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Nanotechnology and Nonwovens: A Synergistic Review of Materials, Method, and Multifunctional Applications

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ABSTRACT

Nanotechnology has significantly expanded the functional scope of nonwoven fabrics, enabling the development of high-performance materials with enhanced properties such as antimicrobial activity, UV protection, electrical conductivity, and filtration efficiency. This review explores the integration of nanomaterials and nanofibre production techniques into nonwoven structures, emphasizing recent advances in electrospinning, nanoparticle functionalization, and smart textile applications. Key challenges and opportunities related to scalability, safety, and sustainability are also addressed. The paper concludes with a forward-looking perspective on the future role of nanotechnology in driving the next generation of nonwoven materials.

Keywords: Nonwoven, Nanoparticles, Bonding, Textile, Nanofibres

INTRODUCTION

The convergence of nanotechnology and nonwoven fabric technology has emerged as a transformative force in the field of advanced materials, leading to the development of textiles with enhanced and multifunctional properties (Xue *et al.,* 2017; Shanmugam *et al.,* 2019). Nonwovens engineered fabrics made by bonding fibres together through mechanical, thermal, or chemical means have long been valued for their lightweight structure, high porosity, and cost-effective production (Russell, 2007). Traditionally employed in filtration, hygiene, and medical sectors, nonwovens are now being reimagined through the incorporation of nanomaterials to achieve superior performance characteristics (Ramakrishna *et al.,* 2005).

Nanotechnology, involving the manipulation of matter at the atomic or molecular scale (1–100 nm), offers remarkable potential to impart properties such as antimicrobial activity, UV protection, electrical conductivity, flame retardancy, and controlled drug delivery (Kaushik and Gopal, 2011; Dastjerdi and Montazer, 2010). When integrated with nonwoven substrates, nanomaterials such as metal and metal oxide nanoparticles, carbon-based nanostructures, and polymeric nanofibres enable the fabrication of smart and responsive textiles (Li *et al.,* 2020; El-Naggar *et al.,* 2023). This synergy has unlocked new possibilities for applications in healthcare, defense, energy, environmental remediation, and wearable electronics (Tiwari *et al.,* 2016).

The advantage of combining nanotechnology with nonwovens lies in the ability to modify surface characteristics without compromising the bulk properties of the material (Xu *et al.,* 2015). Techniques such as electrospinning, surface coating, in situ nanoparticle synthesis, and plasma treatment allow for precise functionalization, often using scalable and eco-friendly processes (Pant *et al.,* 2018; Huang *et al.,* 2003). Moreover, the high surface-area-to-volume ratio of nanostructures enhances the interaction between the textile surface and its environment, enabling high sensitivity and performance (Wang *et al.,* 2019).

Despite the growing promise, several challenges remain. Concerns about nanomaterial toxicity, environmental impact, durability of functional coatings, and scalability of manufacturing processes must be

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addressed to fully realize the potential of nano-enabled nonwovens (Nowack and Bucheli, 2007; Bhattacharya *et al.,* 2021). In parallel, advancements in characterization techniques, material standardization, and regulatory frameworks are essential to ensure safety and consistency across applications (Savolainen *et al.,* 2010).

Historical Evolution of Nonwovens:

Nonwoven fabrics date back to the mid-20th century and were initially developed as inexpensive, disposable alternatives to woven and knitted textiles (Russell, 2007). Their manufacturing involves bonding fibres through mechanical, thermal, or chemical means without converting fibres into yarns (Karthikeyan *et al.,* 2020). Due to their adaptability, light weight, and cost-effectiveness, nonwovens found early applications in hygiene products and filtration systems and have since expanded into automotive, construction, agriculture, and medical sectors (Rhim and Lee, 2013; Horrocks and Anand, 2016).

The late 20th and early 21st centuries saw the rise of nanotechnology, which enabled the manipulation of materials at the atomic and molecular scales (Xue *et al.,* 2017). In textiles, nanotechnology has opened new pathways to create fabrics with enhanced or novel functionalities such as self-cleaning, flame resistance, and microbial defense (Kaushik and Gopal, 2011; Dastjerdi and Montazer, 2010). The nonwoven sector, in particular, has benefited from nanotechnology through the development of nanofibre webs, functional surface treatments, and smart textile applications (Ramakrishna *et al.,* 2005; Bhattacharya *et al.,* 2021).

Overview of Nanotechnology in Textiles:

Nanotechnology has revolutionized the textile industry by enabling the creation of fabrics with novel properties that go far beyond traditional functions such as comfort, aesthetics, and durability. In textile science, nanotechnology refers to the integration of nanomaterials or the application of nano-scale processes to impart functional characteristics to fibres, yarns, or finished fabrics (Dastjerdi and Montazer, 2010; Shahid *et al.,* 2020). These enhancements are achieved without significantly altering the physical structure, flexibility, or appearance of the textile substrate (Kaushik and Gopal, 2011).

Nanotechnology is particularly impactful in textiles because of the high surface-area-to-volume ratio of nanostructures, which significantly increases the interaction of textile surfaces with external stimuli (Ramakrishna *et al.,* 2005). This unique interaction makes it possible to tailor fabric surfaces at the molecular level to achieve multifunctional performance such as:

- Antibacterial and antimicrobial activity (Perelshtein *et al.,* 2008)
- UV radiation protection (Narkhede *et al.,* 2019)
- Water and stain repellency (Montazer and Harifi, 2012)
- Self-cleaning or photocatalytic properties (Jiang *et al.,* 2007)
- Electro-conductivity and sensing capability (Stoppa and Chiolerio, 2014)
- Flame retardancy (Alongi *et al.,* 2011)
- Thermal regulation (Das *et al.,* 2008)

Types of Nanomaterials Used in Textiles:

Nanotechnology in textiles typically involves the use of various nanomaterials, each bringing specific functional advantages:

- ***Metal nanoparticles***: Silver (Ag), copper (Cu), and zinc oxide (ZnO) nanoparticles are widely used for their antimicrobial and UV-blocking properties (Rai *et al.,* 2009).
- ***Metal oxide nanoparticles***: Titanium dioxide (TiO_2) and silica (SiO_2) offer self-cleaning, photocatalytic, and hydrophobic capabilities (Mills and Le Hunte, 1997).
- ***Carbon-based nanomaterials***: Carbon nanotubes (CNTs) and graphene provide excellent electrical conductivity, mechanical strength, and chemical stability (Zhou *et al.,* 2021).
- ***Polymeric nanomaterials***: Electrospun nanofibres and nano-encapsulated agents are used for drug delivery, scent release, and controlled functionalization (Huang *et al.,* 2003).

Methods of Incorporating Nanotechnology in Textiles:

Several methods are employed to apply or embed nanomaterials into textiles:

- ***Surface coating and finishing***: Nanoparticles are applied via techniques such as dip-coating, padding, or spraying to create functional layers on the fabric surface (Montazer and Harifi, 2012).

- ***In situ synthesis***: Nanoparticles are chemically synthesized directly onto the textile substrate, ensuring better adhesion and durability (Dastjerdi and Montazer, 2010).
- ***Electrospinning***: A technique used to create nanofibres or nanocomposites, ideal for filtration and biomedical applications (Ramakrishna *et al.,* 2006).
- ***Sol-gel processing***: Allows the creation of thin, uniform coatings embedded with nanoparticles (Solouk *et al.,* 2014).
- ***Plasma treatment***: Used to modify surface energy and enhance nanoparticle binding (Morent *et al.,* 2008).

Impact on Performance and Industry Adoption:

Nanotechnology has redefined textile performance standards, especially in healthcare, sportswear, military gear, filtration, and protective clothing (Bhattacharya *et al.,* 2021). Smart textiles incorporating nanosensors and conductive nanomaterials are driving the growth of wearable electronics and e-textiles (Stoppa and Chiolerio, 2014).

Despite these advances, industry adoption is tempered by concerns related to long-term durability, cost-effectiveness, and regulatory compliance, particularly regarding the environmental and health impacts of nanomaterials (Nowack and Bucheli, 2007). Sustainable approaches and life cycle assessments are becoming integral to the future of nano-enabled textile development (Shahid *et al.,* 2020).

Nanofibre Production in Nonwovens:

Electrospinning:

Electrospinning is the most widely used technique for producing nanofibres. It employs a high-voltage electric field to draw a polymer solution into fine fibres, which are collected as a nonwoven web. Key parameters affecting fibre morphology include voltage, polymer concentration, flow rate, and needle-collector distance. Innovations in electrospinning such as needleless, centrifugal, and coaxial electrospinning have improved fibre uniformity and production scalability (Persano *et al.,* 2013).

Alternative Techniques:

Other nanofibre production methods include forcespinning, solution blow spinning, and melt electrospinning. These techniques offer advantages in throughput, fibre control, and compatibility with thermoplastic polymers, making them suitable for industrial-scale nonwoven production (Ramakrishna *et al.,* 2005).

Nanomaterial Functionalization of Nonwovens:

Surface Coating and Impregnation:

Nonwoven fabrics can be coated with nanomaterials via methods such as dip-coating, spraying, and layer-by-layer deposition. These approaches enable post-fabrication functionalization, making them adaptable to existing production lines (De Azeredo, 2009).

Incorporation into Fibre Matrix:

Nanomaterials can also be embedded within the fibre matrix during spinning or extrusion. This method offers durable functionality and homogenous distribution of active agents. Examples include silver nanoparticles for antimicrobial properties and $TiO2$ for UV resistance (Monteiro-Riviere and Tran, 2007).

In Situ Synthesis:

In situ synthesis involves generating nanoparticles directly on the nonwoven fabric through chemical processes like sol-gel or hydrothermal methods. This approach ensures strong adhesion and precise control over particle size and dispersion (Rai *et al.,* 2009).

Functional Properties and Applications of Nanotechnology in Nonwovens:

The integration of nanotechnology with nonwoven fabrics has unlocked a wide range of functional properties, transforming traditionally passive textile materials into active and responsive platforms. These enhanced functionalities are particularly valuable in healthcare, environmental protection, defense, and wearable electronics. The following sections detail the most significant properties enabled by nanotechnology and their corresponding applications.

Antimicrobial and Antiviral Activity:

Nanoparticles of silver (Ag), copper (Cu), and zinc oxide (ZnO) are widely recognized for their potent antimicrobial and antiviral effects. These nanoparticles exhibit broad-spectrum activity against bacteria, fungi, and viruses by interacting with microbial cell membranes, disrupting metabolic pathways, and generating reactive oxygen species (ROS) that damage nucleic acids and proteins (Rai *et al.,* 2009; Morones *et al.,* 2005).

- Silver nanoparticles (AgNPs) are the most commonly used antimicrobial agents due to their efficacy at low concentrations and minimal toxicity to human cells. Their use is prevalent in medical textiles, such as wound dressings, surgical masks, and antimicrobial coatings (Lansdown, 2006; Perelshtein *et al.,* 2008).
- Copper nanoparticles (CuNPs) have shown strong antiviral activity, including effectiveness against enveloped viruses such as influenza and coronaviruses. CuNPs are increasingly incorporated into face masks, hospital gowns, and touch surfaces (Borkow and Gabbay, 2009;Pal *et al*., 2007).
- Zinc oxide nanoparticles (ZnO NPs) offer both antibacterial and UV-protective properties and are considered safer for skin-contact applications (Padmavathy and Vijayaraghavan, 2008).

These nanomaterials are integrated into nonwoven substrates through coating, in situ synthesis, or nanofibre embedding to create long-lasting hygienic textiles (Dastjerdi and Montazer, 2010).

UV Protection:

Titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticles have been extensively employed in textiles for their exceptional UV-blocking capabilities. These metal oxide nanoparticles possess a high refractive index and excellent photostability, making them ideal for shielding fabrics from harmful ultraviolet (UV) radiation(Mills and Le Hunte, 1997; Narkhede *et al.,* 2019).

- TiO_2 and ZnO absorb and scatter UV rays, particularly UVA (320–400 nm) and UVB (280–320 nm), preventing them from reaching the skin (Montazer and Harifi, 2012).
- These nanoparticles can be applied as durable coatings or embedded within nanofibres to ensure prolonged UV protection, even after washing.
- Applications include outdoor clothing, military uniforms, tents, and sun-protective gear.

Additionally, nanocoatings with UV protection are used in museum-grade nonwovens for conserving light-sensitive textiles and artifacts (Kaushik and Gopal, 2011).

Enhanced Filtration:

Nanofibres produced via electrospinning provide a unique advantage in filtration due to their extremely high surface area, interconnected pore structure, and small fibre diameters (typically below 500 nm). These characteristics allow them to trap particles at the submicron and nanometer scale through mechanical interception, diffusion, and electrostatic attraction (Ramakrishna *et al.,* 2006; Huang *et al.,* 2003).

- Electrospun nanofibre mats are often layered onto or within nonwoven base fabrics to enhance air and liquid filtration performance.
- Applications include:
  - N95 and N99 respirators
  - HEPA air filters
  - Water purification membranes
  - Industrial and biomedical filtration systems

Electrospun nonwovens also exhibit low pressure drop, ensuring breathability in face masks while maintaining high filtration efficiency (Wang *et al.,* 2013).

Smart Textiles:

Smart textiles, or e-textiles, represent an exciting frontier where conductive nanomaterials such as carbon nanotubes (CNTs), graphene, and metallic nanoparticles are incorporated into textile substrates to create fabrics that can sense, respond, or adapt to environmental stimuli (Stoppa and Chiolerio, 2014; Bhattacharya *et al.,* 2021).

- Nonwoven smart textiles integrated with these nanomaterials enable:
  - Strain sensing
  - Temperature and humidity monitoring
  - Electrophysiological signal detection (e.g., ECG, EMG)
  - Energy harvesting and storage
- Common fabrication methods include dip-coating, inkjet printing, and electrospinning with conductive polymer blends (Zhou *et al.,* 2021; Huang *et al.,* 2003).
- These textiles are being developed for applications in:
  - Wearable health monitors
  - Textile-based sensors
  - Flexible electronics
  - Military and sports apparel

Smart nonwovens are particularly advantageous due to their lightweight structure, customizable architecture, and ability to integrate multiple functionalities in a single layer (Solouk *et al.,* 2014).

Fig. 1 : Application of Nanofibers in Different Field

Challenges and Limitations:

While the integration of nanotechnology into nonwoven fabrics offers tremendous functional benefits, several technical, environmental, economic, and regulatory challenges remain, which must be addressed to realize its full-scale industrial potential.

Scalability of Nanofibre Production:

- Electrospinning, one of the most prominent techniques for producing nanofibres, faces significant scalability issues. Limitations include low throughput, high voltage requirements, and sensitivity to environmental conditions such as humidity and temperature (Ramakrishna *et al.,*2005; Greiner and Wendorff, 2007).
- Emerging techniques like needleless electrospinning, centrifugal spinning, and melt electrospinning offer better throughput but still require optimization for consistent fibre quality in mass production (Teo and Ramakrishna, 2006; Persano *et al.,* 2013).

Nanoparticle Toxicity and Health Concerns:

- The toxicological profile of engineered nanoparticles remains an area of active research. Metal and metal oxide nanoparticles (e.g., Ag, TiO_2, ZnO) can penetrate biological membranes, potentially leading to oxidative stress, DNA damage, and cytotoxic effects (Nel *et al.,* 2006; Oberdörster *et al.,* 2005).
- Inhalation or dermal exposure during manufacturing or use poses potential occupational hazards, necessitating robust risk assessmentsand protective strategies (Fadeel and Garcia-Bennett, 2010; Maynard *et al.,* 2006).

Environmental Impact and End-of-Life Disposal:

- Nanoparticle leaching during washing or disposal raises environmental concerns, especially regarding their impact on aquatic ecosystems and soil microbiota (Keller *et al.,* 2013; Benn and Westerhoff, 2008).
- Many nanofibre-based nonwovens are made from synthetic polymers like polypropylene (PP) and polyacrylonitrile (PAN), which are not biodegradable, posing waste management challenges (Nowack and Bucheli, 2007; Boxall *et al.,* 2007).

Economic and Regulatory Barriers:

- The high cost of raw nanomaterials, processing equipment, and testing protocols make nano-enabled nonwovens economically unfeasible for low-margin markets (Roco, 2005; Diener *et al.,* 2015).
- The lack of standardized regulatory frameworks for the approval, labeling, and usage of nanomaterials in textiles complicates commercialization (Hansen *et al.,* 2008; Stone *et al.,* 2009).
- There is also a lack of consumer awareness and trust, which can affect adoption rates in certain sectors (Pidgeon *et al.,* 2009).

Future Outlook:

Despite these challenges, the future of nanotechnology-enhanced nonwovens is promising, driven by multidisciplinary innovations aimed at improving sustainability, safety, and functionality.

Green Synthesis and Biodegradable Materials

- Future research should prioritize eco-friendly synthesis routes using biological agents (e.g., plant extracts, bacteria) to reduce the ecological footprint of nanomaterials. Green synthesis techniques offer safer and more sustainable alternatives to conventional chemical methods, minimizing hazardous by-products and energy consumption (Iravani, 2011; Ahmed *et al.,* 2016).
- The development of biodegradable nanofibres, such as those based on polylactic acid (PLA),

chitosan, or cellulose nanofibres, can offer sustainable alternatives to petrochemical-derived nonwovens (Rujitanaroj *et al.,* 2008; Liu *et al.,* 2020)..

Integration with Digital Technologies:

- Industry 4.0 technologies, such as artificial intelligence (AI), machine learning (ML), and Internet of Things (IoT), can enhance manufacturing by enabling real-time monitoring, defect detection, predictive maintenance, and quality control (Lee *et al.,* 2015; Lu, 2017)..
- Smart nonwovens may also evolve into self-regulating materials capable of adapting their properties based on environmental inputs. These developments will be enabled by AI-assisted design, feedback loops, and embedded nanosensors that allow continuous data-driven optimization (Zhao *et al.,* 2020).

Cross-sector Collaboration

- Progress in this field will depend heavily on synergistic partnerships between academia, industry, and government, fostering innovation ecosystems that accelerate commercialization and adoption (Bhattacharya *et al.,* 2012).
- Regulatory bodies must develop risk-based frameworks for evaluating the safety and lifecycle impact of nano-enabled textiles (Hansen and Baun, 2012).
- Public-private partnerships (PPPs) can facilitate infrastructure development, technology transfer, and workforce training in nanotechnology and smart textile fabrication, thereby overcoming resource limitations in emerging economies (OECD, 2010; Roco *et al.,* 2011).

Conclusion:

Nanotechnology is poised to revolutionize the nonwoven textile sector by enabling the creation of fabrics that are antimicrobial, UV-protective, self-cleaning, electronically responsive, and more. The synergy between nano-engineered materials and nonwoven platforms offers unprecedented opportunities in sectors ranging from healthcare and defense to filtration and wearable electronics.

However, realizing these opportunities requires overcoming several multidimensional challenges, including manufacturing scalability, environmental impact, health safety, and regulatory compliance. Sustainable practices such as green nanoparticle synthesis, biodegradable substrates, and life cycle assessments will be critical to minimizing negative externalities.

The future of this field lies in transdisciplinary innovationwhere materials science, nanotechnology, textile engineering, and digital intelligence converge. As manufacturing technologies evolve and environmental considerations become paramount, nano-enabled nonwovens will play a key role in the advancement of next-generation smart, functional, and sustainable textiles.

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