**Revolutionising Textiles with Nanotechnology: Advancements, Applications, and Future Directions**

**Abstract**

Nanotechnology has profoundly transformed the textile industry by introducing nanoscale materials and devices that enhance fabric functionality, durability and performance. This multidisciplinary field exploits the unique properties of nanomaterials as increased surface area, superior mechanical strength, and quantum effects, to develop smart and functional textiles. This paper reviews the types, mechanisms and textile applications of nanotechnology, offering insights into its transformative potential and the path forward for sustainable innovation. The integration of nanomaterials like silver, zinc oxide and titanium dioxide into fabrics imparts antimicrobial activity, UV protection, water repellency and self-cleaning capabilities. Nanodevices, including nanosensors and nanoelectromechanical systems, have enabled the development of wearable electronics and health-monitoring garments. Nanophotonic structures are also advancing textiles with features like energy harvesting and colour-changing properties. Top-down and bottom-up approaches guide the fabrication of these advanced materials, each offering unique benefits. The top-down approach in nanotechnology involves starting with a bulk material and reducing it to nanoscale dimensions using various mechanical, chemical, or physical processes. The bottom-up approach, in contrast, involves building nanostructures from the atomic or molecular level, assembling them into larger structures through chemical reactions or physical forces. Despite the promise, challenges remain, including health and environmental risks, high production costs, and a lack of regulatory standards. As research advances, sustainable nanotechnology and recyclable smart textiles are emerging as critical future directions. The future of textiles lies in the seamless fusion of functionality and sustainability, guided by interdisciplinary research and robust regulations. With continued innovation, nanotechnology will redefine the role of textiles in healthcare, fashion, defence and environmental applications.

**Keywords:** Nanotechnology, textile, nanodevices, sustainable nanotechnology, water repellency

**1. Introduction**

Nanotechnology is a multidisciplinary field that focuses on the manipulation and design of materials at the nanoscale, typically between 1 to 100 nanometers (nm). At this scale, materials exhibit unique properties that differ significantly from those of their bulk counterparts. These properties, such as enhanced mechanical strength, increased surface area, improved electrical conductivity and novel optical characteristics, arise due to quantum effects and the increased surface-to-volume ratio (Bhushan, 2017). The application of these principles to various industries has led to significant breakthroughs in diverse fields, including medicine, electronics, energy, and particularly, textiles. Nanotechnology has broad implications across multiple industries, including electronics, medicine, materials science, and energy, and it holds great potential for revolutionising technology and addressing some of the world's most pressing challenges (Sahu et al., 2023).

The concept of nanotechnology dates back to 1959, when physicist Richard Feynman introduced the idea of manipulating matter at the atomic scale, proposing the possibility of "atomic machines" (Feynman, 1960). However, it was not until the 1980s, with the advent of tools such as the scanning tunnelling microscope (STM), that the nanoscale world could be directly observed and manipulated. This development, spearheaded by K. Eric Drexler, brought the potential of nanotechnology into the mainstream (Drexler, 1986). Nanotechnology's influence on the textile industry has been particularly profound. By enabling the incorporation of nanomaterials and nanodevices into fabrics it has given rise to smart textiles, which offer enhanced functionalities such as self-cleaning, antimicrobial properties, and UV protection (Shahidi and Wiener, 2020). These textiles can sense environmental changes, respond to external stimuli, and even perform complex tasks such as monitoring health metrics or generating energy. The fusion of nanotechnology with textiles has resulted in a new class of functional fabrics, pushing the boundaries of what textiles can achieve.

The unique properties of nanomaterials, when applied to textiles, open up possibilities that were once considered impossible. Nanomaterials are finding an increased prominence in the textile industry, although their footprint is smaller relative to other conventional areas. Research in the textile field mainly deals with the inclusion of nanoscaled substances (such as nanofibers, nanocomposites, nano-electronics, etc.) during the manufacturing or finishing steps to impart various novel properties (Chakrabarty & Jasuja, 2022; Singh et al., 2024). For example, nanocoatings can be applied to fabrics to provide water and stain resistance, while nanofibers can be used to produce ultra-lightweight yet durable fabrics with enhanced mechanical strength (Khan and Azhar, 2021). Moreover, the introduction of nanoparticles such as silver, zinc oxide (ZnO) and titanium dioxide (TiO₂) into textiles has significantly enhanced their antimicrobial, UV-blocking, and self-cleaning properties, leading to more sustainable and functional fabrics (Rai *et al.,* 2012). The textile industry, one of the largest and oldest industries worldwide, faces continuous challenges related to sustainability, functionality, and performance. Nanotechnology presents innovative solutions to these problems by enhancing the durability, safety, and versatility of textiles. For instance, nanostructured textiles can be engineered to provide waterproofing without compromising breathability, a challenge that traditional textile technologies have struggled to address effectively (Siddiqui *et al.,* 2015).

In this review, we explore the various types of nanotechnology, their applications in textiles, and the challenges and future directions for this technology. As research progresses, the textile industry is expected to witness significant advancements in smart textiles, functional fabrics, and sustainable practices driven by nanotechnology.

**2. Classification of Nanotechnology**

Nanotechnology encompasses a wide array of applications and technologies, which can be classified based on their application domains or the structural characteristics of the materials involved. Nanotechnology plays a significant role in diverse industries, from medicine and electronics to environmental sustainability and textiles. In the textile industry, nanotechnology has provided innovative solutions, resulting in smart fabrics, functional textiles, and environmentally sustainable products. The primary categories of nanotechnology are nanomaterials, nanodevices, nanophotonics, and nanostructures.

**2.1 Nanomaterials**

Nanomaterials form the foundation of nanotechnology, providing the structural and functional components for a range of applications. These materials can exist as particles, fibres, tubes, rods, or sheets, with at least one dimension at the nanoscale (1–100 nm). Nanomaterials are divided into natural, incidental, and engineered categories, with engineered nanomaterials being the most widely used in commercial and industrial applications (Liu *et al.,* 2017).

**Types of Nanomaterials:**

**Metallic Nanoparticles:** Common metals used in nanotechnology include silver (Ag), gold (Au), copper oxide (CuO), and zinc oxide (ZnO). These nanoparticles are known for their antimicrobial properties, UV-blocking capabilities, and catalytic activity. For instance, silver nanoparticles are frequently used in textile applications for their ability to inhibit bacterial growth, offering antimicrobial finishes for fabrics (Rai *et al.,* 2012).

**Carbon-Based Nanomaterials:** These include fullerenes, carbon nanotubes (CNTs), and graphene. These nanomaterials offer remarkable properties such as high conductivity, mechanical strength, and flexibility. In textiles, carbon nanotubes are used to enhance the electrical conductivity and strength of fabrics, making them ideal for smart textiles (Zhu *et al.,* 2015).

**Polymeric Nanoparticles:** These are organic nanoparticles made from synthetic or natural polymers. They are often used in applications like controlled drug delivery and cosmetic products. In textiles, polymeric nanomaterials are used for enhancing fabric properties such as water resistance and durability (Siddiqui *et al.,* 2015).

**Quantum Dots:** Quantum dots are semiconductor nanoparticles that possess unique optical and electrical properties due to quantum effects. These particles are utilised in applications such as imaging, displays, and photovoltaics. In textiles, quantum dots have been explored for their ability to create colour-changing fabrics and solar energy harvesting textiles (Liu *et al.,* 2017).

**Textile Relevance:** Nanomaterials such as silver nanoparticles are incorporated into antimicrobial fabrics, zinc oxide (ZnO) nanoparticles are added to sportswear for UV protection, and carbon nanotubes are used in wearable electronics embedded into textiles.

**2.2 Nanodevices**

Nanodevices refer to functional systems or machines built at the nanoscale (typically between 1–100 nm) that perform specific tasks such as sensing, actuation, or data processing. These devices utilise the unique properties of nanomaterials and nanostructures, enabling them to function in ways that traditional devices cannot. When integrated with other nanoscale components, nanodevices hold significant potential for creating smart textiles and wearable electronics, thus expanding the range of functionalities textiles can offer.

**Types of Nanodevices:**

**Nanosensors:** Nanosensors are miniature sensors that can detect specific chemical, biological, or physical changes in the environment. These sensors rely on nanoscale materials to interact with their surroundings at an atomic or molecular level, enabling highly sensitive detection and real-time monitoring. The primary advantage of nanosensors is their ability to detect low concentrations of substances, making them ideal for use in medical diagnostics, environmental monitoring, and food safety applications (Zhang *et al.,* 2013).

In textiles, nanosensors are being integrated into wearable fabrics for health monitoring. For example, nanosensors embedded into clothing can monitor heart rate, body temperature, blood oxygen levels, and even muscle activity. This functionality is particularly beneficial in sportswear and medical garments for individuals with chronic health conditions (Kumar *et al.,* 2018).

**Nanoelectromechanical Systems (NEMS):** NEMS are tiny mechanical systems that are integrated with nanoscale electrical and mechanical components to perform tasks like signal processing, data storage, and actuation. NEMS offer superior performance and miniaturisation compared to conventional systems, allowing for the creation of ultra-small memory storage devices, sensors, and actuators that can be used in a range of nanoelectronics (Jiang *et al.,* 2014).

In the context of textiles, NEMS could be used to create fabrics with integrated interactive sensors that can respond to changes in the environment. For instance, smart textiles incorporating NEMS could respond to temperature or pressure by adjusting the garment's properties, such as thermal regulation or shape (Jung *et al.,* 2020).

**Molecular Machines:** Molecular machines are molecular-level devices that can mimic biological processes. These devices can perform mechanical functions such as motion, transport, or assembly at the molecular scale. They are often constructed using synthetic molecules that undergo conformational changes in response to environmental triggers, such as changes in pH, light, or chemical gradients (Stoddart *et al.,* 2016).

While still largely experimental, molecular machines hold the potential for transformative applications in textiles. They could be used to create self-healing fabrics, where the molecular machines would repair any damage to the fabric by molecular rearrangement. Molecular machines may also be applied to develop fabrics that can adapt to environmental changes such as humidity, light, or temperature (Béguin *et al.,* 2018).

**Textile Relevance:** Nanodevices, particularly nanosensors, NEMS, and molecular machines, are poised to play a significant role in the development of smart textiles. By embedding these devices into fabrics, textiles can gain functionalities like health monitoring, environmental interaction, and adaptive response to external stimuli. This opens new possibilities for a range of textile applications, such as:

**Health Monitoring Wearables**: Nanosensors integrated into garments can continuously monitor vital signs and health metrics, such as heart rate, skin temperature, sweat analysis, and posture tracking. These wearables are particularly useful for athletic apparel and medical textiles, where real-time data on physical activity or biomarkers can be used to optimise performance or diagnose conditions (Pérez-Moreno *et al.,* 2017).

**Interactive and Adaptive Clothing:** Clothing that can respond to the wearer's environment and actions is becoming a reality thanks to NEMS and molecular machines. These textiles could change their properties based on external conditions such as temperature, humidity, or pressure. For example, adaptive fabrics could regulate body temperature or even change shape or texture, offering increased comfort or enhancing user experience (Park *et al.,* 2018).

**Environmental Monitoring:** Nanodevices can enable textiles to detect pollutants, allergens, or harmful pathogens in the environment. Self-cleaning fabrics that utilise molecular machines to break down dirt or microbes when exposed to light are one example of such technology (Santos *et al.,* 2021). Textiles embedded with nanosensors can also serve in environments where contamination monitoring is crucial, such as in hospital uniforms or military gear.

**Challenges and Future Directions for Nanodevices in Textiles:**

While nanodevices hold great promise for the textile industry, several challenges remain:

**Integration with Textiles:** Integrating nanodevices into fabric without compromising comfort, breathability, or flexibility remains a significant challenge. The ability to produce soft, flexible, and wearable nanodevices that function seamlessly with textiles is still under development.

**Long-Term Stability:** Many nanodevices, especially nanosensors and molecular machines, may lose effectiveness over time due to factors like wear and tear, exposure to environmental conditions, and mechanical stress (Ouyang *et al.,* 2016).

**Safety and Toxicity:** The use of nanomaterials in textiles must be closely monitored for any potential health or environmental risks. For example, nanoparticles might leach out of the textile and accumulate in the environment, leading to possible toxicity (Rasmussen *et al.,* 2015).

Despite these challenges, research in nanodevices for textiles continues to grow, with interdisciplinary efforts focusing on sustainable development, user safety, and cost-effective production of functional and interactive textiles.

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| **Fig.1 Nanomaterials** | **Fig. 2 Nanodevices** | **Fig. 3 Nanostructures** | **Fig. 4 Nanophotonics** |

**2.3 Nanostructures**

Nanostructures refer to architectural arrangements at the nanoscale that enable novel physical, chemical, and mechanical properties. These structures can be fabricated into films, coatings, or fibres and play a significant role in developing high-performance textiles.

**Nanotextures:** Nanotextures are surface patterns or structures at the nanoscale that can influence light reflection, adhesion, and friction. Textiles with nanotextured surfaces can exhibit self-cleaning properties or enhanced dirt-repellent features (Kim *et al.,* 2020).

**Nanocoatings:** Thin layers of nanomaterials applied to fabrics can provide waterproofing, UV protection, and antibacterial functions. Titanium dioxide (TiO₂), for example, can be applied as a nanocoating to create self-cleaning fabrics by leveraging its photocatalytic properties to break down organic contaminants when exposed to light (Santos *et al.,* 2021).

**Nanofibers:** Nanofibers are fibres with diameters in the range of 1–100 nm, which are often produced through techniques like electrospinning. These fibres have high surface area-to-volume ratios, making them ideal for filtration, medical textiles, and high-performance fabrics (Greiner and Wendorff, 2007).

**Textile Relevance:** Nanocoatings and nanotextures are being used in textiles for UV-blocking, water and stain resistance, and self-cleaning fabrics.

**2.4 Nanophotonics**

Nanophotonics is a subfield of nanotechnology that focuses on the interaction between light (photons) and nanoscale materials. This field exploits the unique properties of materials at the nanoscale to manipulate and control light in ways that cannot be achieved with traditional optical devices. The principles of nanophotonics are based on phenomena such as surface plasmon resonance, photonic band gaps, and light-matter interaction at scales smaller than the wavelength of light. These phenomena offer vast potential for applications in areas such as communication, sensing, imaging, and energy harvesting.

In textiles, nanophotonics can be used to create fabrics that interact with light in novel ways, offering enhanced properties such as colour durability, UV protection, and the ability to harvest solar energy. By incorporating nanophotonic structures, textiles can be engineered to provide added functionality, making them "smart" fabrics capable of adapting to their environment or energy sources.

**Types of Nanophotonic Structures:**

**Photonic Crystals:** Photonic crystals are periodic nanostructures that control the flow of light. These materials are designed to have a band gap for light, similar to how semiconductors have an electronic band gap for electrons. Photonic crystals can manipulate light at wavelengths comparable to the periodicity of the structure, making them useful in applications such as lightwave guiding, deflecting, and bending light (Joannopoulos *et al.,* 2008). In textiles, photonic crystal coatings can enable fabrics that can manipulate and control light to create iridescent or colour-changing fabrics that respond to different environmental stimuli such as light and temperature.

**Plasmonic Nanostructures:** Plasmonics deals with the interaction of light with metallic nanostructures, which can support surface plasmon resonances (SPRs) that amplify light at the surface of the nanostructure. This phenomenon occurs when light interacts with free electrons on a metal surface, causing them to oscillate and enhance the electromagnetic field near the surface. Plasmonic nanostructures are typically made of materials like gold, silver, or copper, and are used to enhance optical signals, improve sensing capabilities, and boost light absorption (Liu *et al.,* 2011). In textiles, these plasmonic structures can be integrated into fabrics for applications such as antibacterial fabrics, where the enhanced light absorption can degrade harmful microorganisms, or to produce reflective or colour-shifting fabrics used in fashion or safety garments.

**Light-Responsive Nanoparticles:** Light-responsive nanoparticles are materials that undergo structural changes when exposed to light, typically ultraviolet (UV) light. These changes can include changes in colour, shape, or chemical composition, and can be used in energy-harvesting textiles. Nanoparticles such as titanium dioxide (TiO₂) and zinc oxide (ZnO) are often used in nanophotonic applications due to their ability to harness energy from light and convert it into useful energy such as electricity or thermal energy (Chen *et al.,* 2018). In textiles, these nanoparticles can be used to create self-cleaning fabrics that break down organic dirt and pollutants upon exposure to sunlight, or solar energy harvesting fabrics that collect sunlight and convert it into electrical energy for powering wearable devices.

**Textile Relevance:** Nanophotonics offers exciting possibilities for integrating light-manipulating technologies directly into textiles, enabling a range of enhanced functionalities:

**UV Protection:** UV-blocking textiles are already common in the market, and nanophotonics can take this functionality a step further by improving the efficiency of UV protection. ZnO and TiO₂ nanoparticles, integrated into fabric fibres, can create textiles that block or reflect harmful ultraviolet light. These textiles not only protect against UV radiation but can also help to maintain the fabric's colour, as these nanoparticles prevent the fading effect caused by prolonged exposure to UV light (Lee *et al.,* 2014).

**Colour Durability and Enhanced Aesthetic Properties:** Nanophotonics can be employed to create iridescent fabrics that change colour depending on the angle of the light. This ability is achieved through the use of photonic crystals or plasmonic nanostructures that alter light's wavelength as it interacts with the fabric's surface. Such fabrics can be used for high-fashion items or in safety applications where visibility is important, as they can reflect light in a dynamic and eye-catching way (Teng *et al.,* 2019).

**Energy Harvesting Textiles:** Nanophotonic materials can be incorporated into textiles to enable solar energy harvesting. Light-responsive nanoparticles like TiO₂ and ZnO can be applied to fabrics to capture sunlight and convert it into usable electricity. Such textiles have the potential to power wearable electronics like smartwatches, fitness trackers, or even communication devices embedded in the clothing itself. The ability to harvest energy from sunlight makes these textiles particularly valuable for sustainable fashion and wearable technology applications (Schmidt *et al.,* 2018).

**Self-Cleaning Fabrics:** Nanophotonic materials can also be integrated into fabrics to create self-cleaning textiles. Utilising the photocatalytic properties of materials like TiO₂, fabrics can break down organic dirt, stains, and pollutants when exposed to light. This self-cleaning ability reduces the need for frequent washing, thus contributing to the longevity of the fabric and offering environmental benefits by minimising water and detergent usage (Xia *et al.,* 2016).

**Challenges and Future Directions in Nanophotonics for Textiles:**

While the potential of nanophotonics in textiles is vast, challenges remain:

**Durability and Wearability:** One of the primary challenges is ensuring that nanophotonic materials remain functional after prolonged use, washing, and exposure to harsh environmental conditions. The integration of nanophotonic structures into fabrics must be done in such a way that their optical properties are maintained over time without causing damage to the textile itself (Liu *et al.,* 2017).

**Cost of Production:** While the technology is promising, the cost of producing nanophotonic textiles at scale remains a significant barrier. The production of materials like photonic crystals or plasmonic nanostructures requires advanced manufacturing techniques, which can be expensive. However, as technology advances and manufacturing processes become more refined, it is expected that the costs will decrease, making nanophotonic textiles more accessible (Gao *et al.,* 2020).

**Health and Environmental Impacts:** The long-term environmental and health impacts of nanoparticles used in nanophotonic textiles need thorough investigation. Toxicity and bioaccumulation of nanoparticles in the environment may pose risks to both human health and the ecosystem. As the industry moves forward, proper safety standards and environmental regulations will need to be established to ensure the safe integration of nanophotonics in textiles (Dada *et al.,* 2017).

**3. Approaches to Nanotechnology**

Nanotechnology encompasses a wide range of methods and techniques to design, fabricate, and manipulate materials at the nanoscale. The approaches used in nanotechnology can be broadly classified into two categories: the top-down approach and the bottom-up approach. These methodologies differ in their strategies for creating nanostructures and offer distinct advantages depending on the application. Both approaches are critical to advancing the potential of nanotechnology, especially in industries such as textiles, where the need for precision engineering and scalability is high.

**3.1 Top-Down Approach**

The top-down approach in nanotechnology involves starting with a bulk material and reducing it to nanoscale dimensions using various mechanical, chemical, or physical processes. This method is similar to traditional manufacturing techniques, where larger pieces are broken down into smaller components. The goal of the top-down approach is to control the shape, size, and functionality of the material by creating nanoscale structures from the macro level.

**Key Techniques in Top-Down Nanotechnology:**

**Lithography:** Lithography, particularly photolithography, is one of the most commonly used techniques for creating nanoscale patterns. It involves using light to transfer geometric shapes onto a substrate coated with a light-sensitive material. This method is widely used in semiconductor fabrication but is also applied to create nanostructures for textiles and electronics.

**Etching:** Etching involves the use of chemicals or physical methods (such as lasers) to remove material from a surface. It is used to create nanoscale patterns or structures by selectively etching away material, leaving behind the desired pattern.

**Mechanical Milling:** Mechanical milling uses mechanical forces to grind bulk materials into fine nanoparticles. It is a less precise method, but can be cost-effective for certain applications where high precision is not required.

**Textile Applications of Top-Down Approaches:**

**Nanofiber Production:** One of the most significant applications of the top-down approach in textiles is the production of nanofibers through techniques such as electrospinning. Electrospinning allows the creation of fibres with diameters in the nanometer range, which can be used in filter fabrics, wound dressings, and protective clothing (Greiner and Wendorff, 2007). These nanofibers offer enhanced properties such as increased surface area, improved mechanical strength, and high permeability.

**Nano-Patterning for Fabric Surface Modification:** Top-down methods can also be employed to modify the surface of fabrics. For instance, laser ablation can be used to create patterns on fabrics that enhance their functionality, such as water repellency or anti-microbial properties (Li *et al.,* 2014).

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| **Fig. 5 Top-down and Bottom-up approach** |

**3.2 Bottom-Up Approach**

The bottom-up approach, in contrast, involves building nanostructures from the atomic or molecular level, assembling them into larger structures through chemical reactions or physical forces. This approach mimics natural processes, such as self-assembly, and is generally used to create more complex, precise, and highly functional nanomaterials.

**Key Techniques in Bottom-Up Nanotechnology:**

**Chemical Vapour Deposition (CVD):** CVD is a process used to produce high-quality thin films and nanostructures. It involves the chemical reaction of gaseous precursors on a heated substrate, which results in the deposition of material in the form of nanoparticles or nanowires. This method is often used in the fabrication of carbon nanotubes (CNTs) and graphene, which are valuable materials for advanced textile applications.

**Sol-Gel Process:** The sol-gel method involves the transition of a solution (sol) into a gel-like state, which can then be processed into various nanomaterials. This method is particularly useful for producing nanoparticles, coatings, and thin films, which can be applied to textiles to provide properties like hydrophobicity or UV resistance (Zhao *et al.,* 2014).

**Self-Assembly:** Self-assembly is a bottom-up process where molecules spontaneously organise into a desired structure without the need for external guidance. This process is crucial for creating highly organised nanostructures and is used in various applications such as nanotube growth and the formation of nanoparticles for textiles (Liu *et al.,* 2018).

**Textile Applications of Bottom-Up Approaches:**

**Nanoparticle Integration:** Bottom-up approaches are particularly useful for creating nanoparticles that can be embedded into textile fibres or fabrics. For instance, silver nanoparticles are often used in textiles to impart antimicrobial properties, while zinc oxide (ZnO) nanoparticles are employed for UV protection (Wang *et al.,* 2012).

**Carbon Nanotubes and Graphene:** Carbon nanotubes (CNTs) and graphene are produced using bottom-up methods and are valued for their high strength, electrical conductivity, and thermal properties. These materials are being integrated into textiles to create smart fabrics that can conduct electricity, making them suitable for wearable electronics or sensors (Rafique *et al.,* 2015).

**Smart Coatings:** The bottom-up approach is also used to create smart coatings for textiles. These coatings can change properties based on environmental conditions, such as temperature-sensitive coatings that make fabrics more comfortable in varying climates, or self-healing coatings that repair minor damage when exposed to light or heat (Baughman *et al.,* 2010).

**Table 1 : Comparison of Top-Down and Bottom-Up Approaches in Nanotechnology for Textiles:**

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| **Characteristic** | **Top-Down Approach** | **Bottom-Up Approach** |
| Scale of Production | Suitable for large-scale production | Suitable for high-precision and low-volume production |
| Cost | Often lower due to existing manufacturing methods | Can be expensive due to the need for specialized equipment and processes |
| Complexity | Less complex but can be limited in precision | More complex and can achieve higher precision in structuring |
| Material Types | Can create large-scale nanostructures like nanofibers | Can create molecular-level structures such as nanoparticles or quantum dots |
| Textile Applications | Fabric surface treatments, nanofiber production | Smart fabrics, nanoparticle integration for specific functions |

**Example in Textiles: Electrospinning for Nanofiber Production**

A prime example of a top-down approach applied to textiles is electrospinning. This technique allows the production of nanofibers with diameters ranging from a few nanometers to a few micrometres, which can be used in a variety of textile applications. The electrospinning process involves applying a high-voltage electric field to a polymer solution, causing it to eject in the form of fine fibres that solidify into nanofibers. These nanofibers have high surface area and porosity, making them ideal for use in filter fabrics, medical textiles, and protective clothing (Greiner and Wendorff, 2007).

**4. Applications of Nanotechnology in Textiles**

Nanotechnology has emerged as a transformative force in the textile industry, bringing revolutionary advancements in fabric properties, functionality, and design. By incorporating nanomaterials and nanodevices into textiles, manufacturers can create fabrics with enhanced properties that were previously unattainable with traditional textile treatments. These innovations are not only improving the performance of textiles but also expanding their potential applications across various fields such as medical textiles, smart clothing, and environmental protection.

**4.1 Antimicrobial Finishes**

One of the most widely applied benefits of nanotechnology in textiles is the creation of antimicrobial fabrics. Silver nanoparticles (AgNPs) are frequently employed for this purpose due to their potent antibacterial and antifungal properties. Silver ions can disrupt microbial cell walls and inhibit the growth of bacteria, fungi, and viruses, making them ideal for textiles used in sportswear, medical fabrics, and socks.

**Silver Nanoparticles (AgNPs):** Silver nanoparticles are known for their antimicrobial activity and are integrated into fabrics to prevent bacterial growth, reduce odour, and extend the lifespan of garments (Rai *et al.,* 2012). They are particularly popular in the production of activewear, hospital linens, and personal hygiene products.

**Zinc Oxide (ZnO) Nanoparticles:** Zinc oxide nanoparticles also exhibit antimicrobial properties and are often incorporated into textiles for added hygiene benefits. ZnO nanoparticles are safer compared to silver nanoparticles, offering an alternative for people who may have sensitivities to silver-based materials (Siddique *et al.,* 2017).

**Textile Applications:**

**Sportswear:** Fabrics with antimicrobial properties prevent the accumulation of odour-causing bacteria during physical activity, ensuring that the garments remain fresh and hygienic.

**Medical Textiles:** In hospitals and healthcare settings, antimicrobial textiles are used to reduce the risk of infections and improve patient outcomes.

**4.2 UV Protection**

Another significant application of nanotechnology in textiles is UV protection. Exposure to ultraviolet (UV) radiation from the sun can lead to skin damage, ageing, and an increased risk of skin cancer. Nanomaterials, particularly zinc oxide (ZnO) and titanium dioxide (TiO₂) nanoparticles, are known for their ability to block harmful UV rays. These nanoparticles can be incorporated into fabrics to provide enhanced UV protection.

**ZnO Nanoparticles:** Zinc oxide is a widely used material in UV-blocking fabrics. When incorporated into textiles, ZnO nanoparticles absorb or scatter UV radiation, preventing it from reaching the skin (El-Tahlawy *et al.,* 2015).

**TiO₂ Nanoparticles:** Titanium dioxide is another effective UV-blocking agent. It works by reflecting UV radiation away from the skin, thus preventing damage. Additionally, TiO₂ nanoparticles are photoreactive, meaning they can activate under UV light to break down harmful substances, such as pollutants and bacteria (Fiorentino *et al.,* 2019).

**Textile Applications:**

**Sportswear:** Fabrics used in outdoor activities, such as hiking or cycling, benefit from UV protection to shield the wearer from harmful sunlight.

**Fashion Textiles:** Clothing designed for everyday use can integrate UV-blocking fabrics to protect the skin during prolonged exposure to sunlight.

**4.3 Water and Stain Repellency**

Nanotechnology also enhances the water- and stain-repellent properties of textiles. Nanoparticles, particularly silica (SiO₂) and fluorinated compounds, are used to create fabrics that resist the absorption of water, oils, and stains, making them ideal for outdoor and performance-based applications.

**Silica Nanoparticles:** Silica is widely used to create hydrophobic (water-repellent) textiles. The incorporation of silica nanoparticles modifies the surface of fabrics, causing water droplets to bead up and roll off the surface (Dong *et al.,* 2018).

**Fluorinated Nanoparticles:** Fluorinated nanoparticles, such as perfluorocyclohexane, provide textiles with enhanced water and oil resistance. These materials form a protective barrier on the fabric, preventing the penetration of water and stains (Xu *et al.,* 2014).

**Textile Applications:**

**Outdoor Apparel:** Jackets, pants, and other outdoor garments benefit from water-repellent coatings that keep the wearer dry during rain or snow.

**Home Textiles:** Nanotechnology is used to create stain-resistant fabrics for upholstery and bedding, ensuring easier maintenance and longer lifespan.



**Fig. 6 Application of nanotechnology in textiles**

**4.4 Self-Cleaning Fabrics**

Self-cleaning fabrics, inspired by nature, are a revolutionary application of nanotechnology. The lotus effect, where water droplets roll off the leaves of the lotus flower without leaving any residue, is mimicked in textiles through the use of titania (TiO₂) nanoparticles. These fabrics exhibit hydrophobic properties, allowing them to resist the accumulation of dirt and stains.

**Titanium Dioxide (TiO₂):** TiO₂ nanoparticles are known for their photocatalytic properties. When exposed to UV light, TiO₂ particles can break down organic pollutants, including dirt and stains, allowing fabrics to remain clean over extended periods without frequent washing (Park *et al.,* 2011).

**Textile Applications:**

**Outdoor Clothing:** Garments designed for outdoor activities, such as camping or hiking, benefit from self-cleaning fabrics that resist dirt and stains, making them more practical for extended use.

**Automotive Upholstery:** Nanotechnology is also used in the automotive industry to create self-cleaning upholstery that remains free of stains and requires less maintenance.

**4.5 Smart Textiles**

Smart textiles, also known as e-textiles, integrate nanotechnology with sensors, actuators, and other electronics to provide additional functionalities, such as monitoring health, adjusting temperature, or interacting with the environment. These textiles are designed to respond to external stimuli like temperature, pressure, or light.

**Nanosensors:** Nanosensors embedded within fabrics can monitor physiological parameters such as heart rate, temperature, or muscle activity. These sensors transmit data to wearable devices for real-time health monitoring.

**Thermochromic and Photochromic Materials:** Materials that change colour in response to temperature or light are increasingly used in smart clothing, enabling garments to adapt to environmental changes. For instance, colour-changing fabrics can be used for fashion purposes or to indicate temperature shifts in work environments.

**Textile Applications:**

**Medical Textiles:** E-textiles embedded with sensors can monitor patients' vital signs, providing real-time health data. This is particularly beneficial for elderly patients or those with chronic conditions.

**Sportswear:** Wearable technology in athletic wear can track performance metrics, such as sweat levels or muscle fatigue, helping athletes optimise their training regimens.

**Military and Security:** Smart textiles with integrated sensors can be used for personal protective equipment (PPE), where soldiers' uniforms can detect exposure to hazardous materials or monitor their health in real-time.

**5. Benefits and Challenges of Nanotechnology in Textiles**

Nanotechnology offers transformative advantages to the textile sector by enabling functionalities and performance enhancements that traditional techniques cannot achieve. However, its widespread adoption comes with certain risks and technical limitations that must be addressed to ensure sustainable implementation.

**5.1 Benefits**

**a. Enhanced Functional Properties:** Nanotechnology allows the incorporation of various functional attributes into textiles without compromising their tactile or visual appeal. For example, silver nanoparticles (AgNPs) are extensively used to impart antimicrobial properties to socks, undergarments, and hospital gowns, preventing the growth of odour-causing and pathogenic bacteria (Rai *et al.,* 2012). Similarly, zinc oxide (ZnO) and titanium dioxide (TiO₂) nanoparticles are incorporated for UV protection, safeguarding users from harmful ultraviolet radiation (Shahidi and Wiener, 2020).

**b. Improved Durability and Wash-Fastness:** Unlike conventional chemical coatings that may degrade over time, nanoparticles exhibit stronger binding interactions with textile fibres. This leads to better wash durability, longer-lasting effects, and reduced need for reapplication, enhancing the lifespan of functional garments (Joshi *et al.,* 2008).

**c. Smart and Responsive Textiles:** Nanotechnology facilitates the integration of nanosensors, nanoactuators, and nanogenerators into fabrics, enabling smart textiles that can sense and respond to environmental or physiological stimuli. These are particularly valuable in medical monitoring, sports performance tracking, and military applications (Stoppa and Chiolerio, 2014).

**d. Lightweight and Breathable Fabrics:** Nanomaterials, due to their extremely small size, add minimal weight to textiles. This helps in creating lightweight and breathable materials with improved comfort and wearability, especially important for sportswear, outdoor clothing, and space suits (Bhushan, 2017).

**e. Eco-Friendly Potential:** Emerging research into green synthesis and biodegradable nanomaterials holds promise for eco-friendly textile production, minimising the use of hazardous chemicals and enabling safer disposal (Iravani, 2011).

**5.2 Challenges**

**a. Health and Environmental Concerns:** A major challenge associated with nanotechnology in textiles is the potential toxicity and environmental persistence of nanoparticles. Studies have shown that silver nanoparticles can leach during washing, entering wastewater systems and affecting aquatic ecosystems (Benn and Westerhoff, 2008). Additionally, inhalation or dermal exposure during manufacturing or wearing raises occupational and consumer health concerns (Maynard *et al.,* 2006).

**b. Lack of Standardisation and Regulations:** There is currently a lack of universally accepted protocols for testing, labelling, and evaluating the safety of nanomaterials in textiles. This regulatory ambiguity hinders consumer confidence and limits the scaling of commercial applications (OECD, 2020).

**c. High Production Costs:** The synthesis, stabilisation, and application of nanoparticles involve complex and costly processes, often requiring specialised equipment and expertise. This results in high manufacturing costs, making nano-enhanced textiles less accessible in mass markets (Mishra *et al.,* 2012).

**d. Difficulty in Recycling and End-of-Life Disposal:** The integration of synthetic nanomaterials may complicate recycling and biodegradation processes. Most current textile recycling systems are not designed to handle nanocomposites, posing a challenge for circular economy practices (Shen *et al.,* 2020).

**6. Future Directions**

As nanotechnology continues to evolve, the future of textile science stands at the brink of major transformations. With ongoing research and technological advancements, several promising trends and areas are emerging that could shape the next generation of textile products.

**6.1 Green and Sustainable Nanotechnology**

One of the most critical areas of focus is the green synthesis of nanoparticles, which utilises biological routes such as plant extracts, bacteria, or fungi, instead of toxic chemicals. This not only reduces environmental hazards but also enhances biocompatibility (Iravani, 2011). Future textile innovations will likely emphasise eco-friendly nanomaterials and biodegradable nanocomposites, aligning with the global push toward sustainability.

**6.2 Fully Integrated Wearable Electronics**

The integration of nanotechnology with electronics will lead to seamless, flexible, and fully integrated wearable devices. These fabrics will be capable of monitoring health parameters (e.g., heart rate, hydration, glucose levels), enabling real-time diagnostics and telemedicine (Wicaksono *et al.,* 2020). Additionally, such textiles may include energy-harvesting components, such as nanogenerators and solar cells, allowing self-powered functionality.

**6.3 Smart Packaging and Responsive Clothing**

Future garments may incorporate responsive nanomaterials that adapt to temperature, light, moisture, or stress. For instance, textiles that regulate body temperature or change colour in response to UV exposure could become commonplace. This could also extend to packaging textiles used in food, pharmaceuticals, or fashion, enhancing product life and safety.

**6.4 Recycling and Circular Economy**

Developing recyclable nanocomposite textiles will be essential to address waste and lifecycle concerns. Research is underway to design nanomaterials that retain functionality through multiple recycling loops or can be safely deconstructed at the end of life (Shen *et al.,* 2020).

**6.5 Policy, Ethics, and Safety Standards**

The future of nanotechnology in textiles will also depend on standardised regulations, ethical frameworks, and safety assessments. There is a growing need for international standards and transparent guidelines regarding the toxicity, environmental release and consumer exposure to nanoparticles (Maynard *et al.,* 2006). Interdisciplinary research between materials science, toxicology, and social sciences will be vital in this context.

**6.6 Collaboration and Multidisciplinary Research**

Lastly, continued collaboration among chemists, engineers, textile scientists, environmentalists, and policymakers will be essential. Only through integrated approaches can the industry bridge innovation with social responsibility, ensuring that nanotechnology fulfils its potential in a safe and sustainable manner.

**7. Conclusion**

Nanotechnology has opened new frontiers in textile innovation, enabling fabrics that are not only functional but also intelligent and responsive. Through the integration of nanomaterials and devices, textiles now possess antimicrobial, UV-protective, self-cleaning and energy-harvesting properties. While the field faces challenges like cost, durability and environmental concerns, ongoing advancements in green nanotechnology and recycling strategies offer promising solutions. The future of textiles lies in the seamless fusion of functionality and sustainability, guided by interdisciplinary research and robust regulations. With continued innovation, nanotechnology will redefine the role of textiles in healthcare, fashion, defence and environmental applications.

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