Functionalization of Cotton Fabrics with Nanotechnology

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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. Therefore, high-tech materials and fabric constructions will improve wearer comfort while incorporating distinctive features. Among natural fibers, cotton is the most popular because of its softness, breathability, safety, low cost, regeneration performance, strength, elasticity, biodegradability, and hydrophilicity. 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. Microorganisms can easily grow and propagate on cotton fabrics because they are able to store humidity and have a high specific surface area. A variety of fields, including health and medicine, have benefited from cotton fibers with antimicrobial properties. 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. Nanoparticles have been incorporated into textile finishing stages to address the inherent problems while also imparting functional properties to textile materials.

multifunctional cotton fabrics | nanotechnology | metal nanoparticles

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 [1]. 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 [2]. 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 [3]. Cotton fabrics have been coated with AgNPs using a variety of techniques [4].

Xu et al., 2018 [5] 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 [6] fabricated functional cotton fabrics with AgNPs.

A seaweed extract (Padina gymnospora) was used to synthesize AgNPs, and citric acid was used as a crosslinker for applied AgNPs. The functionalized cotton fabrics were tested against *S. aureus* (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. [7] 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 [8]. A cotton textile coated with antimicrobial activity inhibited the growth of *S. aureus*, *E. coli*, and *Candida albicans*. In 2020, Maghimaa et al. [9] evaluated the antimicrobial and wound-healing activity of coated cotton fabric with AgNPs. Peltophorum pterocarpum leaf extracts were used in the synthesis of AgNPs. The AgNPs cotton fabrics showed a good zone of inhibition against *S. aureus*, *Pseudomonas aeruginosa*, *Streptococcus pyogenes*, and *C. albicans* and good wound healing activity when tested against fibroblast. The antibacterial activity of functionalized textiles with AgNPs against *Escherichia coli*, *S. aureus*, *P. aeruginosa*, *Klebsiella pneumoniae*, *Klebsiella oxytoca*, and *Proteus mirabilis*, and antifungal activities against *Aspergillus niger* were reported by Aguda and Lateef [10]. AgNPs were synthesized using wastewater from fermented seeds of Parkia biglobosa. 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. [11] developed antibacterial cotton fabrics with AgNPs using the medicinal plant Vitex leaf extract. The fabrics showed 100% antifungal potency against *A. niger*. According to Hamouda et al. [12], 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. [13] also developed cotton fabrics that were antibacterial and antifungal. They used AgNPs to finish the fabric against *E. coli*, *S. aureus*, *C.albicans*, and *A. niger*. Fabrics treated with AgNPs showed 100% antibacterial activity and good antifungal activity.

2. Titanium Dioxide Nanoparticles (TiO2NPs)

TiO_2 is an inorganic material with many applications in textile manufacturing, particularly UV protection [14], self-cleaning, and antimicrobial properties [15]. Due to its unique properties such as stability, non-toxicity, photocatalytic, chemical resistance, and convenient production technique [16], 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 TiO_2 nanoparticles that has been used in antibacterial textiles [17]. The percentage of bacteria killed by combining TiO_2 with other metal/metal oxide/polymer/carbon nanoparticles/matrices has been shown in many studies [18]. Using an in-situ sol-gel approach, Peter et al. [19] investigated how TiO_2 nanoparticles can be produced and incorporated into cotton fabrics for self-cleaning purposes. The self-cleaning performance of cotton fabrics loaded with TiO_2 was improved. The pad-dry-cure process was developed by Wang et al. [20] to finish cotton fabric with multifunctional TiO_2NPs. 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. [21]. Layer-by-layer self-assembly was used to apply TiO_2NPs to cotton fabric. The UPF values According to the UPF values, the TiO_2NPs cotton fabrics provided excellent UV protection.

In 2019, Riaz et al. [22] investigated the applications of TiO_2 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. [23] reported self-cleaning and antibacterial properties of cotton fabrics with TiO_2NPs. As compared to uncoated cotton fabrics, TiO_2NPs-coated materials possess superior self-cleaning and antibacterial properties. Bekrani et al. [24] created antibacterial and UV-protective cotton fabrics coated with TiO_2NPs. 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. [25] developed cotton fabrics with improved antibacterial and ultraviolet properties after treating them with TiO_2NPs with Moringaoleifera extract. The UPF and antibacterial properties of TiO_2NPs cotton fabrics are improved.

The TiO_2NPs were synthesized by using Aloe vera extract in a green method by Saleem et al. [26]. The TiO_2-coated fabric demonstrated excellent self-cleaning properties. The tensile strength of the fabric decreased slightly but increased after the TiO_2 coating.

3. Silica Nanoparticles (SiO_2NPs)

Silica nanoparticles (SiO_2NPs) 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 [27]. In cotton fibers, SiO_2NPs penetrate easily and bind tightly to the fiber structure. Consequently, cellulose hydroxyl groups and SiOH form covalent bonds in SiO_2NPs. SiO_2NPs are added to the surfaces of materials to improve their mechanical properties, durability, function, activity, and stability [28].

Rethinam et al. [29] developed antibacterial/ultraviolet cotton fabrics using SiO_2NPs produced from xerogels at different concentrations (1, 2, and 3% *w*/*v*). Among the different concentrations of SiO_2NPs used, 3% (*w*/*v*) exhibited better mechanical properties, breaking strength, elongation at break, and tearing strength, and demonstrated the highest antibacterial activity against *S. aureus* and *E. coli*, as well as UV protection. Using SiO_2NPs, Riaz et al. [30] developed highly durable superhydrophobic and antibacterial cotton fabrics. Cotton fabric was treated with SiO_2NPs using a pad-dry-cure technique.

The study also revealed excellent antibacterial properties and superhydrophobicity, as well as high comfort properties such as bending rigidity and tensile strength and maximum laundry durability. According to Zakir et al. [31], SiO_2NPs were used to fabricate superhydrophobic cotton fabrics. Dip-coating was used to deposit SiO_2NPs 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. [32], 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 SiO_2NPs have high thermal stability, they can also be used to prepare flame-retardant textiles. In 2021, Shahidi et al. [33] used in-situ synthesis to deposit SiO_2NPs on cotton fabrics. By impregnating the cotton fabrics with SiO_2NPs, the flame-retardant properties have greatly improved, and samples have been found to be hydrophilic. Amibo et al. [34] investigated the antibacterial properties of SiO_2NPs loaded with AgNPs-coated cotton fabrics. Selected strains of bacteria such as *S. aureus*, *E. coli*, and *P. aeruginosa* were tested for antimicrobial activity with improved activities by the treated fabric. Hasabo and Rahma [35] fabricated a superhydrophobicity water-repellent cotton fabric coated with SiO_2NPs and water-repellent agent(WR agent). Water contact angles on the fabric surface of cotton fabrics treated with the WR agent alone remained lower than 20^o approximately at the WR agent concentration of 0.3 wt% or less. The hydrophilic surface of cotton fabric was not changed by SiO_2NPs treatment itself, indicating that water drops were absorbed into fabrics due to the hydroxyl groups on both the cotton and silica NPs surfaces. However, cotton fabrics treated with both silica nanoparticles and the WR agent, a contact angle above 75^o can be achieved even at the extremely low WR agent concentration of 0.1 wt% . Therefore, silica nanoparticles and WR agent treatment might be combined to produce superhydrophobicity cotton fabrics.

4. Zinc Oxide Nanoparticles (ZnONPs)

In textile finishing, zinc oxide (ZnO) has gained popularity because of its following numerous advantages: UV protection , antibacterial and antifungal properties, and the ability to speed wound healing [36]. ZnO nanoparticles have been deposited or incorporated into cotton using various chemical/physical techniques to develop antibacterial, antifungal, and UV-protective nanotextiles.

Using ZnONPs, Fouda et al. [37] 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 ZnONPs 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. [38] also investigated the antibacterial properties of cotton medical fabrics with ZnONPs and gallic acid (GA). Cotton fabric was uniformly coated with ZnONPs. Despite 60 cycles of washing, the antibacterial efficacy of ZnONPs-GA-coated fabrics remained above 60%. To obtain antibacterial fabrics, Souza et al. [39] used the solo chemical process for ZnONPs on cotton fabrics. The antibacterial activity of cotton fabrics against *S. aureus* and *P. aeruginosa* was tested. The antibacterial activity of the treated cotton was higher against *S. aureus* than against *P. aeruginosa*.

In another study, Roy et al. [40] synthesized ZnONPs using a chemical method. ZnONPs were then applied to cotton fabric using dip coating. Antifungal and antibacterial activities of treated samples were examined at various mole concentrations of ZnONPs (1M, 1.5M, 2M, 2.5M, and 3M). The fabrics treated were tested for antifungal activity against *A. niger* as well as antibacterial activity against *S. aureus* and *E. coli*. At a concentration of 2M, the antibacterial and antifungal activity is highest. Mulchandani et al. [41] 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 ZnONPs showed excellent antimicrobial activity against *S. aureus* and *K. pneumoniae*. To impart antibacterial activity to cotton (woven, single jersey, rib/double jersey), Momotaz et al. [42] 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 [43] 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 *S. aureus*, *E. coli*, and *C. albicans*, and the highest UPF values.

Tania and Ali [44] 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 *S. aureus* and *E. 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. [45] prepared ZnONPs using sono synthesis and applied them to cotton fabrics in 2021. Finished fabrics with ZnONPs demonstrated flexural rigidity, tensile strength, water contact angle, and air permeability. Against *E. coli* and *S. aureus* bacteria, they showed excellent antibacterial activities.

5. Copper/Copper Oxide Nanoparticles (Cu/CuONPs)

Due to their abundance, availability, and low cost, copper nanoparticles are gaining popularity [46]. As a result, CuONPs are used in a variety of applications, including antifungal, antiviral, antibiotics, anticancer, photocatalytic, biomedical, and agricultural fields [47]. CuONPs possess antimicrobial activity against *Bacillus subtilis*, *E. coli*, *S. aureus*, *Micrococcus luteus*, *P. aeruginosa*, *Salmonella enterica*, and *Enterobactor aerogenes*, as well as antifungal activity against *Fusarium oxysporum* and *Phytophthora capsici*. Accordingly, CuONPs have shown significant antiviral activity against human influenza A (H1N1), avian influenza (H9N2), and many other viruses, including COVID-19 [48].

In 2018, Nourbakhsh and Iranfar [49] 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 *E. coli* and *S. 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. [50] 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. [51]. Using Cassia alata leaf extract as a reducing agent, CuONPs were synthesized. *E. coli* bacteria were significantly inhibited by nanocotton fabric. Even after 15 washes, these nanocomposites retained antibacterial activity, indicating that they contained permanent CuONPs.

6. Gold Nanoparticles (AuNPs)

The optical, electronic, and magnetic properties of AuNPs have drawn a lot of attention in textile research. Textiles also contain AuNPs for electronic and medical applications [52].

In 2018, Shanmugasundaram and Ramkumar [53] attempted to improve the antibacterial property of cotton fabric by coating it with keratin protein and AuNPs using a padded method. AuNPs were synthesized using a chemical reduction method. Incorporating AuNPs 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.

Ganesan and Prabu [54] 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 *S. aureus* and *E. coli* was excellent. The AuNPs improved the UV-blocking properties of cotton fabric. A study by Baruah et al. [55] 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. [56] synthesized AuNPs by reducing $HAuCl_4$ with *Coleus aromaticus* leaf extract. The antibacterial properties were tested on these fabrics. *Staphylococcus epidermidis*

and *E. coli*. A nano cotton fabric was found to have outstanding UV-blocking and antibacterial properties.

Boomi et al. [57] 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. [58] 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. [59] reported that cotton fabrics containing AuNPs were antibacterial, anticancer, and UV protective. Using Pergulariadaemia leaf extract and chloroauric acid, they prepared AuNPs and loaded them on cotton fabrics using pad-dry-cure. Antibacterial activity was significantly enhanced by AuNPs-coated cotton fabric against

S. epidermidis and *E. coli*, with superior UV-protection efficiency and limited anticancer activity against HepG2.

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/TiO_2NPs) 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 *E. coli*, high UPF values, and are highly self-cleaning. ZnO and TiO_2 coatings on cotton fabric can improve multifunctional properties significantly compared to ZnO and TiO_2 coatings alone [60].

To enhance cotton fabrics' antibacterial properties, Mamatha et al. [61] used Aloe vera leaf extract to generate Ag/Cu NPs. Using aqueous solutions of $AgNO_3$ and $CuSO_4 \cdot 5H_2O$, 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*, *P. aeruginosa*, *Bacillus cereus*, *K.pneumoniae*, and *S.aureus*.

Abbreviations

UV	Ultraviolet
ELS	Electrospinning
NPs	Nanoparticles
AgNPs	Silver nanoparticles
TiO_2NPs	Titanium dioxide nanoparticles
ROS	Reactive oxygen species
UPF	Ultraviolet protection factor
SiO_2NPs	Silicon dioxide nanoparticles (Silica)
ZnONPs	Zinc oxide nanoparticles
Cu/CuONPs	Copper/Copper oxide nanoparticles
ATRP	Atom transfer radical polymerization

AuNPs	Gold nanoparticles
NRs	Nanorods
PAD	Photo-Assisted Deposition

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