

Recent Advances in Functionalization of Cotton Fabrics with Nanotechnology

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Abstract: Nowadays, consumers understand that upgrading their traditional clothing can improve their lives. In a garment fabric, comfort and functional properties are the most important features that a wearer looks for. A variety of textile technologies are being developed to meet the needs of customers. In recent years, nanotechnology has become one of the most important areas of research. Nanotechnology's unique and useful characteristics have led to its rapid expansion in the textile industry. In the production of high-performance textiles, various finishing, coating, and manufacturing techniques are used to produce fibers or fabrics with small nano sizes. Humans have been utilizing cotton for thousands of years, and it accounts for around 34% of all fiber production worldwide. The clothing industry, home textile industry, and healthcare industry all use it extensively. Nanotechnology can enhance cotton fabrics' properties, including antibacterial activity, self-cleaning, UV protection, etc. Research in the field of functional cotton fabrics with nanotechnology is presented in the present study.

Keywords: multifunctional cotton fabrics; nanotechnology; metal nanoparticles

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1. Introduction

Textiles are commonly used in industries and households. The surface modification of textiles to impart multiple functions has recently gained a lot of attention. Researchers have successfully functionalized textiles for antibacterial, self-cleaning, flame retardant, UV protection, and enhanced performance properties [1]. Therefore, high-tech materials and fabric constructions will improve wearer comfort while incorporating distinctive features [2]. Among natural fibers, cotton is the most popular because of its softness, breathability, safety, low cost, regeneration performance, strength, elasticity, biodegradability, and hydrophilicity [3,4]. Cotton fabric does, however, have some disadvantages, including the possibility of microbial attacks on its fibrous structure, the ease with which creases form, and the loss of mechanical strength [5]. Microorganisms can easily grow and propagate on cotton fabrics because they are able to store humidity and have a high specific surface area [6]. A variety of fields, including health and medicine, have benefited from cotton fibers with antimicrobial properties [7]. Hygienic, functional, durable, and comfortable cotton fabrics are expected in modern times. Utilizing nanotechnology in cotton cloth is a significant challenge in achieving these characteristics and advancements [8]. Nanoparticles have been incorporated into textile finishing stages to address the inherent problems while also imparting functional properties to textile materials [9–15].

In a variety of applications, nanotechnology is widely regarded as having enormous potential around the world [16]. The textile industry has discovered nanotechnology,

resulting in a new area of textile finishing called “Nano finishing”. Nano-sized particles have many desirable properties without adding a lot of weight, thickness, or stiffness to fabrics [17]. The first company to use nanotechnology in textiles was Nano-Tex, a subsidiary of Burlington Industries in the United States. As a result, a growing number of textile companies began investing in nanotechnology development [16]. While traditional textile finishing techniques do not always result in permanent effects and their functionality is lost after laundering or use, nanotechnology can provide a highly stable treatment [18,19].

In this review, we discuss recent developments in nanoparticles (primarily metals and metal oxide nanoparticles) used to modify and finish cotton fabrics from 2018 to 2022 to provide antimicrobial (antibacterial, antifungal), antiviral, UV protection, self-cleaning, water-repellent, and flame-retardant properties.

2. Common Types of Nanomaterials

There are many types of nanotechnology-produced materials, but the following four are receiving significant attention:

2.1. Nanofinishing

The process of nanofinishing involves applying colloidal solutions or ultrafine dispersions of nanomaterials to fabrics to improve some of their functionalities [20]. In the case of nanofinishing, a smaller quantity of nanomaterials is required in comparison to the bulk materials used in traditional finishing to achieve a similar effect. These nanofinishings do not alter the aesthetic feel of textile materials. They are more durable because they have a higher surface area-to-volume ratio in textile materials as well as a homogeneous distribution [21]. By using nanofinishing, existing processes can be improved, or new functional properties can be achieved that are not possible with traditional finishes [22].

2.2. Nanocoating

As part of nanocoating, a thin layer of less than 100 nm in thickness is deposited on a substrate to improve some properties or to add new functionality [23] such as enhanced color fastness, flame retardance, water or oil repellency, wrinkle resistance, and antimicrobial properties. Traditionally, textile coatings have thicknesses in the micrometer or millimeter range. However, conventional coatings can make fabrics completely impermeable, affecting their handling, feel, and breathability [24].

2.3. Nanofibers

As compared to conventional fibers, nanofibers have higher stiffness and tensile strength, as well as a very high surface area to weight ratio, low density, and a high pore volume. Because of these characteristics, nanofibers can be used in a wide variety of applications [25]. A variety of techniques can be used to fabricate nanofibers. One example of these techniques is phase separation, template synthesis, self-assembly fibers, and electrospinning (ELS). Electrospinning is a low-cost method for producing nanofibers [26].

2.4. Nanocomposites

It is possible to create nanocomposite fibers by dispersing nanosized fillers within a fiber matrix. Nanocomposite fibers can be developed with high electrical conductivity, superior strength, toughness, and lightweight using fillers such as nanosilicates, metal oxide nanoparticles, graphite nanofibers (GNFs), and single-wall and multi-wall carbon nanotubes (CNTs) [27].

3. Metal Nanoparticles (MNPs)

Among the nanomaterials used, metal nanoparticles (MNPs) are the most popular and versatile. For their diverse functional properties, numerous types of nanoparticles (NPs) have been integrated into various textile materials [28].

Inorganic nanoparticles, such as TiO_2 , ZnO , SiO_2 , Cu_2O , CuO , Al_2O_3 , and reduced graphene oxide, are more commonly used than organic nanoparticles due to their thermal and chemical durability at high temperatures, their permanent stability under ultraviolet rays, and their non-toxicity [29,30]. A summary of the functions of metal nanoparticles can be found in Figure 1. Their ability to stick to fibers is also heavily influenced by their size. It is logical to assume that the largest particle cluster will easily be removed from the fiber surface, but the smallest particles will penetrate deeper and stick more firmly to the fabric. Reduced particle size results in changes in the material's properties [31]. The presence of a reducing and stabilizing agent is essential in the preparation of these metallic nanoparticles. Metal nanoparticles are prepared by the reduction of metal salt solutions [32].

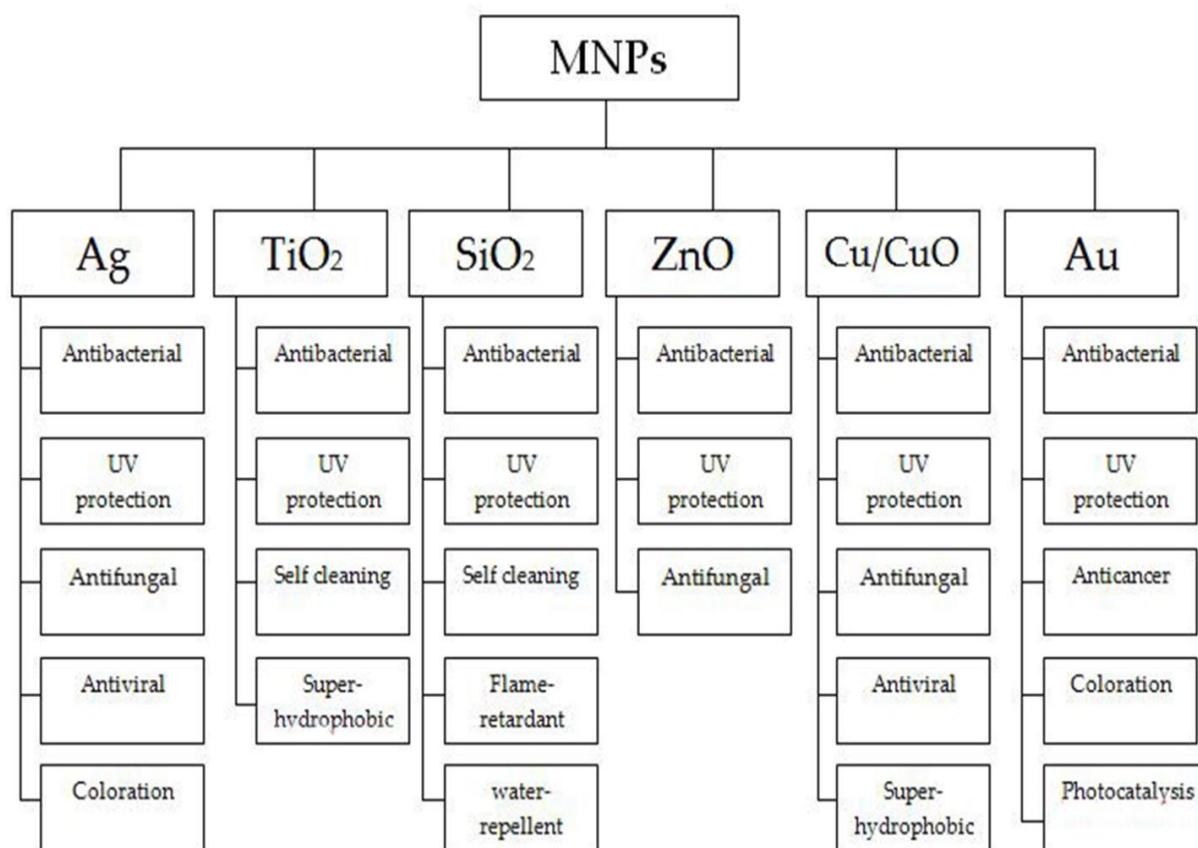


Figure 1. Metal nanoparticles and their functions used in textiles.

Nanoparticles are synthesized using a variety of physical, chemical, and biological methods. [33,34]. The synthesis of NPs can be summarized in Figure 2. The nanoparticles synthesized using the green approach appear to be more stable and beneficial. Besides being simple and inexpensive, it is easy to characterize as well. A major advantage of green synthesis is that it produces nanoparticles with lower toxicity, making them less harmful to the environment [35,36].

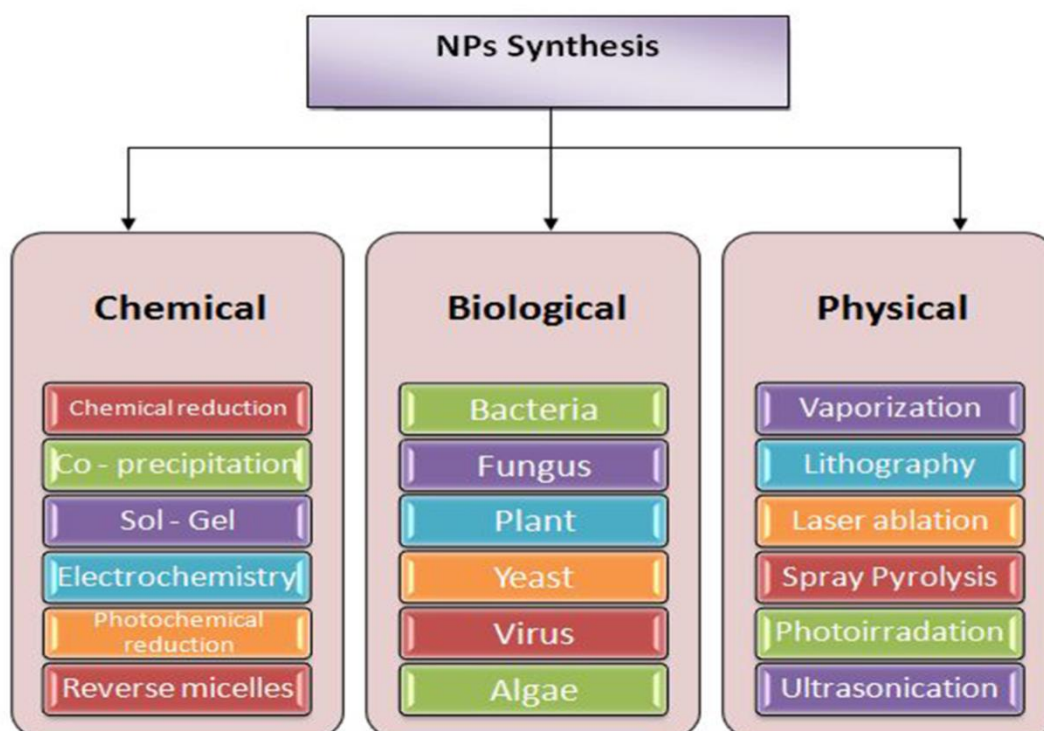


Figure 2. Method of nanoparticles synthesis.

3.1. Silver Nanoparticles (AgNPs)

One of the most used antimicrobial nanoparticles is silver (Ag). It acts as a doping antimicrobial agent and exhibits antimicrobial activity without affecting mechanical properties [37]. AgNPs have strong antiviral properties. Furthermore, AgNPs interactions with viruses can be improved by evaluating their physiochemical properties such as size, shape, surface charge, dispersion, and protein corona effects [38]. As part of a finishing procedure, AgNPs can be deposited on the surface of textile products to functionalize them, such as spraying (using plasma), surfacing by pad baths or coating (sol-gel or “layer-by-layer”), or producing AgNPs directly on fiber surfaces and inside them [39]. Cotton fabrics have been coated with AgNPs using a variety of techniques [40]. The functionalization of cotton fabrics incorporating AgNPs is summarized in Table 1.

Xu et al., 2018 [41] created durable antimicrobial cotton fabrics using AgNPs that were applied to cotton fabric using the pad-dry-cure technique. After 50 washing cycles, the cotton fabrics showed excellent antimicrobial activity (94%) against *Escherichia coli* and *Staphylococcus aureus*. Cotton’s original properties, such as tensile strength, water absorption, and vapor permeability, are not significantly affected by the modification. Rajaboopathi and Thambidura [42] fabricated functional cotton fabrics with AgNPs.

A seaweed extract (*Padinagymnospora*) was used to synthesize AgNPs, and citric acid was used as a crosslinker for applied AgNPs. The functionalized cotton fabrics were tested against *S. auris* (Gram-positive) and *E. coli* (Gram-negative). Cotton functionalized with AgNPs inhibited bacteria growth and provided better UV protection. A study by Patil et al. [43] used sonochemistry and deposition to create AgNP-coated cotton fabrics with antimicrobial properties. They found that AgNPs uniformly deposited on cotton fabrics and showed excellent antibacterial activity against Gram-negative bacteria and Gram-positive bacteria. According to Ramezani et al., AgNPs produced by polyol methods were used to functionalize cotton fabrics with antibacterial and antifungal properties in 2019 [44]. A cotton textile coated with antimicrobial activity inhibited the growth of *Staphylococcus aureus*, *Escherichia coli*, and *Candida albicans*. In 2020, Maghima et al. [45] evaluated the antimicrobial and wound-healing activity of coated cotton fabric with AgNPs.

Peltophorumpterocarpum leaf extracts were used in the synthesis of AgNPs. The AgNPs cotton fabrics showed a good zone of inhibition against *S. aureus*, *P. aeruginosa*, *S. pyogenes*, and *C. albicans* and good wound healing activity when tested against fibroblast. The antibacterial activity of functionalized textiles with AgNPs against *Escherichia coli*, *Staphylococcus aureus*, *Pseudomonasaeruginosa*, *Klebsiellapneumoniae*, *Klebsiellaoxytoca*, and *Proteusmirabilis*, and antifungal activities against *Aspergillus Niger* were reported by Aguda and Lateef [46]. AgNPs were synthesized using wastewater from fermented seeds of *Parkiabiglobosa*. Using a pad-dry-cure approach, AgNPs were applied to cotton and silk. The AgNPs-functionalized textiles prevented bacteria growth up to the fifth cycle of washing. In the same year, Deeksha et al. [47] developed antibacterial cotton fabrics with AgNPs using the medicinal plant *Vitex* leaf extract. The fabrics showed 100% antifungal potency against *Aspergillus Niger*. According to Hamouda et al. [48], cotton treated with AgNPs had the greatest antibacterial, antifungal, and antiviral activity with 51.7% viral inhibition against MERS-CoV, high antibacterial activity against Gram-positive and Gram-negative bacteria, and the greatest antifungal activity against *A. niger* and *C. albicans*. Chavez et al. [49] also developed cotton fabrics that were antibacterial and antifungal. They used AgNPs to finish the fabric against *Escherichia coli*, *Staphylococcus aureus*, *Candida albicans*, and *Aspergillus Niger*. Fabrics treated with AgNPs showed 100% antibacterial activity and good antifungal activity.

Table 1. Summary of the functionalization of cotton fabrics integrated with AgNPs.

Types of Fabric	Nanomaterials	NPs Size	Synthesis Method	Application Method	Functionality	Ref Year
Cotton	AgNPs	* n.a	-	Pad-dry-cure	Antibacterial	[41] 2018
Cotton	AgNPs	* n.a	Seaweed (<i>Padi-nagymnospora</i>) extract	Pad-dry-cure	Antibacterial and UV protection	[42] 2018
Cotton	AgNPs	* n.a	Sonochemical	-	Antibacterial	[43] 2019
Cotton	AgNPs	50–100 nm.	Polyol method	Dip coating	Antibacterial and Antifungal	[44] 2019
Cotton	AgNPs	15–40 nm	Peltophorumpterocarpum leaf extracts	Coating	antimicrobial and wound healing activity	[45] 2020
Cotton	AgNPs	11.00–83.30 nm	<i>Parkiabiglobosa</i> wastewater	Pad-dry-cure	Antibacterial and Antifungal	[46] 2021
Cotton	AgNPs	91–100 nm	Medicinal plant <i>Vitex</i> leaf extract	-	Antibacterial	[47] 2021
Cotton	AgNPs	* n.a	Chemical method	Coating	Antibacterial, antifungal, and antiviral	[48] 2021
Cotton	AgNPs	5–20 nm	Chemical method	Exhaustion method	Antibacterial and Antifungal	[49] 2022

* n.a = not available.

3.2. Titanium Dioxide Nanoparticles (TiO_2 NPs)

TiO_2 is an inorganic material with many applications in textile manufacturing, particularly UV protection [50], self-cleaning, and antimicrobial properties [51]. Due to its unique properties such as stability, non-toxicity, photocatalytic, chemical resistance, and convenient production technique [52], TiO_2 has drawn a lot of attention. In the presence of TiO_2 , reactive oxygen species (ROS) such as superoxide and hydroxyl radicals can be generated. ROS can damage bacteria's cell walls, causing them to die. It is this property of

TiO₂ nanoparticles that has been used in antibacterial textiles [53]. The percentage of bacteria killed by combining TiO₂ with other metal/metal oxide/polymer/carbon nanoparticles/matrices has been shown in many studies [54]. Using an in-situ sol-gel approach, Peter et al. [55] investigated how TiO₂ nanoparticles can be produced and incorporated into cotton fabrics for self-cleaning purposes. The self-cleaning performance of cotton fabrics loaded with TiO₂ was improved. The pad-dry-cure process was developed by Wang et al. [56] to finish cotton fabric with multifunctional TiO₂NPs. In a variety of stains, the finished fabric demonstrated excellent self-cleaning properties. A piece of UV-protective cotton fabric was developed by Cheng et al. [57]. Layer-by-layer self-assembly was used to apply TiO₂ NPs to cotton fabric. The UPF values According to the UPF values, the TiO₂NPs cotton fabrics provided excellent UV protection.

In 2019, Riaz et al. [58] investigated the applications of TiO₂ with 3-(Trimethoxysilyl) propyl-*N,N,N*-dimethyloctadecylammonium chloride and 3-(Glycidoxypropyl)trimethoxy-silane in textiles. As a result, they found that treated cotton showed durable super-hydrophobicity, self-cleaning, and antibacterial properties. Alipourmohammadi et al. [59] reported self-cleaning and antibacterial properties of cotton fabrics with TiO₂ NPs. As compared to uncoated cotton fabrics, TiO₂NPs-coated materials possess superior self-cleaning and antibacterial properties. Bekrani et al. [60] created antibacterial and UV-protective cotton fabrics coated with TiO₂NPs. The nano-textiles displayed excellent activity against Gram-negative and Gram-positive bacteria. The UV-blocking of treated samples revealed that when exposed to UV irradiation, all samples have very low transmission.

In 2020, El-Bisi et al. [61] developed cotton fabrics with improved antibacterial and ultraviolet properties after treating them with TiO₂NPs with *Moringaoleifera* extract. The UPF and antibacterial properties of TiO₂NPs cotton fabrics are improved.

The TiO₂NPs were synthesized by using Aloe vera extract in a green method by Saleem et al. [62]. The TiO₂-coated fabric demonstrated excellent self-cleaning properties. The tensile strength of the fabric decreased slightly but increased after the TiO₂ coating. A list of the functionalization of cotton fabrics integrated with TiO₂NPs is presented in Table 2.

Table 2. A list of the functionalization of cotton fabrics integrated with TiO₂NPs.

Types of Fabric	Nanomaterials	NPs Size	Synthesis Method	Application Method	Functionality	Ref Year
Cotton	TiO ₂ NPs	n.a	In situ sol-gel	Immersion, drying	Self-cleaning	[55] 2018
Cotton	TiO ₂ NPs	Small size	Sol-gel	Pad-dry-cure	Self-cleaning	[56] 2018
Cotton	TiO ₂ NPs	50–120 nm	In situ hydrothermal under sonication	Layer-by-layer self-assembly	UV protection	[57] 2018
Cotton	TiO ₂ NPs	40 nm	Chemical method	Dip coating	Durable super-hydrophobicity, self-cleaning and antibacterial.	[58] 2019
Cotton	TiO ₂ NPs	20–25 nm.	In situ ultrasonic assisted sol-gel	Immersion, drying, curing	Self-cleaning and antibacterial	[59] 2019
Cotton	TiO ₂ NPs	Less than 50 nm	-	Immersion, heating, drying	Antibacterial and UV protection	[60] 2019
Cotton	TiO ₂ NPs	n.a	-	Immersion, pad-dry-cure	Antibacterial and UV protection	[61] 2020
Cotton	TiO ₂ NPs	11.27 nm	Aloe vera extract in a green method	Pad dry	Self-cleaning	[62] 2021

3.3. Silica Nanoparticles (SiO₂ NPs)

Silica nanoparticles (SiO₂NPs) have recently received a lot of attention because of their potential applications in several fields of science and industry. Their properties include self-cleaning, water-repellency, UV protection, and antibacterial properties. Textiles are most modified with nano silica [63]. In cotton fibers, SiO₂NPs penetrate easily and bind tightly to the fiber structure. Consequently, cellulose hydroxyl groups and SiOH form covalent bonds in SiO₂NPs. SiO₂NPs are added to the surfaces of materials to improve their mechanical properties, durability, function, activity, and stability [64].

Rethinam et al. [65] developed antibacterial/ultraviolet cotton fabrics using SiO₂NPs produced from xerogels at different concentrations (1, 2, and 3% *w/v*). Among the different concentrations of SiO₂NPs used, 3% (*w/v*) exhibited better mechanical properties, breaking strength, elongation at break, and tearing strength, and demonstrated the highest antibacterial activity against *Staphylococcus aureus* and *Escherichia coli*, as well as UV protection. Using SiO₂NPs, Riaz et al. [66] developed highly durable superhydrophobic and antibacterial cotton fabrics. Cotton fabric was treated with SiO₂NPs using a pad-dry-cure technique.

The study also revealed excellent antibacterial properties and super hydrophobicity, as well as high comfort properties such as bending rigidity and tensile strength and maximum laundry durability. According to Zakir et al. [67], SiO₂NPs were used to fabricate superhydrophobic cotton fabrics. Dip-coating was used to deposit SiO₂NPs on cotton fabrics. The results showed that cotton sample surface wettability changed from superhydrophilicity to true superhydrophobicity. PFOA-Free Fluoropolymer-Coated SiNPs or Omni Block, created by Kwon et al. [68], demonstrated excellent oil and water repellency on cotton fabrics. PFOA-free fluoropolymer was cross-linked between Si-O-Si groups to produce PFOA-free fluoropolymer-coated Si NPs. After coating the cotton fabric with PFOA-free fluoropolymer-coated SiNPs *via* a dip-dry-cure method, a rough, high-surface-area oleophobic structure developed. The cotton fabric's thermal stability and mechanical strength were improved by the coating.

Because SiO₂NPs have high thermal stability, they can also be used to prepare flame-retardant textiles. In 2021, Shahidi et al. [69] used in-situ synthesis to deposit SiO₂NPs on cotton fabrics. By impregnating the cotton fabrics with SiO₂NPs, the flame-retardant properties have greatly improved, and samples have been found to be hydrophilic. Amibo et al. [70] investigated the antibacterial properties of SiO₂NPs loaded with AgNPs-coated cotton fabrics. Selected strains of bacteria such as *Staphylococcus aureus*, *Escherichia coli*, and *Pseudomonas aeruginosa* were tested for antimicrobial activity with improved activities by the treated fabric. Hasabo and Rahma [71] fabricated a superhydrophobic, water-repellent cotton fabric coated with SiO₂NPs. The hydrophilic surface of cotton fabric was not changed by SiO₂NPs treatment, indicating that water drops were absorbed into fabrics due to the hydroxyl groups on both the cotton and silica NPs surfaces. Abou Elmaaty et al. [64] studied the effects of both adding lycra yarns with different densities and SiO₂NPs on the functional performance of pile cotton fabrics. They concluded that treated cotton/lycra (90.5/9.2%) 19 pick/cm showed excellent antibacterial, highly self-cleaning, and excellent UV protection. The reported functionalization of cotton fabrics with SiO₂NPs is presented in Table 3.

Table 3. A survey of the functionalization of cotton fabrics with SiO₂NPs.

Types of Fabric	Nanomaterials	NPs Size	Synthesis Method	Application Method	Functionality	Ref Year
Cotton	SiO ₂ NPs	20–100 nm	Xerogels synthesis- from cotton pods	ed Immersion, dry- ing	Antibacterial and UV protection	[65] 2018
Cotton	SiO ₂ NPs	20–30 nm	-	Pad-dry-cure	Durable superhydrophobic and antibacterial	[66] 2019

Cotton	SiO ₂ NPs	90–150 nm	Stöber method	Dip-coating	Superhydrophobic	[67] 2020
Cotton	SiO ₂ NPs	200 nm	Stöber method	Dip-dry-cure	Oil and water repellency	[68] 2020
Cotton	SiO ₂ NPs	n.a	In-situ sol-gel	Immersion, dry-ing	Flame-retardant	[69] 2021
Cotton	SiO ₂ /Ag NPs	n.a	SiO ₂ NPs by sol-gel AgNPs by green synthesis	-	Antibacterial	[70] 2021
Cotton	SiO ₂ NPs	150–300 nm	Sol-gel	Immersion, pad-dry-cure	Super hydrophobicity Water-repellent	[71] 2021
Cotton/ lycra	SiO ₂ NPs	10–14 nm	Sol-gel	Pad-dry-cure	Antibacterial, UV protection and self-cleaning	[64] 2021

3.4. Zinc Oxide Nanoparticles (ZnO NPs)

In textile finishing, zinc oxide (ZnO) has gained popularity because of its following numerous advantages: UV protection [50], antibacterial and antifungal properties, and the ability to speed wound healing [72]. ZnO nanoparticles have been deposited or incorporated into cotton using various chemical/physical techniques to develop antibacterial, antifungal, and UV-protective nanotextiles. Table 4. summarizes the functionalization of cotton fabrics treated with ZnO NPs.

Using ZnO-NPs, Fouda et al. [73] fabricated multifunctional medical cotton fabrics. Using secreted proteins from *Aspergillus terreus* AF-1, ZnO nanoparticles were synthesized on cotton fabric to investigate antibacterial activity and UV-protection properties. Bacteria were inhibited by the functionalized fabrics. The ZnO NPs have an excellent ability to block UV rays, resulting in an increase in the UPF value of the cotton fabric treated with them. Salat et al. [74] also investigated the antibacterial properties of cotton medical fabrics with ZnO NPs and gallic acid (GA). Cotton fabric was uniformly coated with ZnO NPs. Despite 60 cycles of washing, the antibacterial efficacy of ZnO NPs-GA-coated fabrics remained above 60%. To obtain antibacterial fabrics, Souza et al. [75] used the solo chemical process for ZnONPs on cotton fabrics. The antibacterial activity of cotton fabrics against *Staphylococcus aureus* and *Pseudomonas aeruginosa* was tested. The antibacterial activity of the treated cotton was higher against *Staphylococcus aureus* than against *Pseudomonas aeruginosa*.

In another study, Roy et al. [76] synthesized ZnONPs using a chemical method. ZnO NPs were then applied to cotton fabric using dip coating. Antifungal and antibacterial activities of treated samples were examined at various mole concentrations of ZnO NPs (1M, 1.5M, 2M, 2.5M, and 3M). The fabrics treated were tested for antifungal activity against *Aspergillus Niger* as well as antibacterial activity against *staphylococcus aureus* and *Escherichia coli*. At a concentration of 2M, the antibacterial and antifungal activity is highest. Mulchandani et al. [77] prepared ZnONPs using a wet chemical method and applied them to cotton fabrics in different concentrations (0.01%, 0.05%, 0.10%, and 0.25%). After 50 cycles of washing, 0.1% of ZnO NPs showed excellent antimicrobial activity against *Staphylococcus aureus* and *Klebsiella pneumoniae*. To impart antibacterial activity to cotton (woven, single jersey, rib/double jersey), Momotaz et al. [78] used spin coating and pad-dry-cure methods. The pad-dry-cure technique gave better antibacterial activity than spin coating. Double jersey fabric showed the highest antibacterial activity against (*S. aureus* and *E. coli*) than woven and single jersey fabric. In the next study, Mousa and Khairy [79] produced cotton defense clothing. They used a liquid precipitation method to synthesize ZnONPs and investigated the antimicrobial and UV protection of cotton fabrics. ZnONPs were incorporated onto cotton fabrics using the dip and curing method. The nano treated

fabrics showed the highest antimicrobial activity for *Staphylococcus aureus*, *Escherichiacoli*, and *Candida albicans*, and the highest UPF values.

Tania and Ali [80] created cotton functional fabrics using the following three different ZnONP recipes: ZnONPs (ZnO-A), ZnONPs with a binder (ZnO-B), and ZnONPs with a binder and wax emulsion (ZnO-C). The treated fabrics were tested within one hour for *Staphylococcus aureus* and *Escherichia coli*. Nanotreated fabrics significantly reduced the growth of the two bacteria by 50.54–90.43%. ZnO-B and ZnO-C nano fabrics showed 99% reductions. Nano ZnO-B and nano ZnO-C have excellent UPF values. Patil et al. [81] prepared ZnONPs using sono synthesis and applied them to cotton fabrics in 2021. Finished fabrics with ZnO NPs demonstrated flexural rigidity, tensile strength, water contact angle, and air permeability. Against *Escherichia coli* and *Staphylococcus aureus* bacteria, they showed excellent antibacterial activities.

Table 4. Summary of the functionalization of cotton fabrics treated with ZnO NPs.

Types of Fabric	Nanomaterials	NPs Size	Synthesis Method	Application Method	Functionality	Ref Year
Cotton	ZnONPs	n.a	(Biological method) secreted proteins by the isolated fungus <i>Aspergillus-terreus</i> AF-1	Pad-dry-cure	Antibacterial and UV protection	[73] 2018
Cotton	ZnONPs	<100 nm	In situ sono-chemical	Coating	Antibacterial	[74] 2018
Cotton	ZnONPs	n.a	Sono-chemical	Immersion, drying	Antibacterial	[75] 2018
Cotton	ZnONPs	n.a	Chemical method	Dip coating	Antibacterial and Antifungal	[76] 2020
Cotton	ZnONPs	n.a	Wet chemical	Pad-dry-cure	Antibacterial	[77] 2020
Cotton	ZnONPs	n.a	-	Spin coating & Pad-dry-cure	Antibacterial	[78] 2020
Cotton	ZnONPs	26 nm	liquid precipitation	Dip and curing	Antibacterial, anti-fungal and UV protection	[79] 2020
Cotton	ZnONPs	70 (\pm 5) nm	Wet chemical	Mechanical thermo-fixation (Pad-dry-cure)	Antibacterial and UV protection	[80] 2021
Cotton	ZnONPs	n.a	Sono synthesis	Coating	Antibacterial	[81] 2021

3.5. Copper/Copper Oxide Nanoparticles (Cu/CuO NPs)

Due to their abundance, availability, and low cost, copper nanoparticles are gaining popularity [82]. As a result, CuONPs are used in a variety of applications, including anti-fungal, antiviral, antibiotics, anticancer, photocatalytic, biomedical, and agricultural fields [83]. CuONPs possess antimicrobial activity against *Bacillus subtilis*, *E. coli*, *Staphylococcus aureus*, *Micrococcus luteus*, *Pseudomonas aeruginosa*, *Salmonella enterica*, and *Enterobacteraerogenes*, as well as antifungal activity against *Fusariumoxysporum* and *Phytophthoracapsici*. Accordingly, CuONPs have shown significant antiviral activity against human influenza A (H1N1), avian influenza (H9N2), and many other viruses, including COVID-19 [84].

In 2018, Nourbakhsh and Iranfar [85] prepared cotton fabrics with antibacterial properties by using CuONPs with different concentrations (0.01, 0.03, 0.05, 0.1, 0.2, 0.5, 10%).

These fabrics were tested against *Escherichia coli* and *staphylococcus aureus* for their antibacterial properties. At 1% of CuONPs, the antibacterial activity of *E. coli* and *S. aureus* increased with increasing CuONP concentration (99% and 98%, respectively). Despite 5 laundering cycles, antibacterial activity for both bacteria decreased by 92%. The recovery angle, bending length, and wetting time all increased with increasing CuONP concentrations. A cotton fabric with antibacterial properties was developed by Sun et al. [86] by synthesizing CuONPs and applying them by ATRP and electroless deposition on cotton fabrics. A uniform distribution of CuONPs was observed on the cotton fabric's surface. CuONP-functionalized cotton fabric exhibited excellent antibacterial activity against *S. aureus* and *E. coli* even after 30 cycles of washing. CuO nanoparticles were incorporated into cotton fabrics by Paramasivan et al. [87]. Using Cassia alata leaf extract as a reducing agent, CuONPs were synthesized. *Escherichia coli* bacteria were significantly inhibited by nanocotton fabric. Even after 15 washes, these nanocomposites retained antibacterial activity, indicating that they contained permanent CuONPs.

Shaheen et al. [88] treated cotton fabrics with CuO NPs to produce antibacterial textiles in 2021. Aspergillusterreus AF-1 biomass filtrate was used to synthesize CuONPs. CuO NP-treated cotton fabrics showed significant antibacterial activity against *Bacillus subtilis* and *P. aeruginosa*, but this efficacy was reduced against *S. aureus* and *E. coli*. Alagarasnet et al. [89] also produced a cotton fabric treated with CuO NPs for enhanced antibacterial and antifungal properties. Cotton fabrics were coated with CuONPs using the pad-dry-cure technique. They tested the antimicrobial activity against *S. aureus*, *E. coli*, *P. fluorescens*, and *B. subtilis*, as well as the antifungal activity against *Candida albicans*. Nanocoated fabrics showed better antibacterial and antifungal properties. CuO NPs-coated cotton fabrics were also investigated by El-Nahhal et al. [90]. The treated fabric showed improved antimicrobial activity against selected strains of bacteria such as *E. coli* and *S. aureus*. In addition to their antiviral properties, they may also be useful in combating the spread of the COVID-19 Corona Virus. Table 5 summarizes the functionalization of cotton fabrics with Cu/CuO NPs.

Table 5. Summary of the functionalization of cotton fabrics with Cu/CuO NPs.

Types of Fabric	Nanomaterials	NPs Size	Synthesis Method	Application method	Functionality	Ref Year
Cotton	Cu NPs	Less than 100 nm	-	Immersion, drying	Antibacterial	[85] 2018
Cotton	Cu NPs	130 ± 20 nm	ATRP and electroless deposition	Immersion, drying	Antibacterial	[86] 2018
Cotton	CuO NPs	40–100nm	Green synthesis (Cassia alata leaf extract)	Dip coating Shaking+	Antibacterial	[87] 2018
Cotton	CuO NPs	11–47 nm	Green synthesis (Biomass Filtrate of Aspergillusterreus AF-1)	Immersion, pad-dry-cure	Antibacterial	[88] 2021
Cotton	CuO NPs	10–100 nm	In situ synthesis	Pad-dry-cure	Antibacterial and Antifungal	[89] 2021
Cotton	CuO NPs	n.a	-	Ultrasonic irradiation	Antibacterial and antiviral	[90] 2021

3.6. Gold Nanoparticles (Au NPs)

The optical, electronic, and magnetic properties of Au NPs have drawn a lot of attention in textile research. Textiles also contain Au NPs for electronic and medical applications [91].

In 2018, Shanmugasundaram and Ramkumar [92] attempted to improve the antibacterial property of cotton fabric by coating it with keratin protein and Au NPs using a padded method. AuNPs were synthesized using a chemical reduction method. Incorporating Au NPs and keratin improved antibacterial efficacy against *S. aureus*, *P. aeruginosa*, *E. coli*, and *K. pneumoniae*. A coating of keratin and AuNPs reduced the fabric's porosity and water absorption. In a recent study, Abou Elmaaty et al. [93] coated cotton and polyester fabrics with Au NPs and Ag NPs using a simple printing and paste method. Gold nanoparticles were synthesized with gold chloride hydrate and sodium citrate, while AgNPs were synthesized with *Pluchea dioscoridis* leaf extract. After that, the solution was made into a paste and printed using a flat screen. There is excellent color fastness, antibacterial activity, and UV protection in nano-printed fabrics.

Ganesan and Prabu [94] modified cotton fabrics with AuNPs synthesized from chloroauric acid and extract of *Acorus calamus* rhizome and then applied them to cotton fabrics using pad-dry-cure technology. In addition, the antibacterial activity of treated cotton against *Staphylococcus aureus* and *Escherichia coli* was excellent. The AuNPs improved the UV-blocking properties of cotton fabric. A study by Baruah et al. [95] focused on improving the catalytic activity of cotton fabrics containing ZnO nanorods and AuNPs. Before AuNPs were deposited on the fabric, ZnONRs were applied. AuNPs were prepared by ex situ synthesis and citrate reduction and applied to a cotton fabric coated with ZnONRs using the dip-coating technique. The photocatalytic dye degradation and recycling properties of the composite materials were excellent. By immersing cotton fabrics in colloidal solutions, Boomi et al. [96] synthesized AuNPs by reducing HAuCl_4 with *Coleus aromaticus* leaf extract. The antibacterial properties were tested on these fabrics. *epidermidis* and *E. coli*. A nano cotton fabric was found to have outstanding UV-blocking and antibacterial properties.

Boomi et al. [97] synthesized AuNPs using *Croton sparsiflorus* leaf extract in 2020 and deposited them on cotton fabric through the pad-dry-cure method to improve their antibacterial, anticancer, and UV properties. Cotton fabrics coated with AuNPs showed excellent antibacterial activity against *S. epidermidis* and *E. coli*, good UPF values, and significant anticancer activity against HepG2. An aqueous extract of *Acalypha indica* was used by Boomi et al. [98] to prepare AuNPs. A pad-dry-cure procedure was used to coat the intact extract onto the cotton fabric. The antibacterial activity of treated cotton fabric against *S. epidermidis* and *E. coli* was evaluated, and it demonstrated remarkable inhibition. Similarly, Dakineni et al. [99] reported that cotton fabrics containing AuNPs were antibacterial, anticancer, and UV protective. Using *Pergulariadaemia* leaf extract and chloroauric acid, they prepared Au NPs and loaded them on cotton fabrics using pad-dry-cure. Antibacterial activity was significantly enhanced by AuNPs-coated cotton fabric against *Epidermidis* and *E. Coli*, with superior UV-protection efficiency and limited anticancer activity against HepG2. Table 6 summarizes the functionalization of cotton fabrics with AuNPs.

Table 6. Summary of the functionalization of cotton fabrics with Au NPs.

Types of Fabric	Nanomaterials	NPs Size	Synthesis Method	Application Method	Functionality	Ref Year
Cotton	Au NPs	8–30 nm Average size 14nm	Chemical reduction	Padding	Antibacterial	[92] 2018
Cotton and polyester	Au and Ag NPs	13–20 nm	Au (Chemical reduction) Ag (dioscoridis leaf extract)	Printing and paste	Coloration, antibacterial, and UV protection	[93] 2018
Cotton	Au NPs	Less than 100 nm	Green method (extract of Acoruscalamusrhizome)	Pad-dry-cure	Antibacterial and UV protection	[94] 2019
Cotton	Au NPs	18.5 ± 2.8nm	Chemical reduction	Dip coating	Photocatalysis	[95] 2019
Cotton	Au NPs	Different sizes (<20 nm)	Biological reduction	Pad-dry-cure	Antibacterial and UV protection	[96] 2019
Cotton	Au NPs	16.6–17 nm	Green synthesis	Pad-dry-cure	Antibacterial, anti-cancer, and UV protection	[97] 2020
Cotton	Au NPs	19 nm	Green synthesis (Acalypha indica extract)	Pad-dry-cure	Antibacterial	[98] 2020
Cotton	Au NPs	15–30 nm	Biological reduction (Pergulariadaemia leaves extract)	Pad-dry-cure	Antibacterial, anti-cancer, and UV protection	[99] 2022

3.7. Mixtures of Metal Nanoparticles

To improve the properties of individual MNPs, binary and tertiary nanoparticles have been developed and studied. To impart multifunctional properties to cotton fabric, bimetallic nanoparticles (ZnO/TiO₂ NPs) were deposited on the fabric using the sol-gel technique and then applied using the pad-dry-cure method. Nanocomposite cotton fabrics have excellent antimicrobial activity against *Escherichia coli*, high UPF values, and are highly self-cleaning. ZnO and TiO₂ coatings on cotton fabric can improve multifunctional properties significantly compared to ZnO and TiO₂ coatings alone [100].

To enhance cotton fabrics' antibacterial properties, Mamatha et al. [101] used Aloe vera leaf extract to generate Ag/Cu NPs. Using aqueous solutions of AgNO₃ and CuSO₄·5H₂O, cotton fabrics infused with Aloe vera leaf extracts were immersed in these metallic source solutions and stirred. Cotton fabrics coated with Ag/Cu NPs exhibit good antibacterial activity against *E. coli*, *Pseudomonas*, *Bacillus*, *Klebsiella*, and *Staphylococcus*.

In addition, Rao et al. [102] generated Ag/Cu NPs in cotton fabrics using aqueous red sand extracts as a reducing agent. NPs matrices were generated by dipping cotton fabrics in red sander extract solutions. The antibacterial activity of Ag and Cu NPs and Ag-Cu bimetallic NPs (BMNPs) was compared. BMNPs generated in cotton fabrics highly showed activity against *E. coli*, *P. aeruginosa*, *S. aureus*, and *B. lichinomonas*. Saraswat et al. [103] developed antimicrobial and self-cleaning cotton fabrics using Ag/TiO₂NPs. The photo-assisted deposition (PAD) method was used to synthesize Ag/TiO₂ NPs. Tetraethyl orthosilicate (TEOS) was added as a precursor to SiO₂ to enhance the hydrophilic and self-cleaning properties of TiO₂ during the modified dip coating process used to impregnate the Ag/TiO₂ treated cotton fabrics. The antimicrobial activity of Ag/TiO₂ NPs-coated cotton fabrics was tested against *E. coli* bacteria and *Candida albicans* fungi. They found that

3% Ag/TiO₂ has excellent antibacterial and antifungal properties, with a disinfection efficiency of 100%. Due to silica's structural effects and high dispersion, SiO₂ coatings demonstrated greater photocatalytic activity than Ag/TiO₂ coatings alone. Another study coated cotton fabrics with Ag/ZnO and Cu NPs to enhance their antibacterial activity, UV protection, and conductivity. For the formation of nanoparticles using functionalized polyethyleneimine (FPEI) or polymethylol (PMC), metal salts such as AgNO₃, Zn (NO₃)₂, and Cu (NO₃)₂ were used as precursors. Even after 20 cycles of washing against *S. ureus* and *E. coli*, the treated cotton fabrics demonstrated excellent ultraviolet and electrical conductivity [104].

Using AgNO₃ and trisodium citrate, Ansari et al. [105] produced Ag, TiO₂, and ZnO nanoparticles, while TiO₂NPs were produced by mixing TiCl₄ and ammonium carbonate. ZnONPs were produced by combining ZnCl₂ and sodium hydroxide. After immersing cotton fabrics in polyurethane solution, they were immediately immersed in ZnONPs solution and TiO₂NPs solution. Using the AgNPs solution, the procedure was repeated. *Shigella*, *Salmonella typhi*, and other bacteria showed the best photocatalytic and antibacterial activities on fabrics coated with Ag, ZnO, and TiO₂NPs.

The Gao research group [106] prepared (Ag/ZnO)NPs by chemical precipitation to obtain treated cotton fabrics with improved hydrophobicity, UV resistance, antibacterial, and anti-mildew properties. A cotton fabric was tested for antimicrobial activity against bacteria (*S. aureus*, *E. coli*) and fungi (*C. albicans*). The antifungal activity of these fabrics was also tested against *A. flavous*. Silver NPs with anti-mildew properties must contain at least 1% silver, with 3% silver NPs being the best for achieving a proof grade 1 (a proof grade 4 means no mildew resistance). Antibacterial and mildew resistance were demonstrated by cotton fabrics treated with Ag/ZnO (3% Ag) NPs. Materescu et al. [107] improved the self-cleaning properties of cotton fabrics using commercial aqueous colloidal dispersions of SiO₂-TiO₂ nanoparticles (1:0.5; 1:1; 1:1.5). A TiO₂/SiO₂ NPs mixture enhanced self-cleaning properties, with the highest photocatalytic activity when the molar concentration of TiO₂/SiO₂ NPs was 1:1.

Silva et al. [108] developed antimicrobial and antiviral cotton fabrics with Ag/TiO₂ NPs synthesized by sonochemistry using AgNO₃ as a reductant and stabilizer. More than 50% of infectious SARS-CoV-2 remains active after prolonged direct contact with self-disinfecting materials that inhibit the proliferation of *Escherichia coli* and *Staphylococcus aureus*. Table 7 summarizes the functionalization of cotton fabrics with NP mixtures and their applications.

Table 7. Summary of the functionalization of cotton fabrics with mixtures of nanoparticles and their applications.

Types of Fabric	Nanomaterial	NPs Size	Synthesis Method	Application Method	Functionality	Applications	Ref Year
Cotton	ZnO/TiO ₂ NPs	n.a	Sol-gel	Pad-dry-cure	Antimicrobial activity, UV protection, and self-cleaning	Various household industrial and medical applications	[100] 2018
Cotton	Ag/Cu NPs	61 nm	In situ generation using Aloe vera leaf extract	Immersion, drying	Antibacterial activity	Dressing, wound healing, packaging, and medical applications	[101] 2018
Cotton	Ag/Cu NPs	80–90 nm Average size 100 nm	In situ method using aqueous red sand extracts	Dip coating	Antibacterial activity	Antibacterial bed and dressing materials	[102] 2019

Cotton	Ag/TiO ₂ NPs	Anatase 34 nm and rutile 39 nm for Ag/TiO ₂	Photo-assisted deposition (PAD)	Dip coating	Antimicrobial activity and self-cleaning	Footwear application	[103] 2019
Cotton	Ag/ZnO/Cu NPs	FPEI 50 nm PMC 24 nm	Chemical synthesis	Immersion, Pad-dry-cure	Antibacterial activity, UV protection, and conductivity properties	Upholster beds, underwear, and protective clothing	[104] 2019
Cotton	Ag/ZnO/TiO ₂ NPs	Silver colloidal (15.79–97.75 nm) TiO ₂ (9–14 nm) ZnO (13–20 nm)	Chemical synthesis	Immersion	Photocatalytic and antibacterial activities	Hospital and sportswear	[105] 2020
Cotton	Ag/ZnO NPs	Ag 15 nm ZnO 30 nm	Chemical precipitation	Immersion, drying	Hydrophobicity, UV resistance, antibacterial, and anti-mildew activity	Protective clothing	[106] 2020
Cotton	TiO ₂ /SiO ₂ NPs	n.a	-	Immersion, pad-dry-cure	Self-cleaning	Self-cleaning textile	[107] 2020
Cotton	Ag/TiO ₂ NPs	1.3 ± 0.4 nm and 27.6 ± 9.9 nm	Sonochemistry method	-	Antimicrobial and antiviral activities	Protective and medical applications	[108] 2021

4. Conclusions

There has been a lot of research performed on the surface modification of cotton fabrics with nanostructures in the last five years to provide them with multifunctional properties such as antimicrobial, antiviral, UV protection, self-cleaning, water-repellent, and flame-retardant properties. This has been accomplished using metal and metal oxide nanoparticles (mainly Ag, TiO₂, SiO₂, ZnO, CuO, and Au) and mixtures of metal and metal oxide nanoparticles (such as ZnO/TiO₂, Ag/Cu, Ag/TiO₂, Ag/ZnO, TiO₂/SiO₂, Ag/ZnO/Cu, and Ag/ZnO/TiO₂). Nanotechnology breakthroughs may be of interest to researchers working on applications such as household industries, dressings, wound healing, packaging, footwear, sportswear, and protective and medical products. The review is primarily focusing on the functionalization of cotton fabrics with Ag, TiO₂, SiO₂, ZnO, CuO, and Au NPs, but the exploitation of different types of NPs is expected to lead to novel capabilities, which could expand the applications of nanotextiles.

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Abbreviations

UV	Ultraviolet
ELS	Electrospinning
GNF	Graphite nanofibers
CNT	Carbon nanotubes

MNPs	Metal nanoparticles
NPs	Nanoparticles
AgNPs	Silver nanoparticles
TiO ₂ NPs	Titanium dioxide nanoparticles
ROS	Reactive oxygen species
UPF	Ultraviolet protection factor
SiO ₂ NPs	Silicon dioxide nanoparticles (Silica)
ZnO NPs	Zinc oxide nanoparticles
GA	Gallic acid
Cu/CuO NPs	Copper/Copper oxide nanoparticles
Au NPs	Gold nanoparticles
NRs	Nanorods
BMNPs	Bimetallic nanoparticles
PAD	Photo-Assisted Deposition
TEOS	Tetraethyl orthosilicate
FPEI	Functionalized polyethyleneimine
PMC	Polymethylol

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