

Review

Emerging Progress in Nanotechnological Influence on Polymeric Textile Finishing

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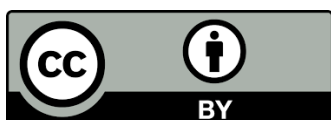
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Abstract

Nanotechnology has revolutionized the textile industry by introducing innovative finishing techniques that enhance the durability and performance of textile materials and the application of nanoscale/nanoparticles/nanomaterials and processes to improve the properties and performance of textiles. The synergism of textile technology and nanotechnological advancements has propelled a paradigm shift, changed the narrative, and formed novel platforms for textile surface engineering at both atomically affiliated and molecular-metric levels, resulting in exceptional enhancements in functionalities, performance, and aesthetic appearance. Escalating advances in nanotechnology have critically influenced evolutions in the textile segment, directly impacting textile finishing. Prospective nanotechnological applications in textile finishes demonstrate an endless



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melimitation in scope and varieties, from intelligent sensors to drug delivery, enhanced fire safety to enhanced water repellency, and to self-repairing and cleaning attributes, resulting in the manufacturing of durable multifunctional textiles for a host of applications. Hence, this paper presents emerging trends of nanotechnology in textile finishes.

Keywords

Nanotechnology; textile nano-finishes; nanoparticles; multifacet applications

1. Introduction

Nanotechnology has revolutionized the textile industry by introducing innovative finishing techniques that enhance the durability and performance of textile materials [1]. Nanotechnology in textile finishing refers to the application of nanoscale/nanoparticles/nanomaterials and processes to improve the properties and performance of textiles, as elucidated in Figure 1, Figure 2, and Figure 3.



Figure 1 Conjugated material-oriented intelligent sportswear (a). Conjugated material-oriented waterproofing sportswear (b). Smart sports shoes and soles are designed with conjugated material (c) and constructed of UV-protected PES fabric (d).

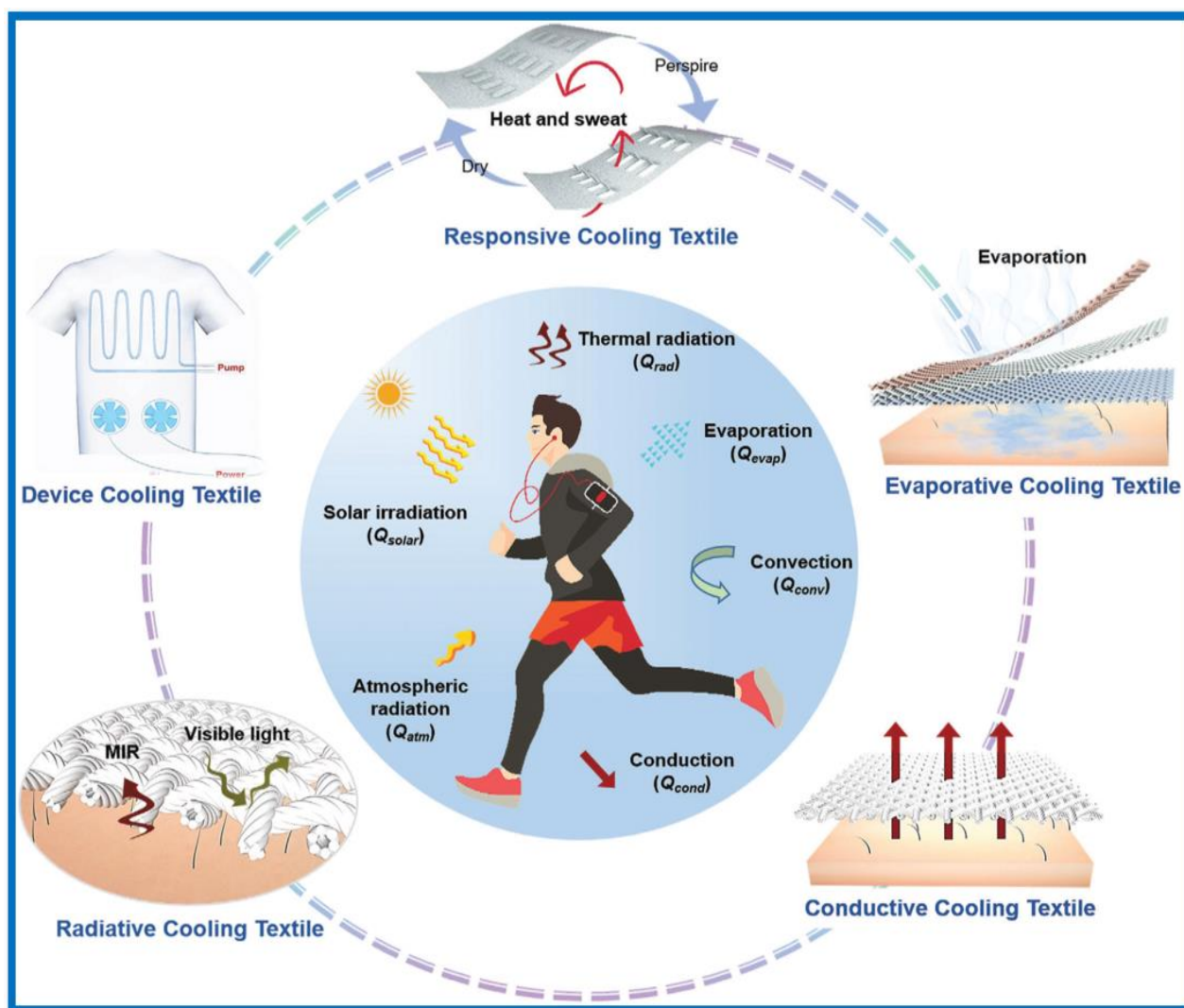


Figure 2 schematic mechanisms for heat transfer of the human body in the exterior environment and five forms of cooling textiles for individual heat management [2].

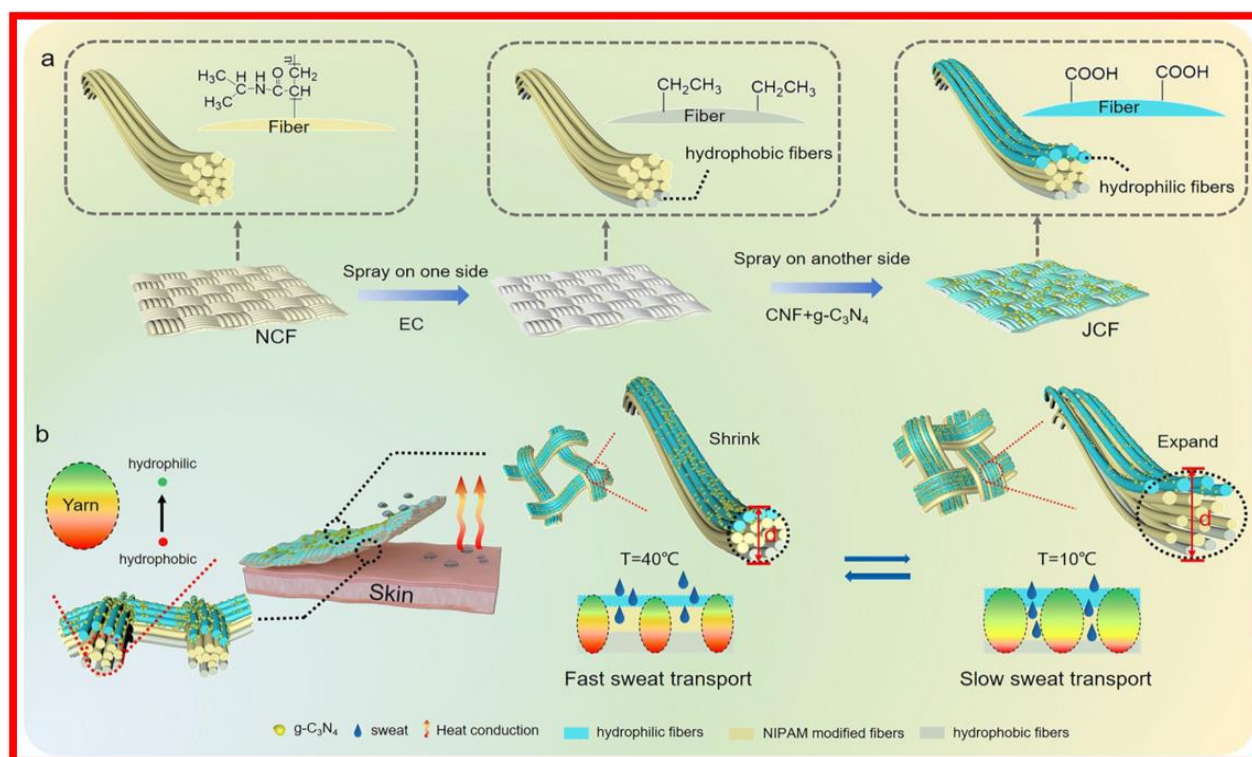


Figure 3 (a) Fabrication of Janus fabrics (JCF) (b) Schematic diagram of the smart fabric with Janus wettability for personal moisture and thermal management [3].

This emerging field combines nanotechnology and textile technology to create innovative finishes that enhance the functionality, sustainability, and aesthetic appeal of textiles [4].

Figure 1a-d depicts the proposed intelligent sportswear PES material. The main sample utilized in this study is a polyester (PES) fabric. Nanoparticle conjugates are finely embedded within the PES matrix for optimal effectiveness. The NMs have been selected based on their special features [4].

Nanocoatings can provide enhanced resistance to wear, tear, and fading. Nanocoatings and nanoparticles offer excellent resistance to washing and drying. Nanotechnologically, nanometric materials including nanoparticulates and nanocoatings are applied to textiles to imbue them with parameters such as stain inhibition, water hindrance, and dynamical color variation (Figure 2) [2].

One significant area of focus is the improvement of wash durability, which is critical for maintaining the quality and lifespan of textiles [2]. Textile materials are subjected to various physical and chemical stresses during washing, leading to degradation and loss of performance. Traditional finishing methods often rely on chemical treatments that can compromise the durability and sustainability of textiles. Nanotechnology offers a promising solution by incorporating nanoparticles and nanostructures to enhance wash durability [5]. Nanotechnology finishing employs various mechanisms to improve wash durability (Nano-coating, nano-encapsulation, and nano-composite). In nano-coating, thin layers of nanoparticles, such as silicon dioxide or titanium dioxide, are applied to the textile surface, creating a barrier against water and detergent penetration [3]. In nano-encapsulation, active agents, like fabric softeners or antimicrobial agents, are encapsulated in nanoparticles, ensuring controlled release during washing. In contrast, in nanocomposites,

nanoparticles are integrated into textile fibers, enhancing mechanical strength and resistance to abrasion.

In a study, graphitic carbon nitride (g-C₃N₄) was embedded within the hydrophilic side to incorporate the fabric with UV shielding protective and photodynamic antibacterial features (Figure 3) [3].

This smart cellulose-oriented Janus fabric with manipulated sweat mobility speed, UV protection, and antibacterial features can undergo application to human moisture management during instant temperature variation. The pore dimension of fabric is paramount for sweat mobility (Figure 4a). Also, as EC and CNF are decorated on the yarn surface, the overall pore architecture of the fabric was generally not changed (Figure 4b-d). Simultaneously, there is increment in the fiber surface roughness on the hydrophilic surface (Figure 4e-g) [3].

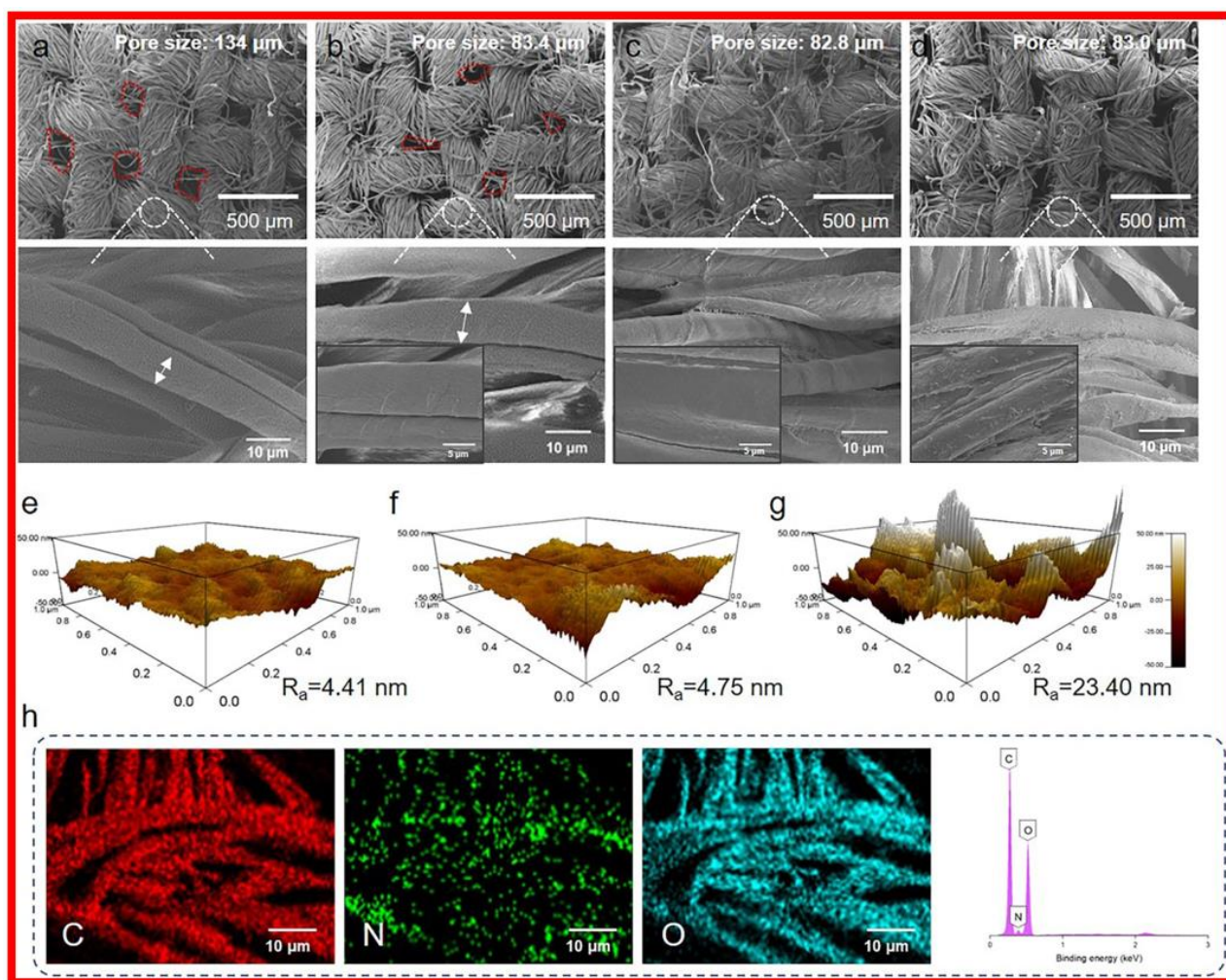


Figure 4 SEM image of (a) CF, (b) NCF, (c) hydrophobic side of JCF, and (d) hydrophilic side of JCF. The fiber surface roughness on (e) NCF, (f) JCF-without C N and (g) JCF hydrophilic side. (h) Element mapping image and EDS spectra of JCF hydrophilic side [3].

The application of nanotechnology finishing techniques has several benefits for wash durability such as improved resistance to shrinkage where nanocoatings reduce fiber contraction, maintaining textile dimensions; enhanced color fastness where nanoparticles prevent dye migration, minimizing color fading; increased soil resistance where nano-structured surfaces reduce soil accumulation,

easing washing; reduced pilling where nanofibers improve fabric smoothness, minimizing pilling and antimicrobial properties where nanoparticles inhibit microbial growth, reducing odor and stain formation [6, 7].

Numerous studies demonstrate the effectiveness of nanotechnology finishing in enhancing wash durability. A study has shown that nano-coated cotton fabrics exhibited 30% less shrinkage and 25% improved color fastness after 20 wash cycles. Another research found that nano-encapsulated fabric softeners reduced fabric stiffness by 40% after 10 wash cycles. Another study demonstrated that nano-composite polyester fabrics exhibited 20% increased tensile strength and 15% reduced pilling after 50 wash cycles [8].

However, despite the benefits, nanotechnology finishing faces challenges such as scalability and cost-effectiveness whereby industrial-scale production and cost reduction are essential in standardization, whereby development of standardized testing methods for wash durability is essential. This is also paramount in environmental impact whereby assessment of the ecological implications of nanomaterials is imperative [9].

Nanotechnology finishing has significantly improved the wash durability of textile materials. By understanding the mechanisms and benefits of nanotechnology finishing, the textile industry can develop sustainable and high-performance materials. Addressing challenges and exploring future directions will further enhance the impact of nanotechnology on wash durability. Therefore, this chapter elucidates recently emerging trends in nanotextile finishes and applications.

2. Organic Nanoparticles Used for Durable Textile Finishes

Here are some organic nanoparticles used for durable textile finishes, along with their properties and applications:

2.1 Cellulose Nanocrystals (CNCs)

CNCs' properties include biodegradable, renewable, high strength, stiffness, and thermal stability. Applications include sustainable textile coatings, improved tensile strength, and thermal resistance [10]. In a study, CNCs isolation from sterilized waste cotton clothing was performed via alkali pulping, bleaching, and acid hydrolysis, as shown in Figure 5. Pulping was conducted by eliminating lignin by positioning sterilized waste cotton cloths in 10 wt.% sodium hydroxide (NaOH) solution at a ratio of 1:20 whereby the mixture underwent heating at 80°C for 3 h [10].

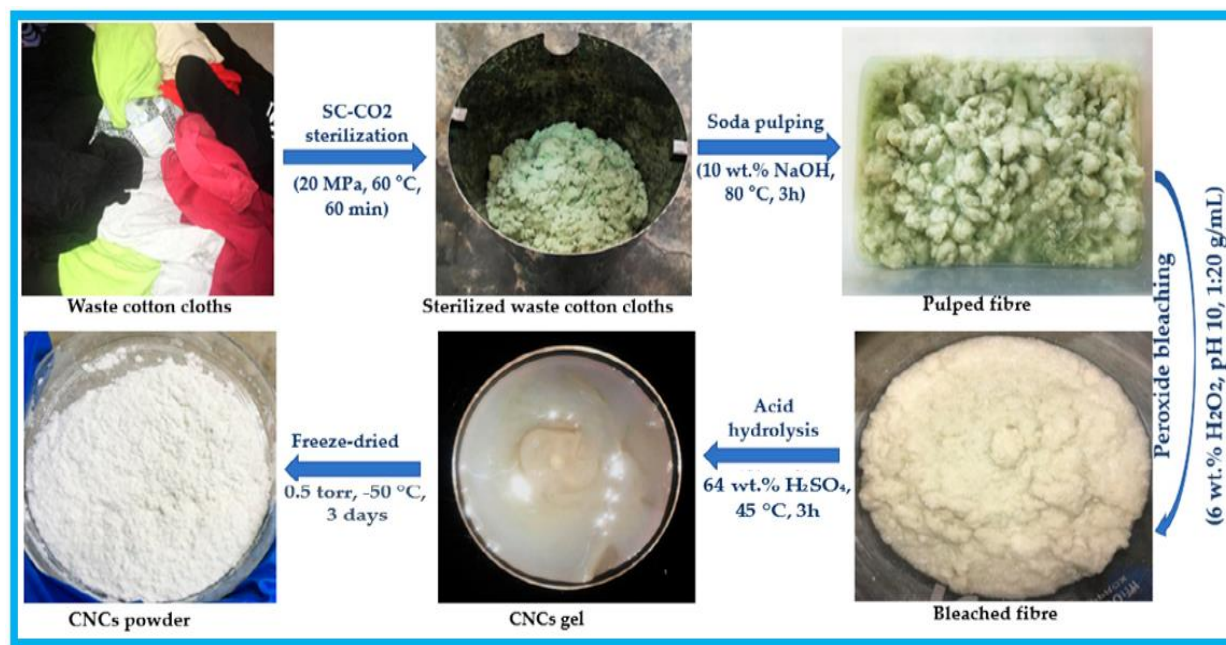


Figure 5 A schematic elucidation of CNCs from waste cotton clothes [10].

The surface morphological images of isolated CNCs were obtained using energy-filtered transmission electron microscopy (EF-TEM), as displayed in Figure 6.

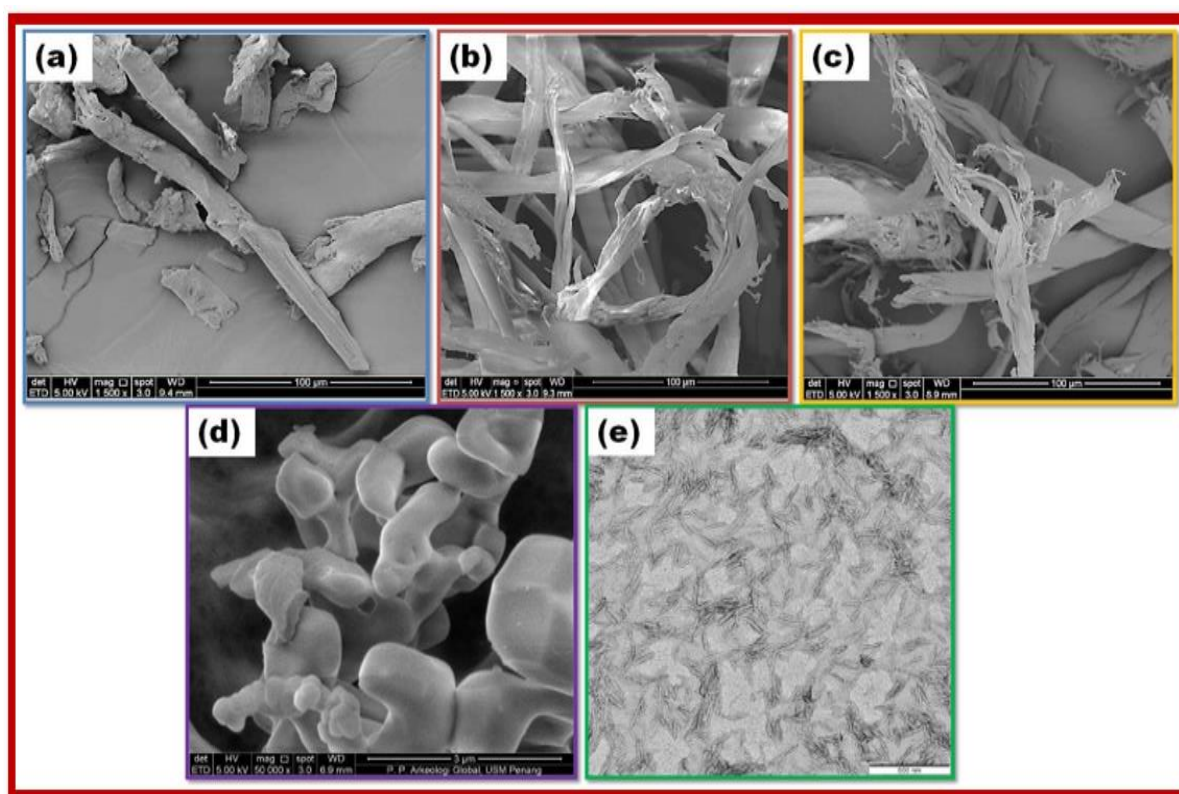


Figure 6 Field emission scanning electron microscope images of (a) waste cotton cloths, (b) pulped fiber, (c) bleached fiber, (d) isolated CNCs, and (e) an energy-filtered transmission electron microscopy image of CNCs.

2.1.1 Chitosan Nanoparticles (CNs)

Properties of CNs include antimicrobial, antifungal, biodegradable, and non-toxic, with applications in antimicrobial textile finishing, wound dressing, and biomedical applications [11].

In a study, chitosan nanoparticles (CSNPs) were fabricated by the ionic gelation route utilizing chitosan (0.2 wt.%) treatment with tripolyphosphate (0.2 wt.%) ultrasonically for 45 min (Figure 7). FT-IR spectroscopy and TEM images were used in characterizing and validating CSNP fabrication. Cellulosic materials with differing concentrations of CSNPs exhibited improved antibacterial and coloring features [11].

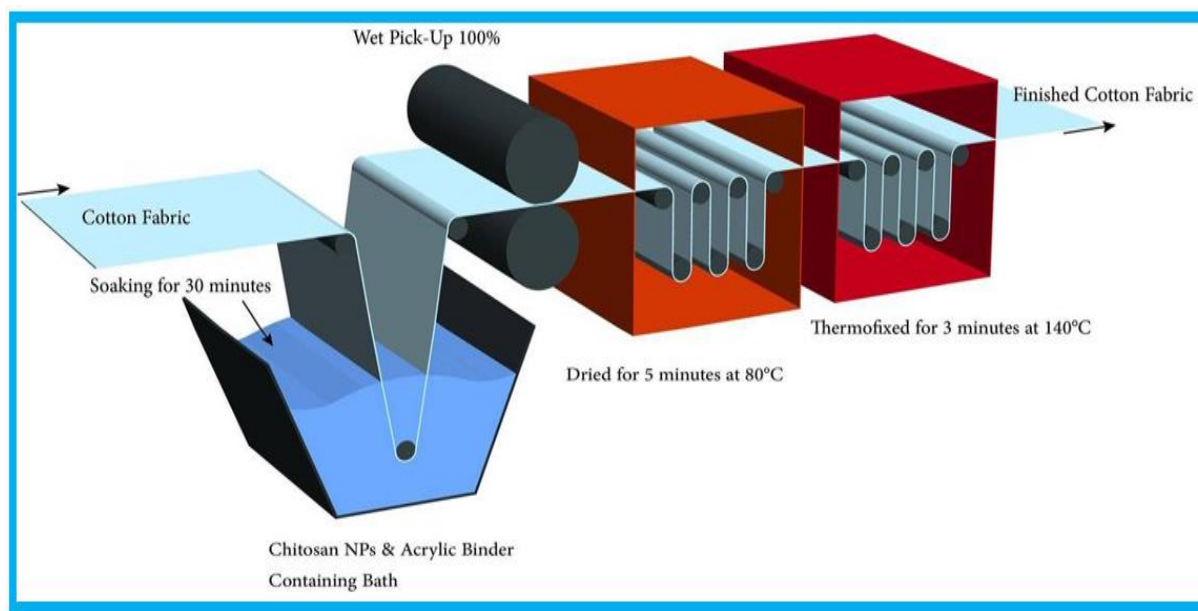


Figure 7 Finishing cellulosic fabrics with chitosan nanoparticles via pad-dry-cure process [11].

Figure 8a depicts a TEM image of constructed chitosan nanoparticles using a chitosan concentration of 0.2 wt.% and 0.1 wt.% TPP for 45 min at a pH value of 5.5.

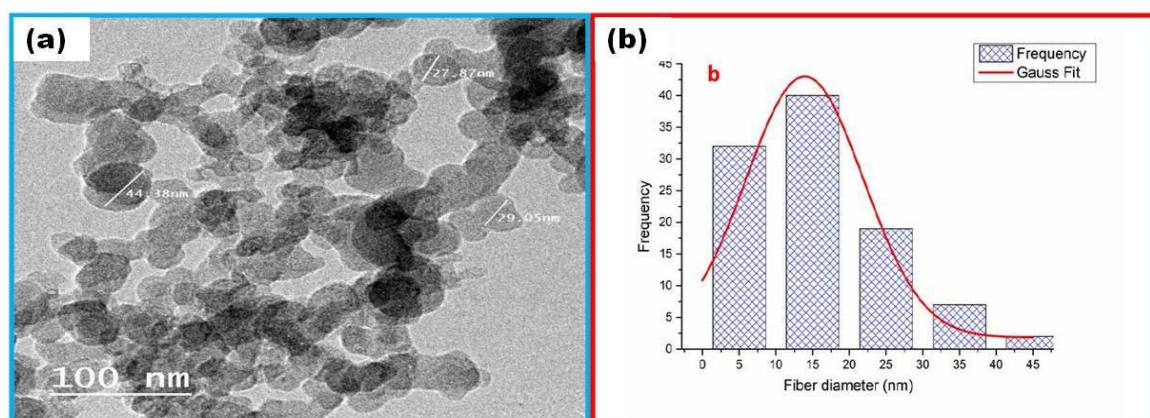


Figure 8 TEM image (a); histogram of the particle size distribution of synthesized chitosan nanoparticles (CSNPs) using a chitosan concentration of 0.2 wt.% and 0.1 wt.% TPP for 45 min of ultra-sonication and a pH value of 5.5 (b).

In acidic media, chitosan (CS) displayed cationic features due to the conversion of NH_2 to NH_3^+ . CS cationic behavior enabled bacterial cell wall permeation, efficiently degrading them [12-14]. Furthermore, CS has a similar impact on fungi. The main CS disadvantage is that it's more active against gram-positive bacteria than against gram-negative bacteria. Hence, CS nanoparticles (CSNPs) may be utilized in addressing this issue as their nanoarchitecture enables their penetration within the microbial (bacterial and fungal) cells, as presented in Figure 9.

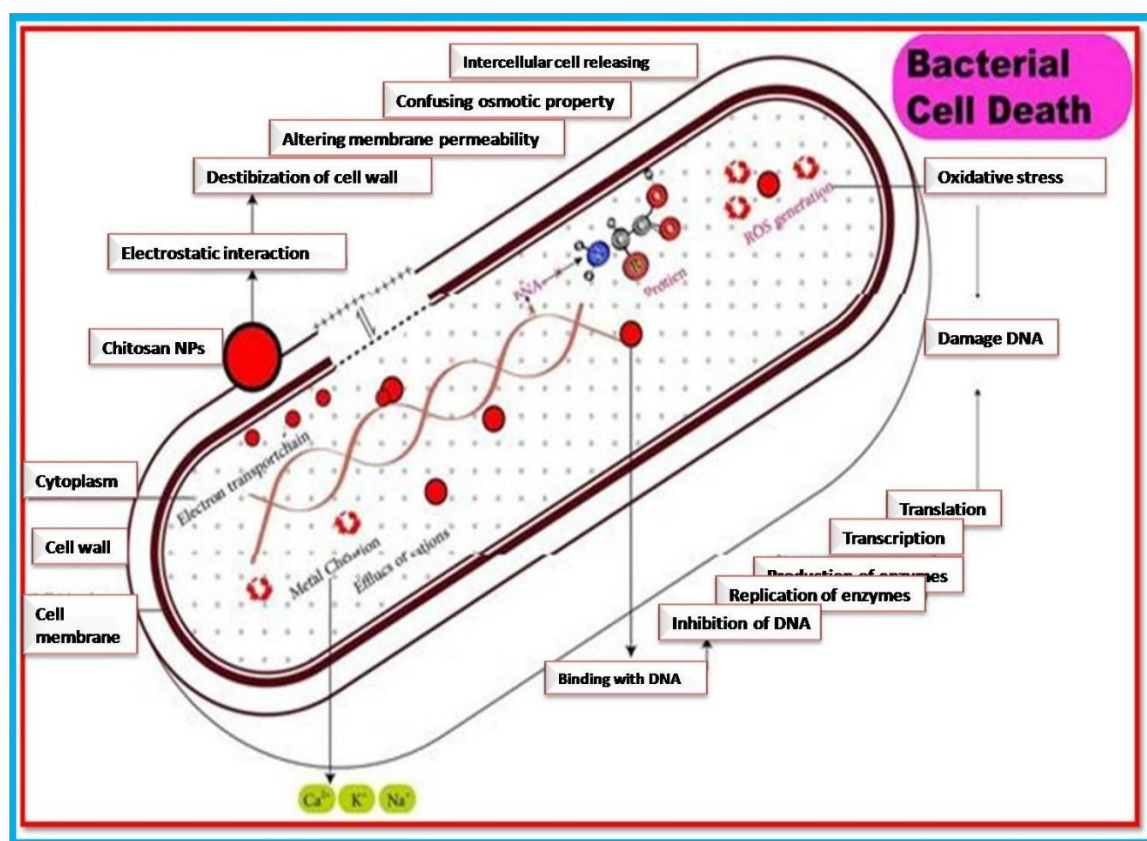


Figure 9 CS nanoparticles antibacterial mechanism [11].

2.1.2 Starch Nanoparticles (SNs)

The properties of SNs include flame retardancy, biodegradability, renewability, and non-toxicity, and applications include sustainable textile coatings, improved tensile strength, and water resistance. Starch-based nanoparticles have been utilized as durable water repellent and flame-retardant cotton fabrics [15].

2.1.3 Alginate Nanoparticles

Properties of alginate nanoparticles include biodegradability, non-toxicity, and hydrophilicity. Applications of alginate nanoparticles include antimicrobial textile finishing, wound dressing, and biomedical applications [16].

2.1.4 Gelatin Nanoparticles

Properties of gelatin nanoparticles include biodegradability, non-toxicity, and hydrophilicity. Applications include sustainable textile coatings, improved tensile strength, and water resistance [17].

2.1.5 Silk Fibroin Nanoparticles

Properties include biodegradability, non-toxicity, and hydrophilicity, and are applied as antimicrobial textile finishing, wound dressing, and biomedical applications [18].

2.1.6 Zein Nanoparticles

Properties of zein nanoparticles include biodegradability, non-toxicity, and hydrophobicity. Applications include sustainable textile coatings, improved tensile strength, and water resistance. Generally, these organic nanoparticles offer a promising alternative to traditional textile finishing methods, providing sustainable, biodegradable, and non-toxic solutions for various textile applications [19].

2.1.7 Plant-Based Polyphenol Nanoparticles

Applications include antimicrobial, anti-odor, and antioxidant finishes [20].

Essential Oil-Loaded Nanoparticles. Applications include antimicrobial, anti-odor, and insect repellent finishes. Essential oil-loaded nanoparticles have been applied to fabrics, demonstrating antimicrobial and insect repellent properties [21].

Newly emerging organic nanoparticles for durable textile finishes include zinc oxide phyto-nanoparticles applied for UV protection, antimicrobial, and self-cleaning finishes. ZnO nanoparticles synthesized using plant extracts were applied to cotton fabrics, exhibiting enhanced UV protection and antimicrobial properties. Another is curcumin nanoparticles used for antimicrobial, anti-inflammatory, and UV protection finishes. Quercetin nanoparticles are antioxidant, antimicrobial, and anti-odor finishes [22].

Chitin nanocrystals are utilized in water repellency, mechanical reinforcement, and biodegradability finishes. Lignin nanoparticles are used as antimicrobial, antioxidant, and UV protection finishes. Ginsenoside nanoparticles also include emerging organic nanoparticles used for antimicrobial, anti-inflammatory, and skin regeneration finishes [23].

Catechin nanoparticles are utilized as antioxidant, antimicrobial, and anti-odor finishes. Silymarin nanoparticles are antioxidant, antimicrobial, and anti-inflammatory finishes. Ferulic acid nanoparticles are antioxidant, antimicrobial, and anti-odor finishes. Hyaluronic acid nanoparticles are utilized in moisture management, skin regeneration, and wound healing finishes [24].

Other newly emerging organic nanomaterials for durable textile finishes are anthocyanin nanoparticles (antimicrobial, antioxidant, and UV protection finishes), Gellan gum nanoparticles (moisture management, skin regeneration, and wound healing finishes) [25]. Cinnamon essential oil nanoparticles are available for (antimicrobial, anti-inflammatory, and insect repellent finishes) [26].

Pomegranate extract nanoparticles (antioxidant, antimicrobial, and anti-odor finishes), sodium alginate nanoparticles (water repellency, mechanical reinforcement, and biodegradability finishes),

Green tea extract nanoparticles (antioxidant, antimicrobial, and anti-inflammatory finishes), chondroitin sulfate nanoparticles, and neem oil nanoparticles used as insect repellent, antimicrobial, and anti-inflammatory finishes [27-31]. Others are guar gum nanoparticles (water repellency, mechanical reinforcement, and biodegradability finishes), and bergamot essential oil nanoparticles (antimicrobial, anti-inflammatory, and insect repellent finishes) [32, 33].

3. Challenges of Organic Nanoparticles Usage

Toxicity and safety concerns are challenging, as the potential toxicity of inorganic nanomaterials to humans and the environment is hazardous. Another is scalability and cost-effectiveness, whereby elevatable production costs and scalability issues for large-scale textile applications are prominent. Stability and durability are notable parameters. Here, maintaining nanomaterial stability and durability during textile processing and use is imperative. Interfacial interactions: It is essential to ensure strong interactions between nanomaterials and textile fibers. Finally, regulatory frameworks are lacking due to a lack of clear regulatory frameworks for nanomaterials in textiles, which induces a lack of control and inherent effects [34, 35].

3.1 Limitations of Organic Nanoparticles

Limited solubility relative to inorganic nanomaterials is notable as it may have limited solubility in water or organic solvents. This is akin to aggregation and agglomeration as the tendency of nanomaterials to aggregate or agglomerate, which reduces effectiveness.

Photo-stability is another parameter as inorganic nanomaterials may degrade or change properties under UV exposure. Chemical resistance is the limited chemical resistance of inorganic nanomaterials to acidic or alkaline environments. Recyclability is another parameter due to the difficulty in recycling textiles with integrated inorganic nanomaterials [36, 37].

3.1.1 Environmental Challenges

Nanoparticle release into the environment during textile production or use is an issue. Water pollution relative to inorganic nanomaterials which may contaminate water sources during textile processing is an issue. Soil pollution is challenging as nanomaterials may accumulate in soil and affect plant growth [38, 39].

3.1.2 Health Challenges

Skin irritation is challenging due to potential skin irritation or allergic reactions to inorganic nanomaterials. Respiratory issues are challenging as inhalation of nanoparticles may cause respiratory problems. Carcinogenicity is an issue due to the potential carcinogenic effects of specific inorganic nanomaterials [40].

3.1.3 Future Research Directions

Green synthesis methods are due to the development of environmentally friendly synthesis methods. Biocompatibility and toxicity studies are imperative relative to the investigation of the biocompatibility and toxicity of inorganic nanomaterials [41]. Scalable and cost-effective

productions are imperative: Improving the scalability and cost-effectiveness of nanomaterial production. Nanomaterial functionalization relative to the enhancement of nanomaterial features through functionalization. Regulatory framework development relative to establishing clear regulatory frameworks for nanomaterials in textiles is critical.

By addressing these challenges and limitations, researchers and industry professionals can develop more sustainable and effective inorganic nanomaterial-based textile finishes.

4. Inorganic Nanoparticles for Durable Nanotextile Finishes

The textile industry has witnessed significant transformations in recent years, driven by the increasing demand for high-performance, functional, and sustainable materials. Nanotechnology has emerged as a key enabler of this transformation, with inorganic nanoparticles playing a crucial role in nanotextile finishing [42]. Nanotextile finishing refers to treating textiles with nanoparticles to impart specific functional properties, such as water repellency, antimicrobial activity, and UV protection. There has been an increase in carbon nanomaterials (CNMs) integration within emerging research, especially within the textile segment, to improve performance and prospects of versatility in application, notably. This insight broadens the essence of embedding three notable carbon-oriented nano-reinforcements relative to carbon nanotubes (CNTs), carbon black (CB), and graphene (GN)-into polyamide 6 (PA6) multifilament yarns (Figure 10) [43].

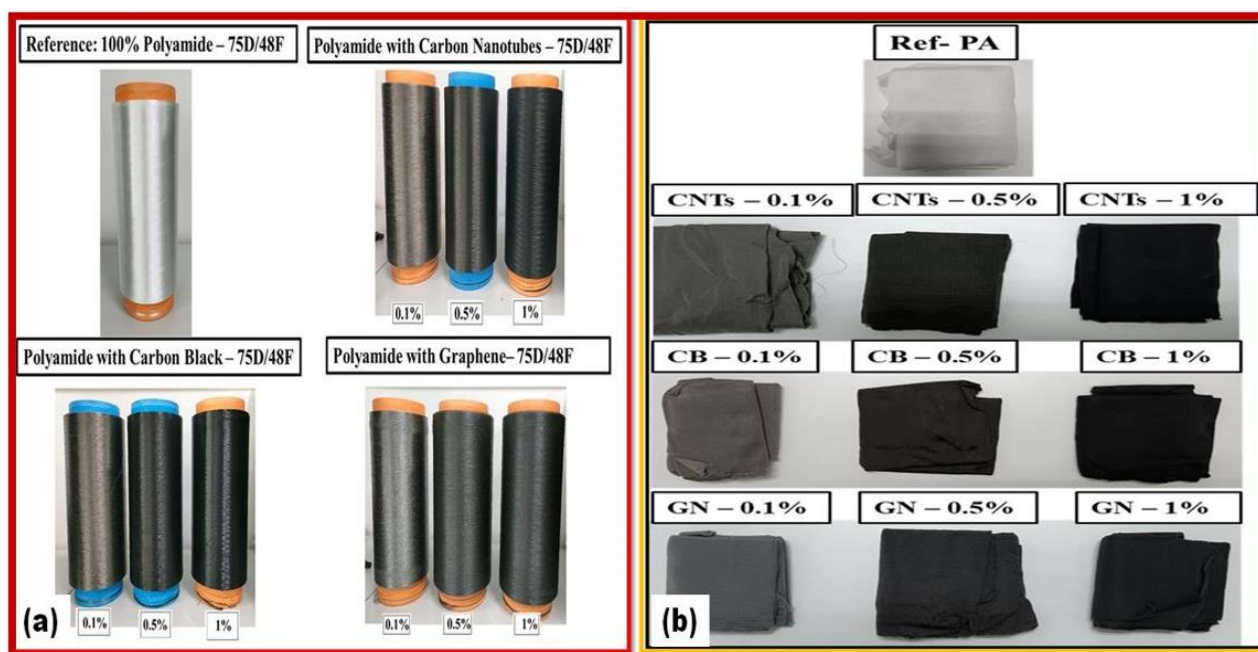


Figure 10 Extruded melt-spun multifilament yarns (a). Developed fabric samples (b) [43].

This investigation offers in-depth insight into the transformative effect of including CNT, CB, and GN within polyamide (PA6) yarns and fabrics, notably varying their mechanical, thermal, and optical features. Garnered results showcase that the form and the concentration of nano-reinforcement play a significant role in describing these material features, affecting tenacity, elongation, heat stability, optical features, and heat management [43].

Inorganic nanoparticles, including metal oxides, silicates, and carbonates, have gained significant attention recently due to their unique properties and versatility. Inorganic nanoparticles have been widely used in nanotextile finishing achieving various functional properties. Some of the key applications include [44-53].

Water repellency as metal oxide nanoparticles, such as titanium dioxide (TiO_2) and zinc oxide (ZnO), have been used to impart water repellency to textiles. These nanoparticles create a hydrophobic surface that repels water, making them ideal for applications such as waterproof clothing and upholstery.

Antimicrobial activity, such as silver nanoparticles (AgNPs), has been widely used in nanotextile finishing to impart antimicrobial activity to textiles. AgNPs have been shown to exhibit broad-spectrum antimicrobial activity against bacteria, viruses, and fungi, making them ideal for applications such as medical textiles and sportswear.

UV Protection as zinc oxide (ZnO) nanoparticles has been used to impart UV protection to textiles. ZnO nanoparticles absorb UV radiation, preventing it from penetrating the fabric and causing damage to the skin. Thus, the highly efficient UV-resisting materials were fabricated utilizing polypropylene and TiO_2 (PPTO) via low-cost and facile routes (Figure 11) [45]. 5 PPTO exhibited the highest UV-inhibiting capability (87.5%) compared to 7.5 PPTO and PPNF. Furthermore, 15 PPTO displayed 1.76 and 1.32 times higher protection than 7.5 PPTO and PPNF, respectively, on exposure to UB-B radiation. The improved activity may be ascribed to the level of TiO_2 because TiO_2 increased the product's absorption and reflection prospects. Generally, the PPTO nonwoven fibers are applied to hinder harmful UV radiation (Figure 12).

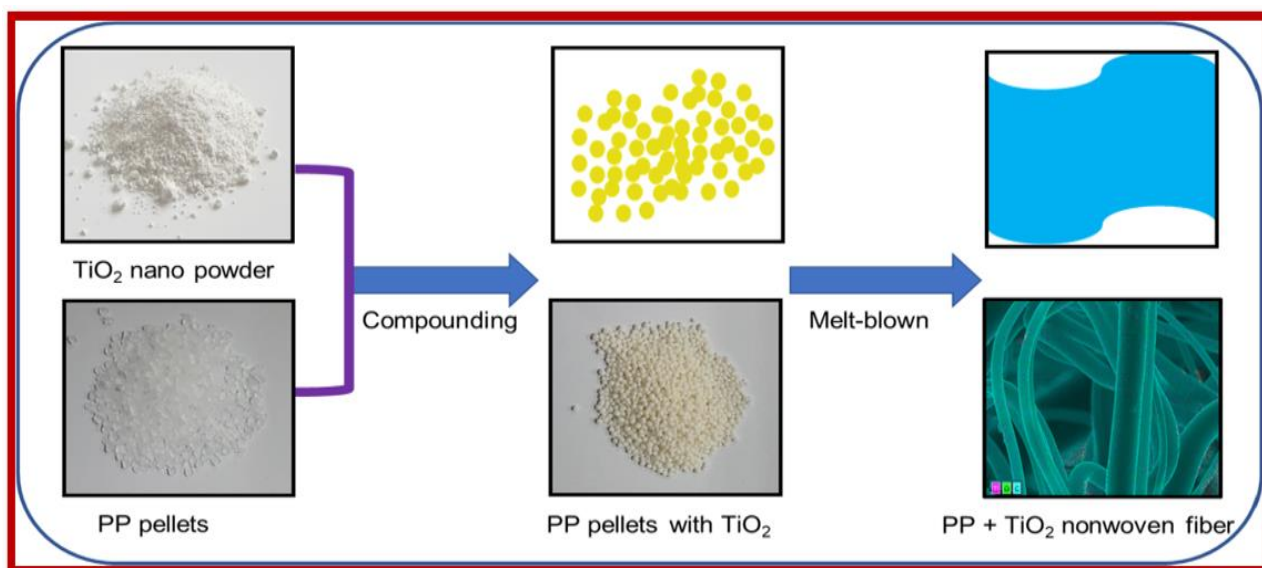


Figure 11 Schematic illustration of the synthesis of polypropylene/ TiO_2 nonwoven fiber [45].

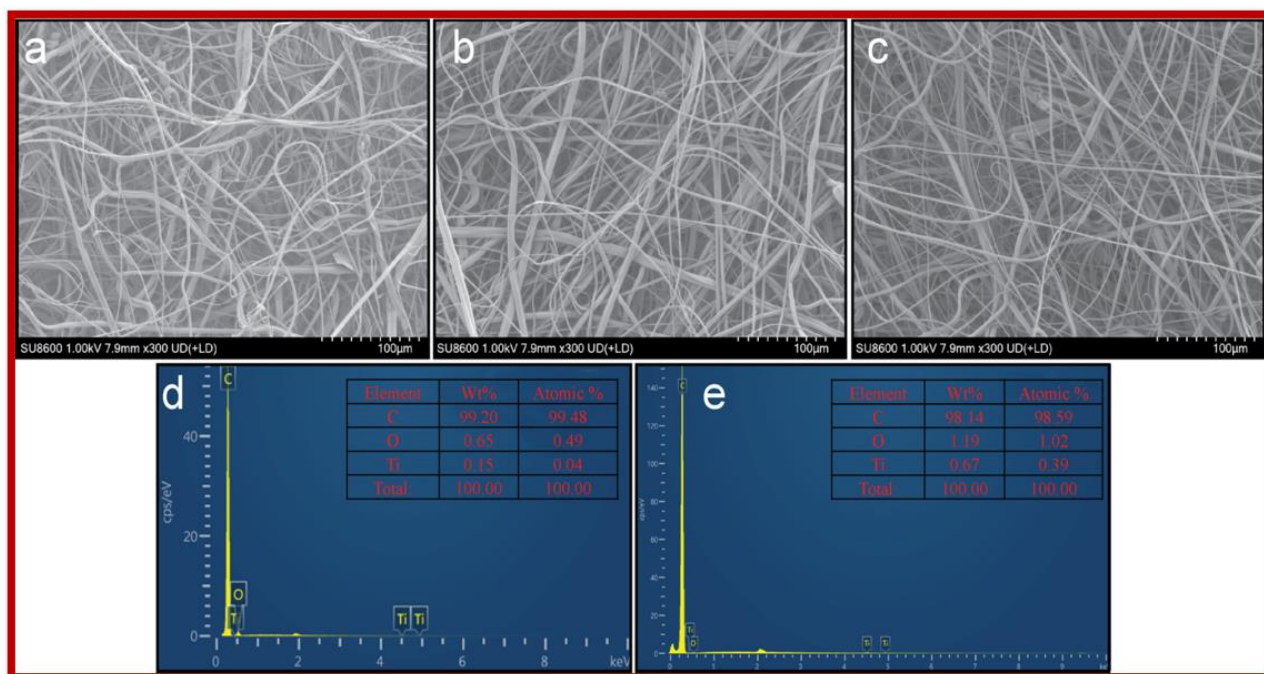


Figure 12 FE-SEM image of (a) PPNF, (b) 7.5 PPTO, and (c) 15 PPTO. EDS spectra of (d) 7.5 PPTO and (e) 15 PPTO [45].

Flame Retardancy as inorganic nanoparticles, such as magnesium hydroxide ($\text{Mg}(\text{OH})_2$) and aluminum hydroxide ($\text{Al}(\text{OH})_3$), have been used to impart flame retardancy to textiles. These nanoparticles release water vapor when heat exposure, cooling the surrounding fabric and preventing ignition. Using inorganic nanoparticles in nanotextile finishing offers several benefits, including: Improved Performance as inorganic nanoparticles can impart specific functional properties to textiles, improving their performance and durability. Sustainability of inorganic nanoparticles can be designed to be sustainable and environmentally friendly, reducing the environmental impact of textile production. Cost-effectiveness as inorganic nanoparticles can be produced at a lower cost than traditional textile finishing agents, making them a cost-effective alternative.

The use of inorganic nanoparticles in nanotextile finishing is expected to grow in the coming years, driven by the increasing demand for high-performance, functional, and sustainable textiles. Some of the prospects of inorganic nanoparticles in nanotextile finishing include:

Development of new nanoparticles as researchers is expected to develop new inorganic nanoparticles with unique properties and functionalities, expanding the range of applications for nanotextile finishing. Scalability and commercialization as the scalability and commercialization of inorganic nanoparticles-based nanotextile finishing technologies are expected to improve, making them more widely available and affordable. Regulatory frameworks governing the use of inorganic nanoparticles in nanotextile finishing are expected to evolve, ensuring the safe and sustainable use of these technologies [12-14, 53-60].

In summary, inorganic nanoparticles for durable textile finishing have emerged as a key component of nanotextile finishing, offering a range of functional properties and benefits. As the demand for high-performance, functional, and sustainable textiles grows, using inorganic nanoparticles in nanotextile finishing is expected to play an increasingly important role. However,

further research is needed to fully realize the potential of inorganic nanoparticles in nanotextile finishing and address the challenges associated with their use as elucidated below. Tungsten oxide (WO_3) nanoparticles are applied for UV protection, self-cleaning, and antimicrobial finishes [61]. Nickel Oxide (NiO) nanoparticles are used in electrical conductivity, thermal regulation, and antimicrobial finishes [62]. Cobalt Oxide (Co_3O_4) nanoparticles are used for magnetic properties, antimicrobial, and UV protection finishes [63].

Zinc Phosphate ($\text{Zn}_3(\text{PO}_4)_2$) nanoparticles are applied for flame retardancy, mechanical reinforcement, and UV protection finishes [64]. Molybdenum Disulfide (MoS_2) Nanosheets are applied in electrical conductivity, thermal regulation, and UV protection finishes [65]. Bismuth Oxide (Bi_2O_3) nanoparticles are applied in antimicrobial, UV protection, and self-cleaning finishes [66]. Silicon carbide (SiC) nanoparticles are applied in mechanical reinforcement, thermal insulation, and UV protection finishes [67]. Tin Oxide (SnO_2) nanoparticles are applied in electrical conductivity, thermal regulation, and UV protection finishes [68]. Cerium Zinc Oxide (CeZnO) nanoparticles are applied for UV protection, antimicrobial, and self-cleaning finishes [69]. Zirconium Oxide (ZrO_2) nanoparticles are applied in mechanical reinforcement, thermal insulation, and UV protection finishes [70]. Graphene oxide (GO) nanoparticles exhibit electrical conductivity, thermal stability, and mechanical strength and are utilized in waterproof, antimicrobial, and self-cleaning textile finishes [71].

Carbon nanotubes (CNTs) have properties of mechanical strength, thermal conductivity, and electrical conductivity. Application areas include durable, waterproof, and self-cleaning textile finishes [72]. Nanocellulose has properties of biodegradability, renewability, and high strength and is applied in sustainable textile coatings, improved tensile strength, and thermal resistance [73]. Nano-silica (SiO_2) has properties of mechanical strength, thermal stability, and water resistance, and is applied for durable, waterproof, and self-cleaning textile finishes [74]. Nano-titanium dioxides (TiO_2) have properties including photocatalytic, self-cleaning, and antimicrobial, and are applied in self-cleaning textile finishes, antimicrobial coatings, and UV protection [75]. Nano-zinc oxide (ZnO) has properties of antimicrobial, UV-blocking, and self-cleaning, and applied antimicrobial textile finishes, UV protection, and self-cleaning coatings [76]. Halloysite nanotubes (HNTs) have properties including mechanical strength, thermal stability, and controlled release and are applied in sustainable textile coatings, improved tensile strength, and thermal resistance [77].

5. Hybrid Synergies of Nanomaterials for Durable Textile Finishes

Nanomaterials (NMs) are capable of prevailing as zero dimensional (0D), one dimensional (1-D), and two dimensional (2-D) nanoscale materials. NMs are referred to as nanoparticles (0D); nano-rods, nanotubes, or nano-wires (1-D); nano-films, nanosheets, or nanoplatelets (2-D) (Figure 13).

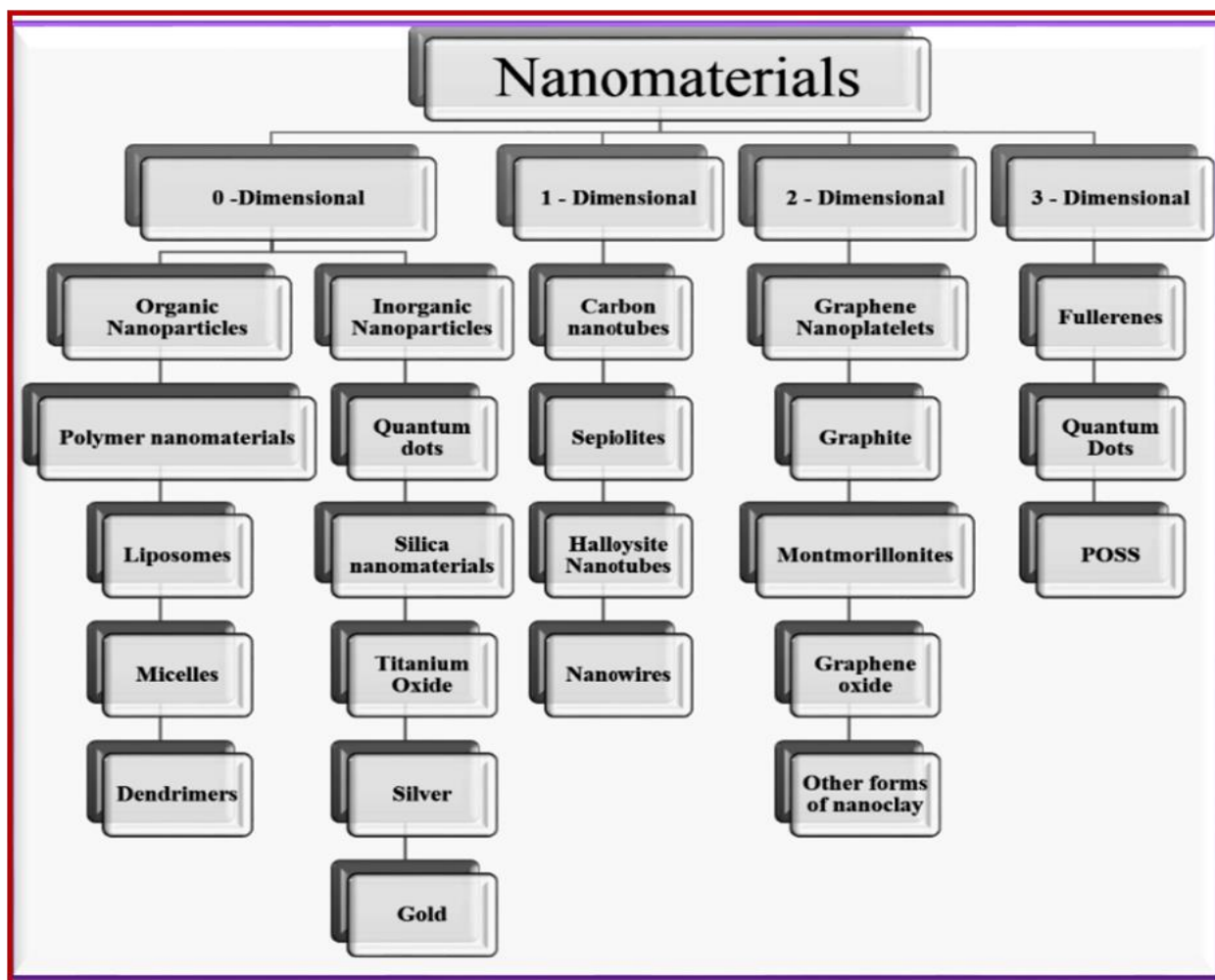


Figure 13 Classifications of NMs.

Hybrid synergies of nanomaterials for durable textile finishes refer to combining different nanomaterials to create textile finishes with enhanced performance, durability, and functionality. This approach leverages the unique properties of individual nanomaterials to achieve synergistic effects, resulting in improved textile characteristics [78]—enhanced durability, as combined nanomaterials can provide improved resistance to wear, wrinkles, and fading. Multi-functional properties as hybrid nanomaterials can offer simultaneous benefits, such as water repellency, antimicrobial activity, and UV protection. Improved sustainability, as some nanomaterials can reduce the environmental impact of textile finishing processes [79].

Nanocellulose adds strength, stiffness, and barrier properties. Nano-silica enhances durability, UV resistance, and antimicrobial activity. Nano-titanium dioxide (TiO₂) offers self-cleaning, UV protection, and antimicrobial properties. Carbon nanotubes improve electrical conductivity, mechanical strength, and thermal stability. Graphene enhances electrical conductivity, mechanical strength, and barrier properties [33-38]. Water repellent textiles, as a combination of nano-silica and fluoropolymers for improved water resistance, have been investigated. Antimicrobial textiles are a hybridization of nano-silver and nano-copper for enhanced antimicrobial activity. UV protective textiles, as a combination of nano-TiO₂ and nano-zinc oxide for improved UV protection, are notable. Conductive textiles: Integrating carbon nanotubes and graphene for electrical conductivity [80]. Smart textiles as hybrid nanomaterials for sensing, energy harvesting, and thermal

regulation have been proven [81]. Scalability and cost-effectiveness are imperative, as developing cost-effective methods for large-scale production is critical. Toxicity and environmental concerns are necessary relative to the assessment of potential risks and the development of eco-friendly nanomaterials. Standardization and regulation, such as establishing standards and rules for hybrid nanomaterial-based textiles, are critical [82-85].

5.1 Instances of Hybrid Synergies of Nanomaterials

Overall, hybrid synergies of nanomaterials offer exciting opportunities for developing durable, high-performance textile finishes with multifunctional properties. Ongoing research and development are needed to overcome challenges and fully realize the potential of these innovative materials. Here are some specific hybrid combinations of nanomaterials for durable textile finishes, along with their benefits and potential applications [86-100]:

Nano-silica/nano-titanium dioxide (TiO₂) hybrid benefits include enhanced UV resistance, self-cleaning, and antimicrobial properties. Applications include outdoor clothing, upholstery, and medical textiles. Nanocellulose/Graphene hybrid benefits include improved strength, stiffness, and electrical conductivity. Applications include Smart textiles, wearable electronics, and biomedical applications. Nano-silver/nano-copper hybrid benefits include enhanced antimicrobial activity against broad-spectrum bacteria and viruses. Application areas include medical textiles, sportswear, and active wear. Nano-zinc oxide/nano-TiO₂ hybrid benefits include improved UV protection, self-cleaning, and antimicrobial properties. Applications include outdoor clothing, sun-protective fabrics, and medical textiles. Carbon nanotube/nano-silica hybrid benefits include enhanced mechanical strength, electrical conductivity, and thermal stability. Applications include smart textiles, wearable electronics, and high-performance composites.

Nanoclay/polyhedral oligomeric silsesquioxane (POSS) hybrid benefits include improved flame retardancy, thermal stability, and mechanical strength. Applications include fire-resistant textiles, aerospace applications, and high-temperature filtration. Graphene oxide/nano-silver hybrid benefits include enhanced antimicrobial activity, electrical conductivity, and sensing capabilities [101]. Applications include smart textiles, wearable electronics, and biomedical sensors. Nano-TiO₂/nano-cellulose hybrid benefits include improved UV protection, self-cleaning, and barrier properties [102]. Applications include packaging materials, paper coatings, and biomedical applications. Nano-silica/fluoropolymer hybrid benefits include enhanced water repellency, durability, and stain resistance [103]. The application includes water-repellent clothing, upholstery, and technical textiles. Carbon nanotube/nano-zinc oxide hybrid benefits include enhanced electrical conductivity, mechanical strength, and UV protection [104]. Applications include smart textiles, wearable electronics, and high-performance composites.

Nanomaterial ratio and dispersion: Uniform dispersion and optimal ratio of nanomaterials. Interfacial interactions are imperative, whereby strong interfacial interactions between nanomaterials are essential. Textile substrate is compatible with textile substrate and finishing processes. Processing conditions as optimization of processing conditions for hybrid nanomaterial deposition is imperative [105-110].

Scalability and cost-effectiveness are critical, as developing cost-effective methods for large-scale production is imperative. Toxicity and environmental concerns, as the assessment of potential risks and the development of eco-friendly nanomaterials, are essential. Standardization and regulation,

as the establishment of standards and rules for hybrid nanomaterial-based textiles, are crucial. These hybrid combinations demonstrate the potential for developing high-performance, durable textile finishes with multifunctional properties. Ongoing research and development are needed to optimize these combinations and address challenges associated with scalability, toxicity, and regulation [111].

Despite the potential benefits of hybrid nanomaterials for durable textile finishes, there are several disadvantages and limitations: High Production Costs: Scalable production methods for hybrid nanomaterials are often expensive. Toxicity Concerns: Potential toxicity of nanomaterials, especially when released during wear and tear. Environmental Impact: Release of nanomaterials into waterways and soil during manufacturing and washing. Interfacial Interactions: Challenges in achieving strong interfacial interactions between nanomaterials.

Dispersion and Aggregation: Difficulty in maintaining uniform dispersion and preventing aggregation. Scalability: Difficulty in scaling up hybrid nanomaterial production while maintaining consistency. Regulatory framework: Lack of clear regulations and standards for hybrid nanomaterial-based textiles. Stability and durability: Potential degradation of hybrid nanomaterials over time. Compatibility with textile substrates: Limited compatibility with certain textile materials. Washing and wear resistance: potential loss of hybrid nanomaterial functionality after washing or wear. Color and appearance: possible changes in color or appearance due to hybrid nanomaterial incorporation. Skin Irritation and allergy: potential skin irritation or allergic reactions. Limited understanding of long-term effects: limited knowledge of long-term effects on human health and the environment. Recyclability and disposal: challenges in recycling and disposing of hybrid nanomaterial-based textiles [112].

Uniform dispersion: Achieving uniform dispersion of hybrid nanomaterials. Interfacial Adhesion: ensuring strong interfacial adhesion between nanomaterials and textile substrate. Scalable deposition methods: developing scalable deposition methods. Nanomaterial functionalization: Functionalizing nanomaterials for improved compatibility. Testing and characterization: Developing standardized testing and characterization methods [113-158].

Toxicity and environmental impact assessment: Investigating potential risks. Scalable production methods: Developing cost-effective production methods. Interfacial Interaction Enhancement: Improving interfacial interactions. Durability and Stability Enhancement: Enhancing stability and durability. Regulatory Framework Development: Establishing clear regulations and standards. Addressing these disadvantages, limitations, and technical challenges is crucial for the successful development and commercialization of hybrid nanomaterial-based textiles [159].

5.2 Application Methods for Durable Nanotechnology Finishing

Sol-gel processing: Creates durable nanocoatings. Electrospinning: Produces nanofibers with enhanced durability. Plasma treatment: Activates fabric surface for nano-coating adhesion. Layer-by-layer deposition: Builds durable nanocoatings. Nano-coating applies nanomaterials to the fabric surface [160-163]. Textile materials benefiting from nanotechnology durability: Cotton: Enhanced durability for clothing and home textiles. Polyester: Improved resistance to abrasion and UV degradation. Nylon: Increased durability for outdoor and technical textiles. Wool: Enhanced resistance to pilling and shrinkage. Synthetic blends: Improved durability for various applications [164-169]. Scalability and cost-effectiveness are notable. Standardization and regulation are notable.

Environmental impact and sustainability are also noteworthy. The development of new nanomaterials is notable. Integration with existing textile manufacturing processes is imperative. Using nanotechnology, textile finishing can enhance durability, performance, and functionality, leading to longer-lasting and higher-quality textiles [170-172].

Nano-based treatments can create water-repellent surfaces, reducing water absorption. Nanotechnology plays a significant role in achieving water repellency in textile finishing, creating surfaces that repel water and maintain their performance over time [173]. Nanotechnology has revolutionized various industries, including textiles, by introducing innovative materials and finishes that enhance performance and functionality. Water repellent textile finishes are crucial for multiple applications, such as outdoor clothing, medical, and technical textiles [174]. Nanocoatings have emerged as a promising solution to achieve water repellency, and this essay will discuss different types of nanocoatings that have contributed to this significant achievement [175].

Silicon-based nanocoatings, particularly silicon dioxide (SiO_2) and silicones are widely used for water repellent textile finishes. These coatings create a hydrophobic surface, causing water to bead up and roll off [176]. Sol-gel processing is a standard method for depositing silicon-based nanocoatings onto textiles. This technique allows precise control over coating thickness and composition, ensuring optimal water repellency [176].

Fluoropolymer-based nanocoatings, such as polytetrafluoroethylene (PTFE) and polyfluoroalkyl methacrylate (PFMA), exhibit exceptional water repellency and durability [177]. These coatings create a low-surface-energy interface, making it difficult for water to penetrate the textile surface. Fluoropolymer-based nanocoatings are commonly applied using plasma-enhanced chemical vapor deposition (PECVD) or spray coating methods [178].

Carbon-based nanocoatings, including graphene and carbon nanotubes, have gained attention for their water repellent properties. Graphene, a single layer of carbon atoms, exhibits exceptional hydrophobicity due to its high surface roughness [179]. Carbon nanotube-based coatings also demonstrate water repellency, attributed to their tubular structure and low surface energy [180]. Ceramic-based nanocoatings, such as titanium dioxide (TiO_2) and zinc oxide (ZnO), offer water repellency and additional benefits like UV protection and antimicrobial properties [181]. These coatings can be applied using sol-gel processing, electrospinning, or electrophoretic deposition.

Hybrid nanocoatings, combining multiple materials, have shown improved water repellency and durability. For example, silicon-fluoropolymer hybrid coatings exhibit enhanced hydrophobicity and resistance to abrasion. These coatings can be tailored to specific applications by adjusting the composition and structure [182].

Nanocoatings for water repellent textile finishes offer several advantages: Improved water repellency and durability: enhanced stain resistance and reduced water absorption. And finally, there is increased UV protection and antimicrobial properties [183, 184]. Applications of water repellent textiles include outdoor clothing and gear, medical textiles, and technical textiles such as filtration and insulation materials. Sports-wear and active-wear are essentially notable [185, 186]. Despite significant achievements, challenges persist: Scalability and cost-effectiveness. Coating durability, stability, and environmental coatings, such as fluoropolymer coatings, along with other parameters like standardization and regulation [187, 188]. Future research should focus on developing eco-friendly and biodegradable nanocoatings and improving coating durability and stability, scaling up production processes, and exploring new materials and applications [189, 190].

Summarily, nanocoatings have revolutionized water repellent textile finishes, offering enhanced performance and functionality. The various types of nanocoatings discussed in this essay, silicon-based, fluoro-polymer-based, carbon-based, ceramic-based, and hybrid, demonstrate the versatility and potential of nanotechnology in this field [191]. As research continues to address challenges and explore new opportunities, nanocoatings will remain a crucial component of water repellent textile finishes, driving innovation and growth in the textile industry.

6. Nanoparticle Deposition as a Nanotechnology Textile Finish

Nanoparticle deposition is a cutting-edge technique to impart desirable properties to textiles, such as water repellency, self-cleaning, and antimicrobial activity. This process involves depositing nanoparticles onto the textile surface, creating a thin layer that alters the fabric's behavior. Nanoparticle deposition has emerged as a promising technique for achieving water repellency in textiles [192]. This approach involves depositing nanoparticles onto the fabric surface, creating a thin layer that repels water. Nanoparticle deposition relies on the unique properties of nanoparticles, which have a high surface area-to-volume ratio, allowing them to interact with the fabric surface and create a hydrophobic (water-repelling) effect. Common nanoparticles include silica, titania, and zinc oxide (ZnO) [193].

The deposition process typically involves sol-gel processing, electrospinning, or layer-by-layer assembly. Research has demonstrated the effectiveness of nanoparticle deposition in achieving water repellency in various textiles. For instance, a study reported that ZnO nanoparticle deposition on cotton fabric resulted in a significant increase in water contact angle, indicating improved water repellency [194]. Another study demonstrated the successful deposition of silica nanoparticles on polyester fabric using the sol-gel method, leading to enhanced water repellency and durability [195]. Nanoparticle deposition offers several advantages over traditional water repellent finishes, including improved durability, breathability, and environmental sustainability.

Furthermore, this technique can be applied to various textile materials, including natural and synthetic fibers. Future research directions may focus on optimizing nanoparticle deposition methods, exploring new nanoparticle types, and investigating the scalability and commercial viability of this technology [196]. The first step involves synthesizing nanoparticles with specific properties. This can be achieved through various methods, such as sol-gel processing, hydrothermal synthesis, or mechanical milling. Researchers have synthesized nanoparticles like ZnO, TiO₂, and SiO₂ for textile applications [197-200]. After synthesis, nanoparticles are dispersed in a suitable medium, such as water or organic solvents, to create a stable suspension. This ensures uniform nanoparticle distribution on the textile surface. Surfactants or stabilizing agents may be added to prevent nanoparticles from agglomeration [201]. The textile substrate is prepared for nanoparticles deposition by cleaning, drying, and possibly treating with a primer or sensitizer to enhance nanoparticles' adhesion [202].

Nanoparticles are then deposited onto the textile surface using Dip coating, spray coating, electrospinning, and layer-by-layer assembly. These methods allow for controlled nanoparticle deposition, ensuring uniform coverage and desired thickness [203-205]. To ensure nanoparticles' adhesion and stability, the treated textile may undergo additional processing, such as heat treatment, UV curing, and chemical cross-linking. This step helps maintain the nanoparticles layer's integrity during wear and use [206, 207].

6.1 Characterization and Testing

The final step involves characterizing the nanoparticles-deposited textile to evaluate its properties, such as, water contact angle, self-cleaning efficiency and antimicrobial activity. These tests confirm the effectiveness of the nanoparticles deposition process in imparting desired properties to the textile. By following these steps, researchers and manufacturers can create nanotechnology textiles with enhanced performance and functionality [208, 209].

Other processes include sol-gel processing, electrospinning, which produces nanofibers with water-repellent properties, and plasma treatment, which activates the fabric surface for nanocoatings adhesion. Nanomaterials for water repellency are fluoropolymers (e.g., Teflon) exhibiting hydrophobic and oleophobic properties. Silicones (e.g., PDMS) exhibiting hydrophobic and flexible properties. Nanosilica (SiO_2) demonstrates enhanced water repellency and durability. Another is nano-titanium dioxide (TiO_2), providing UV protection and self-cleaning properties. Graphene (hydrophobic and flexible properties), and CNTs are additional features enhancing water repellency and mechanical strength [210-213].

Textile materials suitable for nanotechnology-oriented water repellency (Cotton: Enhanced water repellency for clothing and home textiles [214]. Polyester: Improved water repellency for outdoor and technical textiles [215]. Nylon: Increased water repellency for outdoor and technical textiles [216]. Wool: Enhanced water repellency for clothing and textiles. Synthetic blends: Improved water repellency for various applications [217]. Benefits of nanotechnology-oriented water repellency include improved water repellency with enhanced performance and durability). Reduced water absorption minimizes weight gain and maintains fabric breathability. Easy cleaning: water-repellent surfaces facilitate stain removal. Increased UV resistance: Protects against UV degradation [210-214]. Breathability: Maintains moisture vapor transmission. Applications (Waterproof clothing: Jackets, pants, and gloves). Another is outdoor textiles including tents, awnings, and umbrellas. Technical textiles are also used in medical, industrial, and agricultural applications. Sportswear: waterproof and breathable clothing. Upholstery: water-repellent furniture and car seats [215].

Challenges and future directions include scalability and cost-effectiveness, standardization and regulation, environmental impact and sustainability, development of new nanomaterials, and integration with existing textile manufacturing processes. Commercial products include Gore-Tex (waterproof and breathable membranes), nano-sphere (water-repellent textile treatment), Never-wet (water-repellent coating technology), and stain-shield, including water-repellent and stain-resistant treatment. Another is Teflon, a water-repellent and non-stick coating. Nanotechnology-oriented water repellency treatments offer enhanced performance, durability, and sustainability for various textile applications [218].

6.2 Self-Cleaning

Nanoparticles can break down dirt and stains, making textiles easier to clean. Nanotechnological textile finishing has a significant impact on the self-cleaning effect of textiles, enabling the creation of surfaces that resist stains, repel water, and reduce maintenance [219].

6.2.1 Self-Cleaning Mechanisms

Lotus-Effect: Micro- and nano-structures mimic the self-cleaning properties of the lotus leaf. Photocatalytic: Nanoparticles (e.g., TiO_2) break down organic pollutants when exposed to light. Hydrophobic: Water-repellent surfaces prevent liquid penetration. Oleophobic: Oil-repellent surfaces prevent oil-based stains [220-222].

6.2.2 Nanomaterials for Self-Cleaning Textiles

Titanium dioxide (TiO_2): Photocatalytic properties. Zinc oxide (ZnO): Photocatalytic and antimicrobial properties. Silicon dioxide (SiO_2): Hydrophobic and oleophobic properties. Carbon nanotubes (CNTs): Enhanced mechanical strength and self-cleaning properties. Graphene: Hydrophobic and conductive properties [223-225].

6.2.3 Benefits of Nanotechnological Self-Cleaning Textiles

Reduced staining: Resists liquid penetration and stains. Easy cleaning: Self-cleaning surfaces facilitate maintenance. Water conservation: Reduces water usage for cleaning. Extended lifespan: Self-cleaning properties prolong the textile's lifespan. Improved hygiene: Antimicrobial properties reduce bacterial growth [226-228].

6.2.4 Applications

The application includes outdoor textiles (tents, awnings, and umbrellas). Sportswear: Running, cycling, and hiking clothing. Also utilized in medical textiles including hospital uniforms, bed sheets, and surgical gowns. Upholstery in car seats, furniture, and public transportation. Technical textiles: Industrial, agricultural, and construction applications [229].

6.2.5 Challenges and Future Directions

Abounding challenges include scalability and cost-effectiveness, standardization and regulation, environmental impact and sustainability, development of new nanomaterials, and integration with existing textile manufacturing processes [230].

6.2.6 Commercial Products

Nano-sphere including self-cleaning textile treatment, lotus-effect such as self-cleaning coating technology, NeverWet: Water-repellent and self-cleaning coating. StainShield: Self-cleaning and stain-resistant treatment. Teflon: Non-stick and self-cleaning coating [231].

Nanotechnological textile finishing enables the creation of self-cleaning textiles with improved performance, durability, and sustainability. These innovative materials can transform various industries and improve daily life [232].

6.3 UV Protection

Nanoparticles can absorb or reflect UV radiation, protecting skin and preventing fabric degradation—the effect of nanotechnology on UV protection textile finishing. Nanotechnology has

revolutionized UV protection textile finishing, providing enhanced protection against harmful ultraviolet (UV) radiation. Nanoparticles (ZnO, SiO₂, TiO₂, CeO₂, CNTs) absorb UV radiation, preventing penetration. UV Reflection: Nanoparticles reflect UV radiation, reducing fabric absorption. UV Scattering: Nanoparticles scatter UV radiation, reducing intensity [233-238].

6.3.1 Benefits of Nanotechnology-Oriented UV Protection

The advantages of nano-based UV protection relate to improved UV protection in terms of minimizing UV radiation penetration. Another is enhanced durability as UV protection retains performance over time. Relative to breathability, nano UV protection maintains moisture vapor transmission, minimizing the build-up of heat and discomfort while reducing chemical usage and environmental impact [239].

6.3.2 Applications

UV-protected clothing includes outdoor clothing: hiking, camping, and sports apparel. Active wear, including running, cycling, and swimming clothing. Another is work wear relative to construction, agriculture, and industrial uniforms. Upholstery is another relative of car seats, furniture, and public transportation. Further applications include technical textiles, as well as medical, industrial, and agricultural applications.

6.3.3 Challenges and Future Directions

The challenges garnered from these materials include scalability and cost-effectiveness, standardization and regulation, environmental impact and sustainability, and development of new nanomaterials. Also, the integration with existing textile manufacturing processes is a challenge for these materials.

6.3.4 Commercial Products

Commercial products include Cool Dry, which is related to UV protective fabric technology. UV Tech: Nanotechnology-based UV protection.

SolarWeave: UPF 50+ rated fabric. SunProtect: UV protective textile finishing. Texollini: Nanotechnology-based UV protection [240-245].

Nanotechnology has significantly enhanced UV protection textile finishing, providing innovative solutions for various industries. These advancements ensure improved protection, comfort, and sustainability for consumers [240].

7. Antimicrobial Properties

Nanomaterials can inhibit the growth of bacteria, fungi, and viruses. Nanotechnological textile finishing has significantly enhanced antimicrobial finishing in textiles, providing durable protection against microorganisms [246]. Some advantages include improved durability as nanoparticles provide longer-lasting antimicrobial properties than traditional finishes. Enhanced efficacy is another advantage as nanoparticles can target a broader range of microorganisms, including bacteria, viruses, and fungi. Notably, the reduced toxicity of nanoparticles can minimize the release

of toxic chemicals, ensuring safer textiles. Finally, it is multi-functionalization as nanoparticles can provide additional properties, such as UV protection, water repellency, and self-cleaning [246, 247].

NMs used in constructing these fabrics include silver nanoparticles (AgNPs), which are effective against bacteria, viruses, and fungi. Titanium dioxide (TiO₂) nanoparticles are another example due to their photocatalytic properties, enabling self-cleaning and antimicrobial activity. Also, zinc oxide (ZnO) nanoparticles offer broad-spectrum antimicrobial properties. Copper nanoparticles (CuNPs) are also effective against bacteria and viruses [248-250]. These materials are constructed using sol-gel processing, electrospinning, nano-coating, padding, and drying [250].

The advantages of these materials are notable in medical textiles as they minimize hospital-acquired infections, active-wear, and sportswear relative to odor control and freshness. Home textiles are another as they reduce the growth of microorganisms on upholstery and bedding. Military textiles: Enhanced protection against biological agents [251].

7.1 Challenges and Future Directions

Challenges include scalability, cost-effectiveness, standardization of testing methods, environmental impact, toxicity concerns, and developing novel nanomaterials with improved efficacy and safety [252].

Integrating nanotechnology in textile finishing has revolutionized antimicrobial treatments, offering enhanced performance, durability, and safety. Ongoing research aims to address challenges and explore new opportunities in this field.

8. Thermal Regulation

Nanomaterials can enhance the thermal insulation or cooling properties of fabrics [253].

8.1 Mechanisms of Thermal Regulation

Nanotechnology enhances thermal regulation in textiles through radiation trapping. Here, nanoparticles absorb and scatter radiation, reducing heat loss. Conduction blocking, as nanomaterials reduce thermal conduction, minimizing heat transfer. Convection enhancement as nanostructures improves air circulation, enhancing heat dissipation. Relative to evaporation management, nanomaterials regulate moisture evaporation, cooling the body. And as per phase change, nanoparticles store and release thermal energy while regulating temperature. NMs used in fabricating these materials includes carbon nanotubes (CNTs), nano-cellulose, silver nanoparticles (AgNPs), phase change materials (PCMs), graphene, titanium dioxide (TiO₂), Zinc oxide (ZnO) and copper nanoparticles (CuNPs) [254-258]. Textile applications include active-wear and sportswear, outdoor clothing, military textiles, medical textiles, aerospace textiles, smart textiles, and protective clothing [259, 260].

8.2 Nanotechnology-Oriented Thermal Regulation Techniques

These include nanocoating, electrospinning, sol-gel processing, padding and drying, 3D printing, Nanofibers, and nanocomposites [157, 180, 200, 250]. The benefits include enhanced thermal insulation, improved moisture management, temperature regulation, lightweight and flexible, breathability, quick drying, and anti-microbial properties [30, 42, 48, 56].

8.3 Challenges and Future Directions

Accruable challenges include scalability and cost-effectiveness, as well as standardization of testing methods. Durability and wash resistance, environmental impact and toxicity concerns, and integration with wearable technology [28, 35, 46, 120, 240]. Future directions are anticipated to tilt towards developing novel nanomaterials, Hybrid nanomaterial systems, nano-structuring and surface modification, multifunctional textiles, and sustainable and eco-friendly nanotechnology [261].

8.4 Notable Examples

Notable examples include polarguard 3-D (nanotechnology-based insulation), Coolmax (moisture-wicking fabric), Outlast (phase-change materials), Nike's Aeroloft (nanotechnology-based insulation), Patagonia's Tres 3-in-1 Parka (nanotechnology-based insulation) [261-264]. Integrating nanotechnology in thermal regulation textile finishing has revolutionized the textile industry, enabling the development of high-performance textiles with advanced thermal management properties.

9. Sustainability

Nanotechnology can reduce water and chemical consumption in textile finishing processes. Nanotechnology has significantly impacted the sustainability of textile finishing, offering various benefits and challenges. Sustainability benefits, Water conservation: Nanotechnology-based finishing reduces water consumption. Energy efficiency: Nanomaterials enhance thermal regulation, reducing heating/cooling needs. Reduced chemical usage: Nanoparticles minimize chemical application. Improved durability: Nano-finishes extend textile lifespan, reducing waste. Enhanced recyclability: Nanotechnology facilitates textile recycling. NMs used for sustainable textile finishing include nanocellulose (biodegradable, renewable), carbon nanotubes (CNTs) (improve durability, reduce waste), zinc oxide (ZnO) nanoparticles (antimicrobial, UV protection), titanium dioxide (TiO₂) sustainable nanoparticles (self-cleaning, UV protection) and silver nanoparticles (AgNPs) (antimicrobial, reduced chemical usage) [150, 155, 200, 205]. Nano-coating, electrospinning, sol-gel processing, plasma treatment, and enzyme-assisted finishing are construction strategies for these fabrics [211, 240, 245].

Reduced wastewater generation, minimized chemical release, lower carbon footprint, decreased energy consumption, and extended textile lifespan are environmental concerns of these materials [150, 160, 168]. Nanoparticle toxicity and bioaccumulation, ecological impact of nanomaterial production, scalability and cost-effectiveness, standardization of testing methods, and regulatory frameworks for nanomaterials are parameters affecting the environment. The evolution of eco-friendly nanomaterials and hybridized nanomaterial systems is anticipated. Nano-structuring and surface modification, biodegradable nano-finishes, circular economy approaches.

Commercially available forms of these fabrics include Patagonia's Nano-Tex technology (water-repellent, breathable), Nike's flyknit (reduced waste, energy-efficient), Reebok's cotton + Corn (sustainable, biodegradable), H&M's Conscious Exclusive (sustainable, eco-friendly) and Stella McCartney's Greenpeace-approved textiles (eco-friendly, sustainable) [261-264].

Nanotechnology has the potential to transform the textile industry into a more sustainable and environmentally friendly sector. However, addressing challenges and concerns is crucial to ensure a positive impact.

9.1 Key Statistics

Key statistics include a 20% reduction in water consumption (nanotechnology-based finishing), a 30% reduction in energy consumption (nanomaterials), a 50% reduction in chemical usage (nanoparticles), and a 25% increase in textile lifespan (nano-finishes).

Regulatory framework includes the EU's REACH regulation, the US EPA's Nanoscale Materials Stewardship Program, and ISO 10812 (nanotechnology-based textile finishing) [265-268]. Research initiatives include the EU's Horizon 2020, the US NSF's Nanoscale Science and Engineering, and the Textile Institute's sustainability research [269, 270]. The influence of nanotechnology on sustainability in textile finishing is significant, offering various benefits and challenges. Ongoing research and development aim to address concerns and enhance sustainability.

Integrating nanotechnology in textile finishes has revolutionized the textile industry, enabling the development of advanced materials with unique properties. Nanotechnology has improved fabric performance, durability, and sustainability, transforming textiles into high-performance materials. However, despite its vast potential, nanotechnology in textile finishes faces significant challenges that must be addressed to ensure its continued growth and adoption. Nanotechnology has revolutionized various industries, including textiles, by providing innovative solutions for improving fabric performance, durability, and sustainability. Textile finishes, in particular, have benefited significantly from nanotechnology, enabling the development of advanced materials with unique properties. However, despite its vast potential, nanotechnology in textile finishes also poses significant challenges that need to be addressed.

Nanotechnology has been successfully applied in textile finishes to achieve various functions, such as water repellency, UV protection, antimicrobial properties, self-cleaning, and thermal regulation. Nano-coatings with water-repellent properties, like nanowax and nanosilica, enhance fabric water resistance. Nanoparticles like zinc oxide and titanium dioxide provide UV protection and prevent fabric degradation. Nanoparticles like silver and copper exhibit antimicrobial activity, reducing odor and improving fabric hygiene. Nano-structured surfaces with self-cleaning properties reduce fabric maintenance. Additionally, nanoparticles like phase change materials regulate temperature, enhancing fabric comfort.

Despite these benefits, several challenges hinder the widespread adoption of nanotechnology in textile finishes. Scalability and cost-effectiveness are significant concerns, as current production methods are often expensive and difficult to scale up. The potential toxicity of nanoparticles and their environmental impact raise concerns, and the durability and stability of nanoparticles on fabrics during washing or wear compromise performance. Furthermore, the lack of standardized regulations and testing protocols creates uncertainty, and concerns about nanoparticle safety and environmental impact affect consumer acceptance.

To overcome these challenges, researchers and industry stakeholders are exploring green synthesis methods, nano-encapsulation, hybrid nanomaterials, life cycle assessment, standardization, and regulation. Green synthesis methods using natural materials and bio-inspired approaches aim to reduce environmental impact. Nano-encapsulation improves durability and

stability, while hybrid nanomaterials combine nanoparticles with traditional finishes to enhance performance. Conducting thorough ecological and health impact assessments ensures responsible development.

Emerging trends are expected to shape the future of nanotechnology in textile finishes. Nanocellulose, using cellulose nanocrystals, offers sustainable and biodegradable finishes. Graphene-based finishes leverage graphene's exceptional properties for advanced textile applications. Bio-inspired nanomaterials, such as lotus-leaf-like surfaces, provide innovative solutions. Smart textiles integrate nanotechnology with wearable technology and sensor systems.

Nanotechnology has transformed textile finishes, enhancing performance, durability, and sustainability. However, challenges related to scalability, toxicity, and regulatory frameworks must be addressed. Future perspectives hold promise for overcoming these challenges. A collaborative effort between researchers, industry stakeholders, and regulatory bodies is necessary to ensure the responsible development and commercialization of nanotechnology in textile finishes.

10. Conclusion and Perspectives

Nanotechnology has revolutionized the textile industry, particularly in the finishing process. Integrating nanotechnology in textile finishing has created high-performance fabrics with unique properties. These properties include water repellency, self-cleaning, antimicrobial activity, and improved thermal insulation. The application of nanotechnology in textile finishing has also led to the development of sustainable and eco-friendly treatments. For instance, nano-finishing techniques have been used to reduce the environmental impact of textile production by minimizing the use of water, energy, and chemicals. Varying nanomaterials have been utilized in fabricating differing polymeric and biopolymeric nanoarchitectures [271-323].

Moreover, nanotechnology has enabled the creation of innovative textiles with integrated sensors and actuators. These smart textiles have numerous applications in various fields, including medicine, sports, and the military. However, despite the benefits of nanotechnology in textile finishing, there are still concerns about the potential environmental and health impacts of nanoparticles. Therefore, further research is needed to ensure the safe and sustainable use of nanotechnology in textile finishing. In conclusion, integrating nanotechnology in textile finishing has transformed the textile industry, enabling the creation of high-performance fabrics with unique properties. As research advances in this field, it is expected that nanotechnology will play an increasingly important role in developing sustainable and innovative textile products.

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Author Contributions

Engr. Dr. Ezeani O. E. and Engr. Dr. Idumah C. I. conceptualized, developed and wrote this manuscript while Mr. Okoye I. and Chioma Ikebundu J., supervised the project.

Competing Interests

The authors report no conflicts.

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