International Journal of Engineering and Science Invention (IJESI)
ISSN (Online): 2319-6734, ISSN (Print): 2319-6726
www.ijesi.org ||Volume 15 Issue 5 May 2026 || PP 61-72

Nanoparticle-Based Functionalization of Polyester and Its Cotton Blend: Advances, Applications and Safety Considerations

W. M. Raslan (1), J. I. Abd El-Thalouth (2), S. H. Abd El-Salam (2) N. M. Mohammed (2)
[1]*(National Research Centre, Textile Research and Technology Institute, Dokki, Cairo, Egypt, Postal code: 12622)*
[2]*(Textile Printing, Dyeing and Finishing department, Faculty of Applied Arts, Capital University, Egypt)*

ABSTRACT: *Nanotechnology has emerged as a promising approach for developing multifunctional textiles with improved performance and durability. This paper reviews the functionalization of polyester and polyester/cotton blended fabrics using nanomaterials and advanced nano-finishing techniques. Different nanoparticles, including Ag, TiO_2, ZnO, silica, nano-clays, nanofibers, and hybrid nanocomposites, are discussed regarding their ability to enhance antimicrobial activity, UV protection, self-cleaning, flame retardancy, antistatic behavior, wrinkle resistance, and water repellency.*

Advanced processing methods such as sol–gel treatment, electrospinning, plasma treatment, nano-coating, and nanocomposite fabrication are highlighted for improving nanoparticle fixation and multifunctional performance. The study also compares nanoparticle-based treatments with essential oil finishes in terms of efficiency, durability, and environmental sustainability. Although nanomaterials provide superior functional properties, essential oils offer safer and eco-friendly alternatives.

The paper further addresses concerns related to nanoparticle toxicity, environmental persistence, and nanoparticle release during laundering. Therefore, emphasis is placed on green nanotechnology, sustainable synthesis methods, and environmentally responsible textile finishing strategies for future smart and protective textile applications.

KEYWORDS - *Antimicrobial textiles, Functional textiles, Nanotechnology, Polyester fabrics, Polyester/cotton blends, Self-cleaning textiles, Smart textiles UV protection, Flame retardancy.*

Date of Submission: 14-05-2026 Date of acceptance: 28-05-2026

I. Introduction

Nanotechnology, first introduced by Richard Feynman in 1959 and later defined by Norio Taniguchi in 1974, involves manipulating materials at dimensions below 100 nm [1,2]. At the nanoscale, materials exhibit unique physical and chemical properties due to quantum effects, high surface area, and enhanced surface reactivity [3]. Nanofabrication is commonly achieved through top-down and bottom-up approaches, enabling precise control of size, morphology, and composition [4,5]. These techniques have led to the development of various nanomaterials, including graphene, carbon nanotubes, metal and metal oxide nanoparticles, nano clays, and electro spun nanofibers with distinctive optical, thermal, and mechanical properties [6–8].

In textile applications, nanoparticles significantly improve antimicrobial activity, UV protection, flame retardancy, and mechanical durability [9–12]. Their nanoscale dimensions enhance interaction with fibre surfaces, providing better durability and functionality than conventional treatments [13]. Consequently, nanotechnology-based textiles are increasingly applied in healthcare, protective clothing, sportswear, and smart textile systems [14,15].

However, concerns regarding the toxicity and environmental impact of engineered nanomaterials remain critical. Certain nanoparticles may induce oxidative stress, inflammation, and cytotoxicity, while their persistence and bioaccumulation may threaten ecosystems [16–20]. Therefore, green nanotechnology strategies focusing on eco-friendly synthesis, renewable materials, and biodegradable nanostructures have gained increasing attention [21–23]. Continued research is required to optimize nanomaterial–textile interactions and establish safe, sustainable regulatory frameworks for advanced textile applications.

The aim of this work is to provide a comprehensive overview of nanoparticle-based functionalization of polyester and polyester/cotton blended fabrics, with emphasis on nanomaterial classification, finishing techniques, multifunctional performance, and safety considerations. The review also highlights recent advances in nano-finishing technologies and compares nanoparticle systems with eco-friendly essential oil treatments in terms of efficiency, durability, and sustainability.

II. Advanced Applications for Nanomaterials in the Textile Industry

Nanotechnology has significantly advanced the development of multifunctional textiles, known as nanotextiles, through the incorporation of nanomaterials into textile structures (24-34). These materials provide enhanced properties such as antimicrobial activity, self-cleaning, UV protection, flame retardancy, water repellency, and improved mechanical performance [1–4]. Consequently, nanotextiles have found broad applications in medical, sports, protective, and smart textile fields [5,6].

Nano-finishing and nano-coating technologies are widely used to deposit nanoparticles uniformly onto fibre surfaces, improving surface functionality, durability, and mechanical properties [7,8]. Carbon-based nanomaterials, including graphene, carbon nanotubes (CNTs), and carbon nanofibers, are particularly important due to their excellent electrical conductivity, mechanical strength, and high surface area, enabling their use in sensors, smart textiles, and electromagnetic shielding applications [9–11].

Inorganic nanoparticles such as silver, titanium dioxide, zinc oxide, and nano clays are extensively applied for antimicrobial, UV-protective, and flame-retardant functions [12–15]. Silver nanoparticles exhibit strong antibacterial performance, especially in medical and sportswear textiles [16], while TiO_2 and ZnO nanoparticles contribute to self-cleaning and photocatalytic properties [17,18].

Core–shell and composite nanomaterials provide multifunctional performance by combining several properties within one nanostructure, including UV protection, antimicrobial activity, thermal regulation, and mechanical reinforcement [19,20]. Hybrid and polymeric nanomaterials further support the development of responsive and smart textiles capable of reacting to environmental stimuli such as heat, moisture, and light [21–23].

Due to their nanoscale dimensions and high surface area, nanomaterials interact efficiently with textile fibres, resulting in superior functional durability and surface coverage compared with conventional treatments [24,25]. However, challenges including nanoparticle release during laundering, toxicity concerns, long-term stability, and high production costs remain significant [26–28]. Therefore, current research focuses on sustainable synthesis routes, controlled-release systems, and eco-friendly multifunctional nanostructures to improve textile safety and environmental compatibility [29–33].

Shape 1 show **c**lassification of nanomaterials used in textiles and their functional applications:

1. Carbon-based nanomaterials → smart textiles, sensors, reinforcement.
2. Inorganic nanoparticles → antimicrobial, UV protection, flame retardancy.
3. Core–shell nanoparticles → multifunctional surfaces.
4. Composite nanomaterials → synergistic thermal, mechanical, and chemical properties.
5. Hybrid nanomaterials → responsive textiles.
6. Polymeric nanomaterials → flexible and stimuli-responsive coatings.

Shape 1: Diagrammatic Representation of Nanotechnology-Based Textile Applications [34]

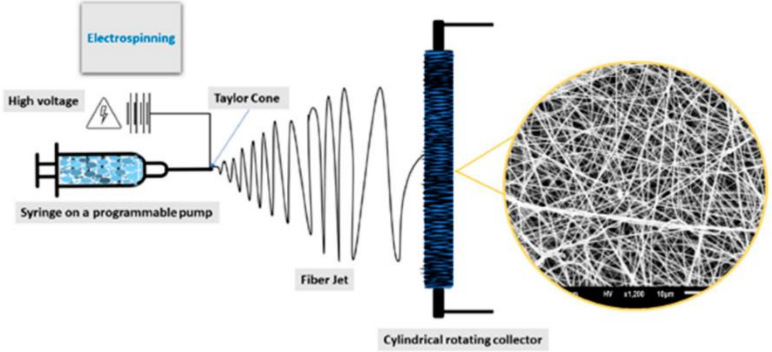
2.1 Innovations in Nanotechnology-Based Textile Applications

Nanotechnology has transformed textile engineering from conventional fabric production to multifunctional, high-performance textile systems. Modern textiles are designed to provide antimicrobial activity, self-cleaning behavior, UV protection, and enhanced durability through four major approaches: nano-finishing, nano-coating, nanofiber engineering, and nanocomposite technology [9,12,24].

Nano-finishing involves depositing nanoscale functional agents onto textile substrates using stable colloidal systems. Compared with conventional finishing, nano-finishing provides stronger fibre–particle interactions, lower chemical consumption, improved washing durability, uniform surface coverage, and preservation of softness and permeability [34–36]. Metal-based nanoparticles such as silver, copper, and copper oxides are widely applied for antimicrobial finishing due to their broad-spectrum activity [12,25,28]. However, nanoparticle release during laundering remains a major environmental and durability concern, encouraging research into safer immobilization strategies and eco-friendly alternatives [16–18].

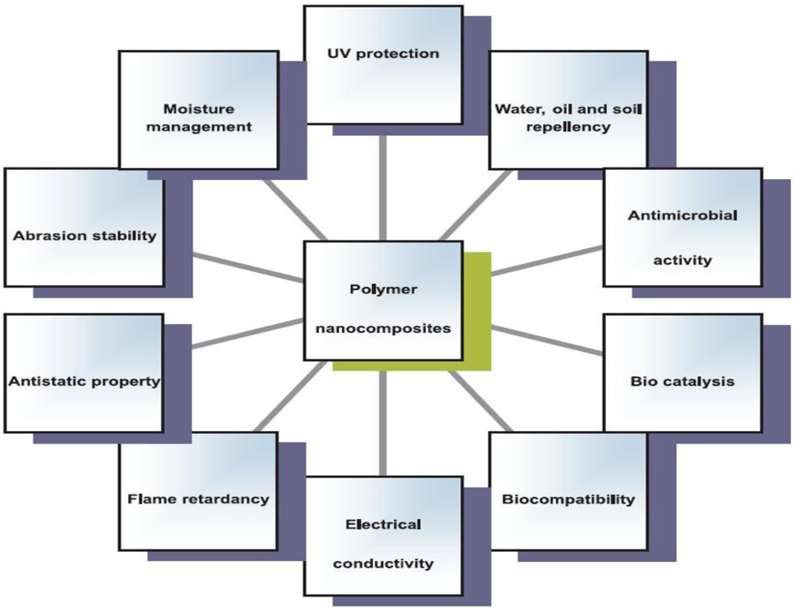
Nano-coating technology produces ultrathin functional layers, generally below 100 nm, without significantly affecting the bulk textile properties. These coatings offer improved abrasion resistance, strong interfacial adhesion, enhanced durability, and minimal influence on fabric handle and air permeability. Functional nano-coatings commonly incorporate TiO_2 and ZnO nanoparticles because of their photocatalytic and UV-blocking properties [13,18,29]. Such coatings enable self-cleaning textiles through light-induced degradation of organic contaminants. Current developments focus on plasma-assisted deposition, binder-assisted fixation, and environmentally sustainable coating systems to improve long-term stability [14,21].

Nanofiber technology represents an advanced textile fabrication route in which fibres are produced at the nanoscale using methods such as electrospinning, melt blowing, self-assembly, and bicomponent spinning [24,31]. Electrospinning (Shape 2) is the most widely used method because of its versatility and controllability. Nanofibers exhibit high surface area, interconnected porosity, tunable morphology, and the ability to incorporate functional nanomaterials within the fibre structure. These features make them highly suitable for filtration, protective textiles, face masks, and biomedical applications. Incorporation of conductive or antimicrobial nanomaterials such as carbon nanotubes and metallic nanoparticles further enhances protection against microorganisms and airborne pollutants [6,8,11]. Nevertheless, large-scale production and cost efficiency remain major challenges for industrial implementation.



Shape 2: Nano-fibres produced by electro-spinning technique [35]

Nanocomposites consist of nanoscale fillers dispersed within polymeric matrices, resulting in synergistic enhancement of mechanical, thermal, and functional properties [24,31]. In textile finishing (Shape 3), nanocomposites are extensively used to improve flame retardancy, antimicrobial activity, and UV resistance. Their effectiveness depends on uniform nanoparticle dispersion and strong matrix interactions, which improve stress transfer and functional stability. Recent studies have focused on hybrid nanocomposites combining metallic nanoparticles with organic or inorganic functional agents to achieve tunable multifunctional performance [25]. Such systems have demonstrated enhanced flame resistance and strong antimicrobial activity against Gram-positive and Gram-negative bacteria [25,28]. However, nanoparticle release, recyclability, and environmental persistence remain important sustainability concerns requiring improved lifecycle assessment and material design strategies [19,32].



Shape 3: Applications of nanocomposites in textile finishing [37]

Despite the significant advances in nanotextiles, challenges related to toxicity, environmental accumulation, durability, and economic feasibility still limit large-scale commercialization. Therefore, current research emphasizes eco-friendly nanomaterials, advanced encapsulation and fixation systems, sustainable processing methods, and comprehensive safety regulations [16–18,32]. The integration of nanotechnology with smart textiles, wearable electronics, and responsive materials continues to expand textile applications, positioning nanotechnology as a key driver in next-generation textile innovation [9,24–39].

2.2 Functional Textiles with Nanomaterials

The incorporation of nanomaterials into textile substrates has enabled the production of multifunctional fabrics with durable and enhanced performance properties. Inorganic nanoparticles such as TiO_2, ZnO, SiO_2, Cu_2O, Ag, Au, and nano clays are widely applied because of their high surface area, thermal stability, chemical resistance, and long-term durability [12,13,25]. Compared with conventional organic finishes, these nanoparticles provide more stable and permanent functionalities when effectively fixed onto textile fibres. At controlled concentrations, many nanomaterials also exhibit relatively low toxicity, supporting their use in textile applications [16,17]. Their applications additionally extend to composites, construction, and tissue engineering due to their multifunctional characteristics [4,5].

Because of their nanoscale dimensions, nanoparticles interact efficiently with textile surfaces, leading to improved functional performance compared with conventional micro-sized materials. As a result, nanoparticle-treated textiles exhibit enhanced stain resistance, flame retardancy, wrinkle resistance, moisture management, antimicrobial activity, antistatic behavior, UV protection, and improved dyeability and color strength [12,40]. These effects are mainly attributed to the high surface reactivity and strong interfacial interactions of nanomaterials with textile fibres.

Several application techniques are used to deposit nanoparticles onto textiles, including padding, spraying, dip-coating, transfer printing, rinsing, and sol–gel processing. Among these methods, padding is the most used industrial technique because of its simplicity, scalability, and compatibility with conventional finishing equipment. In this process, fabrics are impregnated with nanoparticle dispersions, squeezed to control wet pickup, then dried and cured to improve nanoparticle fixation [12,40].

Sol–gel processing is another important nanocoating method involving hydrolysis and condensation reactions that form a three-dimensional inorganic network on the textile surface. This technique offers low processing temperatures, excellent chemical homogeneity, controlled particle morphology, and uniform thin coatings, making it highly suitable for multifunctional textile finishing (Shape 4) [26,29].

Shape 4: Sol–gel coating applications on textiles for enhancing functional properties [37]

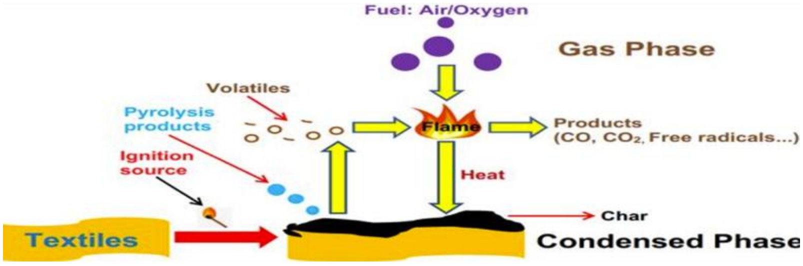
Nanotechnology has enabled the development of several advanced textile categories, including flame-retardant, UV-protective, antimicrobial, water- and oil-repellent, anti-odor, wrinkle-resistant, and antistatic textiles. Metal oxide nanoparticles such as TiO_2 and ZnO provide efficient UV shielding, while silver, copper, and zinc nanoparticles impart antimicrobial activity. Conductive nanomaterials contribute to antistatic performance, whereas nanoscale surface modification enhances repellency and wrinkle resistance. These multifunctional textiles are increasingly utilized in healthcare, protective clothing, sportswear, and smart textile applications [9,13,25].

Current research focuses on improving nanoparticle stabilization, surface functionalization, and green synthesis technologies to enhance textile performance while ensuring environmental sustainability and safety [24–57].

Flame-Retardant Textiles

Nanotechnology has become an effective and environmentally safer approach for developing flame-retardant textiles, replacing conventional halogen-based systems associated with health and ecological concerns. Nanoparticles improve flame resistance through several mechanisms, including formation of thermal barrier layers, promotion of char formation, and suppression of free radicals generated during combustion [57]. The effectiveness of nanoparticle-based flame-retardant systems depends on nanoparticle composition, morphology, dispersion within the polymer matrix, migration behavior during heating, and interfacial compatibility with textile fibres. Uniform nanoparticle distribution and strong adhesion are essential for reducing heat transfer and limiting oxygen diffusion during combustion.

Synthetic fibres such as polyester, nylon, and acrylic are widely used because of their favorable mechanical and economic properties; however, they are highly flammable. Upon heating, these fibres soften, decompose, and release volatile combustible products that accelerate flame propagation (Shape 5) [38,57]. Therefore, efficient flame-retardant treatments are essential for improving textile safety.



Shape 5: Combustion cycle of a typical synthetic textile material [38]

Silica-based nanoparticles are among the most effective flame-retardant additives because they form protective insulating layers that reduce heat transmission and delay thermal degradation [38,57]. Multilayer silica coatings deposited on polyester fabrics significantly improve thermal insulation and flame resistance [38]. Surface activation methods such as plasma treatment further enhance nanoparticle adhesion and coating uniformity, particularly for clay-based nanostructures. Studies have demonstrated that SiO_2 nanoparticles improve the thermal stability of polyester, polyamide, and polyacrylonitrile (PAN) fibres by increasing the ignition energy threshold [38].

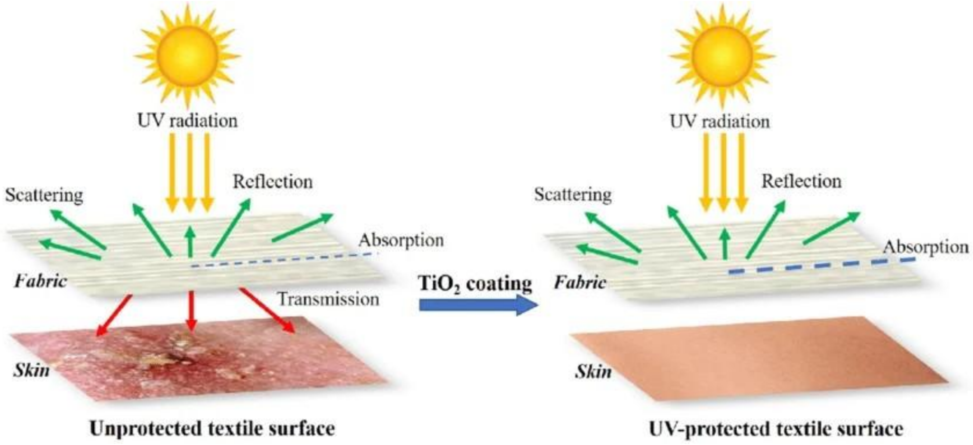
Hybrid nanostructured systems have also shown excellent performance. Layer-by-layer (LbL) assembly of TiO_2 nanoparticles and polyelectrolytes on polyester and polyamide fabrics enhances flame retardancy while simultaneously modifying wettability and surface energy [55–56]. Carbon nanotubes (CNTs) additionally improve thermal resistance by forming stable carbonaceous networks that reduce volatile release and heat transfer. Their incorporation into polyester fabrics has been reported to nearly double combustion time compared with untreated materials [5,7].

Synergistic systems combining nanoparticles with bio-based additives have demonstrated further improvements. Polyamide 6,6 fabrics treated with TiO_2, SiO_2, and inositol hexa-phosphate (IP6) using a pad–dry–cure process showed increased flame resistance and hydrophilicity. The limiting oxygen index (LOI) increased from 19.5% to 24.5%, while incorporation of chitosan reduced the peak heat release rate by approximately 25%. Treated fabrics also exhibited improved tensile strength [58].

Nanoparticle-based flame-retardant systems provide multifunctional and sustainable solutions for textile protection by improving thermal stability, mechanical performance, and surface functionality simultaneously.

UV Protection in Nanostructured Textiles

The depletion of the ozone layer has increased exposure to ultraviolet (UV) radiation, creating serious risks to both human health and textile durability. Prolonged UV exposure can cause skin aging, DNA damage, and skin cancer, while also accelerating textile degradation, discoloration, and loss of mechanical strength. Therefore, UV-protective textiles have become increasingly important in functional textile engineering (Shape 6). Metal oxide nanoparticles such as TiO_2, ZnO, Fe_3O_4, and CeO_2 are highly effective UV-blocking materials because of their strong UV absorption and scattering abilities, high refractive index, and wide bandgap properties. Compared with conventional organic UV absorbers, these nanomaterials exhibit superior photostability, thermal resistance, and long-term durability with lower toxicity [18,19].



Shape 6: Ultraviolet-Blocking Protective Textiles [55]

The UV-shielding efficiency of nanomaterials depends on particle size, crystal structure, and surface characteristics. Nanoscale particles possess high surface area and improved interaction with UV radiation, resulting in enhanced absorption and scattering efficiency [18,19].

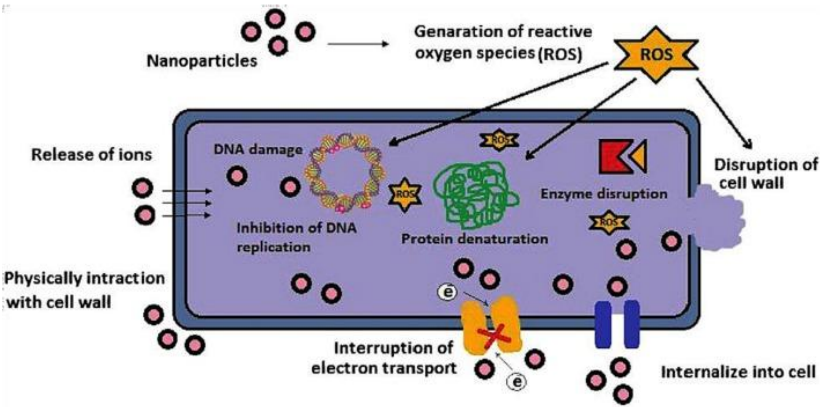
ZnO nanoparticles are among the most widely used UV-protective agents in textiles. ZnO-treated cotton fabrics exhibit excellent UV protection together with antimicrobial properties, while maintaining durability after repeated washing and abrasion. ZnO nanorods deposited on polyester fabrics provide even greater UV shielding because of their high crystallinity and enhanced electronic properties, which improve interaction with UV radiation [18,19]. Several application methods have been investigated to optimize nanoparticle deposition. Polyester fabrics modified by alkali hydrolysis and treated with ZnO nanoparticles through exhaustion techniques showed improved UV protection and self-cleaning properties, particularly at higher nanoparticle concentrations [18,19].

Nanocomposite systems also provide multifunctional performance. MnO_2–$FeTiO_3$ nanocomposite coatings simultaneously enhance UV resistance and flame retardancy while maintaining fabric durability. Similarly, nano clay coatings applied through pad–dry–cure processing significantly improve the ultraviolet protection factor (UPF) of polyester fabrics, with UV-blocking performance increasing as nano clay concentration rises [55]. Nanostructured UV-protective finishes provide durable, multifunctional, and efficient protection against harmful ultraviolet radiation while improving textile performance and longevity.

Antibacterial and Antimicrobial Textiles

Natural textile fibres such as cotton, linen, and regenerated cellulose are highly susceptible to microbial growth because of their hydrophilic structure and moisture retention. Microbial contamination causes odor formation, discoloration, fibre deterioration, and potential health risks, particularly in medical and hygienic textiles [15,27,57]. Consequently, nanotechnology has become an effective strategy for producing durable antimicrobial fabrics.

Metal and metal oxide nanoparticles, including ZnO, TiO_2, CuO, Ag, and Au, are widely used because of their broad-spectrum antimicrobial activity and high stability. Their nanoscale dimensions provide a large surface area that enhances interaction with microbial cells. Antimicrobial activity mainly occurs through several simultaneous mechanisms (Shape 7), including reactive oxygen species (ROS) generation, release of metal ions, membrane disruption, protein denaturation, and DNA damage.



Shape 7: Different Mechanisms of Antimicrobial Activity of Metal Oxides and Metal NPs [37]

Silver nanoparticles have demonstrated excellent antibacterial efficiency when incorporated into cellulosic fibres. Green-synthesized Ag nanoparticles produced from plant extracts showed particle sizes below 100 nm and strong activity against Gram-negative bacteria such as *Escherichia coli*. These systems provide environmentally friendly and cost-effective antimicrobial treatments.

ZnO nanoparticles are among the most investigated materials for antimicrobial textiles because of their low cost, high efficiency, and relatively low toxicity. ZnO coatings are commonly combined with stabilizers or surfactants to improve nanoparticle dispersion, adhesion, and washing durability. Antibacterial efficiencies above 90% have been reported [59]. Various capping agents, including chitosan, cyclodextrins, sodium alginate, and polyamides, are also used to improve nanoparticle stabilization and fixation on textile substrates [59].

Several deposition techniques have been explored to enhance antimicrobial performance. Pulsed laser deposition of ZnO and CuO nanoparticles onto polypropylene nonwoven fabrics produced strong antibacterial activity against both *E. coli* and *Staphylococcus aureus*, making these materials suitable for wound dressing applications [59]. Chemical bath deposition has also been used to grow ZnO nanostructures directly on textile surfaces, where polyamide 6,6 fabrics showed greater nanoparticle loading and superior antibacterial activity compared with PET and polypropylene fabrics [59].

Particle size strongly influences antimicrobial efficiency. Smaller ZnO nanoparticles exhibit higher surface reactivity and improved bacterial inhibition. Polyester fabrics treated with nanoscale ZnO demonstrated enhanced resistance to microbial growth, making them suitable for sportswear and hygienic textiles [14,59]. ZnO-treated polyester fabrics showed inhibition zones of 5.8 cm against *S. aureus* and 3.7 cm against *E. coli*, with bacterial reduction rates reaching 94.16% and 86.5%, respectively [14,15].

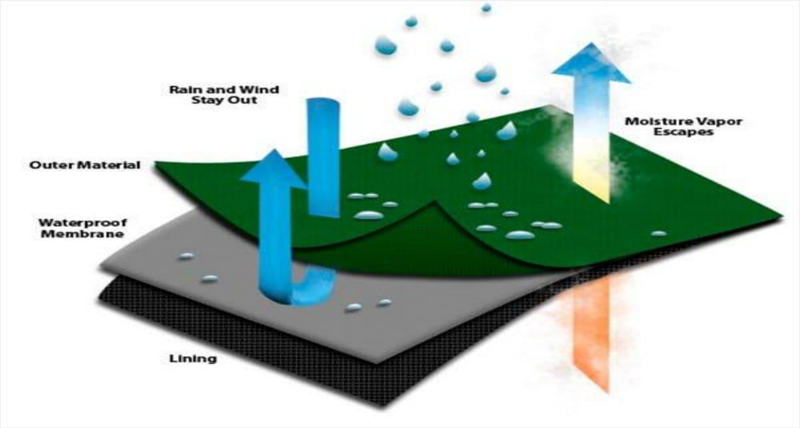
TiO_2 nanoparticles provide multifunctional properties, including antimicrobial, self-cleaning, and UV-protective effects. Their antibacterial activity mainly results from photocatalytic ROS generation under UV irradiation. Techniques such as spraying, sol–gel processing, enzymatic hydrolysis, and corona treatment have been applied to improve TiO_2 fixation on polyester fabrics and enhance antibacterial performance against *S. aureus* and *Klebsiella pneumoniae* [12,15,41]. TiO_2 combined with alginate also improved UV protection and photocatalytic degradation of organic dyes [41].

Hybrid nanoparticle systems exhibit synergistic antimicrobial effects superior to single-component systems. Ag/ZnO nanocomposites showed higher antibacterial activity than ZnO alone because of the combined effects of silver ion release and oxidative stress induction [13]. Similarly, Ag/SiO_2 and TiO_2/Ag nanocomposites demonstrated strong activity against *E. coli*, *S. aureus*, and *Candida albicans* [15,57].

Nanoparticle-based antimicrobial finishes provide durable and multifunctional textile protection suitable for healthcare, sportswear, and protective applications. However, issues related to nanoparticle leaching, long-term stability, and environmental safety remain important challenges requiring further investigation for sustainable textile development.

Water- and Oil-Repellent Textiles

The development of high-performance and protective textiles has increased interest in water- and oil-repellent finishes. Nanotechnology enables the production of fabrics with controlled surface wettability ranging from hydrophobic to superhydrophobic behavior through nano-finishing and nano-coating techniques. These treatments allow fabrics to repel liquids effectively while preserving air permeability and wearer comfort (Shape 8).



Shape 8: Water Repellent Finishing for Textiles [37]

Liquid repellency mainly depends on nanoscale surface roughness combined with low surface energy. Hierarchical nano-structured surfaces create trapped air pockets that reduce liquid–solid contact, allowing droplets to roll easily from the fabric surface. This mechanism is inspired by natural self-cleaning surfaces and forms the basis of advanced hydrophobic textile systems.

Nanotechnology has also contributed to the development of self-cleaning textiles that reduce laundering frequency and improve fabric durability. Two primary mechanisms are responsible for this behavior: photocatalysis and the lotus effect. In photocatalytic systems, semiconductor nanoparticles such as TiO_2 generate reactive oxygen species under UV or solar irradiation, leading to degradation of organic contaminants. Polyester fabrics coated with TiO_2 nanoparticles demonstrated effective removal of stains such as coffee, dyes, and wine upon light exposure. Higher nanoparticle concentration and larger particle size increased nanoparticle deposition and improved self-cleaning efficiency [37].

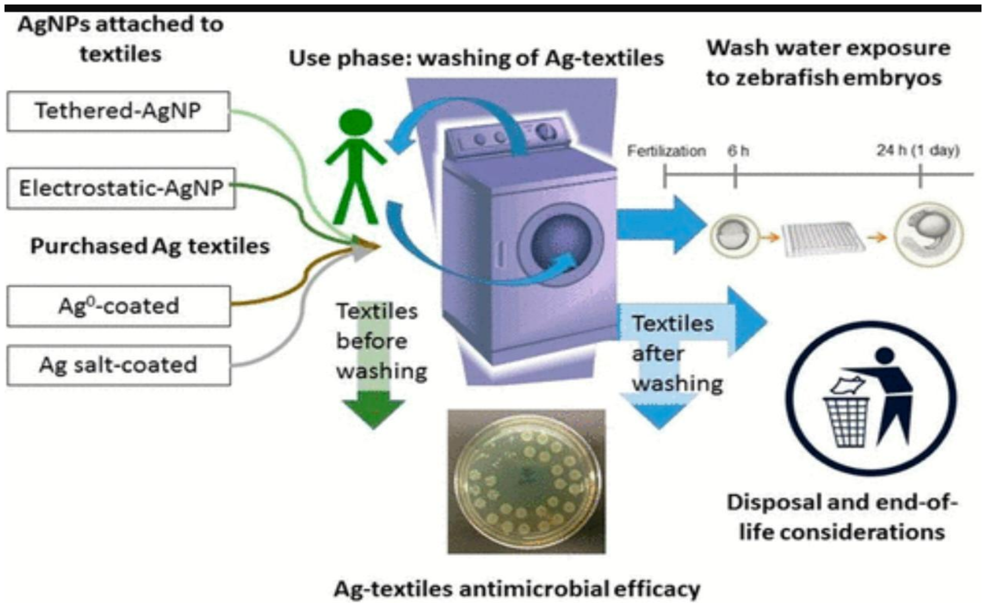
The lotus effect relies on the combination of nanoscale roughness and hydrophobic surface chemistry, causing water droplets to roll across the textile surface and carry away dirt particles. Combining photocatalytic activity with lotus-effect hydrophobicity enables the production of multifunctional, low-maintenance textiles with enhanced water repellency and self-cleaning performance.

Anti-Odor Textiles

Odor formation in textiles mainly results from microbial growth and moisture accumulation within the fabric structure. Nanotechnology-based finishes have been developed to provide durable deodorizing properties by reducing microbial activity and controlling moisture retention. Certain nanomaterials, such as tourmaline, effectively decrease moisture content, suppress bacterial growth, and minimize unpleasant odors, with reported reductions reaching 75% for moisture, 99.99% for bacteria, and nearly 90% for odor generation.

Nano-encapsulation technology has also been extensively applied in fragrance-delivery textiles. Encapsulated aromatic compounds can be released gradually during use through external stimuli such as friction, temperature, or humidity, providing long-lasting freshness and improved wearer comfort.

Despite these advantages, environmental concerns remain important because nanoparticles may be released during laundering and disposal, leading to potential ecological accumulation and toxicity (Shape 9). Therefore, current research focuses on developing biodegradable carriers and environmentally friendly nanomaterials to ensure safer and more sustainable anti-odor textile systems.



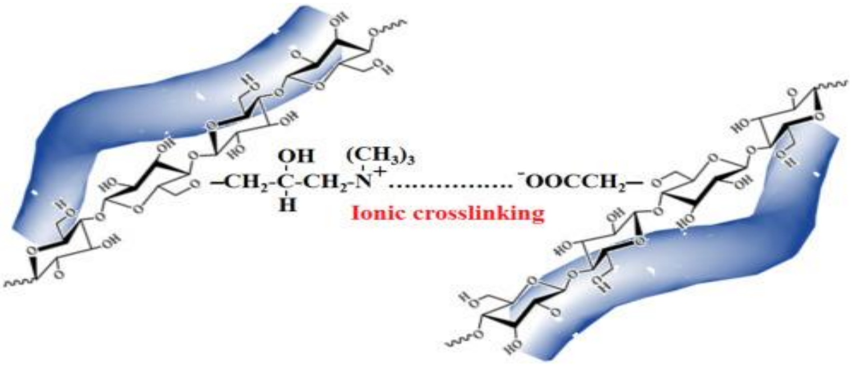
Shape 9: *Environmental impact of anti-odor textiles, illustrating nanoparticle release during washing and disposal and its potential ecological effects [37]*

Wrinkle-Resistant Textiles

Wrinkling is one of the main limitations of cellulosic textiles because their molecular structure easily forms hydrogen bonds during mechanical deformation. Conventional wrinkle-resistant treatments commonly depend on resin-based crosslinking agents, which often reduce fabric strength, flexibility, and handle.

Nanotechnology provides an effective alternative through the incorporation of nanoparticles such as SiO_2 and TiO_2 into textile finishes. These nanoparticles improve wrinkle recovery by reinforcing fibre structure and enhancing crosslinking efficiency while preserving fabric softness and flexibility. TiO_2 nanoparticle treatments have also been reported to provide additional functionalities, including improved durability and flame resistance.

Advanced crosslinking systems further enhance crease recovery performance. For example, combining 1,2,3,4-butanetetracarboxylic acid with nano-polyurethane significantly improves wrinkle resistance in cellulosic fabrics. In these systems, Al_2O_3 nanoparticles act as catalysts during the padding process, promoting efficient crosslink formation between fibre molecules. As a result, treated fabrics exhibit enhanced mechanical stability, flame resistance, and crease recovery properties (Shape 10). Furthermore, post-treatment operations such as direct dyeing may further improve wrinkle resistance, demonstrating the importance of process integration in multifunctional textile finishing [37].



Shape 10: *Schematic illustration of ionic crosslinking interactions between fibre molecules in wrinkle-resistant textile finishing systems [37]*

Antistatic Textiles

Static electricity accumulation is a common problem in synthetic textiles, particularly polyester and polyester blends, because of their low moisture regain and poor electrical conductivity. Unlike natural fibres such as cotton and linen, synthetic fibres tend to retain electrostatic charges due to their hydrophobic structure.

Nanotechnology has provided effective solutions for improving antistatic performance through the incorporation of conductive nanomaterials into textile structures. Nanoparticles such as TiO_2, Ag, ZnO, antimony-doped tin oxide, and silane-based nano-sols create conductive pathways on fibre surfaces, enabling efficient dissipation of electrostatic charges and reducing static buildup [38]. The effectiveness of these finishes depends largely on nanoparticle concentration, uniform dispersion, and compatibility with the textile matrix, which together ensure stable conductivity without negatively affecting fabric appearance or mechanical properties.

Although nanotechnology has significantly enhanced textile functionalities including antistatic behavior, self-cleaning, wrinkle resistance, odor control, and water repellency, important challenges remain. These include maintaining durability after repeated laundering, minimizing nanoparticle release, and reducing potential environmental and health risks. Future developments should therefore emphasize green synthesis methods, biodegradable nanocarriers, and safer nanomaterial design to achieve sustainable multifunctional textile systems.

III. Nanoparticle versus Essential Oil Functionalization in Textiles

Textile functionalization has advanced using both nanomaterials and natural bioactive compounds such as essential oils. Although both approaches improve textile performance, they differ in mechanism, durability, efficiency, and environmental impact.

Metal and metal oxide nanoparticles such as Ag, ZnO, and TiO_2 provide highly durable multifunctional properties due to their high surface-area-to-volume ratio and strong interaction with microbial cells. Their antimicrobial activity results from reactive oxygen species (ROS) generation, metal ion release, and disruption of microbial membranes and intracellular structures [12,15,16]. In addition to antimicrobial activity, nanoparticle-treated textiles can simultaneously exhibit UV protection, self-cleaning behavior, and flame retardancy with good resistance to repeated laundering [13,16,17].

Essential oils, in contrast, represent eco-friendly and biodegradable alternatives for textile finishing. Bioactive compounds including terpenes, phenolics, and aldehydes exert antimicrobial effects mainly through membrane disruption, enzyme inhibition, and leakage of intracellular materials [31–33]. These natural materials are generally safer and more sustainable than inorganic nanoparticles; however, their volatility and sensitivity to environmental conditions reduce their long-term effectiveness when directly applied to fabrics [32].

To improve durability, microencapsulation and nanoencapsulation techniques have been developed to control the release of essential oils from textile substrates [30–33]. Although these systems prolong antimicrobial and anti-odor performance, their washing durability and abrasion resistance remain lower than nanoparticle-based treatments [33].

From a functional perspective, nanoparticles generally provide broader-spectrums and more durable performance. Silver nanoparticles, for example, can achieve bacterial reduction rates exceeding 99% against both Gram-positive and Gram-negative microorganisms, whereas the effectiveness of essential oils depends strongly on composition and concentration [15,32]. Nevertheless, concerns regarding nanoparticle toxicity, environmental accumulation, and nanoparticle release during laundering continue to limit their unrestricted use [23–25]. Essential oils offer lower toxicity and reduce environmental persistence, making them more compatible with green chemistry and sustainable textile processing [19,31, 59]. However, challenges such as limited durability, possible skin sensitivity, and compositional variability still require further optimization before large-scale industrial implementation.

Nanoparticle-based systems provide superior multifunctionality and durability, while essential oils offer safer and more sustainable alternatives. Future developments are expected to focus on hybrid systems that combine nanomaterials with bio-based agents to achieve balanced performance, safety, and environmental compatibility.

IV. Conclusion

This work confirms that nanotechnology has become a major driving force in the development of multifunctional and high-performance textiles. The incorporation of nanomaterials into textile substrates significantly enhances antimicrobial activity, UV protection, flame retardancy, self-cleaning behavior, water and oil repellency, wrinkle resistance, and antistatic performance. These improvements are mainly attributed to the unique physicochemical characteristics of nanomaterials, including their high surface area, elevated surface reactivity, and strong interaction with textile fibres.

Metal and metal oxide nanoparticles such as silver, ZnO, TiO_2, and SiO_2 have demonstrated excellent effectiveness in textile finishing due to their durability, stability, and multifunctional properties. In addition, carbon-based nanomaterials, nanofibers, nano-coatings, and nanocomposite systems have expanded textile applications toward smart textiles, medical fabrics, protective clothing, and wearable electronic devices.

Modern processing methods including electrospinning, sol–gel treatment, plasma technology, and nano-finishing have further improved nanoparticle fixation, coating uniformity, and treatment durability without significantly affecting fabric comfort or flexibility. These technologies enable the production of advanced textile systems with long-lasting functional performance.

The comparison between nanoparticle-based treatments and essential oil functionalization indicates that nanoparticles generally provide superior durability and multifunctionality. However, essential oils remain attractive as biodegradable and environmentally friendly alternatives with lower ecological impact. Consequently, hybrid systems combining nanomaterials with natural bioactive agents represent a promising direction for achieving both high performance and sustainability.

Despite these advances, important challenges remain, particularly regarding nanoparticle toxicity, environmental accumulation, long-term stability, and nanoparticle release during laundering and disposal. Future research should therefore focus on green synthesis methods, biodegradable carrier systems, safer nanomaterials, and comprehensive environmental risk assessment to support sustainable industrial applications.

Nanotechnology offers significant potential for transforming conventional textiles into advanced multifunctional materials capable of meeting the increasing demands of healthcare, sportswear, protective clothing, and smart textile technologies while supporting the future of sustainable textile engineering.

References

[1] R.P. Feynman, There's plenty of room at the bottom, *Engineering and Science*, *23*(5), 1960, 22–36.

[2] N. Taniguchi, On the basic concept of nanotechnology, Proc. International Conference on Production Engineering, Tokyo, Japan, 1974, 18–23.

[3] B. Bhushan, *springer handbook of nanotechnology* (Berlin: Springer, 2017).

[4] G. Cao and Y. Wang, *nanostructures and nanomaterials: synthesis, properties and applications* (Singapore: World Scientific, 2011).

[5] S. Iijima, Helical microtubules of graphitic carbon, *Nature*, *354*, 1991, 56–58.

[6] A.K. Geim and K.S. Novoselov, The rise of graphene, *Nature Materials*, *6*(3), 2007, 183–191.

[7] P.M. Ajayan, Nanotubes from carbon, *Chemical Reviews*, *99*(7), 1999, 1787–1800.

[8] R. Dastjerdi and M. Montazer, A review on the application of inorganic nanostructured materials in textiles, *Colloids and Surfaces B: Biointerfaces*, *79*(1), 2010, 5–18.

[9] M. Montazer and T. Harifi, *nanofinishing of textile materials* (Cambridge, UK: Woodhead Publishing, 2018).

[10] I. Perelshtein, G. Applerot, N. Perkas, E. Wehrschuetz-Sigl, A. Hasmann, G.M. Guebitz and A. Gedanken, Sonochemical coating of ZnO nanoparticles on textile fabrics for antibacterial activity, *Nanotechnology*, *20*, 2009, 245705.

[11] V. Dhand, L. Soumya, S. Bharadwaj, S. Chakra, D. Bhatt and B. Sreedhar, Green synthesis of silver nanoparticles using *Coffea arabica* seed extract and its antibacterial activity, *Materials Science and Engineering C*, *58*, 2016, 36–43.

[12] M.A. Khan et al., Nanotechnology in textiles: progress and prospects, *Progress in Organic Coatings*, *148*, 2020, 105831.

[13] M. Rai et al., Silver nanoparticles as antimicrobial agents, *Biotechnology Advances*, *30*(3), 2012, 939–957.

[14] R. Singh et al., Metal nanoparticles for antimicrobial textiles, *Journal of Materials Chemistry B*, *6*, 2018, 10420–10434.

[15] I. Perelshtein et al., Antibacterial properties of nanomaterials in textiles, *Nanotechnology*, *19*, 2008, 155705.

[16] A. Fujishima, X. Zhang and D.A. Tryk, TiO_2 photocatalysis and related surface phenomena, *Surface Science Reports*, *63*(12), 2008, 515–582.

[17] X. Zhang et al., TiO_2-based self-cleaning textiles, *RSC Advances*, *7*, 2017, 10134–10144.

[18] A. Becheri et al., ZnO nanoparticles for UV-protective textiles, *Journal of Nanoparticle Research*, *10*, 2008, 679–689.

[19] P. Dhiman et al., ZnO nanoparticles in textile UV protection, *Materials Science and Engineering C*, *97*, 2019, 659–674.

[20] S. Iravani et al., Green synthesis of nanoparticles, *Green Chemistry*, *16*(2), 2014, 69–103.

[21] P. Singh et al., Biogenic synthesis of nanoparticles, *Applied Microbiology and Biotechnology*, *102*(12), 2018, 5131–5146.

[22] P. Raveendran et al., Green synthesis using natural stabilizers, *Journal of the American Chemical Society*, *125*(46), 2003, 13940–13941.

[23] G. Oberdörster et al., Nanotoxicology: emerging discipline, *Environmental Health Perspectives*, *113*(7), 2005, 823–839.

[24] A. Nel et al., Toxic potential of nanomaterials, *Science*, *311*(5761), 2006, 622–627.

[25] B. Fadeel et al., Safety assessment of nanomaterials, *Nature Nanotechnology*, *13*(8), 2018, 537–544.

[26] F. Gottschalk and B. Nowack, Environmental exposure of nanomaterials, *Journal of Environmental Monitoring*, *13*, 2011, 1145–1155.

[27] S. Burt, Essential oils: antibacterial activity, *International Journal of Food Microbiology*, *94*(3), 2004, 223–253.

[28] F. Bakkali et al., Biological effects of essential oils, *Food and Chemical Toxicology*, *46*(2), 2008, 446–475.

[29] M. Hyldgaard, T. Mygind and R.L. Meyer, Essential oils in food preservation: mode of action, synergies, and interactions with food matrix components, *Frontiers in Microbiology*, *3*, 2012, 12.

[30] R. Ribeiro-Santos, M. Andrade, N.R. Melo and A. Sanches-Silva, Use of essential oils in active food packaging: recent advances and future trends, *Trends in Food Science & Technology*, *61*, 2017, 132–140.

[31] C. Dima and S. Dima, Essential oils in foods: extraction, stabilization, and toxicity, *Current Opinion in Food Science*, *5*, 2015, 29–35.

[32] M.M.M. Specos, J.J. García, J. Tornesello, P. Marino, M.V.D. Della Vecchia and L. Hermida, Microencapsulated citronella oil for mosquito repellent finishing of cotton textiles, *Transactions of the Royal Society of Tropical Medicine and Hygiene*, *104*(10), 2010, 653–658.

[33] S.N. Rodrigues, I. Fernandes, I.M. Martins, V.G. Mata, M.F. Barreiro and A.E. Rodrigues, Microencapsulation of limonene for textile application, *Industrial & Engineering Chemistry Research*, *47*(12), 2008, 4142–4147.

[34] D.T. Leong (Ed.), *nano safety: nanotoxicology and nanomedicine* (Boca Raton, FL, USA: CRC Press, 2017).

[35] X. Du, X. Hou, Y. Guo and D. Jiang, Application and performance of cellulose acetate/polyglutamic acid/TiO_2 electrospun fibrous membrane, *Fibers and Polymers*, *22*(3), 2021, 685–693.

[36] Z. Abdullaeva, Nanomaterials for clothing and textile products, in *nanomaterials in daily life* (Cham, Switzerland: Springer, 2017) 111–132.

[37] N. Vigneshwaran and A. Arputharaj, Functional finishing of cotton textiles using nanomaterials, in *advances in functional finishing of textiles* (Singapore: Springer, 2020) 43–56.

[38] Ş.S. Uğur and M. Bilgiç, A novel approach for improving wrinkle resistance and flame retardancy properties of linen fabrics, *Bilge International Journal of Science and Technology Research*, *1*, 2017, 79–86.
[39] D. Hanaor and C. Sorrell, Review of the anatase to rutile phase transformation, *Journal of Materials Science*, *46*, 2011, 855–874.
[40] H.G. Völz, J. Kischkewitz, P. Woditsch and A. Westerhaus, Pigments, inorganic, in *ullmann's encyclopedia of industrial chemistry* (Berlin, Germany: Wiley-VCH Verlag GmbH, 2006).
[41] E. Baldini, Strongly bound excitations in anatase TiO_2 single crystals and nanoparticles, *Nature Communications*, *8*, 2017, 13.
[42] J. Howard, *current intelligence bulletin 63: occupational exposure to titanium dioxide* (Cincinnati, OH, USA: National Institute for Occupational Safety and Health, 2011) 79–82.
[43] *nanotechnology: nanomaterials are widely used in commerce, but EPA faces challenges in regulating risk* (Washington, DC: U.S. Government Accountability Office, 2010).
[44] H. Zhang, G. Chen and D.W. Bahnemann, Photo-electro catalytic materials for environmental applications, *Journal of Materials Chemistry*, *19*(29), 2009, 5089–5121.
[45] Y. Zhang, Y. Leu, R. Aitken and M. Riediker, Inventory of engineered nanoparticle-containing consumer products available in the Singapore retail market and likelihood of release into the aquatic environment, *International Journal of Environmental Research and Public Health*, *12*(8), 2015, 8717–8743.
[46] International Organization for Standardization (ISO), *ISO/TS 11937:2012 nanotechnologies — nanoscale titanium dioxide in powder form — characteristics and measurement* (Geneva, Switzerland: ISO, 2012).
[47] F. Piccinno, F. Gottschalk, S. Seeger and B. Nowack, Industrial production quantities and uses of ten engineered nanomaterials in Europe and the world, *Journal of Nanoparticle Research*, *14*(9), 2012, 1–11.
[48] A. Keller, S. McFerran, A. Lazareva and S. Suh, Global life cycle releases of engineered nanomaterials, *Journal of Nanoparticle Research*, *15*(6), 2013, 1692.
[49] M.E. Vance, T. Kuiken, E.P. Vejerano, S.P. McGinnis, M.F. Hochella, D. Rejeski and M.S. Hull, Nanotechnology in the real world: redeveloping the nanomaterial consumer products inventory, *Beilstein Journal of Nanotechnology*, *6*(1), 2015, 1769–1780.
[50] P.A. Schulte, G. Roth, L.L. Hodson, V. Murashov, M.D. Hoover et al., Taking stock of the OSH challenges of nanotechnology, *Journal of Nanoparticle Research*, *18*, 2016, 159.
[51] Organisation for Economic Co-operation and Development (OECD), *future challenges related to the safety of manufactured nanomaterials* (Paris, France: OECD Publishing, 2016).
[52] R. Kessler, Engineered nanoparticles in consumer products: understanding a new ingredient, *Environmental Health Perspectives*, *119*(3), 2011, A120–A125.
[53] S. Koul, N. Gulati, D. Verma, S. Mukherjee and U. Nagaich, Role of nanotechnology in cosmeceuticals: a review of recent advances, *Journal of Pharmaceutics*, *2018*, 2018, 3420204.
[54] J.L. Topmiller and K.H. Dunn, Current strategies for engineering controls in nanomaterial production and downstream handling processes, *Journal of Chemical Health and Safety*, *20*(6), 2013, 35–41.
[55] C.J. Jang, H. Lee and W. Lyoo, Effect of UV irradiation on cellulose degradation of cellulose acetate containing TiO_2, *Fibers and Polymers*, *8*, 2007, 19–24.
[56] O. Carp, C.L. Huisman and A. Reller, Photo induced reactivity of titanium dioxide, *Progress in Solid State Chemistry*, *32*(1–2), 2004, 33–177.
[57] A. El-Shafei, M. El-Shemy and A. Abou-Okeil, Eco-friendly finishing agent for cotton fabric to improve flame retardant and antibacterial properties, *Carbohydrate Polymers*, *118*, 2015, 83–90.
[58] O. Semperger, Z. Osváth, S. Pásztor and A. Suplicz, The effect of the titanium dioxide nanoparticles on the morphology and degradation of polyamide 6 prepared by anionic ring-opening polymerization, *Polymer Engineering & Science*, *62*(6), 2022, 2079–2088.
[59] C. SenthilKumar, S. Anusuya and V. Anbazhagan, A critical review on the fabrication of ZnO nanoparticles and their antidiabetic and anticancer activities, *Next Nanotechnology*, *8*, 2025, 100248.