

## CHAPTER 4

# Advancements in Textile Industry through Nanomaterials: Applications, Challenges, and Future Prospects

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**Abstract:** Nanotechnology has revolutionized the textile industry by enabling the development of smart, functional, and high-performance fabrics. This chapter explores the synthesis, classification, and integration of nanomaterials including metal, metal oxide, carbon-based, polymeric, and silica nanoparticles into textile substrates. Various incorporation techniques such as sol–gel coating, nanoencapsulation, electrospinning, and traditional finishing methods like padding and exhaustion are discussed in detail. The functional properties imparted by nanomaterials, such as antimicrobial activity, UV protection, water and stain repellency, flame retardancy, and enhanced mechanical strength, are critically examined along with their applications across healthcare, sportswear, military, and fashion sectors. The chapter also addresses environmental and health concerns associated with nanomaterial

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usage, recent technological advancements, and future prospects, including the emergence of IoT-enabled smart textiles and sustainable nanofabrication techniques. This comprehensive overview provides valuable insights for researchers, industry professionals, and stakeholders aiming to harness nanotechnology for sustainable textile innovation.

**Keywords:** Nanotechnology in Textiles, Green Synthesis of Nanoparticles, Functional Finishes, Smart and Technical Textiles, Magnesium Oxide Nanoparticles

## 1. Introduction

Nanotechnology has revolutionized numerous industries, including textiles. The integration of nanomaterials into textiles has resulted in fabrics that are not only functional but also responsive, adaptive, and sustainable. Nanoparticles, nanofibers, and other nanoscale structures have significantly enhanced textile properties such as durability, comfort, antimicrobial resistance, ultraviolet (UV) protection, and water repellency [1]. Nanotechnology is an interdisciplinary field encompassing the design, synthesis, characterization, and application of materials at the nanoscale typically within the 1 to 100 nanometer range [2]. At this scale, materials exhibit unique optical, mechanical, electrical, and biological properties due to their increased surface area and quantum effects [3]. These characteristics make nanomaterials highly attractive for a range of industrial applications, particularly in the textile sector. In recent years, there has been a marked increase in the demand for nanomaterials in textiles, driven by the need for advanced fabric functionalities such as antimicrobial performance, UV protection, self-cleaning, stain resistance, and odor control [4]. Natural phenomena such as the superhydrophobicity of lotus leaves, self-cleaning properties of certain plant surfaces, and the vibrant structural colors of butterfly wings have inspired textile engineers and researchers to develop fabrics with enhanced performance and multifunctionality [5].

A diverse array of nanomaterials has been studied for textile applications, including metal nanoparticles (e.g., Ag, Cu), metal oxides (e.g., ZnO, TiO<sub>2</sub>, MgO), carbon-based nanomaterials (e.g., carbon nanotubes, graphene), and nanoclays. These materials exhibit a high surface-to-volume ratio, reactive surfaces, and tunable morphologies ideal traits for imparting durable and multifunctional characteristics to textiles. For example, ZnO and Ag nanoparticles are well-known for their antimicrobial efficacy, while TiO<sub>2</sub> is widely used in self-cleaning applications due to its photocatalytic activity [6,7]. Traditional textile finishing techniques often involve the use of harsh chemicals and energy-intensive processes, which can pose environmental and health hazards and result in limited durability of functional coatings [8]. In contrast, modern approaches such as sol-gel processing, plasma-assisted deposition, and electrospinning enable the precise and eco-friendly application of nanomaterials [9]. Plasma-based finishing techniques, especially those employing low-temperature plasma, are increasingly used for antimicrobial and surface-modification purposes, as they deliver functional enhancements without altering fabric bulk or requiring toxic chemicals [10–12]. For instance, TiO<sub>2</sub>-coated fabrics that are pre-treated

with plasma exhibit significantly improved self-cleaning abilities under UV light [13]. The development of conductive textiles—using carbon-based or metallic nanomaterials has also opened up new possibilities for electronic textiles (e-textiles) with applications in sensing, electromagnetic interference (EMI) shielding, and energy harvesting [14]. A notable example is the work by Suryaprabha and Park (2023), who developed graphene oxide–Ag coated cotton fabrics that demonstrated low resistivity, wearable heating capability, and EMI shielding effectiveness [15]. Amidst these technological advancements, green synthesis of nanomaterials has emerged as a promising, environmentally benign alternative to conventional chemical methods. This approach uses natural reducing agents typically plant extracts rich in flavonoids, alkaloids, and other phytochemicals to synthesize nanoparticles under mild, non-toxic conditions. Green synthesis is a bottom-up method that assembles nanoparticles atom by atom, in contrast to top-down methods that physically break down bulk materials [16]. Numerous plant species, including *Azadirachta indica* [17], *Ocimum sanctum* [18], and *Trigonella foenum-graecum* [19], have been effectively used to biosynthesize nanoparticles with functional properties suitable for textile applications. These plant-mediated nanoparticles have demonstrated potential in a range of smart and technical textiles, such as antimicrobial fabrics, UV-protective clothing, and even electrically conductive garments. For instance, fabrics treated with ZnO or MgO nanoparticles synthesized using plant extracts have shown improved antibacterial activity and UV resistance [20]. The synthesis of nanomaterials for textile use typically involves several stages, including precursor preparation, nanoparticle formation (through physical, chemical, or biological routes), application to fabrics (via methods such as dip-coating, padding, or spraying), and subsequent testing for functional performance and durability [21]. Today, industrial applications extend across diverse sectors—from medical textiles to sportswear, military uniforms, and home furnishings [22].

## 2. Use of nanoparticles in Textiles

### a) Use of Metal Nanoparticles in Textiles

Metal nanoparticles have emerged as one of the most promising classes of nanomaterials in textile applications due to their unique physicochemical properties. Among these, silver (Ag), zinc oxide (ZnO), and titanium dioxide (TiO<sub>2</sub>) nanoparticles are most widely studied and commercially utilized.

Silver nanoparticles (AgNPs) are especially valued for their broad-spectrum antimicrobial properties, which help inhibit the growth of bacteria, fungi, and viruses on fabric surfaces. These properties are highly desirable in medical textiles such as surgical gowns, wound dressings, and hospital bed linens, as well as in sportswear and socks where odor control is important. The mechanism of antimicrobial activity is believed to involve the release of silver ions that interact with microbial membranes and DNA, ultimately leading to cell death.

Zinc oxide (ZnO) and titanium dioxide (TiO<sub>2</sub>) nanoparticles offer dual functionalities—they are both antimicrobial and provide ultraviolet (UV) protection. These nanoparticles absorb and scatter UV radiation, thus protecting the wearer from harmful UV-A and UV-B rays. TiO<sub>2</sub>, in particular, is also used

for self-cleaning textiles because of its photocatalytic activity under sunlight, which helps break down organic stains and pollutants on fabric surfaces.

The integration of these nanoparticles is typically achieved through coating, padding, or in-situ synthesis on textile fibers. The main advantage lies in enhancing the fabric's functionality without significantly affecting its texture, breathability, or appearance.

However, concerns regarding the long-term durability, release of nanoparticles during washing, and potential toxicity to humans and the environment have led researchers to explore safer and more sustainable methods of synthesis and application, such as green synthesis using plant extracts.

### ***b) Carbon-Based Nanomaterials***

Carbon nanotubes (CNTs) enhance mechanical strength and conductivity. Graphene is used for smart textiles due to its conductivity and strength. Carbon-based nanomaterials, particularly carbon nanotubes (CNTs) and graphene, have garnered significant attention in textile applications due to their exceptional electrical, mechanical, and thermal properties. These nanomaterials offer opportunities for developing smart, durable, and high-performance textiles.

Carbon nanotubes (CNTs) are cylindrical structures composed of rolled-up sheets of graphene. They exhibit remarkable tensile strength, flexibility, and electrical conductivity, making them ideal for use in functional textiles. When incorporated into fabrics, CNTs can enhance mechanical strength, improve electrical conductivity, and enable electrostatic discharge protection, which is particularly useful in industrial and military clothing. Moreover, CNTs can be integrated into strain- or pressure-sensitive garments, enabling wearable sensors for health and motion monitoring.

Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, is another promising material. Graphene and its derivatives (e.g., graphene oxide) can impart antimicrobial, UV-protective, and antistatic properties to textiles. Additionally, graphene-coated textiles exhibit excellent thermal conductivity, making them useful for thermoregulatory clothing and energy storage fabrics. For instance, graphene-enhanced fabrics are being developed to function as components in flexible supercapacitors, wearable electronics, and smart garments that respond to environmental stimuli.

The application methods include dip-coating, spray-coating, layer-by-layer assembly, and in situ polymerization. These techniques ensure uniform dispersion and adherence of nanomaterials onto textile substrates without compromising fabric flexibility.

However, challenges remain, such as aggregation of CNTs, cost of production, and concerns about biocompatibility and toxicity. Current research focuses on optimizing dispersion techniques, exploring biodegradable carbon nanomaterials, and scaling up production in a cost-effective and environmentally friendly manner.

### c) *Polymeric and Silica Nanoparticles*

These are used for controlled release of fragrances or drugs in medical textiles. Polymeric and silica-based nanomaterials are increasingly being explored in the textile industry for their versatile functional capabilities, especially in controlled-release systems, self-cleaning surfaces, and comfort enhancement. These nanomaterials offer advantages such as chemical tunability, compatibility with textile substrates, and potential for green synthesis routes.

Polymeric nanomaterials, such as nanoencapsulated polymers, are widely used for delivering active agents like fragrances, insect repellents, antimicrobial agents, and vitamins. These nanoencapsulated systems allow for controlled and sustained release, improving the durability and functionality of the fabric. For example, microcapsules containing essential oils or phase change materials (PCMs) are embedded into textiles to provide aromatherapeutic, thermoregulatory, or mosquito-repelling properties. Moreover, polymers like chitosan and polyethylene glycol (PEG) can be used to enhance biocompatibility and moisture management in medical and sportswear textiles.

Silica nanoparticles, on the other hand, are primarily utilized to impart hydrophobicity, self-cleaning, and mechanical strength to textile surfaces. Functionalized silica particles can create a lotus-leaf effect when coated onto fabric, enabling water and stain repellency without affecting breathability. Additionally, silica nanoparticles can act as UV blockers and carriers for antimicrobial agents or dyes, allowing for multifunctional finishes. Their thermal stability, low toxicity, and chemical inertness make them especially suitable for technical and outdoor fabrics.

The integration of these nanomaterials is typically achieved through sol-gel processing, dip-padding, or plasma-assisted deposition techniques, ensuring good adherence and longevity of function. As with other nanotechnologies, ongoing research aims to optimize application methods to improve wash durability and address environmental safety concerns.[23]

## 3. Methods of Incorporation of nanomaterials into Textiles

### a) *Surface functionalization via sol-gel coating*

Sol-gel coating is a versatile and widely used method for functionalizing textile surfaces with nanomaterials. It involves the formation of an inorganic or hybrid organic-inorganic thin film on the surface of textile fibers through the hydrolysis and condensation of metal alkoxides or metal salts. The sol-gel process begins with a liquid solution ("sol") containing precursors like metal alkoxides (e.g., tetraethyl orthosilicate – TEOS for silica) or metal salts. This sol undergoes hydrolysis and condensation reactions to form a colloidal suspension or gel-like network. The resulting gel is then deposited as a thin coating on textile fibers, where it adheres and solidifies, often embedding functional nanoparticles. A sol is prepared using precursors like TEOS, water, alcohol (as solvent), and a catalyst (acid or base). Functional nanoparticles (e.g.,  $\text{TiO}_2$ ,  $\text{ZnO}$ ,  $\text{Ag}$ ,  $\text{SiO}_2$ ) can be dispersed into the sol. The textile is immersed in the sol (dip-coating) or passed through it (pad-dry-cure method). This allows the sol to uniformly coat the surface of the fibers. The coated textile is dried at moderate temperatures to remove solvents.

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thermal curing step (typically 100–150 °C) ensures solidification and adhesion of the sol-gel coating. For example, a cotton fabric coated via sol-gel with a silica matrix embedding silver nanoparticles (AgNPs) will gain antimicrobial properties. The sol-gel network helps fix AgNPs onto the fibers, preventing leaching and ensuring wash durability.

**b) *Nanoencapsulation for slow release (fragrance, insect repellent)***

Nanoencapsulation is an advanced technique used to enclose active substances—such as fragrances, essential oils, insect repellents, and antimicrobial agents—within nanometer-sized carriers or capsules. These nanocapsules serve to protect the active agents and enable their controlled or sustained release over time. In the textile industry, this method proves particularly beneficial, offering long-lasting functionality even after repeated washing or extended use. It finds applications in functional clothing, medical textiles, and home furnishing materials. A typical nanocapsule comprises a core, which contains the active substance (e.g., citronella oil or lavender fragrance), and a shell made of a biocompatible polymer or inorganic material (such as chitosan, silica, polyurethane, or polylactic acid) that encapsulates the core. For instance, in fragrance textiles, essential oils like lavender or rose can be encapsulated in polymer-based nanocapsules, releasing their scent gradually when the fabric is rubbed or exposed to body heat. Similarly, insect-repellent fabrics incorporate substances like citronella or permethrin within chitosan or silica nanocapsules, offering extended mosquito protection when applied to outdoor clothing or curtains.

**c) *Electrospinning***

It is a versatile fiber fabrication technique that employs a high-voltage electric field to produce ultra-fine fibers, typically in the nanometer range, from a polymer solution or melt. These nanofibers can be directly deposited onto textile substrates to impart enhanced functionalities such as improved filtration, moisture management, drug delivery, UV protection, and antimicrobial properties. The process involves placing a polymer solution in a syringe connected to a high-voltage power supply. When the voltage is applied, electrostatic repulsion overcomes the surface tension at the tip of the polymer droplet, leading to the formation of a Taylor cone. A fine jet of polymer is ejected from this cone and travels toward a grounded collector, undergoing elongation and solvent evaporation along the way. The resulting solid nanofibers are deposited on the collector, often forming a nonwoven mat or aligned pattern. For example, a nanofiber mat composed of polyvinyl alcohol (PVA) embedded with silver nanoparticles can be electrospun onto cotton fabric to create antimicrobial and breathable materials, ideal for applications such as face masks or wound dressings.

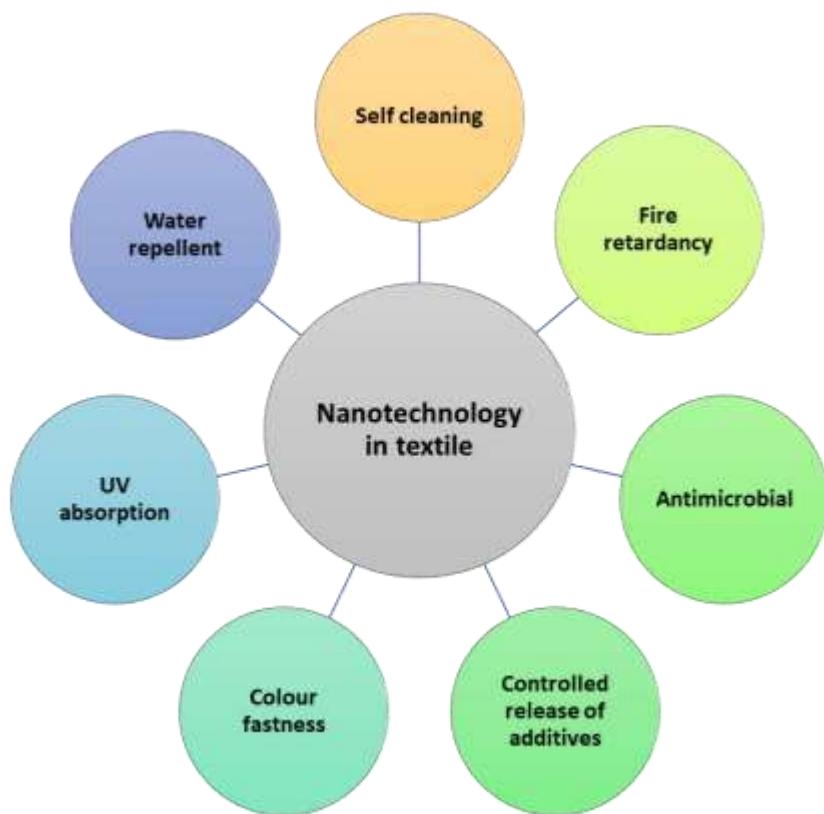
#### **4. Functional Properties Achieved**

Nanomaterials play a crucial role in enhancing the functional properties of textiles. Antimicrobial effects can be achieved using silver nanoparticles (AgNPs) and zinc oxide (ZnO), which effectively kill or inhibit the growth of bacteria. For UV protection, titanium dioxide (TiO<sub>2</sub>) and ZnO are commonly used due to their ability to absorb and block harmful ultraviolet rays. Water and stain repellency is imparted through the application of fluorinated silica nanoparticles, which create a hydrophobic surface on fabrics. Flame

retardancy can be improved by incorporating various metal oxide nanoparticles that reduce flammability and delay ignition. Additionally, mechanical strength is significantly enhanced with the use of carbon nanotubes (CNTs), which reinforce textiles by improving their tensile strength and durability.[25]

## 5. Applications in the Textile Industry

Nanotechnology has significantly advanced the development of functional textiles across various sectors. In healthcare, textiles enhanced with silver nanoparticles (AgNPs) are used in surgical masks and wound dressings to provide antimicrobial protection and promote healing. Sportswear benefits from nanomaterials that create breathable, moisture-wicking, and odor-resistant fabrics, enhancing comfort and performance. In the military and industrial domains, nanotechnology enables the production of flame-retardant and chemical-resistant suits, offering improved safety in hazardous environments. The fashion industry utilizes self-cleaning and anti-wrinkle textiles incorporating nanostructures that reduce maintenance and enhance fabric longevity. Finally, smart textiles integrate nanosensors and thermoregulatory materials to enable wearable electronics, health monitoring, and responsive clothing that adapts to environmental conditions.[26]



**Fig. 1.** Application of nanotechnology in textile

## 6. Environmental and Health Aspects

While nanotechnology offers transformative benefits to the textile industry, it also raises important questions about safety, human health, and environmental sustainability. Addressing these concerns is essential to ensure responsible innovation and long-term public acceptance.

### a) *Toxicological Concerns*

One of the primary issues is the potential toxicity of nanoparticles when used in wearable textiles. Due to their ultra-small size and high surface reactivity, certain nanoparticles such as silver (Ag), zinc oxide (ZnO), and titanium dioxide (TiO<sub>2</sub>) may penetrate the skin, enter systemic circulation, or be inhaled as airborne particles, especially during manufacturing or wear. Although some studies have shown minimal absorption through intact skin, chronic exposure or use on compromised skin could pose health risks. Further research into nanoparticle behavior in biological systems, along with rigorous toxicological testing, is needed to ensure consumer safety.

### b) *Environmental Release of Nanoparticles*

Another significant concern is the release of nanoparticles into the environment, particularly through the washing of nano-treated textiles. These particles can enter wastewater streams and ultimately contaminate aquatic ecosystems. Nanoparticles like Ag<sup>+</sup> ions are known to exhibit toxicity to beneficial microorganisms and aquatic life, disrupting ecological balance. Additionally, nanoparticles may accumulate in the food chain, posing risks to both animals and humans. The absence of standardized waste treatment protocols for nanopollution exacerbates the problem.

### c) *Sustainable Solutions through Green Synthesis*

To mitigate these concerns, researchers are exploring eco-friendly and sustainable approaches for nanomaterial production. Green synthesis of nanoparticles using plant extracts, microbes, or biopolymers eliminates the need for hazardous chemicals, reduces energy consumption, and enhances biocompatibility. Plant-derived phytochemicals like flavonoids, tannins, and alkaloids act as reducing and stabilizing agents, producing nanoparticles under mild, environmentally safe conditions. These green-synthesized nanoparticles have demonstrated effective antimicrobial, UV-protective, and functional properties suitable for textile applications, while also offering a lower ecological footprint [27].

## 7. Recent Advances and Innovations

### *Recent Advances and Innovations in Nanotechnology for Textiles*

The textile industry is undergoing a technological transformation, driven by rapid advancements in nanotechnology. These innovations are enabling the development of intelligent, multifunctional fabrics that combine comfort, aesthetics, and performance. Below are some of the most promising recent breakthroughs:

**a) Self-Cleaning Nanocoatings**

Inspired by the **lotus leaf effect**, self-cleaning textiles have been developed using nanostructured coatings made of materials such as silica ( $\text{SiO}_2$ ) or titanium dioxide ( $\text{TiO}_2$ ). These coatings create a superhydrophobic surface that repels water and dirt, allowing contaminants to roll off with minimal contact. The inclusion of photocatalytic materials like  $\text{TiO}_2$  further enables the degradation of organic stains under sunlight, making these fabrics ideal for outdoor wear, uniforms, and home furnishings. This innovation not only reduces the need for frequent washing but also contributes to water conservation.

**b) Thermal-Regulating Textiles Using Phase-Change Materials (PCMs)**

Thermal comfort is a crucial property in modern textiles. The incorporation of phase-change materials such as paraffin waxes or fatty acids encapsulated in nanocapsules has led to the development of thermoregulating fabrics. These PCMs absorb, store, and release heat during phase transitions (solid  $\leftrightarrow$  liquid), maintaining a stable microclimate near the skin. Nanotechnology enhances the distribution, stability, and responsiveness of PCMs in fabrics, making them effective for sportswear, military uniforms, and climate-adaptive clothing.

**c) Energy-Harvesting Textiles**

A significant innovation is the creation of energy-harvesting textiles using piezoelectric and triboelectric nanogenerators (TENGs). These fabrics convert mechanical movements—such as walking, stretching, or bending—into electrical energy. Nanomaterials like zinc oxide ( $\text{ZnO}$ ) nanowires, graphene, and polyvinylidene fluoride (PVDF) are commonly employed to create flexible and lightweight generators. Such fabrics enable wearable electronics to power small sensors, LEDs, or communication devices without external batteries, opening doors to next-generation smart garments.[28]

## 8. Challenges and Limitations of Nanotechnology in Textiles

Despite the remarkable advancements and potential of nanotechnology in the textile sector, several critical challenges and limitations must be addressed to ensure its sustainable, safe, and widespread adoption.

**a) Durability of Nanocoatings**

A primary concern is the limited durability of nanomaterial-based coatings on textiles. Many nanoparticles are applied using surface treatments such as dip-coating or spraying, which may not provide strong adhesion to fabric fibers. As a result, repeated washing, abrasion, or exposure to environmental conditions can lead to the gradual loss of functional properties, such as antimicrobial or UV resistance. Ensuring long-term stability and wash-fastness of nanofinishes remains a key research area.

**b) High Production Costs and Scale-Up Limitations**

Although lab-scale synthesis of nanomaterials is well established, scaling up to industrial levels poses financial and technical hurdles. The high cost of raw materials, complex equipment, energy requirements, and quality control during mass production make the commercial viability of nano-enhanced textiles

challenging. Moreover, incorporating nanomaterials uniformly across large fabric surfaces without compromising fabric aesthetics or comfort is a technical bottleneck.

**c) Regulatory and Safety Concerns**

The lack of standardized regulatory guidelines for the use of nanomaterials in consumer products, particularly wearable textiles, raises safety concerns. Potential risks include nanoparticle release through skin contact, inhalation, or washing effluents, which may lead to health and environmental hazards. As research on nanotoxicology is still evolving, comprehensive assessments and global regulations are necessary to ensure safe usage.

**d) Public Perception and Acceptance**

Consumer skepticism about nanotechnology, especially regarding its safety, can hinder market acceptance. Reports on possible nanotoxicity have raised concerns about the long-term effects of wearing nanomaterial-treated textiles. Public education, transparent labeling, and rigorous safety testing are essential to build trust and informed acceptance of these advanced fabrics. In conclusion, while nanotechnology offers groundbreaking innovations for textiles, addressing the challenges of durability, scalability, safety, and public perception is crucial for its responsible and successful implementation.[29]

## 9. Future Prospects

The future of textiles is poised to be revolutionized by the integration of nanotechnology with cutting-edge tools such as artificial intelligence, the Internet of Things (IoT), and sustainable materials. These advancements are paving the way for a new generation of smart, responsive, and eco-conscious textiles that go beyond conventional applications.

One of the most transformative developments is the rise of smart textiles integrated with IoT. These textiles are embedded with nanosensors and wireless communication systems, enabling real-time monitoring of physiological parameters such as heart rate, body temperature, hydration levels, and motion. Such fabrics hold immense potential in healthcare, fitness, sports, and defense, where they can enhance safety, performance, and preventive care. The miniaturization made possible by nanomaterials ensures that these sensors do not compromise comfort or aesthetics.

Another promising avenue is the development of biodegradable nanomaterials to address environmental sustainability. With growing concern over the persistence of synthetic fibers and microplastic pollution, researchers are exploring nanomaterials derived from natural polymers and plant-based sources. These include cellulose nanocrystals, chitosan-based nanoparticles, and green-synthesized metal oxides. Their application in textiles could drastically reduce the environmental impact and enable the production of fully compostable or recyclable garments.

Artificial Intelligence (AI) is also emerging as a powerful tool in textile engineering. AI algorithms can now predict the behavior of nanomaterials under various environmental conditions, optimize synthesis parameters, and assist in the rapid design of functional fabrics. Through AI-assisted

nanofabrication, the efficiency, scalability, and performance of nanotechnology-enhanced textiles are expected to improve significantly.

Furthermore, personalized and responsive textiles are becoming a reality through the fusion of 3D printing and smart nanomaterials. These textiles can be custom-designed to fit individual requirements while incorporating nanomaterials that respond to stimuli such as temperature, moisture, or mechanical stress. This approach opens avenues for clothing that can adapt to the wearer's environment, such as self-ventilating activewear or shape-changing garments.

In conclusion, the future of nanotechnology in textiles lies in the convergence of intelligence, sustainability, and personalization. With ongoing interdisciplinary research and technological integration, textiles will not only serve basic needs but also function as intelligent, adaptive, and environmentally conscious materials of the future[30].

## 10. Conclusion

The integration of nanotechnology into the textile industry has opened new frontiers in the development of advanced fabrics with enhanced and multifunctional properties. From antimicrobial and UV-protective coatings to self-cleaning, thermoregulating, and energy-harvesting textiles, nanomaterials have significantly expanded the scope of textile applications across healthcare, defense, fashion, and sportswear.

Despite these advancements, the field faces critical challenges related to the durability, cost-effectiveness, scalability, and safety of nano-enhanced fabrics. Concerns regarding nanotoxicity, environmental release, and lack of regulatory guidelines highlight the need for rigorous risk assessment and the adoption of sustainable practices.

The emergence of green synthesis techniques using plant-based materials offers a promising pathway toward eco-friendly nanotechnology in textiles. Looking forward, the convergence of nanomaterials with AI, IoT, and 3D printing will drive the development of personalized, responsive, and intelligent textiles, shaping the future of wearable technology.

Continued interdisciplinary research, coupled with responsible innovation and regulatory oversight, will be essential to harness the full potential of nanotechnology while ensuring safety, sustainability, and societal acceptance.

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