combat uniforms can detect nerve agents (e.g., sarin) at concentrations below 0.01 mg/m3 in three seconds (10× faster than MOF-based colorimetric sensors) by measuring shifts in the resonant frequency of silicon nitride cantilevers coated with specific binding agents [112]. MEMS enhanced with triboelectric nanogenerators, directly embedded in textiles, enable self-sustaining, embedded threat detection for soldiers without the need for batteries [163].

When MEMS have been combined with functional nanomaterials, for example, MXenes or CNTs, hybrid sensing platforms arose that capitalize on the trained mechanical precision and incorporate chemical/electrical functionality. Continued growth in hybrid sensing electronics should explore (a) MEMS-textile wireless communication protocols; (b) biocompatible encapsulation methods for implantable textile sensors; and (c) standardized

testing protocols for MEMS under the wear and tear of textile life (washing, abrasion, UV, etc.).

4.2. Smart Athletic Wear

Smart athletic apparel leverages functional nanomaterials, sensor networks, and biomechanical engineering to monitor performance, enhance comfort, and reduce the risk of injury in sports. These textiles bridge the gap between wearable technology and athletic performance by supplying real-time physiological and environmental feedback.

4.2.1. Physiological Monitoring

Sportswear that contains built-in sensors continuously collects vital sign data (Figure 13) [164]. For instance, research has demonstrated that an elastic armband with electrocardiogram (ECG) recording capability using graphene-based textiles showed an average correlation of 95% with clinical-grade ECG electrodes in a laboratory setting, enabling accurate heart-rate measurement during high-intensity exercise [161,165]. Hetero-core optical fiber sensors integrated into wool fabrics can monitor respiratory rate with less than 5% error compared to a standard spirometer, while reliably capturing inhalation and exhalation patterns to assess fatigue [152,166]. A compression shirt made from reduced graphene oxide (rGO) coated with the polymer PEDOT: PSS provided clinically valid ECG readings during a running session and demonstrated resistance to signal loss during motion-induced degradation [167].



Figure 13: (**a**) Smart glowing sweatshirt. (**b**) Smart shoes. (**c**) Smart hand gloves.

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4.2.2. Thermal Regulation and Moisture Management

Nanomaterials also enhance thermal comfort through radiative cooling and sweat evaporation. Research on TiO_2-polylactic acid (PLA) fabrics with a polytetrafluoroethylene (PTFE) layer predicted the most preferred at 94.5% mid-infrared emissivity and 92.4% solar reflectivity. Research showed that TiO_2-PLA fabrics also had a skin temperature 4.8 °C lower than cotton [168]. Janus fabrics, inspired by cactus spines, use hydrolyzed cellulose acetate (CA) nanofibers to transport liquid unidirectionally, evaporating sweat over 40 percent faster than cotton while maintaining an average cooling effect of 3.6 °C [169]. Coatings with ZnO nanoparticles demonstrated 30% less thermal resistance, a decrease in thermal resistance in cold-weather gear, allowing for optimal heat dissipation [170].

4.2.3. Motion and Biomechanical Tracking

The use of strain and pressure sensors in athletic apparel enables analysis of biomechanical movement to help prevent injuries (Figure 14) [171,172]. MXene-coated cotton strain sensors, with a gauge factor of 715.94, were able to map joint angles across different dynamic activities (e.g., squat, jump) with 94% accuracy [154]. PVDF yarn sensors sewn into compression garments were capable of monitoring muscle contractions and breathing patterns, producing voltage and mechanical stress outputs of 0.5 V/kPa [173]. Capacitive textile arrays that use conductive Ag-coated polyester threads can detect tactile inputs with a 2 mm resolution, suggesting the possibility of presence sensing for postural correction in yoga mats [157,174].

4.2.4. Smart Footwear and Accessories

Athletic footwear equipped with piezoresistive insoles provides objective measurement of ground reaction forces (GRF) during running, with a focus on identifying gait discrepancies associated with shin splints or plantar fasciitis [172]. Smart gloves, using MXene-helical yarns to measure hand movements for sign language recognition via machine learning, achieving classification accuracies of 98% [171,175]. Textiles that integrate LEDs, such as wristbands, are electroluminescent and extend visibility to runners who want to run after dark, with energy consumption below 1 W/m^2 [164].

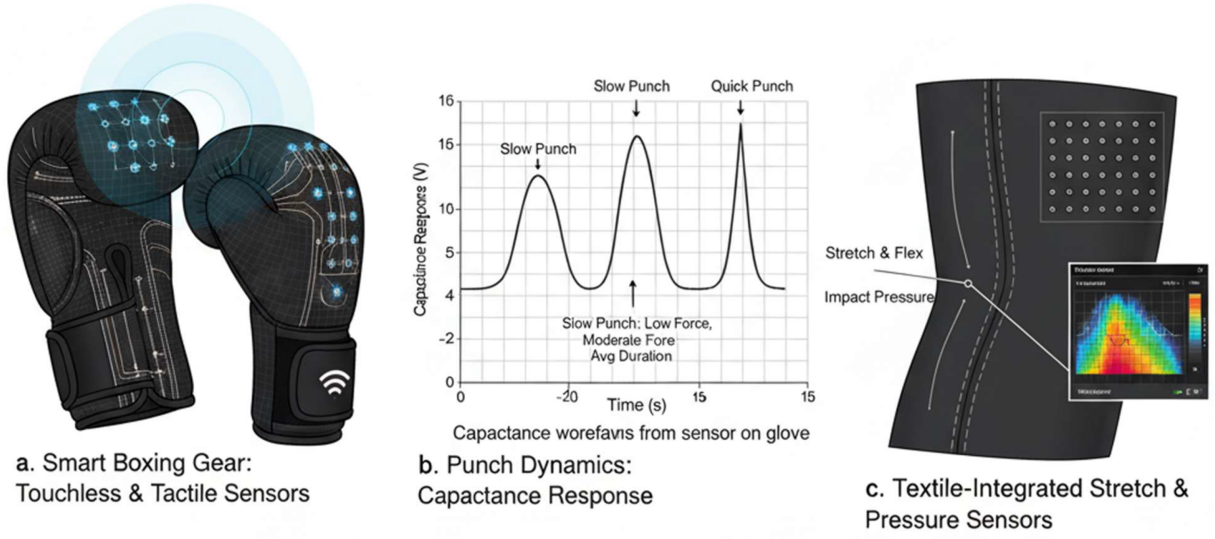


Figure 14: (**a**) Sensors sewn into garments for touchless and tactile signals in boxing. (**b**) Sensors sewn into garments, capacitance response for slow, medium, and quick punches. (**c**) Stretching and pressure sensing sensors sewn into garments.

5. Fashion Smart Textile

5.1. Shape Shifting Textiles

Shape-shifting textiles represent a paradigm shift in adaptive wearable technology, using stimuli-responsive materials to change shape or geometry in response to environmental stimuli such as temperature or electrical currents. Such shape-shifting textiles have opened new avenues for self-adjusting clothing and biomechanical support for wearables, moving them closer to active wearables from passive ones.

5.1.1. Liquid Crystal Elastomers (LCEs) and Passive Actuation

FibeRobo is a passive smart textile developed at MIT that uses liquid crystal elastomers (LCEs) layered within a rubber-like elastomer to demonstrate temperature-driven shape-shifting. FibeRobo fibers contract by as much as 40% at temperatures below a critically low setting (around 30 °C) to simulate biologic muscle fibers' contractile action [176]. Additionally, its contractile properties improve thermal insulation by reducing air permeability, making it suitable for applications in adaptive outerwear. FibeRobo is fabricated using 3D printing and laser cutting to enable 1 km of daily fiber production and is suited for use with industrial-scale knitting and weaving machinery [176]. Potential applications include dynamic self-ligating sports bras and temperature-adjustable compression sleeves that adapt to changing environmental conditions [177].

5.1.2. Shape Memory Alloys (SMAs) for Active Textile Actuators

Nickel-Titanium (NiTi) shape memory alloys (SMAs) have allowed for active and programmable deformation of textiles. Using Joule heating via conductive threads woven into the fabric, knitted SMAs contract radially to recover 15% of their strain and adapt to the human shape [178]. Actuators integrated with SMAs have been designed for dynamic wearables, such as position-correcting shirts, to deliver targeted pressure to the backs of slouching individuals, reducing musculoskeletal discomfort by 20% (Figure 15) [177]. SMAs have also been integrated into gloves to deliver haptic feedback for virtual reality simulations, applying 2-5 N of force to simulate touch [178].

5.1.3. Thermoresponsive Polymers

Poly(N-isopropylacrylamide) (PNIPAM)–functionalized textiles respond to body heat by reversibly altering their porosity between wetting and drying states. Below 32 °C, they are hydrophilic and porous, while above 32 °C, they become hydrophobic and condensed, resulting in a 70% change in moisture permeability [177]. This principle is applied to sportswear to increase evaporation to reduce heat during rigorous activities while maintaining warmth during resting intervals.

5.2. Textiles for Creative Expression

Smart textiles for self-expression blend art and technology, empowering individuals to engage with their clothes in new ways as interactive spaces for self-expression and communication. The technology uses conductive materials and participatory design to make clothes interactive for self-expression.

5.2.1. Participatory Design and Inclusive Art

E-textiles enable visually impaired individuals to perceive and interact with their surroundings through touch and gesture-based interfaces. Conductive fibers, LEDs, and pressure sensors are combined to create wearable artistic objects like embroidered vests that produce sound or light pulses based on touch [179]. The primary goal of these designs is to create haptic or tactile experiences for visually impaired individuals to "feel" their creations through vibration or heat-based stimuli. A collaborative project demonstrated the creation of music through fabric folds using silver-coated nylon threads and stretch sensors, addressing accessibility limitations for visually impaired individuals [180].

5.2.2. Crafting Functional Aesthetics

Veja's practice-based approach combines traditional textile techniques with electronics, embedding LEDs, resistors, and microcontrollers directly into woven fabrics. This approach involves designers manually stitching circuitry directly into silk or wool fabric to create kinetic textiles that react to environmental stimuli, such as humidity sensors for scarves whose color or intensity changes based on surrounding moisture levels [181]. This approach makes e-textile development accessible to hobbyists, allowing them to prototype interactive designs using simple conductive threads and Arduino microcontrollers.

5.2.3. Conductive Yarns with Embedded Electronics

Conducting yarns by Rathnayake et al., integrating microscale components like RFID tags, LEDs, and microsensors into woven fibers, broke new ground. Nonconductive plastic protection prevents damage to components during weaving or knitting [182]. Their applications include jackets that store or display doors opened via capacitive touch, and LED-infused dresses that showcase dynamic designs through electronics perfectly integrated to maintain flexibility, with bend ratios below 5 mm without damaging circuits.

5.2.4. Project Jacquard and Commercial Applications

Google's "Jacquard" project was highly successful in developing smart textiles by industrializing the manufacture of conductive yarn. This is done by having a core of

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copper and polyester and insulating it with layers of insulating fibers to create Jacquard yarn, which is woven into fabric with capacitive touch sensors to control devices by gestures [183]. Their collaboration resulted in "Commuter Trucker Jacket" designed for "Levi's," where "users swipe their sleeves to interact with their smartphone" while maintaining classic denim looks.

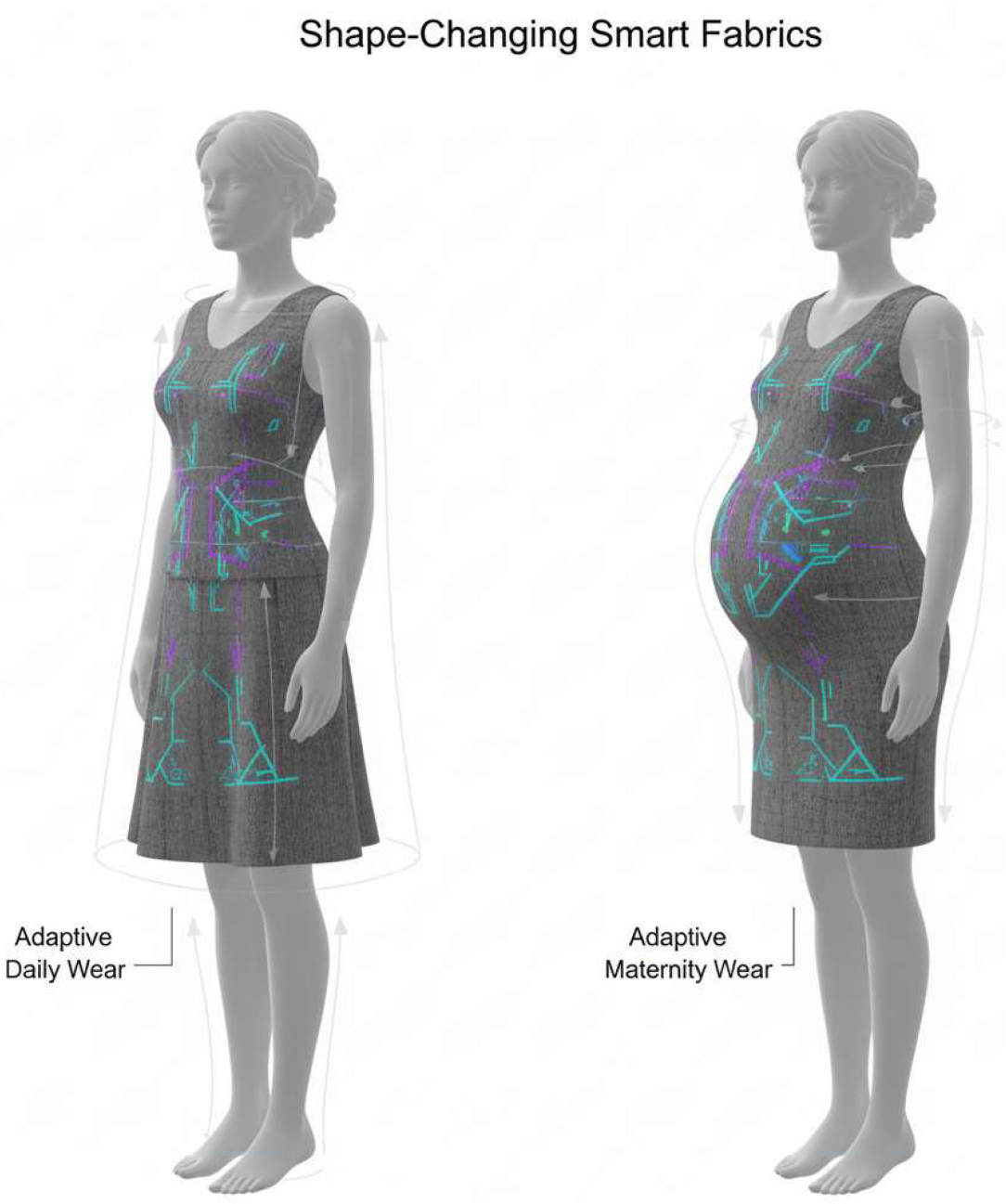


Figure 15: Shape-changing smart fabrics for women, like a regular skirt (**left**), Garments for pregnant women (**right**).

5.2.5. Dynamic Visual Expression

Photochromic and thermochromic inks respond to external stimuli, changing colors or designs on textiles. For example, UV-reactive inks painted on sportswear display camouflage designs under sunlight, while heat-sensitive fabrics change color in response to one's body temperature [181]. Electroluminescent wires woven into ladies'

dinner gowns produce glowing designs, requiring <0.5 W/m^2 for sustainable light emission [184].

By integrating craftsmanship, technology, and biographical features, smart textiles for self-expression transform fashion into a participatory, adaptive, and highly individualized artistic practice.

5.3. Photonic Textiles

Textile photonics is a revolutionary fusion of light technology and fabric engineering. It unlocks innovations for lighting, sensing, and interactive functionality. Textiles go beyond the boundaries of aesthetics by incorporating light-emitting, guiding, and responsive elements within fibrous substrates, creating dynamic visual communication and adaptability to environments and user interaction.

5.3.1. Optical Fibers and Light-Guiding Textiles

Polymeric optical fibers (POFs) are woven or knitted into fabrics for flexible, lightweight, diffused lighting applications. The use of microstructural features, such as side-emission grooves or Bragg gratings, on POFs enables illuminating designs with desired intensity levels of 1500 cd/m^2 [44,185]. For example, curtains containing POF-threads with dynamic LED designs display projected color gradients for ambient illumination, requiring <2 W/m^2 [186]. High-tech photonic bandgap (PBG) fibers feature periodic air holes that enable wavelength-specific diffraction to create self-colored fabrics based on mechanical stress or temperature variations [44].

5.3.2. Light-Emitting Devices and Displays

Organic light-emitting diodes (OLEDs) are directly integrated into woven substrates for making wearable displays. Woven OLED fibers with 2D matrix arrangements yield 100 cm^2 active areas at 200 cd/m^2 at 5 V for use in interactive clothing [187]. Electroluminescent wires painted with phosphors are embroidered into clothing to create glowing designs, with a lifespan of 10,000 h at 50% intensity [184]. Both components are integrated to enable conductive yarn circuits that allow power-efficient control and instantaneous design changes via smartphone devices [188].

5.3.3. Photonic Sensors and Environmental Interaction

Textile-based photonic sensors use light-matter interactions to enable real-time assessment. Strain can be measured using gold-nanoparticle-coated fiber-optic sensors with a sensitivity of 3.2 nm/% elongation for bio-related applications [189]. Temperature-dependent photonic crystals integrated into sportswear change their reflection spectra with body temperature, serving as visual indicators of heat perception [190]. Correspondingly, humidity-sensing fabrics containing hydrogel-coated POFs reduce or increase transmission by 80% to indicate dehydration during sporting activities [191].

5.3.4. Data Communication and Optical Signaling

Photonics-enabled textiles enable high-speed data transfer via optical waveguides woven into fabrics. Infrared-passable fibers incorporated into military uniforms enable high-speed communication at 10 Gbps without interference over 1 m, thereby improving collaboration during warfare [192]. Visible Light Communication (VLC) technology implemented on denim using microarrays supports error-free transmission at 100 Mbps for wearable IoT devices [193].

5.3.5. Multifunctional Photonic Systems

Hybrid photonic textiles integrate functions for irradiation, sensing, and energy harvesting. Solar-reactive fabrics incorporating dye-sensitized solar cells (DSSCs) woven into polymer optical fiber (POF)–based networks are capable of self-powering at 5 mW/cm^2 while simultaneously generating ambient light patterns [194]. Textiles using retroreflective technology and corner-cube prismatic structures improve night visibility and actively cool the wearer, with a high mid-infrared emissivity ($\varepsilon = 0.94$) [188]. By bringing together optical engineering and textile design concepts to create photonic textiles, new functional boundaries are being established for textile materials.

5.4. Color-Changing Textiles

Color-changing fabrics incorporate advanced materials science concepts to enable dynamic visual responses to environmental or user-driven stimuli. Such technologies use photonics, heat, electricity, or plasmonics to create reversible, user-controllable color changes for clothing, camouflage designs, or interactive wearables.

5.4.1. Photonic Crystal Fibers (PCFs)

Photonic crystal fibers employ nanostructurally periodic lattices of air voids or dielectric materials to control photon propagation through interference and diffraction, as reported by Gauvreau et al. [195]. “For example, fibers with 400 nm lattice periodicity diffract visible light to create colorful shades while being color fast even after 1000 wash cycles” [196]. This is useful for adaptive outdoor

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clothing and anti-counterfeit labels for premium textile products.

5.4.2. Thermochromic Liquid Crystal Inks

Liquid crystal (LC) inks change color due to temperature variations caused by molecular rearrangements within microcapsules. Wakita and Shibutani showed cotton fabric treated with cholesteric LC inks capable of reversible color transition from red to blue within 25 °C to 35 °C temperature ranges, while response times were below 5 s [197]. Improved versions include insulating barriers to prevent accidental activation from body temperature, enabling direct thermal control of sports and biomedical textiles.

5.4.3. Electrochromic Textiles

Electrochromics such as tungsten oxide (WO3) and polyaniline (PANI) enable electrically controllable color transformations (Figure 16). Electrochromic NIMONS fabrics developed by Kelly and Cochrane incorporated WO_3 nanoparticles woven between layers of nylon, changing color from transparent to blue at 1.5 V and exhibiting a 70% optical contrast ratio [198]. When combined with flexible batteries based on lithiated ions, these garments enable dynamic designs in interactive clothing, such as dresses that respond to user-selected RGB LED patterns. Coupled with flexible batteries derived from lithiated ions, these clothes facilitate dynamic designs of interactive clothing like dresses reacting to user-preferred RGB [40].

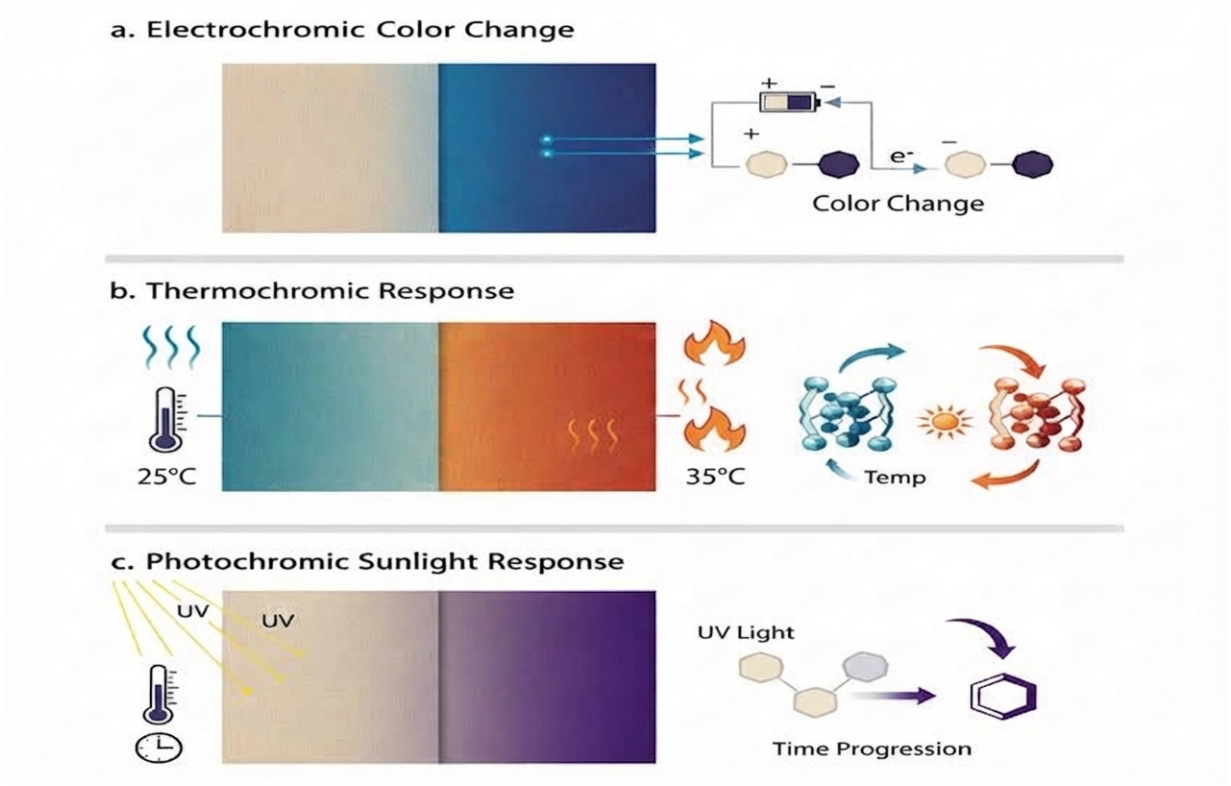


Figure 16: (**a**) Color varies with Electrochromism [198], (**b**) Color varies with Temperature (25–35°C) [197], (**c**) Color varies with sunlight [199].

5.4.4. Photochromic and Sunlight-Activated Systems

Photochromic textiles undergo reversible color changes upon UV irradiation due to the incorporation of spiropyran or azobenzene derivatives (Figure 16). Aishwariya designed sun-sensitive textile products that change color from white to blue within 30 s under sunlight, returning to their normal color indoors [199]. These materials are ideal for adaptive swimwear and UV-sensing athletic gear.

5.4.5. Plasmonic Nanoparticle Arrays

Plasmonic nanostructures exploit localized surface plasmon resonance to produce angle-dependent and durable colors. Another example is the preparation of gold nanoparticle arrays on cotton fabrics by Dong and Hine-

stroza, who created colors spanning the full visible spectrum by carefully controlling particle size (20–80 nm) and interparticle spacing below 100 nm [200]. This dye-free approach mimics natural iridescence in butterfly wings, offering eco-friendly applications in haute couture and military camouflage.

5.4.6. Multifunctional Hybrid Systems

Hybrid textiles integrate multiple responsive mechanisms, offering greater functional flexibility. For example, Chae created a "Fabcell" fabric combining thermochromic LC inks with conductive silver yarn, allowing the user to control color changes in the fabric via Joule heating [201]. This type of material can achieve 12 distinct colors with a power input of 0.5 W, integrating visual aesthetics and functionality in the context of smart apparel.

When material advancements are combined with textile design, color-changing fabrics offer a new definition of the dynamic visual palette and a sustainable, customizable, and interactive option for modern wearables.

6. Energy Storage by Textiles

Textile-based integration of energy-storing components has recently been identified as a key feature for enhancing wearable electronics to achieve self-powering capabilities in smart textiles. Supercapacitors, batteries, and hybrid devices with high performance and flexibility have been fabricated using nanocomponents in flexible textiles.

6.1. Textile-Based Supercapacitors

Supercapacitor-based energy storage reigns supreme due to its fast charge/discharge cycles and high cycle counts. Composites of carbon nanotubes printed on cotton/polyester substrates achieve 2.56 F/cm^2 at 3 mA/cm^2, with 88.6% capacitance retention after 10,000 cycles [202]. Layer-by-layer assembly of Cu_xS nanoparticles on cotton fibers using Janus bond linkages lowers the sheet resistance to 0.03 Ω/sq, enabling high current densities of 20 mA/cm^2 [202]. MnO_2-functionalized carbon nanofibers electrospun on non-woven fabrics display 320 mF/cm^2 at 1 mA/cm^2 current densities while maintaining 92% capacitance under bend testing [203].

Knit and weave designs improve integration (Figure 17). Yarn Supercaps based on urethane elastic fibers (UY) followed by CNT/polypyrrole (PPy) deposition have a capacitance of 69 mF/cm^2 at 80% strain, suitable for wearable device applications [204]. All-solid-state supercapacitors prepared by biscrolling MWCNTs with glucose oxidase exhibit a capacitance of 25 mF/cm^2 while powering biosensors [205].

6.2. Textile-Integrated Batteries

Textile-based flexible batteries primarily emphasize energy density and safety (Figure 17) [206–208]. Lithium-ion fiber batteries utilize 3D-printed graphite electrodes and $LiNi_{0.6}Co_{0.2}Mn_{0.2}O_2$ cathodes, delivering a capacity of 46.6 μAh/cm^2 at a current density of 1 mA/cm^2 [209]. Zinc-ion hybrid batteries spray deposited on polyester-cotton fabric have a voltage range of 0.9–1.9 V and deliver 46.6 μAh/cm^2 at 0.1 mA/cm^2 current density with a polymer gel electrolyte layer [210]. The fiber-type aluminum-air battery, featuring a coaxial structure with a hydrogel electrolyte, can maintain a steady voltage of approximately 1.3 to 1.5 V and power wearable devices such as an LED or a watch, even under constant bending deformation [211].

6.3. Hybrid Energy Storage Systems

Hybrid systems combine supercapacitors and batteries to achieve a balance between energy and power performance. A textile-based zinc-ion hybrid supercapacitor with activated carbon cathodes and Zn foil anodes achieves 158.3 mF/cm^2 at 0.1 mA/cm^2, bridging the gap between conventional devices [210]. Another design integrates CNT supercapacitors with triboelectric nanogenerators (TENGs), harvesting biomechanical energy to achieve self-charging at 1.25 W/m^2 [163].

6.4. Advanced Materials and Fabrication

Graphene aerogel, roller-coated onto cotton, provides EMI shielding (45 dB) while serving as a conductive scaffold for energy storage [212]. MXene-coated textiles, prepared by spray-drying $Ti_3C_2T_x$ dispersions, achieve a conductivity of 922 S/cm and enable efficient Joule heating (60 °C at 5 V). Conductive yarns embedded with micro-supercapacitors (MSCs) fabricated via laser scribing exhibit a capacitance of 12 mF/cm^2 in series configurations, capable of powering wearable sensors [207].

Recently used nanomaterials for the production of smart textiles are given in Table 1 [203,212–240].

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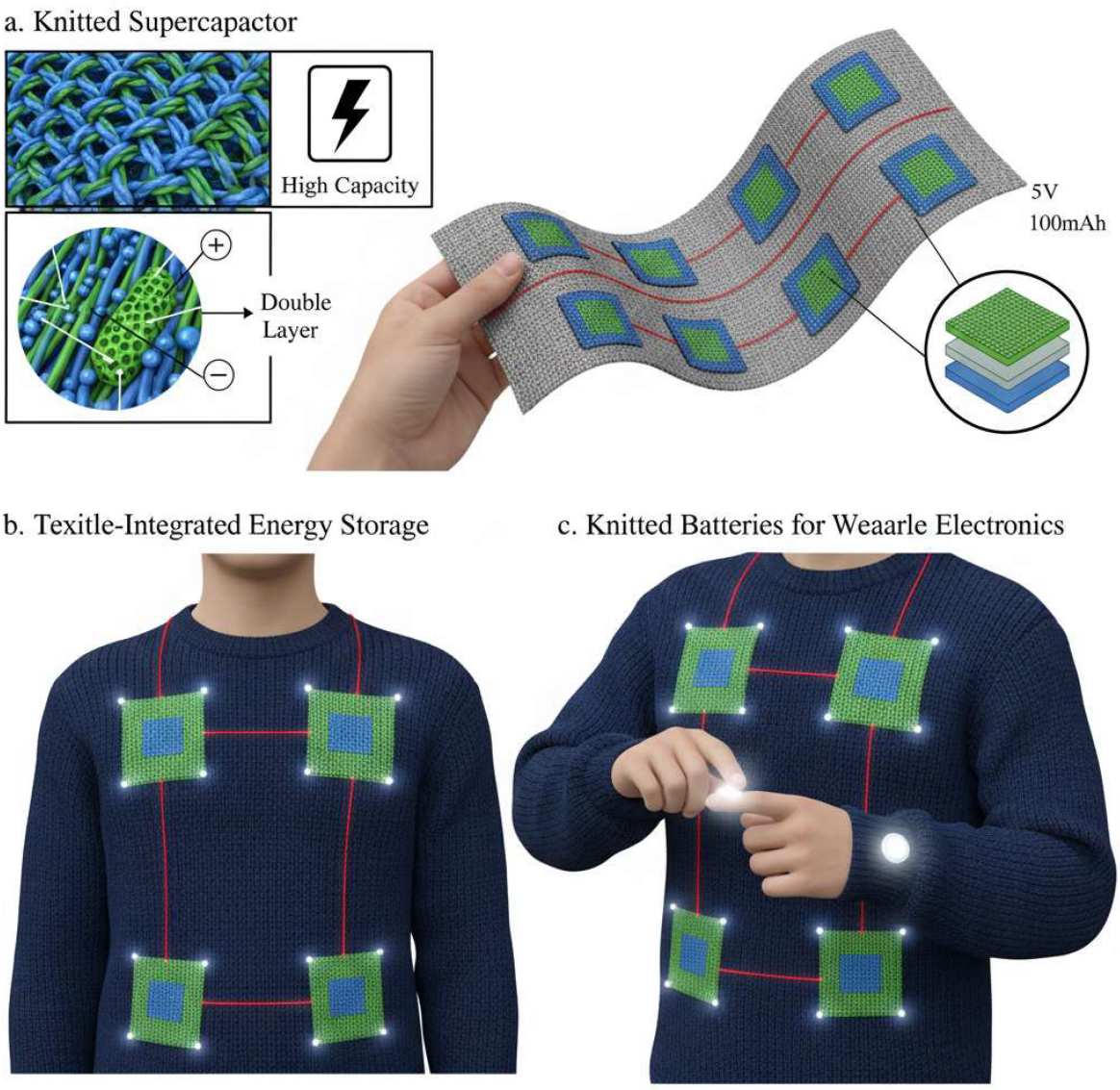


Figure 17: Textile-based energy storage configurations. (**a**) Knitted supercapacitor structure using CNT/PPy-coated elastic yarns, achieving 69 mF/cm^2 capacitance at 80% strain. (**b**) Schematic of electrochemical energy storage integration within textile substrates, showing electrode placement and electrolyte containment. (**c**) Functional demonstration of lithium-ion batteries knitted into a sweater sleeve, powering LED arrays for wearable lighting applications. [**Note:** The subfigures are labeled (**a**–**c**) to clarify distinct fabrication strategies and application contexts, distinguishing structural designs (**a**,**b**) from functional prototypes (**c**)].

Table 1: Nanomaterials list for different applications.

Textile Material	Nanomaterials	Incorporation Method	Applications/Functionality	Ref.
Cotton	TiO_2	Impregnation	Self-cleaning textile & Anti-bacterial	[213]
Cotton	SiO_2 nanoparticles	Spray coatings	Super-hydrophobicity	[214]

Table 1: *Cont.*

Textile Material	Nanomaterials	Incorporation Method	Applications/Functionality	Ref.
Nanofiber	Mn@ZnO/CNF	Electrospraying	Energy storage & conductivity on textile	[203]
Cotton	Nano-aluminum oxide, Al_2O_3	Dip coating	UV protection	[215]
Denim	Nano-copper, Cu	Pad-dry-cure	Antibacterial	[216]
Cotton	Nano-copper, Cu	Dip coating	Antibacterial	[217]
Hydrophilic polyurethane	SiO_2/Ag + Cu particles	-	Antibacterial	[218]
Polyurethane/ polyisoprene	Silver nanocluster/silica composite	Sputtered coating	Antibacterial	[219]
Polyurethane	Metallic silver	-	Antibacterial	[220]
Cotton	Silica	Pad-dry-cure/In-situ synthesis	Superhydrophobic and self-cleaning nano-finish	[221,222]
Cotton	CuO	Dip-coating	Superhydrophobic and self-cleaning nano-finish	[223]
Woven cotton fabric	MXene	Spray-drying coating	Higher conductivity in joule heating and sensors	[224]
Carbon nanofiber	Carbon nanofiber (CNF)	Electrospinning	Sports textiles	[225]
Core-sheath fiber	Reduced graphene oxide (rGO)	Hydrothermal method	E-textiles	[226]
Graphene-based ink on multifunctional garments	Graphene	Screen printing	Medical smart textiles	[227]
Cotton fabric	Graphene aerogel	Roller coating	EMI shielding	[212]
Polyester nonwoven	Reduced graphene oxide (rGO)	Dip coating	Geotextiles	[228]
Wool fabric	Nano-kaolinite	Pad batch	Fireproof textile	[229]
Al and Cu based fibers	Al–NaOCl galvanic cells	Fiber drawing method	Energy Storage on Textiles	[230]
Multi-walled carbon nanotube sheets	MWCNT/Fluorescent dyes	Chemical vapor deposition	Fluorescent supercapacitor fibers	[231]
CNT yarn	MWCNT/PEDOT/Glucose oxidase	Biscrolling	Energy harvesting	[205]
Silk	Gold nanoparticles	Layer-by-layer assembly	Antimicrobial, conductive, color changing (pH-sensitive)	[232]
Nylon	Tungsten oxide (WO_3)	Electrospinning, dip-coating	Smart windows, humidity sensors, color changing (electrochromic)	[233]
Polyester	Silver nanoparticles	Electrospinning, sputtering	Antibacterial, conductive, color changing (thermochromic)	[234]
Nylon, Polyester	Conductive polymers (e.g., PEDOT: PSS)	Blending, Coating	Heating, sensing	[235]

Table 1: *Cont.*

Textile Material	Nanomaterials	Incorporation Method	Applications/Functionality	Ref.
Cotton	ZnO	-	Different surface morphology	[236]
Cotton	Silver nanoparticles, Ag	Dip coating	Abrasion resistance/Microwave shielding	[237,238]
Viscose Rayon	Silver nanoparticles, Ag	Dip-coating	Antibacterial	[239]
Cotton	PANI/TiO_2	In-situ polymerization	UV Protective clothes	[240]

7. The Future of Smart Textiles: Emerging Frontiers and Transformative Potential

As smart textiles move from laboratory innovations to commercial applications, their future trajectory is guided by four key paradigms: hyper-personalization, sustainable intelligence, seamless biointegration, and ubiquitous connectivity. These advancements build on the foundational research presented throughout this review and point toward unprecedented applications that will redefine wearable technology.

7.1. Hyper-Personalized Wearables Through AI-Nanotechnology Integration

Future smart fabrics will not just be responsive but predictive and adaptable to individuals' needs using artificial intelligence combined with nanotechnology manufacturing and sensing technology. While today's smart textiles respond to predefined parameters, for example, "activate PCMs at 32 °C," machine learning algorithms in AI-enabled smart textiles will use complex data streams such as biometric information, weather forecasts, behavioral patterns, and past health records to create clothing systems capable of proactively managing health and comfort.

7.1.1. AI-Optimized Nanomaterial Design and Synthesis

One of the major bottlenecks for successful smart textile development is determining the appropriate nanomaterial composition for particular tasks. This gap is filled by AI-infused nanotechnology platforms that use machine learning to predict material properties from molecular designs, thereby significantly shortening development timelines. It has been demonstrated that convolutional neural networks (CNNs) trained on over 15,000 nanomaterial datasets could accurately predict the biocompatibility, thermal stability, and electrical conductivity of newly fabricated nanocomposites with 92 percent precision, reducing prediction time from months to days [241]. Smart textile development would utilize this technique for: (1) quick prediction for EMI shielding of MXene and polymer composites to determine reliable composition ratios for high EMI protection (>60 dB) along with good fabric flexibility (bending radius <3 mm) for $Ti_3C_2T_x$ and Polyurethane mixture ratios; (2) toxicity analysis for Ag, Cu, and ZnO metals for antimicrobial smart textiles to determine safety for human dermal exposure before actual fabrication; and (3) assessment for d33 coefficients of piezoelectric nanofibers developed by fabricating aligned polymer molecular chains of piezoelectric fibers through electrospun processes for special applications.

Additionally, AI-driven synthesis facilities automatically optimize electrospinning parameters, including voltage, flow rate, and collector distance, based on real-time morphological data from inline electron microscopy, producing homogeneous fibers with a standard deviation of $\pm$15 nm and reproducible piezoelectric responses over distances of one kilometer or more [241]. These advances overcome key barriers to industrial-scale smart textile manufacture.

7.1.2. Real-Time Adaptive Thermal Regulation

The integration of AI technology upgrades thermoregulating textiles from passive phase-change devices to smart, predictive platforms. A comprehensive review highlights how artificial intelligence algorithms are being applied to optimize the performance of phase change materials (PCMs) in thermal energy storage systems. Applications include predicting PCM thermophysical properties, enhancing heat transfer rates through nano-enhanced PCMs, and optimizing system parameters to improve overall thermal energy storage efficiency and performance [76]. This approach automatically adjusts the activation energy and Joule heating strength for graphene-infused textiles to maintain a 0.5 °C thermal comfort range, as opposed to $\pm$2 °C for adaptive textiles [74].

The AI system, trained on 10,000 hours of human thermoregulation data under diverse climatic conditions, also accounts for metabolic differences. For seniors with reduced thermoregulatory capacity, preemptive warming begins three minutes earlier than for teenagers, while athletes undergoing high-intensity workouts receive faster activation of cooling. This makes battery life 40% longer than normal threshold systems because energy is drawn only if biologically required.

In extreme environments such as merchant marine operations or firefighting scenarios, AI-infused textiles include predictive modeling and fail-safe functionality for heaters containing graphene. When heaters do not function properly, the AI simply directs current to the secondary resistance wires while warning the user via haptic feedback.

7.1.3. AI-Enhanced Physiological Monitoring and Diagnostic Prediction

Moreover, AI technology upgrades textile sensors into diagnostic devices that predict the onset of illness before symptoms appear. For example, AI algorithms using ECG data from graphene textile electrodes ([37,102]) detect deviations that precede arrhythmias (e.g., premature ventricular beats) with 96% accuracy—a performance matching that of commercial-grade Holter monitors—for patients undergoing timely treatment for heart-related disorders. In this context, AI employs recurrent neural networks to selectively filter artifact ECG signals caused by physical motion or electrode detachment from genuine biotic data across 50,000 samples, improving specificity by 78 percent compared with rule-based algorithms.

For diabetes care, AI-enabled sweat sensors integrated into socks can predict hypoglycemic events up to 30 minutes in advance by monitoring lactate and cortisol levels, allowing for timely glucose intake before an attack occurs [120]. This method utilizes ensemble learning (integration of support vector machine (SVM), random forest, and gradient boosting techniques) to reach 89% accuracy for all types of patients.

7.1.4. Challenges and Future Directions

Despite its transformative capabilities, AI-enabled smart textiles have several challenge areas: (1) Data privacy: Continuous biometric monitoring raises privacy concerns, requiring edge AI computation rather than cloud-based analysis to ensure data security; (2) Energy limitations: The high power demands of deep learning AI require further development of efficient ultra-low-power AI microchips (less than 1 mW) that can integrate with the energy-harvesting capabilities of textiles; (3) Personalized ethics: AI-driven personal recommendations for activities (e.g., exercise intensity and drug dosages) need careful balancing between autonomy and medical supervision, especially for seniors.

Future studies should focus on several key areas: federated learning frameworks to improve AI models collaboratively without compromising individual privacy; neuromorphic computing architectures to replicate the efficiency of biological neurons in textile-based microprocessors; and human-AI interaction paradigms that enable individuals to interpret and override AI-driven decisions for personal health management.

This is because the integration of AI technology with nanomaterial development and textile engineering enables the creation of smart clothing capable of anticipating or responding to various situations, with applications ranging from healthcare to security services.

7.2. Sustainable Intelligent Textiles

The community is moving toward the development of self-managing material systems that ensure functionality while promoting environmental sustainability. Examples of such inventions include self-wired microbial fuel cells capable of biodegrading sweat [242], and solar textiles employing biodegradable perovskite solar cells [243]. Current developments in chitosan flame retardants [52] and plant-based conductive polymers indicate that future textiles may become fully biodegradable while maintaining functionality.

7.3. Biological Integration

Advances in biocompatible technology raise expectations for direct interaction between textiles and human physiology. Projects building on ECG-monitoring graphene armbands [37] and MOF-based drug delivery systems [91] are being developed to create “living fabrics” that integrate:

- Wound dressings containing stem cells to promote tissue regeneration
- SynBio textile solutions for generating medicinal substances triggered by biomarkers
- Neural interface clothing to translate intended motor actions to control devices

7.4. Ubiquitous Connectivity Ecosystems

The convergence of 6 G networks and textile antennas [144] will transform clothing into nodal points in the Internet of Everything. Emerging designs combine:

- MXene-based EMI shielding [43] with energy-harvesting triboelectric fabrics [163]

- Quantum dot displays [192] with holographic communication interfaces
- Self-healing circuits [113] that maintain connectivity in extreme conditions

This evolution will be facilitated by advances in modular design, enabling consumers to upgrade functionality through interchangeable textile-based "apps," ranging from medical diagnostic patches to augmented reality haptic suits.

7.5. Industrial and Societal Impact

The maturation of smart textile technologies promises to disrupt multiple sectors:

- **Healthcare**: Continuous, unobtrusive monitoring replacing clinical devices [167]
- **Defense**: Adaptive camouflage systems with chameleon-like capabilities [110]
- **Energy**: Wearable solar farms using high-efficiency textile photovoltaics [132]
- **Fashion**: Democratized design through user-programmable color and texture [199]

As these technologies develop, they will establish new practices of human-technology interactions while solving the problems of sustainability, accessibility, and ethical use of data, rendering smart textiles ultimately an invisible yet necessary layer of our lives.

7.6. Concrete Research Priorities for Next-Generation Smart Textiles

Transitioning smart textiles from laboratory prototypes to commercial products is a complex process, with several technical and translational challenges that the field still needs to address:

7.6.1. Standardization and Durability Benchmarking

Research Need: Establish general performance testing practices for smart textiles in the field. Studies on wash durability report results in various ways (10–100 cycles), but there is no standardized protocol (water temperature, type of detergent, agitation speed), which limits our ability to the compare each study.

Concrete Directions:

- Develop International Organization for Standardization (ISO)-standard washing protocols specifically for conductive textiles, evaluating conductivity retention across 200+ industrial wash cycles (75 °C, alkaline detergents)
- Establish abrasion resistance benchmarks using Martindale testing (≥50,000 cycles) for sensor textiles in high-wear applications (military uniforms, athletic gear)
- Create accelerated UV aging protocols to predict 5-year outdoor performance within 6-month testing periods, critical for UV-protective and photovoltaic textiles

7.6.2. Scale-Up Manufacturing Technologies

Research Need: Bridge the "valley of death" between benchtop fabrication and kilometer-scale production.

Concrete Directions:

- Switch from conventional electrospinning to multi-nozzle arrays (≥1000 nozzles) with inline quality monitoring via machine vision, targeting a production rate of 500 m^2/h, noting that these sensors rely on nanofibers
- Move roll-to-roll printed graphene inks onto textiles, without disrupting planarity with uniformity in sheet resistance (5%) over 1 km of fabric
- Move continuous LBL assembly systems into textile and finishing line, with antimicrobial nanoparticle coatings deposited at speeds of 20 m/min in a web process.

7.6.3. Energy Autonomy and Power Management

Research Need: Eliminate battery dependence through integrated energy harvesting and storage.

Concrete Directions:

- Design hybrid energy systems coupling piezoelectric generators (10 mW/m^2 from walking) with thin-film batteries (50 mAh/cm^2) to power health monitoring sensors continuously
- Develop power management integrated circuits (PMICs) consuming <100 μW, compatible with textile flexibility (10 mm bending radius)
- Investigate wireless charging protocols optimized for textile substrates (e.g., resonant inductive coupling through fabric layers)

7.6.4. Biocompatibility and Skin Safety

Research Need: Ensure prolonged skin contact safety, particularly for nanoparticle-containing textiles.

Concrete Directions:

- Conduct 6-month dermal irritation studies (ISO 10993-10) for silver and copper nanoparticle coatings, quantifying nanoparticle migration through perspiration

- Develop encapsulation strategies (e.g., silica shells, polymer crosslinking) that retain antimicrobial efficacy while preventing nanoparticle release during 1000-h wear periods
- Establish cytotoxicity thresholds for emerging nanomaterials (MXenes, metal-organic frameworks) in textile applications through in vitro keratinocyte assays

7.6.5. Data Security and Privacy Frameworks

Research Need: Address ethical concerns surrounding continuous biometric monitoring.

Concrete Directions:

- Implement on-device AI processing (edge computing) to eliminate cloud-based data transmission, reducing privacy risks
- Develop encrypted data protocols for textile-to-smartphone communication (AES-256 standard)
- Establish user consent frameworks allowing granular control over data collection (e.g., toggling heart rate monitoring vs. activity tracking)

7.6.6. Circular Economy and End-of-Life Management

Research Need: Mitigate environmental impacts through recyclable smart textiles.

Concrete Directions:

- Design modular architectures where electronic components (sensors, batteries) detach from fabric substrates for separate recycling streams
- Develop biodegradable conductive polymers (e.g., PEDOT: PSS with cellulose binders) that decompose within 6 months in composting environments while maintaining 10^4 S/cm conductivity
- Investigate chemical recycling methods to recover precious metals (Ag, Au) from electronic textiles at >90% efficiency
- By approaching these priority areas in an organized manner through coordinated academic-industry partnerships, the discipline can make progress toward commercially viable, ethically responsible smart textiles that merge into everyday living while still addressing global sustainability imperatives.

8. Conclusions

Smart textiles have transformed fabrics from passive to active systems, using nanotechnology, flexible electronics, and innovative designs to enable functionalities beyond conventional wear. This discussion aims to present the role of nanotechnology-enabled textiles as key enablers of innovative developments across diverse fields, including biomedical, energy, military, and fashion applications.

Crucial technological foundations such as conductive nanomaterials (e.g., graphene, MXenes, and CNTs), stimulus-responsive polymers (e.g., PCMs and SMAs), and hybrid energy solutions have enabled effective smart fabric development that is not only useful but also flexible and scalable. This is further assisted by advanced fabrication methodologies such as electrospinning, dip coating, screen printing, and layer-by-layer assembly processes for effective and cost-effective manufacture of smart fabrics.

Compared with smart protective textiles, its primary emphasis is on safety and hygiene, provided by flame-retardant and antimicrobial finishes, whereas for health-monitoring textiles, sensors for biomedical measurements take precedence. Energy-harvesting and energy-storing textiles take self-sufficiency to new dimensions, and fashion-based smart textiles combine functionality and expression through dynamic media of light, motion, and color.

The fusion of artificial intelligence, sustainable materials, and bio-integrated systems is poised to deliver a new generation of hyper-personalized, sustainable, and seamlessly connected textile technology solutions. Ranging from self-powered diagnostic medical capabilities to adaptive camouflage and dynamic wearables, smart textiles are poised to become key enablers of the new human experience paradigm.

It is apparent that to realize their full transformative power, future initiatives should:

- Achieving robustness and easy cleanliness without affecting capability
- Scaling up sustainable production techniques
- Handling concerns surrounding ethics and data privacy in wearability
- Improving cooperation between materials researchers and textile engineers, data analysts, and designers

Smart textiles have evolved from conceptual ideas into platforms at the intersection of science, engineering, and design, with the potential to transform daily life through smart, interactive, and integrated fabric systems.

List of Abbreviations

AgNW	Silver Nanowire
AI	Artificial Intelligence
Al_2O_3	Aluminum Oxide
ANF	Aramid Nanofiber
APP	Ammonium Polyphosphate

CA	Cellulose Acetate
CNF	Carbon Nanofiber
CNT	Carbon Nanotube
CS	Chitosan
Cu	Copper
CVD	Chemical Vapor Deposition
DSSC	Dye-Sensitized Solar Cell
ECG	Electrocardiogram
EL	Electroluminescent
EMI	Electromagnetic Interference
FBG	Fiber Bragg Grating
FO-SPR	Fiber Optic Surface Plasmon Resonance
FR	Flame Retardant
FTIR	Fourier Transform Infrared Spectroscopy
GF	Gauge Factor
GRF	Ground Reaction Forces
HVAC	Heating, Ventilation, and Air Conditioning
ICP	Inherently Conductive Polymer
IR	Infrared
LBL	Layer-by-Layer
LC	Liquid Crystal
LCE	Liquid Crystal Elastomer
LED	Light-Emitting Diode
LOI	Limiting Oxygen Index
LSPR	Localized Surface Plasmon Resonance
MEMS	Micro-Electro-Mechanical Systems
MIC	Minimum Inhibitory Concentration
MIR	Mid-Infrared
MOF	Metal-Organic Framework
MSC	Micro-Supercapacitor
MWCNT	Multi-Walled Carbon Nanotube
MXene	Two-dimensional transition metal carbides/nitrides
NBC	Nuclear, Biological, Chemical
NP	Nanoparticle
OCA	Oil Contact Angle
OD	Optical Density
OLED	Organic Light-Emitting Diode
PAN	Polyacrylonitrile
PANI	Polyaniline
PCF	Photonic Crystal Fiber
PCM	Phase-Change Material
PDA	Polydopamine
PDMS	Poly(dimethylsiloxane)
PEDOT:PSS	Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate
PEG	Polyethylene Glycol
PENG	Piezoelectric Nanogenerator
PHRR	Peak Heat Release Rate
PLA	Polylactic Acid
PMIC	Power Management Integrated Circuit
PNIPAM	Poly(N-isopropylacrylamide)
POF	Polymeric Optical Fiber
PPy	Polypyrrole
PSC	Perovskite Solar Cell
PTFE	Poly(tetrafluoroethylene)
PVDF	Poly(vinylidene fluoride)
RGO	Reduced Graphene Oxide
RFID	Radio-Frequency Identification
RGB	Red, Green, Blue
RH	Relative Humidity
RMG	Ready-Made Garment
RNN	Recurrent Neural Network
ROS	Reactive Oxygen Species
SE	Shielding Effectiveness
SEM	Scanning Electron Microscopy
SMA	Shape Memory Alloy
SVM	Support Vector Machine
STF	Shear Thickening Fluid
TEG	Thermoelectric Generator
TENG	Triboelectric Nanogenerator
TEOS	Tetraethyl Orthosilicate
UHMWPE	Ultra-High Molecular Weight Polyethylene
UPF	Ultraviolet Protection Factor
UV	Ultraviolet
VLC	Visible Light Communication
VOC	Volatile Organic Compound
WCA	Water Contact Angle

Author Contributions

Conceptualization: F.I.O., M.H.R.; Methodology: F.I.O., R.J.S., N.C.G.; Software: F.I.O.; Validation: M.H.R., N.C.G.; Formal Analysis: F.I.O., R.J.S.; Investigation: F.I.O.; Resources: F.I.O.; Data Curation: F.I.O., R.J.S.; Writing—Original Draft Preparation: F.I.O.; Writing—Review and Editing: All authors contributed equally to reviewing and editing all sections; Visualization: F.I.O., Supervision: M.H.R., N.C.G., Project Administration: F.I.O. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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