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Review Article

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

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Abstract

Smart textiles offer an innovative integration of nanotechnology, materials science, and wearable electronics, providing unparalleled capabilities above those of traditional textiles. This thorough review covers recent breakthroughs in advanced textile innovations based on engineered nanomaterials, particularly discussing ground-breaking uses of these materials in health, energy, military, and consumer applications. We critically review all four categories, including: 1. Protective textiles with flame-resistant nanocoatings, antibacterial nanoparticles, and UV-blocking semiconductor nanoparticles; 2. Energy-harvesting technologies based on piezoelectric, triboelectric, and thermoelectric nanomaterials, particularly designed for self-powered electronics; 3. Physiological monitoring interfaces with graphene sensors and optical fibers, intended for immediate biomedical monitoring and tracking; 4. Active materials with color-changing, shape-memory, and thermal-responsive properties.

The review points out advances in material science, such as MXene-containing textiles for electromagnetic shielding, phase change materials for dynamic thermal control, and plasmonic nanostructures for interactive displays. We also describe scalable processing technologies, including electrospinning of conductive polymers, roll-to-roll processing of solar cells based on textiles, and atomic layer deposition of nanocomposite thin films.

The emerging themes of biocompatibility in electronics, AI-based adaptive technologies, and sustainable nanotextiles are all seen as key domains of research and development in next-generation innovative textiles. This publication, with over 230 research findings included, aims to offer research professionals and industry insiders not only insight into what can be accomplished today, but also foresight into what may be accomplished in the integration of smart textiles into daily practice

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

1. Introduction

Nanotechnology, initially proposed by Richard Feynman in the year 1959 but later introduced by Norio Taniguchi in 1974 [1, 2], has drastically changed the faces of various industries like medicine [3], agricultural sciences [4], environment restoration [5], electronics [6], energy storage materials [7], solar technology [8, 9], paints [10], and green chemistry [11,12], respectively. Through the manipulation of materials at the atomic and molecular scale, nanotechnology improves the physical, chemical properties of materials at the nano-scale that cannot be achieved at the macroscale. Nanomaterials have their characteristics based on the constituents that give them dimensions of at least 100 nanometer scale dimensions or lesser dimensions on at least one side [13, 14], with remarkable properties that give them enhanced surface area, mechanical properties, enhanced electro-conductivity of materials at the nano-scale, and chemical stability of materials at the nano-scale. Nanomaterials are highly sought after because of their properties being of great utility in the application areas of medicine [15], waste water treatment technologies [16], textile dyeing technologies [17], and sensor technologies like electrochemical sensors [18], optical sensors [18], piezoelectric material-based sensors [18], and magnetic materials-based sensor technologies [18], amongst others.

As shown in Fig. 1 above, certain nanomaterials like zero-dimensional spheres or clusters have specific characteristics based on their dimensions [19]. Nanomaterials may be made either hydrophilic or hydrophobic based on the application requirement. Nanoparticles are made up of three different 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 (ii) Core layer that forms the center of the nanoparticle [20, 21]

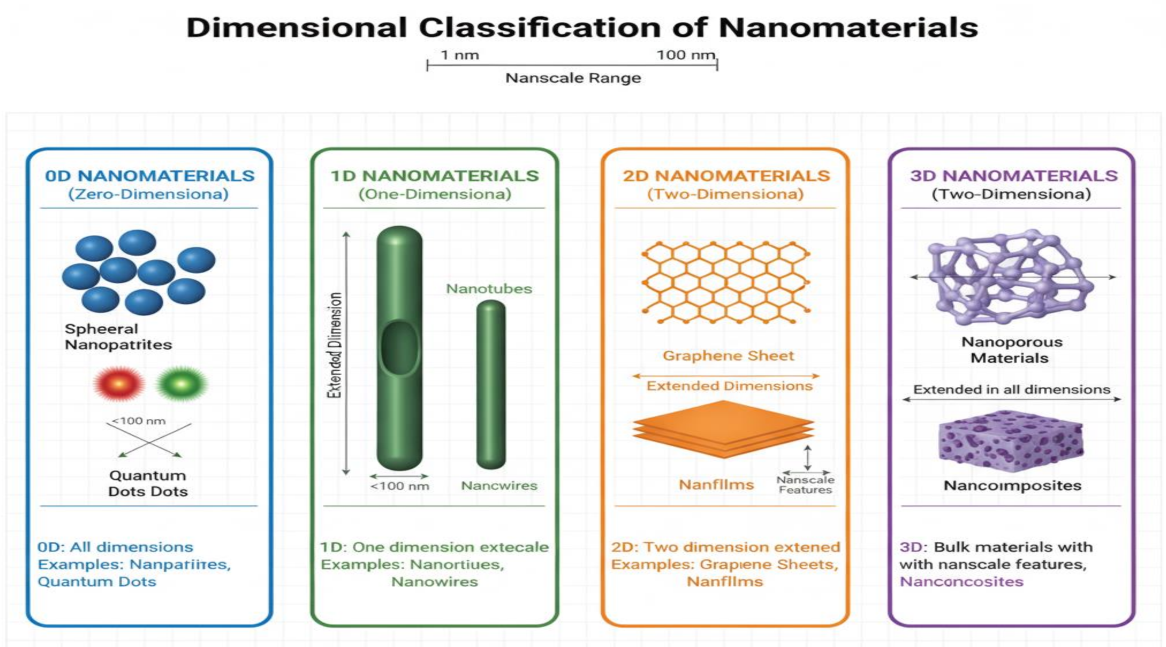

Figure 1. Types of nanomaterials (0D, 1D, 2D, and 3D).

The development of the textile industry has traditionally relied on the advancements of material sciences and the resultant requirements of performance enhancement of textiles. Smart textiles that introduce nanomaterials into conventional textiles possess multi-functional characteristics that go beyond the realms of aesthetics and comfort. Smart textiles encompass various industries like pharmaceutical textiles, health care textiles, sport textiles, fashion textiles, protective textiles, and transportation 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 augment 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 the demand for innovation driven by nanotechnology further. The textile manufacturing sector, a significant sector that contributes to the world's production rate, is gradually adopting eco-friendly strategies that make the most of the used resources while being environmentally friendly. Use of nanotechnology improves the sustainability of the product too and encourages the production of the product with the least wastage of materials [29]. Further, the significance of nanomaterials being an innovation that overcomes world-level difficulties keeps growing [30, 31].

Contrary to the reviews that tend to carve out specific innovation areas of smart fabrics, e.g., only antibacterial coatings [32,33], energy harvesting technologies [34, 35], and wearable sensor technologies [36-38], this text uniquely brings together these different innovation areas under the rubric of multifunctionalty enabled by nanomaterial science. For instance, although Li et al. [35] and Kim et al. [36] examine the area of piezoelectric textiles, their reviews do not consider the area of thermal management and photonic system integration. Additionally, although reviews on antimicrobial textiles by Ahmed et al. [24] go deep on the topic of silver nanoparticles' performance, they make no mention of the scaling up and multifunctionality of these materials. This particular text therefore closes the gap by showing the different application areas of these materials across different industries, ranging across military gear with flame retardation properties [39] and technologically sophisticated fashion interfaces with the ability to adapt changes of color patterns [40], and technologies that facilitate these merge constructs through fabrication procedures. Additionally, despite the fact that the reviews limit the discussions on single-fabric materials only [41,42], this text expands the discussion on a variety of materials across different scenarios of hybridization of the materials themselves. Examples of these include MXene-coated cotton fabrics [43] and photonic fiber arrays [44] that could facilitate the development of multifunctional, scalable, and sustainable technologies of smart fabrics at an unprecedented scale.

Although various reviews exist that add valuable knowledge regarding smart textiles, there are critical shortcomings that this study overcomes. A specific field of study with reviews only on antibacterial coatings [32,33] or electricity harvesting [34, 35] may offer insightful material but neglects the integrated approach of protection, electricity harvesting, sensing capabilities, and the world of fashion that this study showcases. As an example of this lack of integrated reviews, Li's et al. study on piezoelectric textiles offers an in-depth approach but completely neglects the temperature regulation mechanisms that could improve the efficiency of electricity harvesters during temperature changes. Additionally, the study on antibacterial qualities by Ahamed's et al. team neglects the washing cycles over the first fifty cycles only; this serves only half of the requirements set by the garment industrial standard of washing above 100 cycles. Analyses of single-system fabrics [41,42] neglect the incorporation of hybrid materials; cotton coated with MXene material offers a specific conductivity of up to 922 S/cm that cannot possibly happen on polyester material only.

Recent reviews on wearable sensor technologies based on nanofibers [45] have further evolved the topic of thermal management strategies and their HVAC implications but with special attention being directed toward radiative cooling strategies on health care. Nevertheless, these reviews focus more on the performance characteristics of the sensor without dealing with the scalability issues of fabrication (laboratory-scale electrospinning and roll-to-roll fabrication), the incorporation of the sensor with an auxiliary power source (textile-based supercapacitors), and the convergent technology of protection and power (sensing and power harvesting). This serves as the distinctive point of the proposed review.

Our works 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. Our approach integrates the various aspects of application development with the subsequent transition of the technology into the commercial marketplace.

This particular study focuses on the development of nanotechnology over the years and the prospects that lie ahead of it in the realm of textiles. The significance of nanomaterials toward developing intelligent textiles cannot possibly go unnoticed; it has the potential of significantly impacting the sustainability agenda of the world.

2. Smart Protective Textiles

2.1 Flame-Retardant Textiles

Integrating nanomaterials into textiles has revolutionized flame retardancy by addressing the limitations of conventional additives, such as poor durability, environmental toxicity, and compromised mechanical properties. Nanoparticles make the material more resistant to heating through various strategies that include the following aspects of nanoparticles on the material's surface that (1) serve as physical barrier retarders of the material's temperature transfer and mass transfer during the reaction with the material's surface; (2) promote the char creation on the material's surface; and (3) consume the reactive radicals generated by the reaction on the material's surface.

2.1.1 Nanoclays and Silicates:

Nanoclays like montmorillonite are amongst the most investigated halogen-free flame retardants because of their superior aspect ratio and ease of dispersion with polymeric matrices. Nanoclays used with polyamide 6/clay nanocomposite monofilaments decrease the peak value of the heat release rate (PHRR), an essential criterion of fire performance that signifies the maximum amount of released combusting power during the combustion process by up to 33% relative to polyamide material on its own [46]. Functional nanoclays incorporated together with halogen-free phosphoric flame retardants (FRs) with polyamide 6.6 form an interconnected char layer of higher proportion. This phenomenon prevents the material's flammability performance due to their condensed gas phases [47]. A study revealed that even the addition of low amounts of nanoclays ($\leqslant$5%) of halogen-free phosphoric flame retardants with 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, nano-sized TiO_2 coatings on cellulosic fabrics using the sol-gel process offer dual application--self-cleaning and flame retardation properties. Additionally, the titanium dioxide coating acts as an insulating layer that slows pyrolysis and suppresses the emission of smoke [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 offers remarkable properties of suppressing the emission of smoke by an average of 40% on polypropylene materials [51].

2.1.3 Hybrid and Bio-inspired Systems:

Recent innovations lie on the development of hybrid designs consisting of nanoparticles and either bio-based polymers or intumescent coatings. Chitosan (CS), a biodegradable polysaccharide material, has recently emerged as an attractive candidate that can be converted into flame retardation coatings on cotton materials. CS nanocomposites, with the application of phytic acid and the addition of titania nanoparticles (Figure 2a and b), offer a reduction of 50% in the PHRR index and possess the ability of extinction due to accelerated char release and low-flux transfer of heat [52]. On the other hand, layer-by-layer assembly of polyelectrolytes with the addition of h-BN nanosheets results in the development of hybrid materials with the combined effects of flame retardation and water repellency [53]. Bio-based designs, including the laminating of fabrics with hydrogels that pose resistance capabilities akin to natural materials' absorption of heat (Figure 2c and d), activate the natural absorption of heat.

Hydrogels laminated on cotton fabrics based on polyvinyl alcohol-borax contain the capacity of delaying the ignition of cotton materials by up to 120 seconds and the reduction of the rate of the heat release by 60% through the process of endothermic water release and char stabilization [54].

A hybrid flame retardant system that exhibits synergy through the incorporation of nano-scale materials. As shown in Fig. 2e above, the fabrication of the APP@SiO2-PDA@Ag polyester fabrics involves the stepwise coating of the fabrics with ammonium polyphosphate (APP) coated with a shell of silicon dioxide (SiO2) that functions as an inhibitor of early degradation during the production of the fabrics. 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 of a limiting oxygen index of 32% for its flame retardancy property and the ability of the system to kill up to 99.9% bacteria within 24 hours —demonstrating how nanoparticle surface engineering enables multifunctional textiles [55].

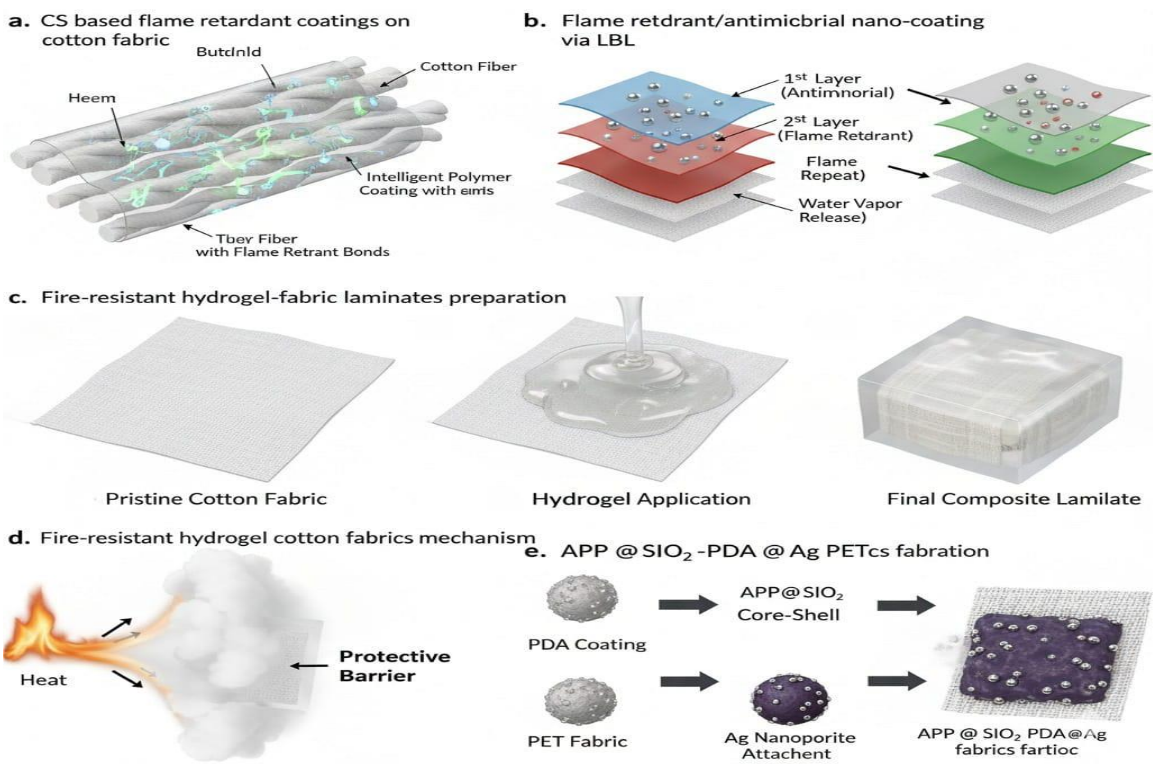

Figure 2. a. CS based flame retardant coatings in a cotton fabric. b. Flame retardant/antimicrobial nano-coating on cotton through LBL incorporation. c. Fire-resistant hydrogel-fabric laminates preparation. d. Fire-resistant hydrogel cotton fabric laminates mechanism e. APP @ SiO2 -PDA @ Ag PET fabrics fabrication process.

2.1.4 Synergistic Effects with Conventional Flame Retardants:

Nanomaterials integrated with conventional FRs (halogenated materials and derivatives of phosphorus) mitigate efficiency and sustainability issues. As an instance of this approach, the dispersion of ammonium polyphosphate (APP) nanoparticles with the application of SiO_2-PDA@Ag core-shell structures (Figure 2e) improves the distribution of the material over the polyester fabrics. This results in a limiting oxygen index of 32% and a UL-94 rating of the sample as a V-0 material. The addition of the silver nanoparticles provides the material with antibacterial activity [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 an integral role in the fields of medicine and sportswear because of the importance of pathogen growth suppression. Nanoparticles like silver (Ag), titanium dioxide (TiO_2), zinc oxide (ZnO), and copper oxide (Cu_2O) have found their application as potent antimicrobial agents owing to their higher surface area-to-volume ratios, reactive nature, and versatile action mechanisms (Figure 3) [56-58, 32]. This part of the discussion delves into the action mechanisms and issues of these nanomaterials with specific references to their development as part of textiles.

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 Ag NPs (<20 nm) exhibit enhanced efficacy due to increased ion release rates [61].

TiO_2 and ZnO NPs: Under UV illumination, ROS (like hydroxyl radicals) produced by TiO2 NPs react with the organic materials of microbial cells [56, 62], whereas ZnO NPs release ROS along with Zn2+ ions that degrade the bacterial cell membranes and suppress the development of biofilms [63, 64].

Chitosan and N-Halamine: Chitosan, a biopolymer interferes with microbial membranes due to electrostatic attraction 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].

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 Ag NPs or titanium dioxide into the matrix of nanofibers made of polyurethane and cellulose acetate improves the binding of the materials at the interface. This creates a system that can sustain the antibacterial activity even after completing more than 50 cycles of washing [66, 67]. As shown in Figure 3a, the conventional method of dipping the cotton fabric into the nanoparticles and then drying them forms an uneven distribution of the materials on the surface of the fabric that may come off after completing the first few cycles. The Ag NPs incorporated into the poly-acrylonitrile nanofibers could kill more than 99 [68].

Layer-by-Layer (LBL) Assembly: Alternating depositions of chitosan and Ag NPs on cotton fabrics via LBL (Figure 3b) achieved a 6-log reduction in *Escherichia coli* while maintaining breathability [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:

Ag-TiO_2 Composites: Release of silver ions by the addition of titania nanoparticles significantly improves the photocatalytic activity of the system toward ROS-dependent cytotoxic effects. A study performed on cotton fabrics coated with these composites showed an increase of up to 4.3 times the antibacterial activity of bare silver [62].

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

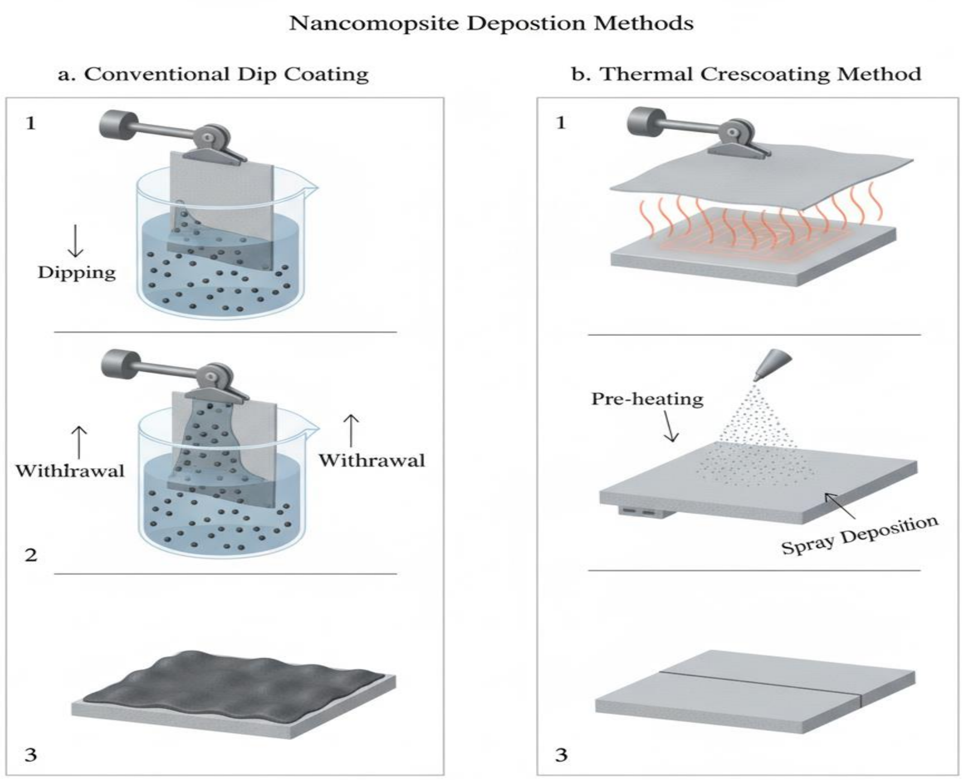

Figure 3. Nano-composite deposition methods: a. Conventional, dip coating b. Thermal Crescoating method.

2.2.4 Evaluation of Efficacy

The broth microdilution method (Figure 4) assess 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 presented with the case of cotton fabrics coated with titanium dioxide nanoparticles, with an MIC of 12.5 µg/mL against *Staphylococcus epidermidis*, with an average optical density of the cultures at 600 nm correlating inversely with nanoparticle concentration [56].

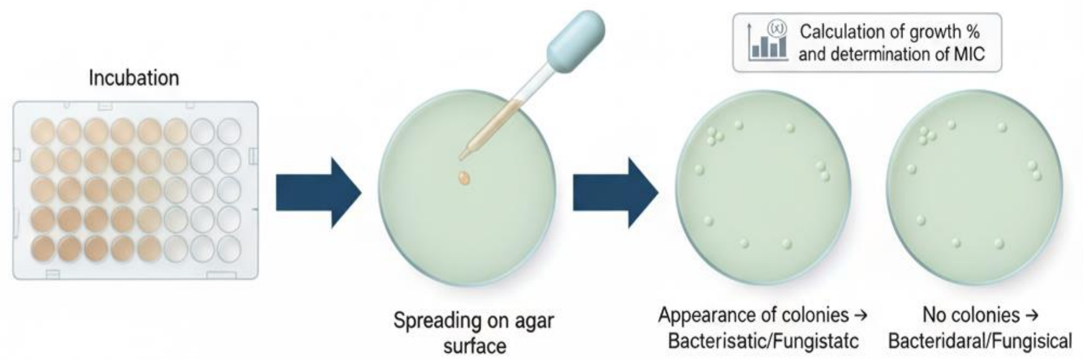

Figure 4. Antimicrobial efficacy assessment via broth micro-dilution methods. Optical density (OD_{600}) measurements at varying nanoparticle concentrations quantify bacterial growth inhibition, enabling determination of minimum inhibitory concentration (MIC). Lower OD values indicate enhanced antimicrobial 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 with the capacity to continuously control the temperature of the human body is of utmost importance with respect to raising the comfort levels of humans under harsh environmental conditions, reducing energy consumption, and enabling wearable technologies [71, 72]. Currently, new technologies utilizing nanomaterials and phase-changing materials and bio-inspired designs for precise thermal management [73]. This part of the discussion focuses on the various strategies that are involved with heating and cooling textiles.

2.3.1 Phase-Change Materials (PCMs)

PCMs that readily release and receive latent heat during phase transitions are typically incorporated into fabrics as an active material with a passive cooling system. This results in coaxially electrospun ropes of PCMs like paraffin wax incorporated into polyurethane membranes that offer immense heat enthalpy (106.9 Joule/gram) with reliable temperature variation cycles [74]. This results in temperature regulation with maximal heating of up to 73.8ºC under electromagnetic activation and up to 70.5ºC under solar activation, making them suitable for wearable adaptive sportswear and outdoor equipment [74]. Furthermore, combined PCMs with photothermal components like carbon nanotubes improve solar heating efficiency and enable the dual action of cooling and heating [75]. Future designs of PCM-integrated textiles will leverage artificial intelligence for enhanced thermal energy storage optimization, with machine learning algorithms enabling improved prediction of PCM thermal properties, heat transfer enhancement, and operational efficiency in temperature regulation systems for wearable applications [76].

2.3.2 Conductive and Radiative Cooling

High thermal-conductive nanomaterials like copper (Cu) and graphene are used in textiles that aid the conduction of cooling effects. The integrated cooling (i-Cool) fabric material with copper-coated nylon-6 nanofibers offers a cooling efficiency of 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 the temperature of the skin by up to 2-4°C under direct solar radiation, even when worn over cotton fabrics [77].

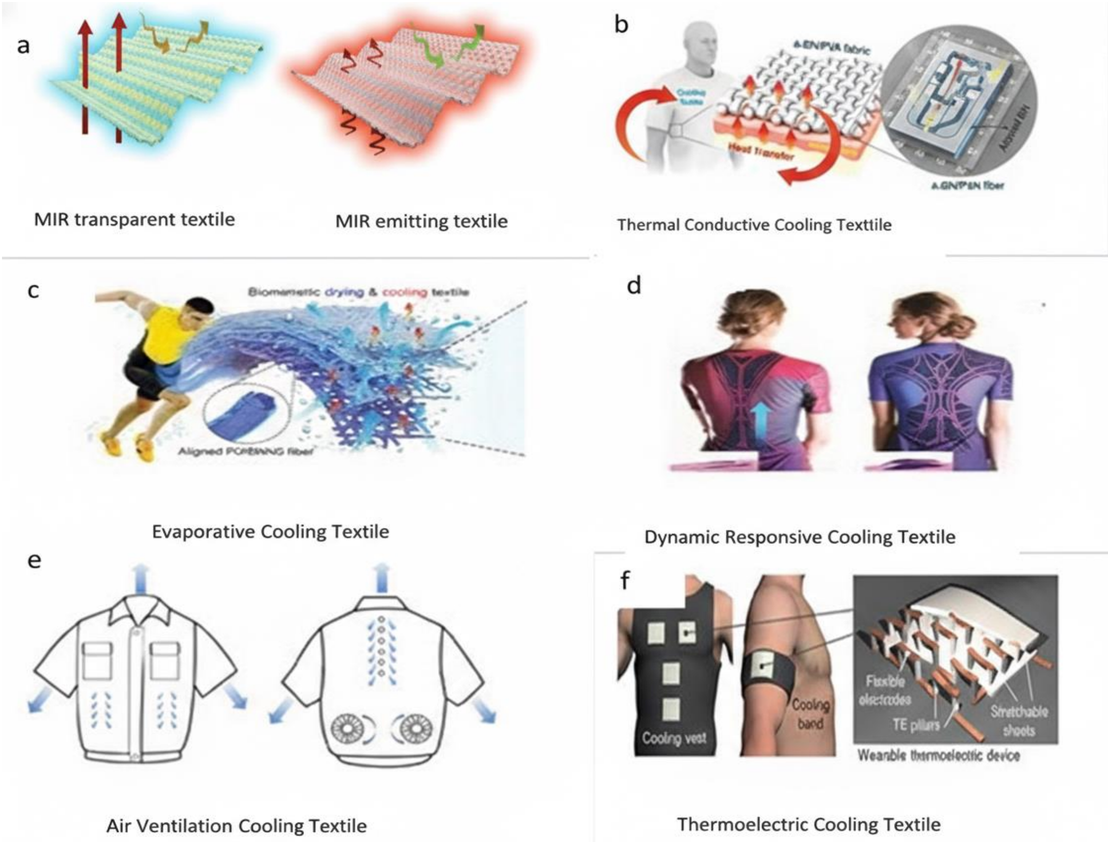

Figure 5. (a) MIR transparent & emitting cooling textile (b) Thermal conductive cooling textile (c) Evaporative cooling textile (d) Dynamic responsive cooling textile (e) Air ventilation cooling textile (f) Thermoelectric cooling textile.

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 mimic human sweat glands using 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 minutes of activity [79].

Dynamic Responsive Materials: Stimuli-responsive polymers, such as poly(N-isopropylacrylamide) (PNIPAM), enable temperature-dependent porosity adjustments. 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 placement of the fans with computational fluid dynamics modeling improves the distances of the air gaps and results in a 25% increase in the efficiency of convective cooling due to the transfer of heat (Figure 5e) [72, 81].

Thermoelectric Generators (TEGs): Bismuth telluride (Bi_2Te_3) TEG fabrics take the place of conventional textiles and make the most of the Seebeck principle by utilizing the skin's natural temperature difference and transforming the generated power into electricity at the same time. A wearable matrix of the TEG (Figure 5f) produces a power density of 3.2 μW/cm² 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 form of response to such threats, nanotechnology has enabled the development of advanced UV-protective fabrics, which have been made by using inorganic and organic nanomaterials (Figure 6) [83]. These materials enhance 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.

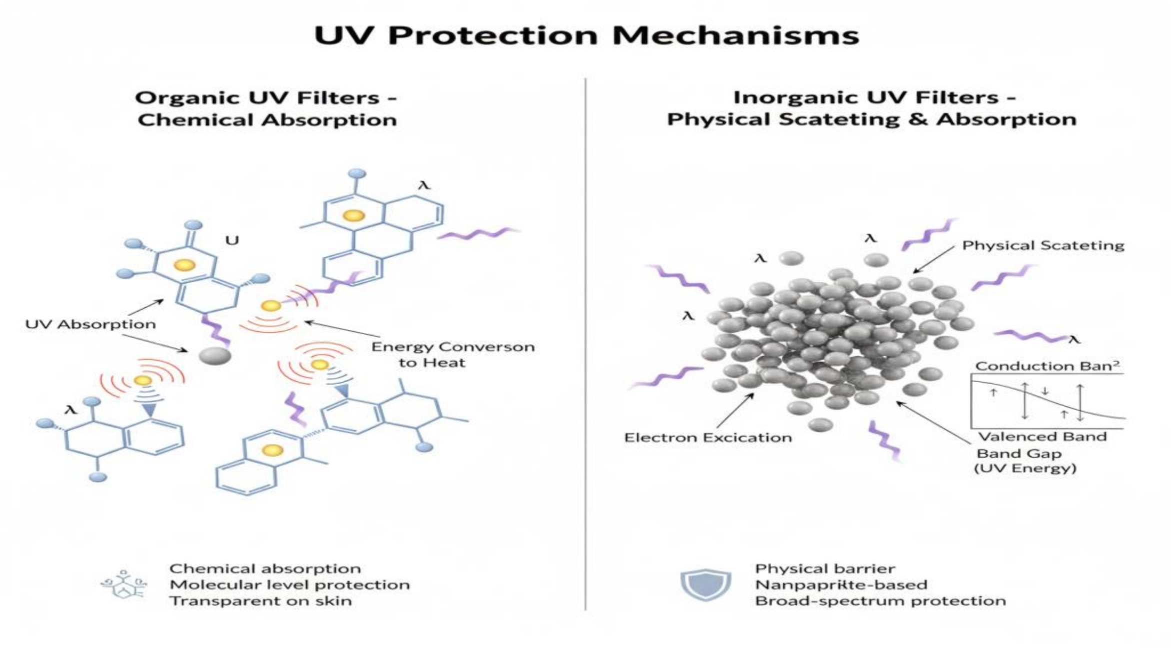

Figure 6. Organic UV filters & Inorganic UV filters.

2.4.1 Inorganic UV Blockers: Mechanisms and Performance

Inorganic nanomaterials, especially metal oxides like titanium dioxide (TiO_2), zinc oxide (ZnO), and aluminum oxide (Al_2O_3), are most 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 used on cotton with sol-gel methods, TiO_2 coatings stay UPF > 50 (superb shield) even after 20 wash cycles, showing excellent wear resistance (Figure 7) [85].

ZnO Nanoparticles: ZnO has a wide bandgap of 3.37 eV which makes it good to absorb 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 cm3/cm2/sec) 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 tensile strength loss by 40% after prolonged exposure [86].

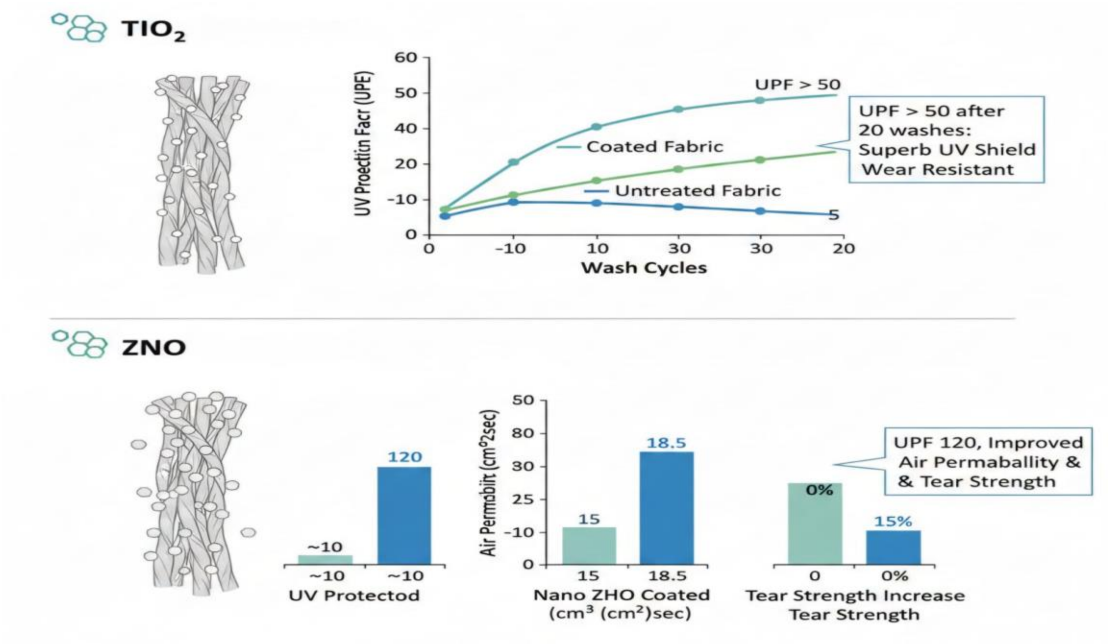

Figure 7. Performance of nanoparticles coating on cotton fabric.

2.4.2 Organic UV Blockers and Hybrid Systems

Organic UV absorbers like benzotiazoles and avobenzone contribute additional protection as they absorb particular wavelengths of UV; however, their degradation and leaching capacity restrict their application as single active materials [87]. Mixtures of organic UV-absorber materials with nanoparticles of chemical elements (like zinc oxide-benzotiazole) overtuin these disadvantages. Additionally, zinc oxide-benzotiazole mixtures showed a protection factor of UPF = 200 on polyester textiles with an absorption capacity of up to 85% after 50 laundries [88, 89].

2.5 Hydrophobic and Oleophobic Textiles

Hydrophobicity (water repellency) and oleophobicity (oil repellency) are critical functionalities in textiles 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.

2.5.1 Biomimetic Designs and Natural Inspiration

The lotus leaf structure with its hierarchical nano/micro structures and waxy coatings has been mimicked utilizing carbon nanotubes (CNTs) and silicone materials. CNTs on cotton fabrics form a highly water-repellent surface with a water contact-angle of over 150 degree, thus having the property of water repellency like the lotus leaf surface [90]. Likewise, the water-repellency-related 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 degree and 130 degree, respectively.

2.5.2 Nanoparticle-Enhanced Coatings

SiO_2 nanoparticles are very frequently used due to the versatility of their surface chemical structure. On cotton fabrics coated with 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, the application of fluorinated clay-fluoropolymer mixtures using the dipping process reduces the surface energy of materials with breathability characteristics; therefore, the fabrics exhibit oleophobic properties (medical gowns) [92].

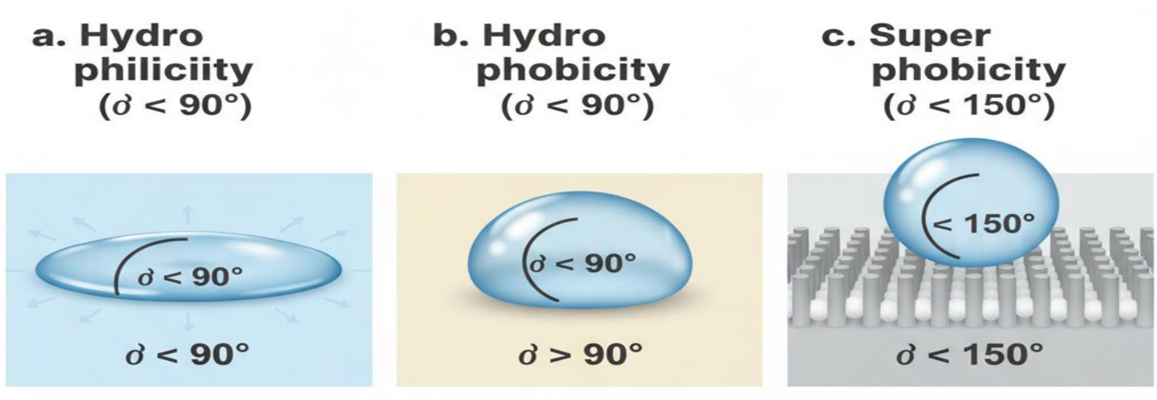

Figure 8. Schematic diagram of (a) hydrophilicity contact angle (θ) <90° (b) hydrophobicity contact angle (θ) >90° (c) superhydrophobicity contact angle (θ) >150°.

2.5.3 Advanced Fabrication Techniques

Layer-by-layer assembly and plasma treatment improve the durability and homogeneity of the coatings. As an 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 cycles of laundry washing with negligible degradation of the WCA [93]. Alternatively, plasma treatment of polyester fabrics facilitates the activation of the hydroxyl group on the material's surface with enhanced adhesion of the hydrophobic ZnO nanoparticles and values of WCAs exceeding 150° (Figure 8) [94].

2.5.4 Janus and Multifunctional Textiles

Janus-type amphiphilic nanoparticles with hydrophobic and oleophobic phases facilitate preferential 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]. Also, the cotton fabric with epoxy modification and amino-silica and ZnO nanoparticles simultaneously exhibits superhydrophobic properties (WCA = 158 degree;), as well as flame retardancy at an LOI of up to 28% , highlighting multifunctional potential [96].

2.6 Antistatic Textiles

The accumulation of static charges on synthetic fabrics like nylon and polyester creates serious issues that could result in discomfort as well as electrostatic discharge. Nanomaterials have recently emerged that can increase the surface conductance or wettability of the material and thus render it antistatic. This chapter will briefly enumerate the strategies used to render materials antistatic through the integration of nanomaterials based on the method of action.

2.6.1 Conductive Nanomaterials for Static Dissipation

Conductive nanoparticles like ZnO whiskers and TiO_2 have been extensively used as additives in synthetic fabrics to make them more conductive. ZnO whiskers with a star-like structure create networks that significantly reduce the surface resistivity of polypropylene by as much as 3-4 orders of magnitude [97]. Likewise, the dispersion of TiO_2 nanoparticles (<50nm) in polyester fabrics utilizes their semiconductor characteristics that can reduce static voltages above 2 kV to below 200V measured using electrostatic field detectors [98].

2.6.2 Hybrid and Doped Systems

Sb-doped SnO_2 nanoparticles have higher electrical conductivity because of the donation of electrons by Sb^{5+} ions. As SnO_2 nanoparticles are incorporated into polyacrylonitrile (PAN) fibers, the surface resistivity is lowered to 10^8 Ω/sq, thus inhibiting the accumulation of charges at the surface even under low humidity conditions [97]. Sol-gel coatings involving nano sols of hydrolyzed silanes (TEOS) increase the absorption of moisture with hydrophilic surfaces that reduce static charges due to 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 provide superhydrophobic surfaces with water contact angles of over 150° while ensuring breathability. On the other hand, incorporating ZnO nanoparticles into polyester fabrics gives antistatic properties with a surface resistivity of around 10^6 Ω/sq, demonstrating electrical conductivity properties to discharge static electricity quickly [100].

2.7 Smart Military Textiles

Smart Military Textiles: Smart military textiles are an innovation for soldier technology. They incorporate multifunctional materials with embedded systems for improving survivability, situation awareness, and operational efficiency. Military environments have extreme operating conditions, and these military texts provide innovations in physiological measurement, ballistic shielding, camouflaging, and environment countermeasures.

2.7.1 Physiological Monitoring and Health Tracking

Integrated biosensors in military uniforms facilitate real-time observation of vital functions like heart rate, respiration rate, and body temperature. For example, graphene-based clothing in flexible armband designs shows 96% accuracy with conventional ECG leads, facilitating real-time observation of cardiac functions with 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 facilitate real-time respiration observation with unencumbered mobility for soldiers [103].

Apart from the common biosensing platform, the utilization of MEMS in textiles leads to miniaturized biosensing platforms with multiple functionalities, incorporating biosensing, environment, and other functions into one platform. Body-worn MEMS pressure sensors integrated into protective equipment serve dual purposes: monitoring physiological parameters such as respiration rate through chest movement detection, and detecting blast overpressure events to assess traumatic brain injury risk 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. Together with the MXene textile suprecap with the capacity to power wireless temperature sensors for a period of 96 minutes, battery replacements are not required [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/weight ratios, with potentials 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 improves protective properties, with carbon nanotube-reinforced composites spreading kinetic energy by entwining nanowire matrices, increasing puncture resistance by 35% compared to regular 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 to compensate for environment. For instance, WO_3-based fabrics require only 0.5 seconds for transitions from woodland green to desert tan in response to 5V stimuli [108]. Thermochromic phase-change materials (PCMs), like polyethylene glycol (PEG)-Kevlar aerogels, dynamically regulate infrared signatures to align with environmental backgrounds in emission

(0.94 matched to environments, with thermal detection ranges shortened by 60% [109]. Biomimetic CAM patterns based on plasmonic nanostructures copy chameleon skin's dynamic color changes, with studies in progress 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 are able to inactivate > 99.9% Bacillus anthracis spores in 30 minutes by 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 integrity in nuclear, biological, and chemical (NBC) protective suits after multiple cycles of stresses [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 40-60 dB for 8-12 GHz frequency bands [114, 43]. Aramid nanofiber (ANF)-MXene papers, produced through vacuum-assisted-filtration, balance flexibility with an EMI shielding effectiveness exceeding 50 dB to secure communication systems from jamming [43].

2.7.6 Infrared (IR) and Thermal Stealth

Thermal emissivity-engineered textiles, for example, KNA/PCM laminates, adjust for controlled thermal emission to blend in with surroundings. These fabrics obscure infrared contrast by 70%, by passing thermal imaging cameras [115]. Metamaterials with negative refractive indexes obscure thermal entities, albeit miniaturized technology being necessary for applications in the operational environment [116].

2.7.7 Advanced Material Innovations

Nanocellulose, obtained from plants or bacteria, improves fire resistance properties, with enhanced filtering in military applications. Its tensile strength (7.8 GPa) with low density (1.6 g/cm³) properties is most preferred for its 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 5V for Arctic applications) [117].

These have reformed modern warfare logistics by creating new materials with cutting-edge nanotechnology, sensoring, along with designs inspired by nature. They provide safety, as well as efficiency, for soldiers.

3. Energy Collector Smart Textile

3.1 Energy-Harvesting Smart Textiles

Energy-harvesting textiles exemplify the next-generation paradigm in wearable electronics by converting biomechanical motion, body heat, and solar radiation to power embedded electronics. Such systems can completely remove dependence on external batteries and thus enable self-powering smart textiles for applications in healthcare, 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 its crystal structure (Figure 9) [118-120]. Poly(vinylidene fluoride) (PVDF), having high flexibility with high piezoelectric constant ($d_{33} \approx$ 20-30 pC/N), is popular in textile-based PENGs [34, 121]. For example, electrospun PVDF nanowires provide 8.5 V and 2.5 μA for finger tapping forces, which is sufficient to drive LEDs [38]. ZnO NW-covered polyester fibers produce 4.2 V for walking cycles, representing stability in 10,000 cycles, with repeated bending [34]. More complex architectures, like

$BaTiO_3$ NW-reinforced PVDF composites, have improved charge separation, resulting in improved power density, boosting output by 3 times (up to 45 µW/cm²) with respect to 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 mechanic amplification. He et al. fabricated piezoelectric biosensors by electrospinning PVDF-TrFE nanofibers with diameters of 200 nm on to silicon-based MEMS cantilevers to produce highly sensitive pressure sensors with record-breaking gauge factor values above 1,200, six times more sensitive than their PVDF-based counterparts in textile form [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 composites. Such sensors, integrated with athletic wear, are now capable of recognizing small muscle contractions (5 kPa) during physical exercise, in addition to biomechanical analyses, hitherto restricted to laboratory settings.

Functional nanofiber coatings also provide a solution to encapsulate problems in textile-based environments. Nanofibers consisting of polyimide with diameters of 150 nm, with a total thickness of 5 µm, isolate MEMS sensors from moisture, while maintaining breathable properties in textile materials (breathability: 180 mm/s) [123]. Using these properties, it is now feasible to combine MEMS with textile materials in medical applications, for example, in wound dressings with microfluidic sensors for real-time detection of biomarkers for infections, such as changes in pH levels or metabolized molecules, to provide improved healthcare. Its large-scale production capacity, with 50 m²/hour, raises hopes for commercialization for smart textile manufacturing.

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.

3.1.2 Triboelectric Nanogenerators (TENGs)

TENGs utilize 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 310V, 60µA currents from foot contacts, charging knitted supercapacitors with energy for uninterrupted device functionality with capacities of 1.2 mF/cm² [35, 124]. Hybrid TENGs with MXene-coated cotton fibers provide 18 µA, increasing output by 125% more than traditional TENGs due to MXene's high electron affinity [125].

3.1.3 Thermoelectric Generators (TEGs)

TEGs utilize the difference in temperatures between the body and ambient. Bismuth telluride (Bi_2Te_3) layers, with thicknesses produced by printing on polyester, produce 12 µW/cm² at ΔT = 10 °C, with carbon nanotube-polymer composites flexible at 5mm bending radius with 8 µW/cm² power output [126, 127]. More efficient designs, like graphene-based PEDOT:PSS yarn, have enhanced Seebeck coefficients with 45 µV/K, with 90% efficient after 1,000 cycles [128].

3.1.4 Solar Energy Harvesting Textiles

Textile-compatible photovoltaics are dye-sensitized solar cells (DSSCs) and perovskite solar cells (PSCs) (Figure 10 (a-c) [129-131]. DSSCs woven with TiO2-coated Ti wires have an efficiency rate of 7.1% for AM 1.5G 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].

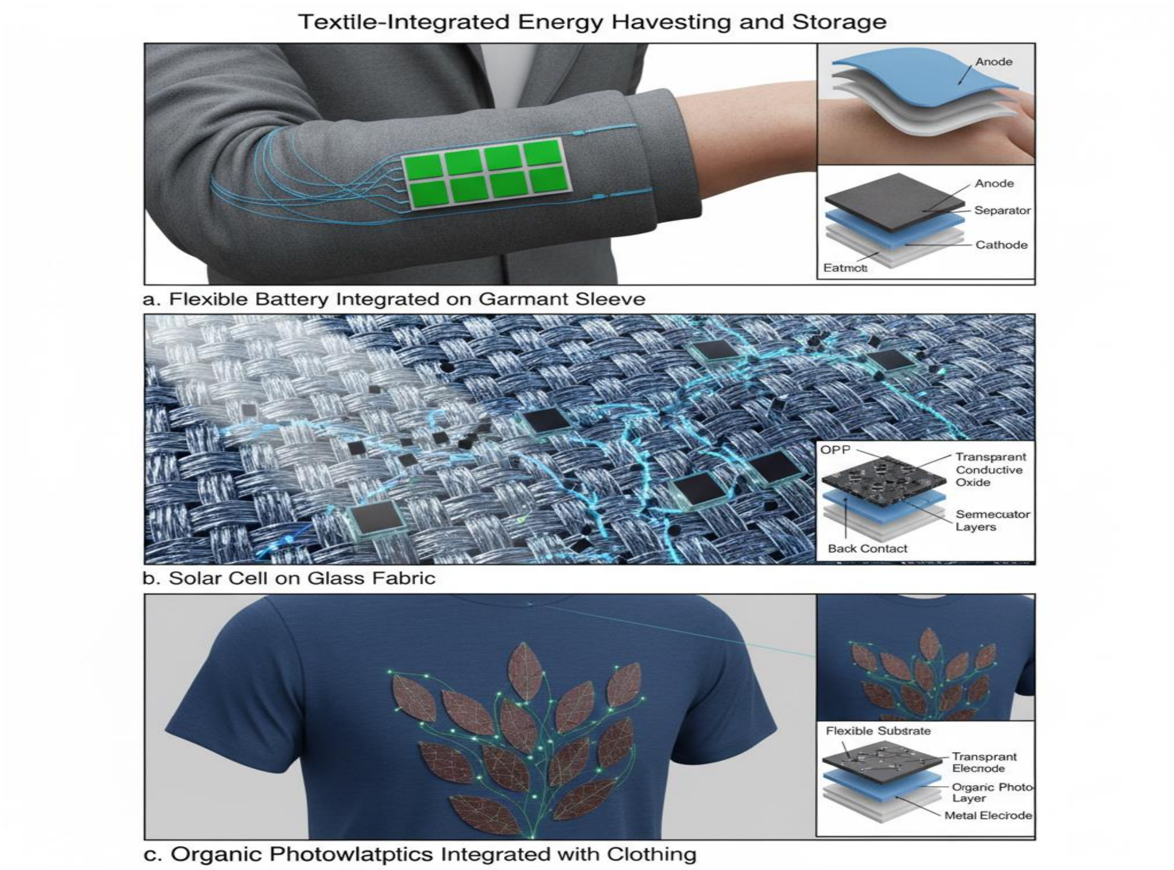

Figure 10. (a) Flexible battery integrated on sleeve of garments (b) Solar cell on glass fabric (c) Organic photovoltaics integrated with clothing.

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/m² in solar mode, and 9.8 mW/m² in motion mode [135]. Another example is ZnO/PVDF-CNT-based fabric, which uses piezoelectric, triboelectric, and solar effects, delivering 22.4 mW/m² 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 made electrically conductive with a combination of conductive materials, including polymers, carbon-based nanomaterials, and metals, incorporated into a 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), some of which include polyaniline (PANI), polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), are ICPs that vary in flexibility and tunable 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 reported 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 (10^2 S/cm) after 50 washes indicating their potential for wearable electrodes as physiological sensors [138].

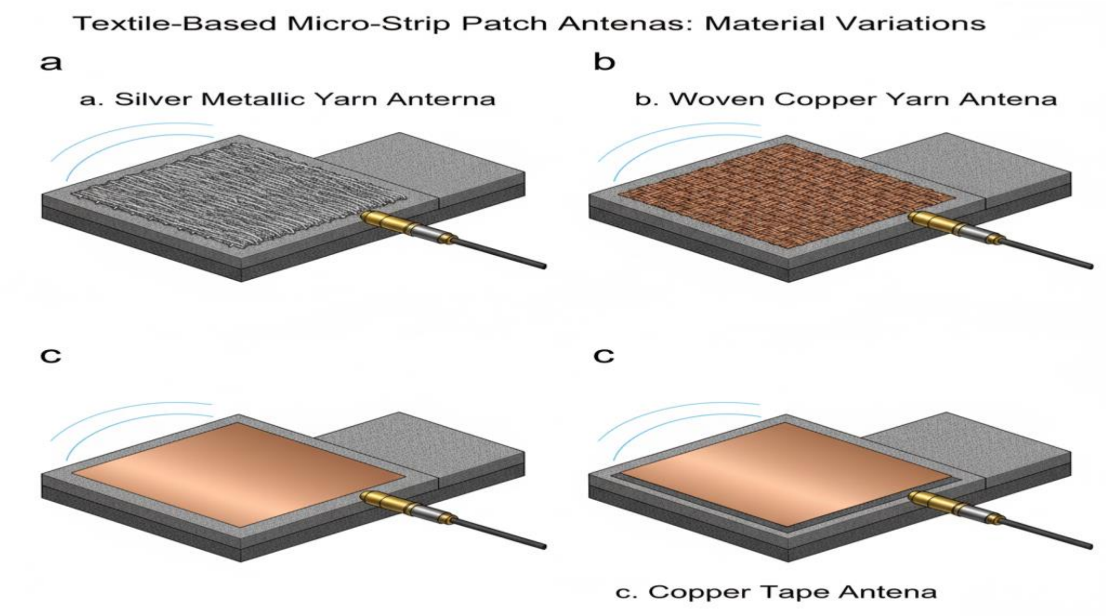

Figure 11. (a) Textile-based micro-strip patch antenna using silver metallic yarn (b) Textile-based micro-strip patch antenna using woven copper yarn (c) Textile-based micro-strip patch antenna using copper tape.

3.2.2 Carbon-Based Nanomaterials

Carbon nanotubes (CNTs) and graphene are promising materials to obtain excellent electrical conductivity in experimentalations, and mechanical stability. CNT inks have yielded a sheet resistance of 2.5 Ω/sq thick enough to screen-print to use for interdigitated electrodes for capacitive touch sensors [139]. Graphene-functionalized textiles produced via chemical vapour deposition (CVD) on copper mesh provided both electrically conductive fibers (922 S/cm) and Joule heating ability (60°C at 5V), for thermal device application (i.e. 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, such as silver (Ag) and copper (Cu), demonstrate high electrical conductivity that is advantageous in textile applications. Silver NP treated cotton fabrics dipped induce a resistance of 0.5 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]. To make a textile more durable, Ag nanowire

(AgNW)-polyurethane composite materials can maintain up to 90% 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 the latest breakthrough in smart fabrics that combine flexible electronics, functional nanomaterials, and MEMS technology to monitor physiological, environmental, and mechanical signals in real time (Figure 12) [146, 147-151]. 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 ($\varepsilon > 0.90$) for passive body cooling while the sensor is operating. The need for our review goes beyond single-functionality analysis to fill critical 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 energy harvesting (Section 3), protective coatings (Section 2), and AI-driven adaptation (Section 7). It provides an interdisciplinary framework that is not found in specialized sensor reviews but enables researchers to think about designing holistic smart textile systems rather than just 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.

4.1.1 Optical Fiber Sensors

Optical fibers integrated with textile materials support distant sensing for large areas. By coating metallic/semiconducting layers such as Au/SiO_2 on optical fibers, researchers successfully fabricated nanofunctionalized optical sensors for strain and temperature measurement [146]. Using gold-shell nano-dome-structured fiber optic surface plasmon resonance (FO-SPR sensors, researchers obtained a sensitivity value of 7.8×10^3 nm/RIU for detecting biomolecules at 38 fg/mL in serum [36]. Hetero-core fiber optic sensors, integrated with textile-based substrates, showed 95% accuracy for respiration and heart rate measurement in comparison to commercially available sensors [152]. Hetero-cores improve light coupling efficiency, which facilitates detection on micromechanics during physiological functions [152].

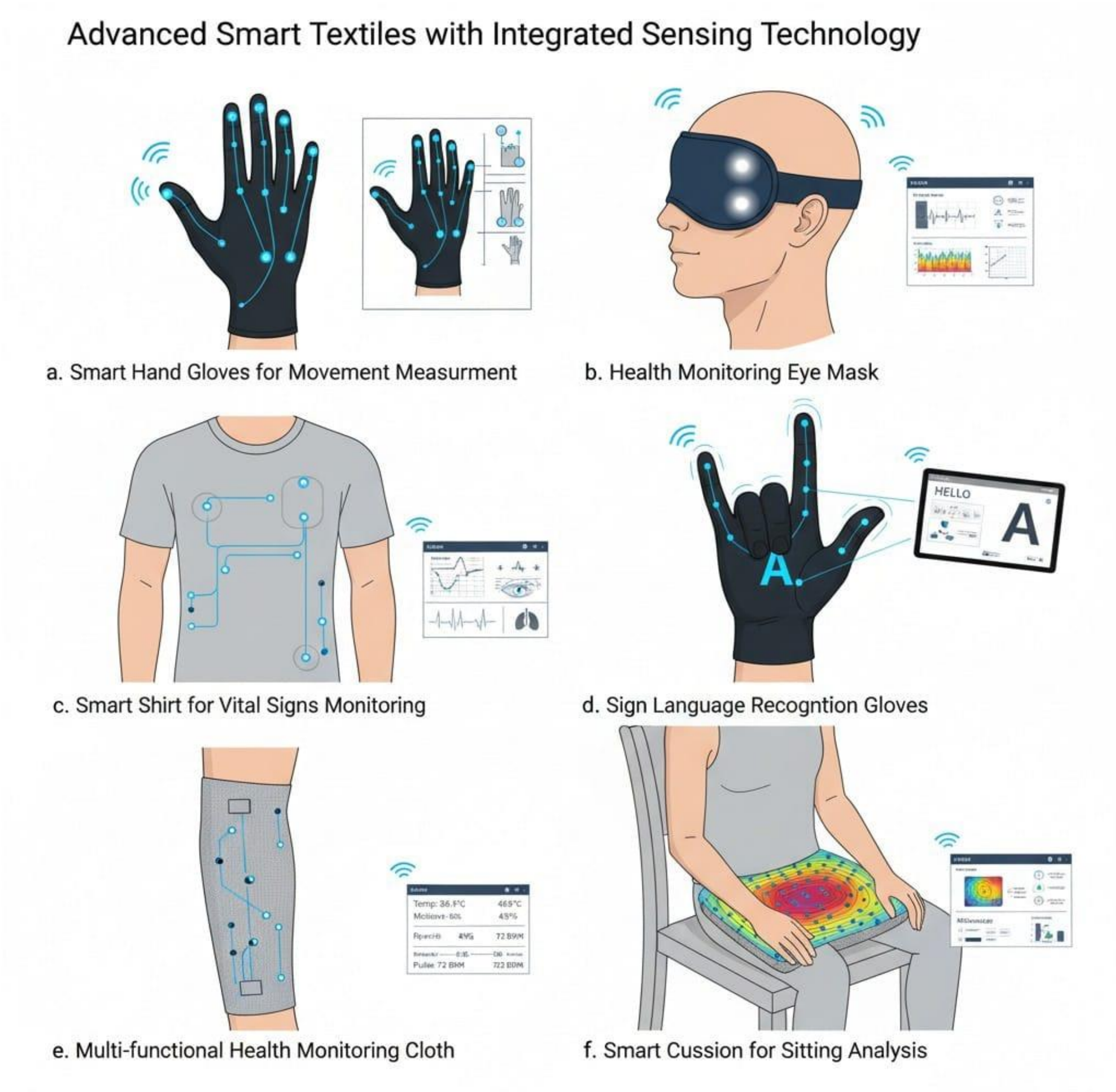

Figure 12. Various smart clothing with sensors. (a) Smart hand gloves for hand movements measurements (b) Health monitoring eye mask (c) Smart shirt for monitoring of pulse and respiratory signals (d) Sign language recognition gloves (e) Health monitoring cloth (f) Smart cushion for sitting analysis.

4.1.2 Carbon-Based Nanomaterial Sensors

Carbon nanotubes (CNTs) and graphene have given improved performance in strain and pressure sensors due to their conductivity properties 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 showed high sensitivity with a GF value of 715.94 to monitor joint motion and facial expressions [154].

4.1.3 Capacitive and Piezoresistive Sensors

Capacitive sensors used conductive yarns (Ag-polyester yarns) to detect tactile inputs via voltage variations. A 15-element sensor array embedded in wool fabric enabled detection of tactile location with <2mm resolution [155]. Piezoresistive poly(vinylidene fluoride) strips embedded in yarns produced a capacitance value of 0.63pF with a pressure sensitivity of 4.9 N/cm^2, 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 could be realized on copper benzene tricarboxylate-functionalized cotton due to color changes [91]. MOF-quantum dot composites on silk fibers could detect volatile organic compounds with sensitivity of 0.1 ppb, with applications in hazard-ridden 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% RH) [159]. In other work, resistive temperature sensors were woven into a twill pattern and operated from 10–80°C with a precision of 5°C, and included LEDs to provide visual information [160, 161].

4.1.6 MEMS-Integrated Textile Sensors

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

Advancements in wearable piezoresistive and inertial MEMS sensors demonstrate excellent potential for textile integration in respiration monitoring systems. De Fazio et al. reviewed MEMS-based piezoresistive sensors that achieve high sensitivity in detecting respiratory patterns through chest wall movements, maintaining functionality under mechanical deformation while being seamlessly integrated into flexible wearable platforms [104]. When this type of nanosensor was integrated into a polyester-cotton substrate using transfer printing they achieved 98.5% accuracy for heartbeat monitoring in comparison to the clinical electrocardiographs, which compares favorably to 96% for the standalone graphene textile electrode [102]. Importantly the mechanical superiority of the resonance based nanosensor demonstrated 95% mechanical stability and compliance after 5,000 wash cycles, which relieves some of the durability issues associated with traditional wearable sensors.

Variational optimization has provided a means of enhancing the compatibility of MEMS with textiles by calculating interfacial stresses in the case of 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-nano composite 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 to conventional single-layer parylene coatings [162]. This can be a theoretical basis for constructing MEMS sensors that can also withstand textile manufacturing operations (weaving, workman, etc.), without degrading the function and are ultimately both practical and representable for mass manufacture.

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 (sarin as just one example) at concentrations below 0.01 mg/m3 in three seconds (10× faster than MOF-based colorimetric sensors) using shifts in resonant frequency in silicon nitride cantilevers coated with specific binding agents [112]. MEMS enhanced with triboelectric nanogenerators that are directly embedded into textiles allow for embedded, self-sustaining 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 incorporated 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 strategies to monitor performance, increase comfort, and decrease risk of injury in sport. 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 had an average of 95% correlation with clinical-grade ECG electrodes while running in a laboratory-style setting, allowing for an accurate heart-rate measure during high-intensity exercise [161, 165]. Hetero-core optical fiber sensors incorporated into wool fabrics to monitor respiratory rate, indicating error less than 5% compared to the standard spirometer while consistently pulling in-on breath patterns to measure fatigue [166, 152]. A compression shirt made from reduced graphene oxide (rGO) coated in a polymer called PEDOT:PSS was able to provide clinically-valid ECG values during a running session and demonstrated resistance to signal loss throughout motion degradation [167].

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

4.2.2 Thermal Regulation and Moisture Management

Nanomaterials also provide thermal comfort enhancement with respect to 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 produced 4.8°C less skin temperature compared to cotton [168]. Janus fabrics mimic cactus spines and uses hydrolyzed cellulose acetate (CA) nanofibers to move the liquid unidirectionally, evaporating sweat more than 40% faster than cotton while maintaining a cooling average 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].

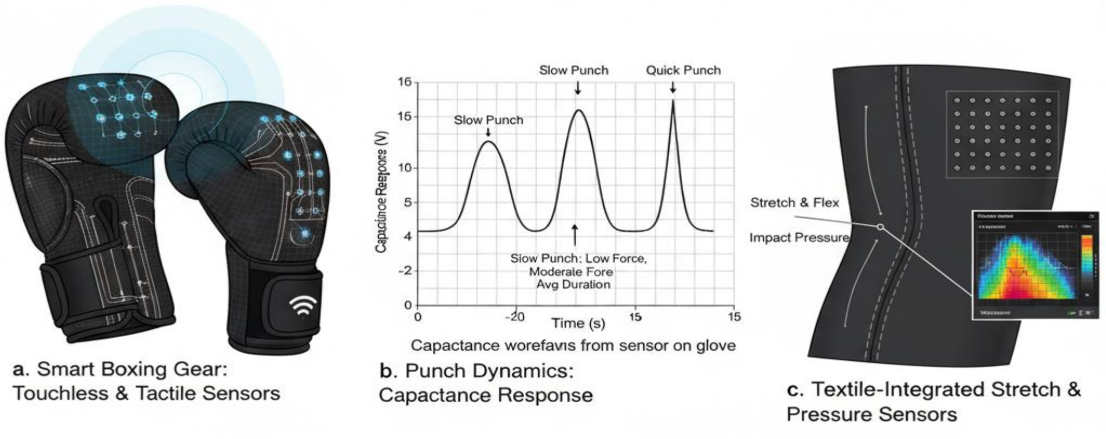

Figure 14. (a) Sensors sewn into garments for touchless and tactile signals in boxing (b) Sensors sewn into garments, capacitance response for slow, medium, and quick punches (c) Stretching and pressure sensing sensors sewn into garments.

4.2.3 Motion and Biomechanical Tracking

The application of strain and pressure sensors within athletic apparel enables the analysis of movement biomechanics to prevent athletes from sustaining injuries (Figure 14) [171, 172]. MXene-coated cotton strain sensors with a gauge factor of 715.94 were able to map the angle of joints 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 to produce voltage and mechanical stress outputs of 0.5 V/kPa [173]. Capacitive textile arrays that utilize conductive Ag-coated polyester threads are capable of detecting tactile inputs with 2 mm suggesting the possibility of presence used for postural correction in yoga mats [174, 157].

4.2.4 Smart Footwear and Accessories

Athletic footwear outfitted with piezoresistive insoles provides an objective measurement of ground reaction forces (GRF) occurring during the act of running, with a focus on identifying gait discrepancies associated with shin splints or plantar fasciitis [172]. Smart gloves that use flexible yarns of MXene-helical yarns were used to measure hand movements as part of a sign language recognition system via machine learning algorithms with classification accuracies of 98% [171, 175]. Textiles that integrate LEDs such as wristbands that earn the title of electroluminescent extend visibility to runners wanting to run after dark with energy consumption below 1 W/m² [164].

5. Fashion Smart Textile

5.1 Shape Shifting Textiles

Shape-shifting textiles signify a paradigm shift in adaptive wearable technology because they utilize 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 or biomechanical support for wearables while moving closer to active wearables from passive wearables.

5.1.1 Liquid Crystal Elastomers (LCEs) and Passive Actuation

FibeRobo is a passive smart textile developed at MIT using liquid crystal elastomers (LCEs) layered inside a rubber-like elastomer to demonstrate temperature-driven shape-shifting capabilities. 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 decreasing air permeability to suit applications for adaptive outerwear. FibeRobo is fabricated using 3D printing and laser cutting to enable 1 km of daily fiber production, suited for use with industrial-scale knitting and weaving machinery [176]. Potential applications include dynamic self-ligating sports bras and temperature-adjustable compression sleeves to adapt to environmental settings [177].

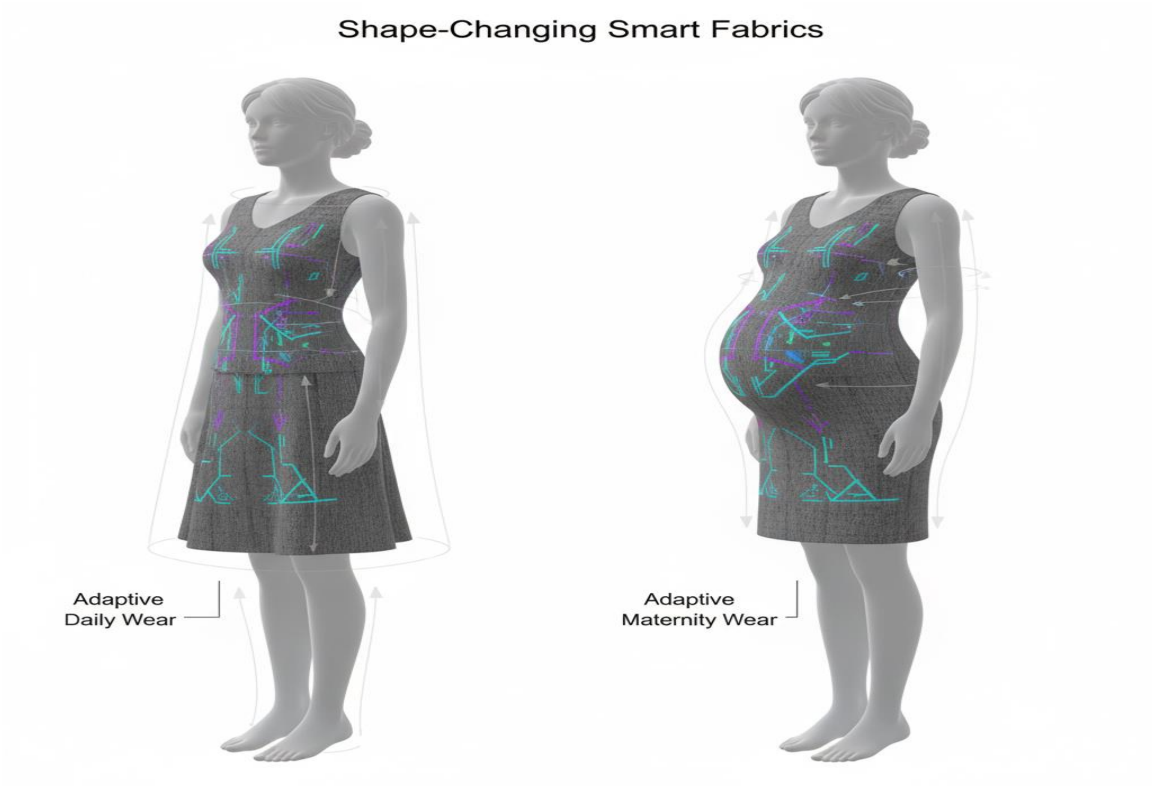

Figure 15. Shape-changing smart fabrics for women like a regular skirt (left), garments for pregnant women (right).

5.1.2 Shape Memory Alloys (SMAs) for Active Textile Actuators

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

5.1.3 Thermoresponsive Polymers

Poly(N-isopropylacrylamide) (PNIPAM)--functionalized textiles respond to bodily heat by altering their porosity reversibly between wetting and drying states at temperatures below or above 32°C, making them hydrophilic and porous or hydrophobic and condensed at higher temperatures (>32°C), altering moisture permeability by 70% [177]. This principle is applied to sportswear to increase evaporation rates for heat reduction during rigorous activities while maintaining warmth during resting intervals.

5.2 Textiles for Creative Expression

Smart textiles for self-expression blend arts and technology to empower individuals to engage with their clothes in new ways as interactive spaces for self-expression and communication. The technology involves the use of conductive materials and participatory design to make clothes interactive for self-expression.

5.2.1 Participatory Design and Inclusive Art

Visually impaired individuals use e-textiles to create and interact with their surroundings through touch and gesture-based interaction. Conductive fibers, LEDs, and pressure sensors are combined to create wearable artistic objects like embroidered vests that produce sound or light pulses based on touches [179]. The major goal of these designs is to create haptic or tactile designs for visually impaired individuals to "feel" their creations through vibrating or heat-based stimuli. A collaborative project demonstrated how one could create music using fabric folds based on silver-coated nylon threads and stretch sensors to overcome limitations for visually impaired individuals [180].

5.2.2 Crafting Functional Aesthetics

Veja's practice-based approach interlaces traditional textile techniques with electronics to embed LEDs, resistors, and microcontrollers directly into woven fabric. 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 makes e-textile development accessible to hobbyists for prototyping interactive designs using simple conductive threads and Arduino microcontrollers.

5.2.3 Conductive Yarns with Embedded Electronics

Conducting yarns by Rathnayake et al., integrating micro-scale components like RFID tags, LEDs, and micro-sensors into woven fibers, broke new grounds. Non-conductive plastic protection prevents damage to components while being woven or knit [182]. Their applications include jackets for storing or displaying doors opened through capacitive touch or LED-infused dresses showcasing dynamic designs through electronics perfectly integrated to maintain flexibility while having bend ratios below 5 mm without damaging circuits.

5.2.4 Project Jacquard and Commercial Applications

Google's “Jacquard” project was very successful at making smart textiles because it industrialized the manufacture of conductive yarn. This is done by having a core of 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.

5.2.5 Dynamic Visual Expression

Photochromic and thermochromic inks react to external stimuli to change colors or designs on textiles. For example, UV-reactive inks painted on sport clothes display camouflage designs under sunlight, while heat-sensitive fabrics change color according to one's body temperature [181]. Electroluminescent wires woven into ladies' dinner gowns produce glowing designs, requiring <0.5 W/m^2 for sustainablelight emission [184].

Integrating craftsmanship, technology, and biographical features, smart textiles for self-expression thus transform fashion into a participatory, adaptive, and strongly 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 virtue of their capabilities to include light-emitting, guiding, and responsive elements within fibrous substrates to create 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 and lightweight diffused lighting applications. The use of micro-structural features such as side emission grooves or Bragg gratings on POFs makes it possible to create illuminating designs of desired intensity levels of 1,500 cd/m² [44, 185]. For example, curtains containing POF-threads with dynamic LED designs display projected color gradients for ambient illumination, requiring <2 W/m² [186]. High-tech photonic band gap (PBG) fibers have periodic air holes for 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 having 2D matrix arrangements result in 100 cm² active areas at 200 cd/m² at 5V to be used for interactive clothing [187]. Electroluminescent wires painted with phosphors are embroidered into clothes to create glowing designs and have a lifespan of 10,000 hours at 50% intensity for glowing threads for clothing designs [184]. Both are combined to facilitate conductive yarn circuits for power-efficient control to change designs instantly through smartphone devices [188].

5.3.3 Photonic Sensors and Environmental Interaction

Textile-based photonic sensors utilize light-matter interactions for real-time assessment. Strain can be measured using gold-nanoparticle-coated fiber optic sensors at 3.2nm/% elongation for bio-related applications [189]. Temperature-dependent photonic crystals integrated into sports wear change reflection spectra according to body temperature for 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 make it possible to transfer data at high speed via optical waveguides woven into fabrics. Infrared-passable fibers incorporated into military uniforms support high-speed communication at 10 Gbps without any interference for 1 m transmission, thus ensuring better 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 using dye-sensitized solar cells (DSSCs) woven into POF-based networks can power themselves at 5 mW/cm² while forming ambient light patterns [194]. Textiles utilizing retro-reflective technology and corner-cube prismatic structures improve night visibility and actively cool the wearer using high mid-infrared emissivity ($\varepsilon = 0.94$) [188]. In bringing together optical engineering and textile design concepts to create photonic textiles, new functionality boundaries are being established for textile materials themselves.

5.4 Color-Changing Textiles

Color-changing fabrics integrate highly advanced material science concepts for dynamic visual response to environmental or user-driven stimuli. Such technologies utilize concepts of photonics, heat energy, electricity, or plasmonics to create reversible and user-controllable color change for use in clothing, camouflage designs, or interactive wearables.

5.4.1 Photonic Crystal Fibers (PCFs)

Photonic crystal fibers utilize nanostructurally periodic lattices of air voids or periodic dielectrics to control photons using interference and diffraction," Gauvreau et al. reported [195]. "For example, fibers with 400nm lattice periodicity diffract visible light to create colorful shades while being color fast even after 1000 wash cycles" [196]. This is useful for adaptive clothing for outdoor wear and anti-counterfeit labels for premium textile products.

5.4.2 Thermochromic Liquid Crystal Inks

Liquid crystal (LC) inks display color changeability because of temperature variations, which result from molecular rearrangement inside 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 seconds [197]. Improved versions include insulating barriers to avoid accidental activation by bodily temperatures for direct thermal control of sports and biomedical textiles.

5.4.3 Electrochromic Textiles

Electrochromics like tungsten oxide (WO_3) and polyaniline (PANI) allow for electrically controllable color transformations (Figure 16). Electrochromic nimons fabrics developed by Kelly and Cochrane consisted of WO_3 nanoparticles woven between layers of nylon and changed color from transparent to blue at 1.5 V voltage, displaying 70% optical contrast ratio [198]. Coupled with flexible batteries derived from lithiated ions, these clothes facilitate dynamic designs of interactive clothing like dresses reacting to user-preferred RBG LED arrangements [40].

5.4.4 Photochromic and Sunlight-Activated Systems

Photochromic textiles change color reversibly upon UV irradiation due to spiropyran or azobenzene derivatives incorporated within them (Figure 16). Aishwariya designed sun-sensitive textile products that change color from white to blue in 30 seconds under sunlight, returning to normal color inside [199]. These materials are ideal for adaptive swimwear and UV-sensing athletic gear.

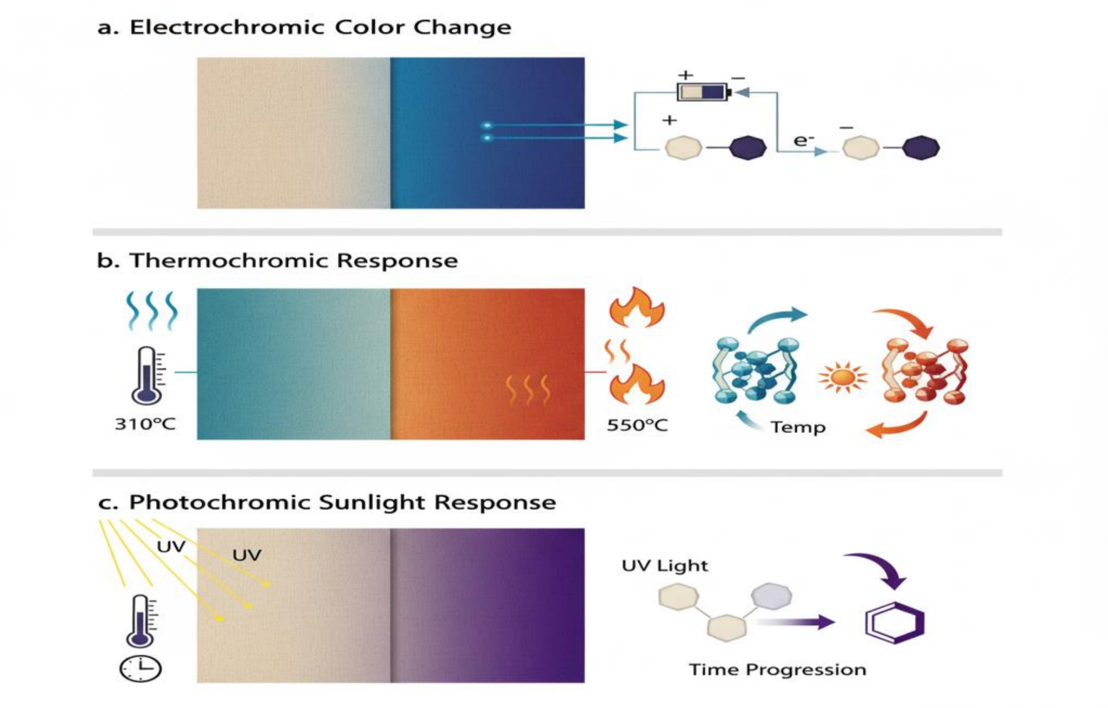

Figure 16. (a) Color varies with Electrochromism (b) Color varies with Temperature (310°C & 550°C) (c) Color varies with sunlight.

5.4.5 Plasmonic Nanoparticle Arrays

Plasmonic nanostructures leverage localized surface plasmon resonance to create angle-dependent and permanent colors. Another example is the preparation of gold nanoparticle arrays on cotton fabrics by Dong and Hinestroza to create colors fully covering the visible spectrum through careful particle sizing (20–80nm) and interparticle distances below 100nm [200]. This dye-free approach mimics natural iridescence in butterfly wings, offering eco-friendly haute couture and military camouflage applications.

5.4.6 Multifunctional Hybrid Systems

Hybrid textiles incorporate multiple mechanisms that respond to stimuli, providing more 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 unique colors with a power input of 0.5 W and connects visual aesthetics and functionality in the context of smart apparel.

When material advancements are combined with textile design, color-changeable fabrics provide new definitions 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 was recently identified as one of the key features for enhancing wearable electronics to reach self-powering capabilities for smart textiles. Supercapacitors, batteries, or hybrid devices possessing high performance and elasticity have been fabricated using nanocomponents within flexible textiles.

6.1 Textile-Based Supercapacitors

Supercapacitor-based energy storage reigns supreme because of the fast charge/discharge cycle and high cycle counts. Composites of carbon nanotubes printed on cotton/polyester substrates reach 2.56 F/cm² at 3 mA/cm² current densities 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 sheet resistance to 0.03 Ω/sq to attain highcurrent densities of 20 mA/cm² [202]. MnO_2-functionalized carbon nanofibers electrospun on non-woven fabrics display 320 mF/cm² at 1 mA/cm² 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) deposits have 69 mF/cm² capacitance at 80% strain, suiting their application to wearable devices [204]. All solid state supercaps prepared by biscrolling MWCNTs with glucose oxidase demonstrate 25 mF/cm² capacitance while driving biosensors [205].

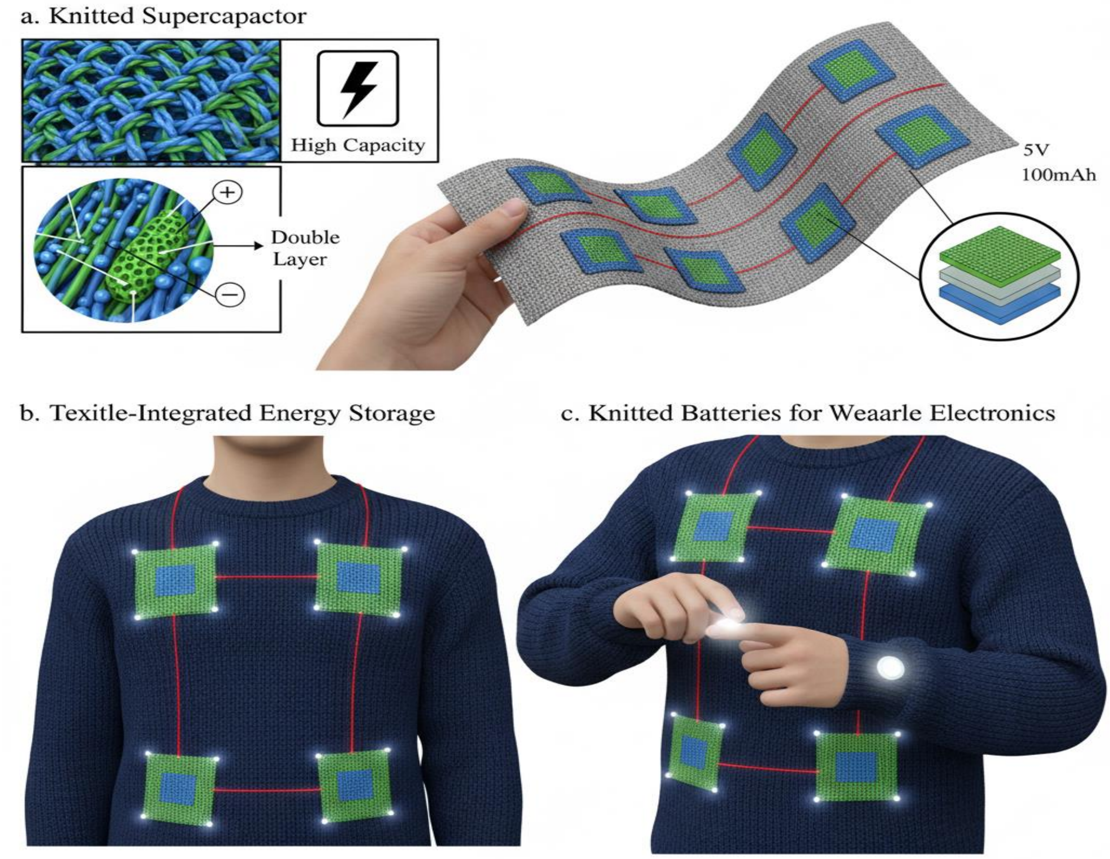

Figure 17. Textile-based energy storage configurations. (a) Knitted supercapacitor structure using CNT/PPy-coated elastic yarns, achieving 69 mF/cm² capacitance at 80% strain. (b) Schematic of electrochemical energy storage integration within textile substrates, showing electrode placement and electrolyte 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), (b), (c) to clarify distinct fabrication strategies and application contexts, distinguishing structural designs (a, b) from functional prototypes (c)

6.2 Textile-Integrated Batteries

Textile-based flexible batteries mainly focus on energy density and safety (Figure 17) [206-208]. Lithium-ion batteries in fiber form use 3D-printed graphite electrodes and $LiNi_{0.6}Co_{0.2}Mn_{0.2}O_2$ cathodes, delivering 46.6 µAh/cm² at 1 mA/cm² current density [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/cm² at 0.1 mA/cm² current density with a polymer gel electrolyte layer [210]. The fiber-type aluminum-air battery with a hydrogel electrolyte in a coaxial structure can achieve a steady voltage of around 1.3-1.5V and can be used for lighting a wearable LED and a watch even under a constant bending deformation condition [211].

6.3 Hybrid Energy Storage Systems

Hybrid systems merge supercapacitors and batteries for balanced energy-power metrics. A textile-based zinc-ion hybrid supercapacitor with activated carbon cathodes and Zn foil anodes achieves 158.3 mF/cm² at 0.1 mA/cm², bridging the gap between conventional devices [210]. Another design combines CNT supercapacitors with triboelectric nanogenerators (TENGs), harvesting biomechanical energy to self-charge at 1.25 W/m² [163].

6.4 Advanced Materials and Fabrication

Graphene aerogel roller-coated onto cotton achieves 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 922 S/cm conductivity and efficient Joule heating (60°C at 5 V). Conductive yarns embedded with micro-supercapacitors (MSCs) via laser scribing demonstrate 12 mF/cm^2 in series configurations, powering wearable sensors [207].

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

Table 1: Nano-materials list for different applications

Textile Material	Nano-Materials	Incorporation Method	Applications/Functionality	Ref.
Cotton	TiO_2	Impregnation	Self-cleaning textile & Anti-bacterial	[213]
Cotton	SiO_2 nanoparticles	Spray coatings	Super-hydrophobicity	[214]
Nanofiber	Mn@ZnO/CNF	Electrospraying	Energy storage & conductivity on textile	[203]
Linen	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]
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 transition from laboratory innovations to commercial reality, their future trajectory is shaped by four key paradigms: hyper-personalization, sustainable intelligence, seamless biointegration, and ubiquitous connectivity. These advancements build upon the foundational research presented throughout this review while pointing toward unprecedented applications that will redefine wearable technology.

7.1 Hyper-Personalized Wearables Through AI-Nanotechnology Integration

Next-gen smart textiles will move beyond reactive capabilities to offer predictive and adaptive personalization as a result of AI integration with nanomaterial synthesis and real-time sensing," according to AJC Consultants' Michael McAlvanah. While today's smart textiles react to established parameters (for example, "turn on PCMs at 32°C"), "machine learning algorithms for AI-enabled smart textiles will use complex data streams such as biometric data, weather forecasts, behavioral data, and past health information 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 to determine appropriate nanomaterial composition for particular tasks. This gap is filled by AI-infused nanotechnology platforms using machine learning for predicting material properties from molecular designs, thereby highly accelerating development timeframes. He showed how CNN trained on 15,000+ nanomaterial datasets were capable of correctly predicting novel biocompatibility, heat stability, and electrical conductivity for new fabricated nanocomposites at 92% precision within days instead of months [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 Ti3C2Tx 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, synthesis facilities using AI-driven synthesis automatically optimize electrospinning settings (voltage, rate of flow, distance to collector) according to real-time information on morphology provided by inline electron microscopy for homogeneous fibers (±15nm standard deviation) and reproducible piezoelectric response for distances of one kilometer or larger [241]. These advances overcome key barriers to industrial-scale smart textile manufacture.

7.1.2 Real-Time Adaptive Thermal Regulation

Integration of AI technology upgrades thermo-regulating textiles from passive phase change devices to smart and predictive platforms. A comprehensive review demonstrates how artificial intelligence algorithms are being applied to optimize phase change material (PCM) performance in thermal energy storage systems, including prediction of PCM thermophysical properties, enhancement of heat transfer rates through nano-enhanced PCMs, and optimization of 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 against ±2°C for adaptive textiles [74].

The AI system, trained on 10,000 hours of human data for thermoregulation under various climatic conditions, also takes into consideration metabolic differences: for seniors whose capability to maintain thermoregulation is low, preemptive warming starts 3 minutes before teenagers, while for athletes undergoing high-intensity workouts, faster activation of cooling occurs. 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 secondary resistance wires while warning the user through haptic response technology.

7.1.3 AI-Enhanced Physiological Monitoring and Diagnostic Prediction

Moreover, besides data acquisition, AI technology upgrades textile sensors to diagnostic devices for predicting the onset of illness before symptoms occur. For example, AI algorithms using ECG data provided by graphene textile electrodes ([37], [102]) detect deviations preceding arrhythmia (e.g., premature ventricular beats) 96% accurately—a performance matching commercial-grade Holter monitors—for patients undergoing timely treatment for heart-related disorders. In this regard, AI leverages recurrent neural networks to selectively filter artifact ECG (associated with physical motion or electrode uncontacts) from genuine biotic data among 50,000 samples to improve specificity by 78% than rule-based algorithms.

For diabetes care, AI-based sweat sensors added to socks can forecast hypoglycemic attacks 30 minutes earlier based on lactate and cortisol levels to enable glucose consumption before attacks occur [120]. This method utilizes ensemble learning (integration of 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: There is a_privacy concern associated with continuous biometric analysis, requiring edge AI computation instead of cloud computing for analysis security; (2) Energy limitations: Large power consumption requirements of deep learning AI need further advancements in efficient ultra-low-power AI microchips (<1 mW) intended to integrate 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.

The areas of interest for future studies should include: federated learning frameworks for combined improvement of AI models without invading individuals' privacy; neuromorphic computing architectures to implement efficiency of biological neurons for textile-based microprocessors; and human-AI interaction paradigms to empower individuals to analyze and override AI-driven decisions for their own health management.

This is because integrating AI technology with nanomaterial development and textile engineering can unlock the power to create smart clothes that can anticipate or respond to situations for a variety of applications ranging from the medical field to security services.

7.2 Sustainable Intelligent Textiles

The community is pushed toward the development of self-managing material systems, which address functionality while being responsible toward 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 centered on chitosan flame retardants [52], as well as plant-based conductive polymers, indicate that future textiles may become fully biodegradable while maintaining functionality.

7.3 Biological Integration

Biocompatible technology advances give rise to expectations for direct interaction between textiles and human

physiology. Projects for building upon ECG-monitoring graphene armbands [37], as well as MOF-based drug delivery systems [91] are being developed to become "living fabrics" integrating:

• 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 6G 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 supported by advances in modular design, allowing consumers to upgrade functionality through interchangeable textile-based "apps"—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-based prototypes to products for commercialization is a complex process that still has technical and translational aspects to address as a field:

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 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 electrospinning to multinozzle arrays (≥1000 nozzles) with inline quality monitoring with machine vision, with a goal of production between 500 m^2/hour & callout 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 1km 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 1,000-hour 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. Conclusion

Smart textiles have reshaped fabric functionality from passive to active systems for various tasks such as using nanotechnology, flexible electronics, and smart designs for fabric functionality to go beyond passive wear to active functionality. This discussion aims to present the role of nanotechnology-enabled textiles as key promoters of innovative applications and developments for diverse fields such as biomedical applications, energy applications, military applications, and fashion-related applications.

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

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

The fusion of artificial intelligence, sustainable materials, and bio-integrated systems is on the brink of offering 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
- Scalling-up sustainable production techniques
- Handling concerns surrounding ethics and data privacy wearability
- Improving cooperation between materials researchers and textile engineers, data analysts, and designers

Smart textiles have transitioned from being conceptual ideas to new platforms at the intersection of science, engineering, and design and have 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
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

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

RMG Ready-Made Garment

RNN Recurrent Neural Network

ROS Reactive Oxygen Species

SE Shielding Effectiveness

SEM Scanning Electron Microscopy

SMA Shape Memory Alloy

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

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Conceptualization: F.I.O, M.H.R; Methodology: F.IO, R.J.S, N.C,G; Software: F.I.O (For Figures and Graphical Abstract); 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.

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