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Recent advances in nanotechnology in the textile industry

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Abstract
Textiles have evolved from basic materials for clothing and protection to advanced fabrics offering multifunctional properties. With increasing demands for performance, comfort, and interactivity, the textile industry is transforming nanotechnology. Nanoparticles, with their unique physical and chemical properties at the nanoscale, are being integrated into textiles to impart enhanced functionalities such as antimicrobial activity, UV protection, self-cleaning, conductivity, and mechanical strength. This paper re-explores recent advancements in nanotechnology within the textile sector, emphasizing the incorporation of various nanoparticles—such as carbon nanotubes (CNTs), graphene, fullerenes, and metal/metal oxide nanoparticles (ZnO, TiO_2, Ag, CuO)—into both natural and synthetic fibers including cotton, silk, wool, nylon, and polyester. Techniques like dip-coating, pad-dry-cure, electrospinning, and layer-by-layer assembly are employed to achieve durable and functional nano-enhanced fabrics. Highlighted innovations include CNT-based smart textiles for wearable electronics, graphene-infused fabrics for thermal management, and fullerene-modified cotton with ion-sensing capabilities. Additionally, ZnO-coated fabrics demonstrate significant antimicrobial efficacy and wash durability. The study also acknowledges organic nanomaterials and biopolymers such as chitosan for sustainable applications. While the potential of nanotechnology in textiles is vast, further efforts are needed to address integration, durability, and safety. This paper provides a comprehensive view to guide future developments in smart and high-performance textiles.

Keywords: Nanotechnology, smart textiles, antimicrobial fabrics, functional nanoparticles

Introduction
Nanotechnology is emerging as a transformative force in the field of textile engineering, offering remarkable advancements in the performance and functionality of textile materials (Yetisen *et al*., 2016) [4]. Through the integration of nanomaterials and nanofibers into textile matrices, it is possible to significantly augment properties such as mechanical strength, chemical resistance, longevity, and multi functionality. These innovations have paved the way for next-generation textiles capable of self-cleaning, self-repairing, and real-time monitoring of physiological and environmental parameters. Textiles engineered to deliver such enhanced functionalities-ranging from resistance to water, oil, stains, odours, and chemicals to protection against ballistic threats, stabs, and extreme environmental conditions-are classified as high-performance textiles (HPTs) (Loughlin and Paul, 2018) [49].

Nanomaterials, including nanoparticles and nanofibers, are increasingly being incorporated into textiles to elevate their performance and functional attributes. Defined by having at least one dimension within the 1 to 100 nanometre (nm) scale, these materials exhibit exceptional properties that differ markedly from those of their bulk counterparts. Owing to their high surface-area-to-volume ratio and distinctive physical, chemical, and biological behaviours at the nanoscale, nanomaterials impart superior characteristics to textiles, such as enhanced durability, responsiveness, and adaptability (Sawhney *et al*., 2008; Saleh and Gupta, 2016) [5, 107].

The integration of nanotechnology into textiles holds immense importance and significance due to its potential to revolutionize the textile industry. Engineered nanoparticles with altered surface properties are used in the textile industry. A few examples of such nanoparticles include silica, fullerene, carbon nanotubes, gold, silver, iron oxide, titanium dioxide, zinc oxide, etc. (Ahmad *et al*., 2020; Göcek, 2019; Gowri *et al*., 2010) [45, 48, 96].

Nanoparticles can be synthesised using two principal strategies: the top-down and bottom-up approaches. These synthesis pathways can be implemented through physical, chemical, or biological methods (Shnoudeh *et al*., 2019; Jamkhande *et al*., 2019) [3, 83]. In the top-down method, larger structures or bulk materials are mechanically or chemically broken down into nanoscale particles. Conversely, the bottom-up approach involves the assembly of nanoparticles from atomic or molecular units, allowing precise control over particle formation. Among the various techniques available for synthesizing metal-based nanoparticles, biological or green synthesis has garnered increasing attention from researchers. This preference is attributed to several advantages, such as process simplicity, high yield, environmental sustainability, and enhanced biocompatibility of the resulting metal nanoparticles (Nasrollahzadeh *et al*., 2019) [70]. Consequently, a wide range of bio-resources-including metabolites derived from plants, microorganisms, and animals-have been extensively employed in the green synthesis of metal nanoparticles for diverse applications (Adelere *et al*., 2016; Akintayo *et al*., 2020; Lateef *et al*., 2021; Elegbede *et al*., 2021; Adelere *et al*., 2021; Adebayo *et al*., 2021; Dutta and Das, 2021; Thakur *et al*., 2022; Nazir *et al*., 2020) [43, 35, 23, 52, 44, 23, 20, 71, 92].

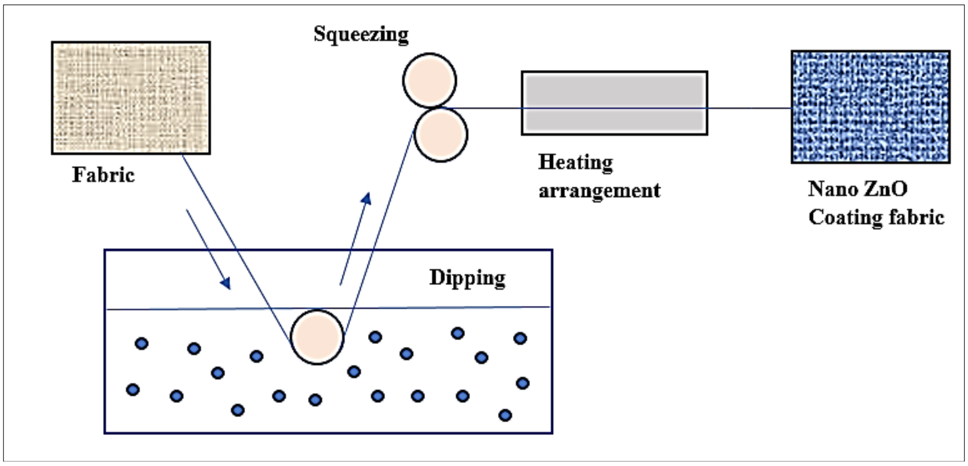
Comprehensive Classification of Nanomaterials

A wide array of materials can be developed through nanotechnology; however, four specific categories have garnered considerable scientific and industrial interest due to their unique properties and broad application potential.

1 Nano Finishing: It is an advanced surface modification technique that entails the application of colloidal solutions or nanoscale dispersions of functional materials onto textile substrates to enhance their performance characteristics (Ghosh *et al*., 2018) [34]. Unlike conventional finishing methods, nano finishing requires significantly smaller quantities of materials to achieve comparable or superior effects. This is primarily due to the exceptionally high surface area-to-volume ratio of nanoparticles, which promotes better adhesion and uniform distribution across the fabric surface. Notably, nano finishes preserve the original texture and aesthetic appeal of textiles, while offering superior durability and long-lasting functionality (Saleem and Zaidi, 2020) [99]. Moreover, nano finishing not only refines existing treatment processes but also enables the incorporation of novel functionalities such as antimicrobial activity, UV protection, or water repellency-that are often unattainable through traditional finishing techniques (Montazer, 2018) [75].

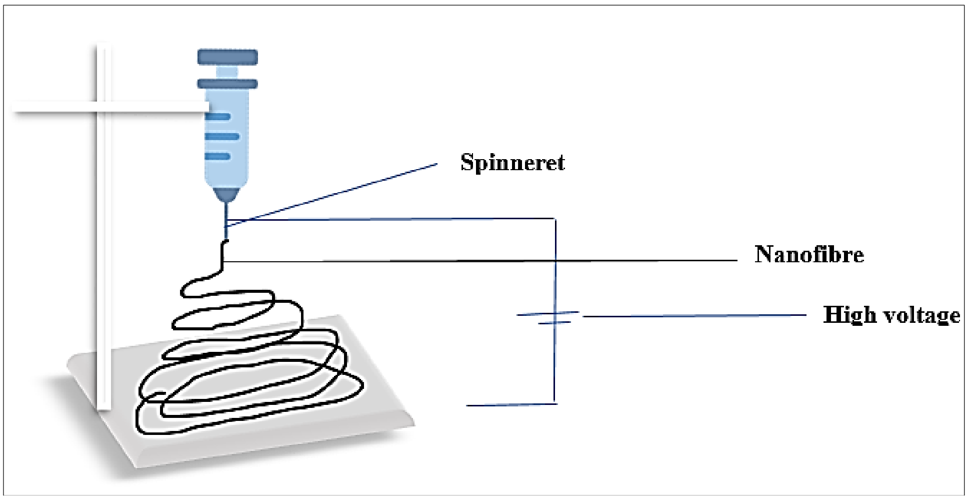
2. Nano Coating

Nano coating refers to the deposition of an ultra-thin film-typically less than 100 nanometres thick-onto the surface of a substrate to enhance existing properties or impart new functionalities (Joshi and Adak, 2019; Makhlouf *et al*., 2011) [52, 72]. This advanced technique enables the development of textiles with superior attributes such as improved colour fastness, flame retardancy, resistance to water and oil, wrinkle resilience, and antimicrobial activity. In contrast, conventional textile coatings, which are often applied in micrometre to millimetre thicknesses, can significantly compromise the fabric's tactile qualities, flexibility, and breathability by creating a dense, impermeable layer (Joshi *et al*., 2011) [52]. Nano coatings overcome these limitations by forming a uniform and transparent barrier that retains the original texture and comfort of the textile while delivering high-performance functionality.



3. Nano Fibres

Nano fibres exhibit exceptional mechanical and structural properties when compared to conventional fibres, including greater stiffness, higher tensile strength, an extremely large surface-area-to-weight ratio, low density, and significant pore volume (Islam *et al*., 2019; Xue *et al*., 2017) [47, 120]. These unique attributes make nanofibers highly versatile and suitable for a broad spectrum of advanced applications. Typically defined as fibres with diameters of 100 nanometres or less (Ramakrishna, 2005) [89], nanofibers are particularly distinguished by their ultra-fine structure, enhanced surface-area-to-volume ratio, minute pore sizes, and outstanding mechanical resilience (Huang *et al*., 2003) [42]. These characteristics position nanofibers as promising candidates in fields such as filtration, biomedical engineering, protective textiles, and energy storage.



4. Nano Composites

Nanocomposite is a solid material composed of several phases where at least one of the phases has one, two or three dimensions in the nanometre size. Through the nanoscale phase process, the goal of synergy between different constituents is achieved (Kiesler, 2015) [57].

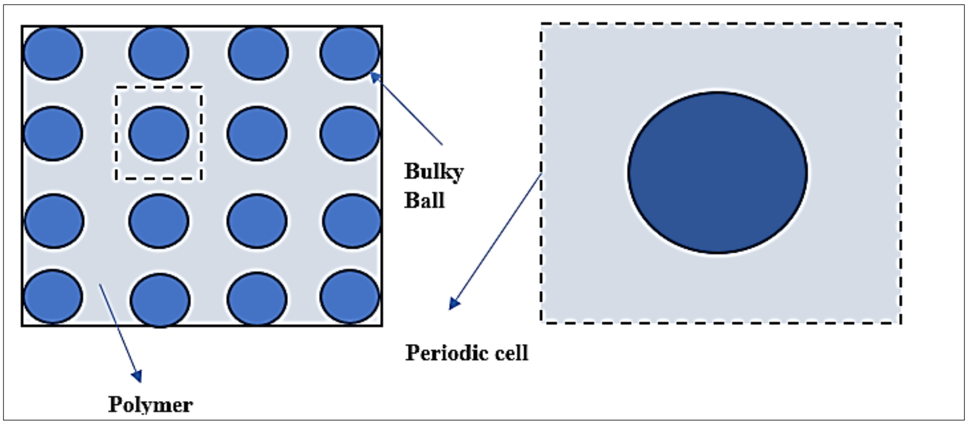


Table 1: Recent Advancements in Nanomaterial-Enhanced Fibres: Incorporation Methods, Functional Attributes, and Industry Applications

Types of fibre	Nanomaterials	Incorporation method	Attributes	Applications in different industries	Reference
Cotton	Silver nanoparticles	Soaking method	Dielectric, wave-absorbing, shielding, and electrically active properties	Healthcare and manufacturing	(Safdar *et al*., 2022; Jagadeshvaran and bose, 2023) [98, 51]
Cotton	Zinc nanoparticles	Pad-dry-fix technique	Antibacterial, ultraviolet-protection, mechanical strength, and increased resistance	Healthcare, manufacturing, and increased recovery	(Abou *et al*., 2022; Mohammadipour *et al*., 2023) [6, 73]
Cotton	Copper oxide nanoparticles	Pad-dry-fix technique	Antibacterial, fungus-resistant, ultraviolet blocking, and auto-cleaning	Healthcare and manufacturing	(Verma *et al*., 2023) [115]
Cotton	Titanium dioxide nanoparticles	Dip and spin layering	Antifungal	Healthcare and manufacturing	(Granados *et al*., 2021) [38]
Silk	Nano emulsion	Continuous padding and batch exhaustion	Antibacterial, fungus-resistant, mechanical strength, air permeability	Healthcare	(Morris and Murray 2020; Xing *et al*., 2023) [78, 118]
Silk	Nano silica	Soaking method	Hydrophobicity, ultraviolet resistance, wrinkle resistance, and auto-cleaning	Industrial	(Mollick *et al*., 2023; Gao *et al*., 2020) [74, 32]
Silk	Platinum nanoparticles	Soaking method	Antibacterial, catalytic activity and dyeability	Healthcare and manufacturing	(Zou *et al*., 2018; Arumugam *et al*., 2024) [128, 10]
Silk	Gold nanoparticles	Electro fibre spinning	Wound dressing and healing	Healthcare and cell scaffolding	(Akturk *et al*., 2016; Zhu *et al*., 2020) [7, 127]
Silk	Cadmium telluride	Sequential layering method	Immunoglobulin detector	Healthcare and biological sensing	(Haroone *et al*., 2018) [40]
Wool	Silver nanoparticles	Soaking method	microbe-resistant, water-repellent, static-resistant, improved ultraviolet absorption	Healthcare and manufacturing	(Hassan, 2019) [41].

Wool	Bio nano mordant	Ultrasonic-assisted synthesis	microbe-resistant	Healthcare and manufacturing	(Pour *et al*., 2020) [86]
Wool	Zinc nanoparticles	Pad-dry-fix technique	Antibacterial, fungus-resistant, static-resistant, and auto-cleaning	Healthcare and manufacturing	(Farooq *et al*., 2025) [29]
Wool	Selenium nanoparticles	Soaking method	Antibacterial and ultraviolet-blocking properties	Healthcare and manufacturing	(Razmkhah *et al*., 2021; Elmaaty *et al*., 2020) [90, 27]
Nylon	Zinc oxide nanoparticles	Sequential layering method	Antibacterial, ultraviolet-protection stain-proof	Healthcare and manufacturing	(Ram, 2022) [88]
Nylon	Titanium dioxide nanoparticles	Sequential layering method	Antibacterial, ultraviolet-protection stain-proof	Healthcare and manufacturing	(Ram, 2022) [88]
Polyester	Nanocomposites	Sequential layering method	Anti-droplet and flame retardancy	Industrial	(Rui *et al*., 2021) [95]
Polyester	Titanium dioxide nanocomposites	Sequential layering method	Photocatalytic, solar light-activated self-decontaminating textile, and protection against chemical warfare agents	optical field	(Grandcolas *et al*., 2011) [39]

Layer-by-Layer (LbL) Method

The layer-by-layer (LbL) method builds nanolayer films by alternately depositing oppositely charged polyelectrolytes through electrostatic attraction. Each adsorption step, using solutions of a few mg/mL, is followed by rinsing to remove excess and prevent contamination. The outer layer enables further adsorption of the opposite charge. Multilayers may include polyions, charged molecules, or colloids, with layer times ranging from minutes to hours. Factors like ionic strength, temperature, and rinsing/drying time affect the film's structure and thickness (Stawski, 2012) [103].

The layer-by-layer method was used to create self-assembled multilayers on cotton textiles by dip-coating. The particle-based coatings provided dual functions, modifying both the textile surface morphology and chemistry (Babaeipour *et al*., 2024) [12].

Silver nanoparticles were immobilized on nylon and silk using the layer-by-layer method. Silk showed better film growth and uniformity than nylon, confirmed by higher K/S values and SEM analysis. Both fibres exhibited antimicrobial activity, with silk achieving 80% and nylon 50% bacterial reduction, highlighting the method's potential for antimicrobial textiles (Dubas *et al.*, 2006) [22].

Pad Dry Cure Method

The pad-dry-cure technique is one of the most widely employed methods for the application of nanoparticles onto textile substrates, particularly for producing durable, long-lasting functional fabrics. In this process, a formulation containing the crosslinking agent, catalyst, softener, and other auxiliaries is uniformly applied to the fabric surface, followed by a drying phase. The actual crosslinking reaction is then initiated during the subsequent curing stage, ensuring the stable fixation of nanoparticles onto the fibres. In a recent study, Lemo *et al*. (2017) utilized this technique to impregnate cotton fabric with silver nanoparticles (AgNPs) at concentrations of 10 and 20 parts per million (ppm), aiming to assess their antibacterial efficacy against *Staphylococcus aureus*. The treated fabrics exhibited remarkable antimicrobial performance, achieving bacterial reduction rates ranging from 98.86% to 99.94%. Similarly, Nadi *et al*. (2020) [80] engineered magnetically responsive cotton textiles using Fe_3O_4 (magnetite) nanoparticles synthesised through the reverse coprecipitation method. The nanoparticles were applied using the pad-dry-cure process. Characterisation via Vibrating Sample Magnetometry (VSM) confirmed the magnetic behaviour of the treated fabric, while Thermogravimetric Analysis (TGA) indicated enhanced thermal stability. Moreover, electrical conductivity assessments revealed improved conductive properties, emphasising the multifunctional capabilities of Fe_3O_4-functionalized cotton textiles.

Electro Spinning

Electrospinning is an innovative method for fibre production based on the use of electrostatic force to create charged threads of polymer solutions. Electrospinning shows great potential since it provides control of the size, porosity, and mechanical resistance of the fibres (Stramarkou *et al.*, 2024) [104].

Table 2: Recent developments in antimicrobial nano textiles: Nanomaterials, enhanced properties, and targeted microorganisms

Types of fibre	Nanomaterials	Properties of nano textiles	Targeted bacteria and fungi	References
Cotton	Silver nanoparticles	Fungus-inhibiting, microbial-resistant	S. aureus, E. coli, P. aeruginosa	(Arif *et al*., 2015; Arenas *et al*., 2022) [9, 8]
Cotton	Zinc nanoparticles	Fungus inhibiting, microbial resistant	S. aureus, E. coli	(Nahhal *et al*., 2020; Roy *et al*., 2020) [25, 94]
Cotton	Copper oxide nanoparticles	Fungus inhibiting, microbial resistant	S. aureus, E. coli, P. fluorescens and B. subtilis	(Román *et al*., 2020; Abou *et al*., 2022) [25, 94]
Cotton	Titanium dioxide nanoparticles	Fungus inhibiting, microbial resistant	S. aureus, E. coli, P. aeruginosa, P. mirabilis	(Naggar *et al*., 2022; Abou *et al*., 2022) [28, 6]
Silk	Silver nanoparticle	Fungus inhibiting, microbial resistant	S. aureus, E. coli, P. aeruginosa	(Khan *et al*., 2022) [56]
Silk	Copper nanoparticles	Fungus inhibiting, microbial resistant	S. aureus, E. coli, P. aeruginosa	(Khan *et al*., 2024; Bhattacharjee *et al*., 2021) [55, 16]
Silk	Platinum nanoparticles	Microbial resistant, catalytic activity and coloration ability	E. coli	(Zou *et al*., 2018) [128]
Wool	Silver nanoparticles	Microbial resistant, water-attracting and auto-purifying	B. cereus, E. coli, P. aeruginosa, S. typhi and S.	(Luceri, 2024; Singh *et al*., 2023; Pietrzak *et al*., 2016; Singh *et al*.,

			aureus	2023) [69, 102, 85, 102]
Wool	Zinc nanoparticles	Microbial resistant, fungus inhibiting, ultraviolet resistant, and auto-purifying	S. aureus, E. coli	(Mohammadipour *et al*., 2023; Singh *et al*., 2023) [73]

(Arenas *et al.*, 2022) [8] Revealed that silver nanoparticle-carboxymethyl chitosan (AgNPs-CMC) nanocomposite was evaluated for antimicrobial properties on cotton fabric. It showed 100% antibacterial activity against *E. coli* and *S. aureus*, and strong antifungal effects against *C. albicans* and *A. niger*, suggesting potential for hospital garments to reduce infections.

(Nahhal *et al.*, 2020) [25] Revealed that ZnO-NPs were coated on cotton using ultrasound and stabilized with corn starch, enhancing nanoparticle adhesion and durability. A 3% starch solution improved ZnO-NP retention by 53% after washing and boosted antibacterial activity. Further functionalization with AgNPs and curcumin enhanced antimicrobial performance against *S. aureus* and *E. coli*.

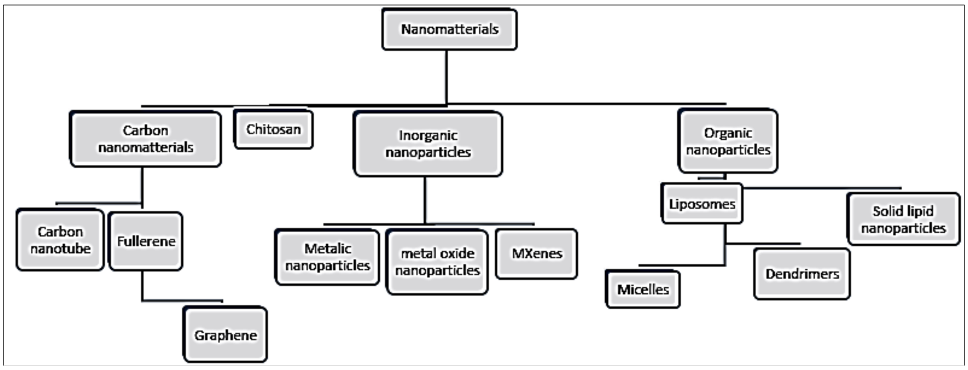
CuO nanoparticles were green-synthesized using *Ruellia tuberosa* extract, avoiding toxic chemicals. The nanorods (avg. size 83.23 nm) showed strong antimicrobial activity against *S. aureus*, *E. coli*, and *K. pneumoniae*. When embedded in cotton, they exhibited bactericidal and photocatalytic properties, offering eco-friendly solutions for hospital and industrial use (Vasantharaj *et al.*, 2019) [114].

(Khan *et al*. 2022) [56] Revealed that BioAgNP-propolis-coated silk sutures exhibited potent antibacterial properties against *E. coli* and *S. aureus*. They were biocompatible using 3t3 fibroblast cells, it promoted cell proliferation in wound healing scratch assays. These sutures hold potential for improving infection control and accelerating healing in surgical wounds, making them promising for medical applications.

Wool fabrics were functionalized with SiO_2, TiO_2, and Ag nanoparticles using a non-toxic method. Ag NPs provided antibacterial effects against *Escherichia coli*, SiO_2 enhanced hydrophilicity, and TiO_2 offered self-cleaning properties. Combined NPs gave optimal results-SiO_2 and Ag made wool super hydrophilic with strong antibacterial activity, while TiO_2-treated fabrics showed superior self-cleaning under sunlight (Mura *et al.*, 2015).

Recent advancements in nanomaterials used in High-Performance Textiles

Nanoparticles are defined as colloidal dispersions or solid particulates with sizes ranging from 10 to 1000 nanometers. These particles can be engineered to encapsulate, entrap, or attach drugs to their matrix, depending on the synthesis method. The resulting structures can take the form of nanospheres or nanocapsules. Nanocapsules are designed with a core cavity that houses the drug, which is surrounded by a distinctive polymeric membrane. In contrast, nanospheres are matrix systems where the drug is uniformly distributed throughout the particle. In recent advancements, biodegradable polymeric nanoparticles, particularly those coated with hydrophilic polymers such as poly (ethylene glycol) (PEG), have gained significant attention as promising drug delivery systems. Known for their "long-circulating" properties, these particles can remain in circulation for extended periods, allowing targeted delivery to specific organs. Additionally, they serve as efficient carriers for DNA in gene therapy and can facilitate the delivery of proteins, peptides, and genes, making them versatile tools in medical applications (Kommareddy *et al.*, 2005; Lee and Kim, 2005; Langer, 2000; Bhadra *et al.*, 2002) [58, 64, 63, 15].



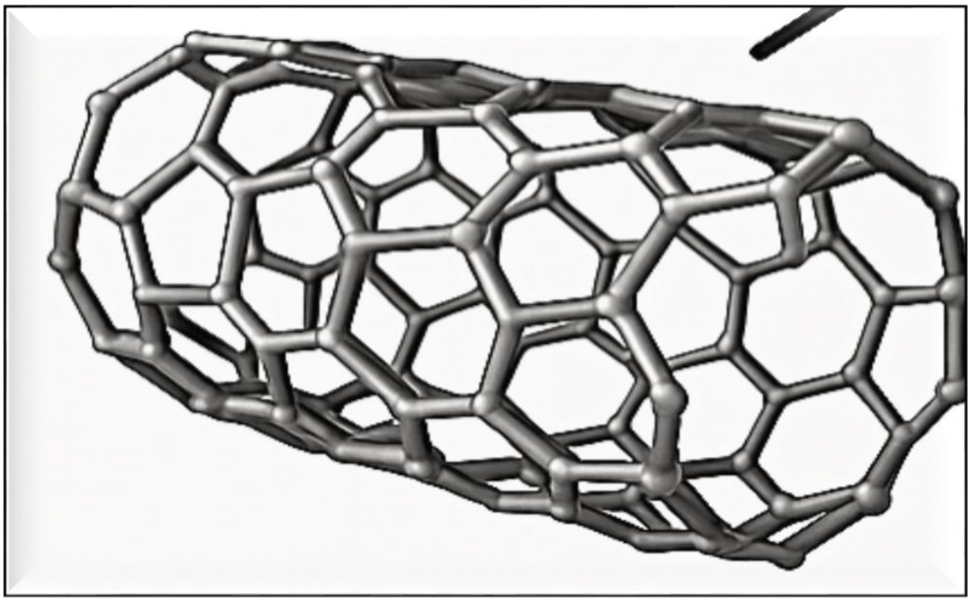
Carbon Nanomaterials

The discovery of carbon nanoparticles (CNPs) dates back to the 1980s (Sgarma, 2010; Kroto *et al.*, 1985) [59]. CNPs encompass a diverse array of carbon-based materials, which include amorphous carbon nanoparticles (such as ultrafine carbon particles, carbon nanoparticles, and carbon dots), sp^2-hybridized carbon nanomaterials (including fullerenes, carbon nanotubes, carbon nanohorns, graphene, and graphene quantum dots), and nano diamonds (Chen and Haifang, 2016) [18]. Formed entirely from pure carbon, CNPs exhibit remarkable properties, such as exceptional stability, superior electrical and thermal conductivity, and outstanding mechanical attributes—including extreme stiffness, strength, and toughness. Additionally, they are highly biocompatible With minimal toxicity, making them ideal candidates for various biomedical applications. Due to their sp^2 hybridization, CNPs are also highly hydrophobic, further enhancing their functional versatility (Chaudhary, 2014) [19].

1.1 Carbon Nanotubes

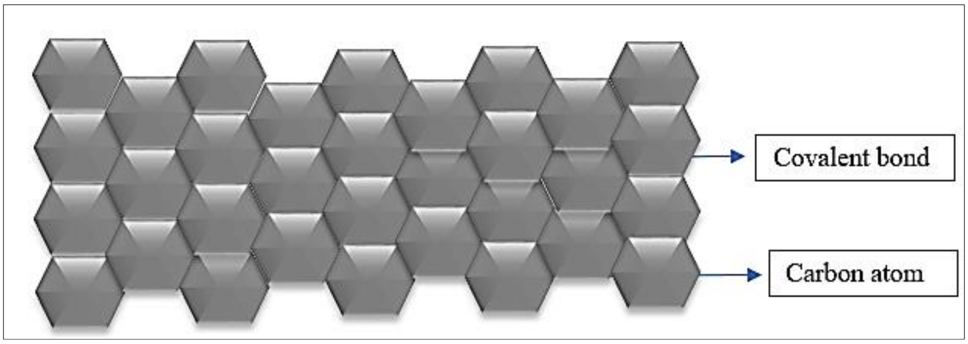
Carbon nanotubes (CNTs) are a class of nanoparticles characterized by cylindrical tubular structures with diameters at the nanoscale, formed by the rolling of graphene sheets. CNTs are typically classified into single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs), based on the number of graphene layers (Eatemadi *et al.*, 2014) [24]. The most commonly employed techniques for synthesizing carbon nanotubes include chemical vapour deposition (CVD), arc discharge, and pulsed laser ablation. In the CVD process, carbon-containing precursor gases such as carbon dioxide (CO_2), acetylene (C_2H_2), ethylene (C_2H_4), and other hydrocarbons are utilized. The process typically occurs at temperatures ranging from 350 to 1000 °C. Several parameters, including reaction time, temperature, catalyst particle size, and the type and flow rate of the reactive gases, significantly influence the growth and quality of the CNTs produced (Wang *et al*., 2019) [117].

In a study by Thanga kameshwaran and Santosh kumar (2014), it was found that cotton fabric coated with MWCNT ink exhibited enhanced electrical conductivity, mechanical strength, and thermal stability, making it an ideal candidate for smart textile applications. Multiple coating layers further improved the fabric's conductivity and abrasion resistance, and piezoelectric testing demonstrated its potential for energy storage. Although promising for integration into wearable electronics, further research is needed to evaluate the long-term effects of skin contact with MWCNT-coated fabrics.



1.2 Graphene: Among the most extensively researched carbon nanoparticles (CNPs) is graphene, which serves as the fundamental structure for a variety of carbon allotropes, often referred to as graphenoids? These include nano rings, single-walled, double-walled, and multi-walled nanotubes, graphite, carbon fibres, and graphyne (Lu and Li, 2013; Tiwari *et al*., 2016) [68, 112].

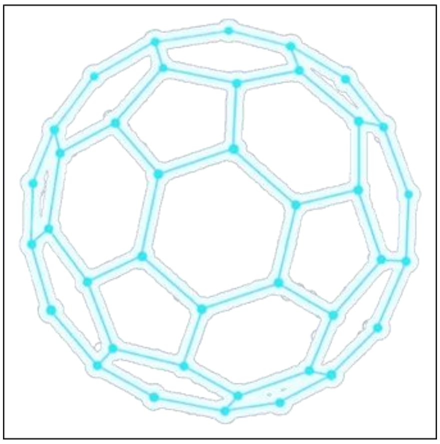
Graphene's high thermal and electrical conductivity makes it ideal for smart textiles in thermal management. It can be applied as fibre fillers or surface coatings, with scalability improving as costs drop. Challenges like durability and integration with current textile tech remain. Future opportunities lie in combining graphene with other 2D materials (Ge *et al*., 2022) [33]



1.3 Fullerene

C60 fullerene, or buckyball, is a carbon allotrope with a soccer ball-like structure formed by single and double bonds in a truncated icosahedron consisting of 12 pentagonal and 20 hexagonal faces. It has a diameter of about 0.71 nm and a molecular weight of approximately 720 atomic mass units (Xu *et al*., 2020) [119]. Meanwhile, fullerene-C60 (C60) nanoparticles served as nano fillers due to the unique spherical structure with a nano sized diameter to reinforce the polymer matrix (Bai *et al*., 2017; Wang *et al.*, 2019) [13, 116]. Compared to CNTs and GNPs, the presence of C60 nanoparticles improved both corrosion resistance and mechanical properties (Liu *et al.*, 2016) [66].

(Zhang *et al*., 2021) revealed RGO/C60@CF fabric with ion sensing ability was developed using industrial methods. The material showed high sensitivity to ions due to fullerene's dispersion interactions, even at low concentrations (1 mmol/L). It remained effective after repeated bending, proving flexibility. This study supports future development of smart, flexible ion sensors.



2. Inorganic Nanoparticles

Inorganic nanoparticles are highly stable and hydrophilic when compared to organic nanomaterials (Paul and Sharma, 2020) [84]. Inorganic nanoparticles do have intrinsic outstanding physicochemical properties (magnetic, thermal, optical, and catalytic performance) and therefore, these nano sized materials offer a sturdy framework where two or more dopants can be integrated to give multifunctional abilities (Liong *et al.*, 2008; Zhou *et al.*, 2020; Zhang *et al.*, 2012; Zhang *et al.*, *2013*) [65,125,122,123].

2.1 Metallic Nanoparticles

Noble metals such as gold, silver, and platinum, renowned for their beneficial effects on health, are frequently employed in the synthesis of metallic nanoparticles (Bhattacharya and Mukherjee, 2008) [17]. Currently, there is a growing focus among researchers on the development of metal nanoparticles, nanostructures, and nanomaterials due to their distinctive properties, which make them highly advantageous for various applications, including catalysis (Narayanan and Sayed, 2004) [81], polymer-based composites (Moura *et al*., 2017) [79], disease diagnosis and therapeutic treatments (Banerjee *et al*., 2017) [14], sensor technologies (Gomez-Romero, 2001; Shaikh *et al*., 2016) [36, 100], and the labelling of optoelectronic media (Gracias *et al*., 2000) [37].

New functionalities in textiles which incorporate metallic NPs include self-cleaning characteristics (ZnONPs and TiO2NPs) (Zhu *et al.*, 2017; Tung *et al.*, 2011) [126, 113], hydrophobicity (SiO2NPs and ZnONPs) (Yetisen *et al.*, 2016; Montazer, M.; Harifi, 2018; Rivero and Urrutia, 2015) [4, 75, 91], antibacterial properties (AgNPs, CuONPs, ZnONPs, and TiO2NPs) (Yetisen *et al.*, 2016; Dastjerdi, R.; Montazer, *et al.*, 2010; Zhang *et al.*, 2016) [4, 21, 124] UV blocking activity (TiO2NPs, ZnONPs, CeO2NPs, and Al2O3NPs) (Yetisen *et al.*, 2016; Montazer, M.; Harifi, 2018) [4, 75], and electromagnetic wave shielding (Cu-, Ni-, Fe-, and Co-based NPs) (Montazer, M.; Harifi, 2018) [75], among others.

2.2 Metal Oxide Nanoparticles

Metal oxide nanoparticles (MONPs) are among the most widely utilized nano particles due to their exceptional properties, which include distinctive optical characteristics, enhanced ductility at elevated temperatures, cold welding tendencies, superparamagnetic behavior, and remarkable catalytic activity. These unique attributes have positioned metal oxide nanoparticles as promising solutions for tackling dye pollution challenges. Their specialized characteristics make them highly effective in addressing dye contamination in aqueous environments (Suhaimi *et al.*, 2022) [105].

In a study by Rajendra *et al*. (2010) [87], a straightforward method was developed to coat cotton fabric with nano-Zinc Oxide (ZnO), endowing it with robust antimicrobial properties. The nano-ZnO particles demonstrated significantly superior antibacterial activity, particularly against *Staphylococcus aureus*, when compared to bulk ZnO. Scanning Electron Microscopy (SEM) confirmed the successful entrapment of the nanoparticles within the fabric. The durability of the antimicrobial effect was found to be dependent on both the particle size and concentration. This technique holds substantial potential for enhancing hygiene-related textiles.

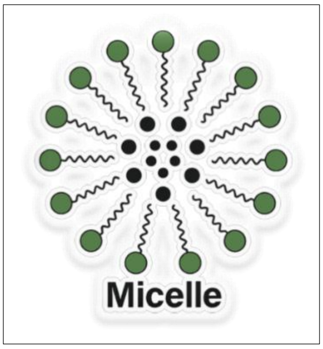
2.3 MXenes

Two-dimensional (2D) nanomaterials have garnered significant attention due to their multifunctional properties, making them valuable across a broad spectrum of scientific disciplines, including functional electronics, catalysis, supercapacitors, batteries, and energy materials. The general formula for MXenes is expressed as Mn+1AXn, where M represents a transition metal, A denotes a main-group element (typically from groups IIIA or IVA), and X refers to carbon or nitrogen, with n being 1, 2, or 3 (Gong *et al.*, 2021; Ihsanullah, 2020) [54, 46].

Applications of MXenes-based materials in textiles are diverse and include energy storage textiles, flexible sensors, flexible displays, thermal management textiles, and health monitoring smart textiles (Ahmed and Sharma, 2022)[1].

4 Organic Nanoparticles

Organic nanoparticles are diminutive particles composed of aggregated molecules or polymers. These materials have attracted considerable interest due to their simple fabrication processes and the diverse range of structures that can be synthesized (Liu *et al.*, 2010) [67]. The use of organic nanomaterials in textiles aligns with the increasing demand for environmentally sustainable solutions. These nano particles offer essential benefits, such as enhanced resistance to environmental stressors, improved durability, and the ability to respond swiftly to external stimuli (Fernandes *et al.*, 2022; Fu and Yao, 2001) [30, 31].

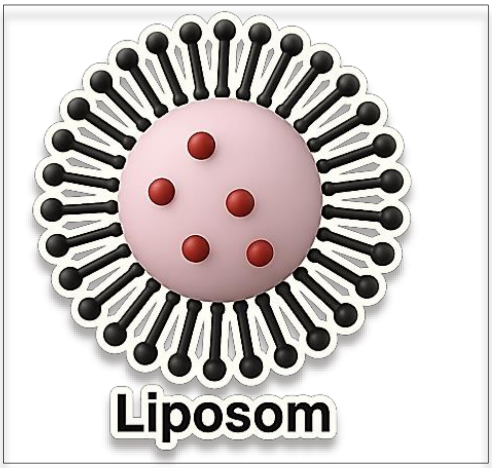


4.1 Micelles: Are specialized structures formed by the self-assembly of lipid molecules into spherical monolayers. These lipid molecules are amphiphilic, meaning they possess both a hydrophilic (water-attracting) polar head group on the exterior and hydrophobic (water-repelling) fatty acid chains on the interior. This unique molecular structure allows micelles to encapsulate various substances,

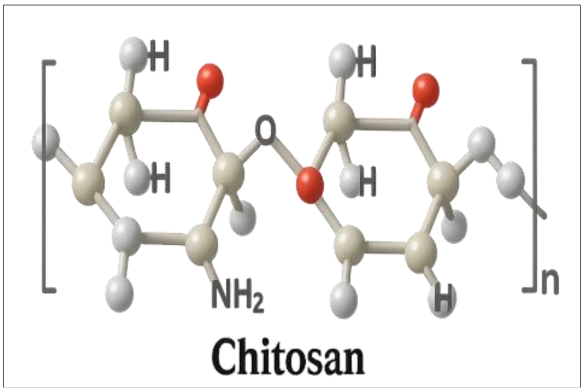
such as drugs, within their hydrophobic core, while their hydrophilic outer surface enables interaction with aqueous environments (Dakal *et al*., 2016; Singh *et al*., 2017) [108, 62].
In the field of nanomedicine, micelles are widely employed due to their ability to enhance the stability of encapsulated drugs, prevent premature dissociation, and provide controlled release. This capability significantly improves the pharmacokinetics of medications, allowing for a more targeted accumulation at specific sites in the body, thereby increasing their therapeutic effectiveness while reducing side effects. The unique properties of micelles, such as their ability to encapsulate both hydrophobic and hydrophilic substances, make them invaluable for delivering a wide range of therapeutic agents in medical applications.

4.2 Liposomes: Are spherical structures composed of lipid bilayers, which form an internal aqueous core distinct from their external environment. These vesicles typically range in size from 80 to 300 nanometers. Notable for their remarkable properties, liposomes offer enhanced solubility, rapid metabolism, and a high degree of biocompatibility. Furthermore, they are non-toxic and biodegradable, making them particularly suitable for a variety of medical and pharmaceutical applications (Thakuria *et al*., 2021) [109].

4.3 Dendrimers
Are highly branched polymeric nanoparticles (PNPs), characterized by a central core, multiple layers of repeating units known as Dendron's, and an array of surface functional groups. These intricate structures allow dendrimers to offer a variety of useful properties, making them ideal for applications in fields like drug delivery and nanomedicine. As illustrated in Figure the diverse types of organic nanoparticles include (a) micelles, (b) liposomes, (c) dendrimers, and (d) solid lipid nanoparticles (Wilczewska *et al*., 2012) [11]



5. Chitosan
Chitosan is a biopolymer derived from the deacetylation process of chitin, a naturally abundant polymer found in the shells of crustaceans. Due to its remarkable solubility, along with its unique chemical and biological properties, chitosan has become a versatile material with numerous applications in diverse fields. In addition to its biodegradability and biocompatibility, chitosan features a significant number of reactive amino side groups, which enable easy chemical modifications. This ability to modify its structure results in the creation of a wide range of beneficial derivatives, making chitosan highly adaptable for various industrial and biomedical uses (Elamri *et al*., 2023) [28].
Among biomaterials, chitosan stands out due to its outstanding attributes, such as biodegradability, biocompatibility, and antimicrobial activity. Furthermore, the compounds resulting from the degradation of chitosan are known to be non-toxic, non-allergenic, and non-carcinogenic, making them highly suitable for use in sensitive applications, particularly in the medical and pharmaceutical sectors (Tian *et al*., 2020) [113].



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