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Significance Advantages, and Disadvantages of Nanotechnology in Textile Finishing

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Abstract

Nanotechnology has emerged as one of the most significant fields of study in recent years. Due to its special synthesis methods and advantageous properties, nanotechnology is quickly taking over the textile sector. Various finishing, coating, and manufacturing procedures are utilized to create fibers or fabrics with nano-sized particles in the production of high-performance textiles. Nanomaterials have been used to provide antibacterial, UV-resistant, electric conductivity, photocatalytic and self-cleaning qualities to fabrics and clothing in a sustainable way. nanofibers, silver, gold, and zinc nanoparticles, as well as stretchable textiles and wearable solar textiles, triboelectric nanogenerators, and one-piece self-power/self-charging power textiles have all been used in smart wearable textiles.

Keywords: Nanotechnology, Nanomaterial, Nanofibres, Applications, Photocatalytic Textiles, UV resistant Textiles.

Introduction

Nanotechnology is a developing technology that is still expanding in many parameters. Nanotechnology is an emerging interdisciplinary field that is expected to have broad implications in all fields of science and technology such as material science, mechanics, electronics, optics, medicine, energy, and also a useful tool in improving the performance of textiles nanomaterials indicate as a new tool to improve properties and gain multifunctionalities. [1, 2] Organized nanostructures, as demonstrated by fibers, nanocoatings, Nanofinishing, nanofibers, and nanocomposites, appear to have enormous potential to revolutionize the textile industry with new functionality such as self-cleaning surfaces, conducting textiles, antimicrobial properties, controlled hydrophilicity or hydrophobicity, protection against fire, UV radiation, and so on, without affecting the bulk properties of fibers and fabrics. [3-23]

The aim of Nano finishing is the manipulation of individual atom molecules to create a structure. Nanotechnology can provide high durability to fabrics because nanoparticles have a large surface area to volume ratio, High surface energy. Thus presenting better affinity towards the fabric without affecting their breathability or feel. Nanotech research efforts in textile have focused on two main areas:

1. Upgrading existing functions and performance of textile materials.
2. Developing intelligent textiles with completely new characteristics and functions. Depending upon the dimensional aspects, there are three main approaches for the application of nanotechnology in textiles

For nanomaterials, which are at the Nanoscale in one dimension, there appear to be many opportunities for the application of very thin surface coatings. [4, 5, 24, 25]

Nanofibres and nanotubes are at the nanoscale in two dimensions and their utilization in many forms of composite materials offers opportunities for improving the mechanical properties and altering electrical, optical, or biological characteristics. [26]

The approach involves the use of nano-particles having nanoscale in three dimensions for incorporation in fibers, coatings, and films to provide

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several possibilities such as imparting antimicrobial, flame retardant, and chemical softening effects to textiles. [4, 5, 7-13, 25, 27-31]

Classification of nanomaterial Based on Dimensionality

(1) Zero-dimensional (0D) NMs include quantum dots (carbon, graphene, inorganic) and other spherical NMs (noble metals, fullerenes, polymers)Due to their chemical inertness, biocompatibility, optical stability, cell permeability, and wavelength-dependent photoluminescence, they are interesting for biomedical and optoelectronic applications [32]

(2) One-dimensional (1D) NMs (one dimension > 100 nm) In this case, nanotubes, nanorods, nanowires, and nanofibers are made of polymer, carbon, metals, and metal oxides and are good electron emitters in a weak electric field. Other 1D NMs, such as veils, mats, and nonwovens, are made of polymer nanofibers. Due to their important surface-to-volume ratio and small pores, they are used for filtration, decontamination, and catalysis and as scaffolds and super-absorbents for wound dressing and tissue engineering [32].

(3) Two-dimensional (2D) NMs (two dimensions > 100 nm) include platelet-like forms, graphene (graphene oxide and re-reduced graphene oxide), transition metal-metal oxides, silicates, and black phosphorus. Their physicochemical, biological, and optical properties explain their uniform shape, surface charge, and high surface-to-volume ratio [32].

(4) Three-dimensional (3D) NMs (no dimension in the nanoscale range) include nanoporous powders, nanowire bundles, nanotube bundles, nanolayers, and nanostructured electrodes. Much research has been done on the development and fabrication. These complex NMs are important components of biomedical devices, solar cells, and microelectromechanical systems. The use of 3D printing of NMs will allow the development of architectures with improved functional integration [32].

Classification of Nanomaterials Synthesis

Textile synthesis By using environmentally friendly materials, nanomaterials have better control over particle morphology, size distribution, quality, purity, and quantity. [32].

There are two ways the synthesis of Nanomaterial: as shown in figure (1)

1. A top-down approach involving breaking down the bulk materials to Nano sizes (Eg. Mechanical alloying)
2. Bottom-up approach the nanoparticles are also made by building atom by atom (Eg. Inert gas condensation).

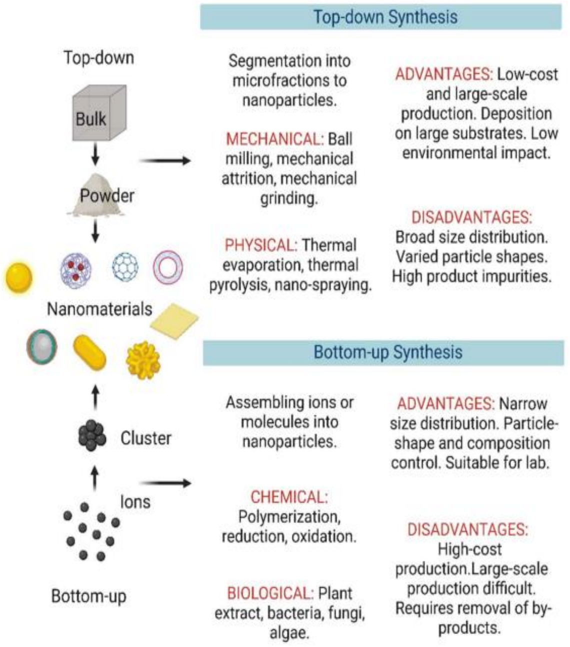


Figure (1) Schematic representation of top-down and bottom-up techniques for nanomaterial fabrication [32]

Top-Down Approaches

Mechanical and chemical fabrication techniques are examples of top-down approaches to NM synthesis. Top-down approaches produce NMs by dissolving the bulk material into nanoparticles, typically through attrition, milling, and etching. Top-down approaches are better suited for producing thin films and NMs larger than 100 nm in size. These techniques are used to create electrical circuits with high integration and connectivity. Top-down approaches are used in the fabrication of integrated circuits. The main disadvantage of current top-down methods is their resolution limitation.[32] .

Mechanical Methods

Top-down synthesis methods include mechanical processes that separate solid materials into small fractions (e.g., grinding, refining, high-energy ball milling, sequential cutting).

Grinding reduces the size of microparticles in mechanical manufacturing (for example, metallic and ceramic NMs). To be more specific, metallic nanoparticles. This method does not allow for complete control of particle shape. The fact that no waste is released into the environment is their primary advantage[1].

The most common mechanical methods are

(1) mechanical compaction, followed by metal powder melting and cooling to form nanoparticles from the obtained atomic structures. This allows monitoring and verification [32].

(2) deformation techniques, in which the structure of crystalline materials (e.g., metals, porcelain) is modified to increase the nanoparticle hardness and ductility [32].

(3) milling in which the starting material is pulverized by steel balls to produce powdered nanoparticles of a size range between 3 and 25 nm. This method requires very high energy[32].

(4) scrubbing in which thin silicon strips are rubbed with chemicals (e.g., hydrogen fluoride) to obtain silicone particles on the surface. Then, the strips are immersed in a solution and nano-sized droplets are formed using an ultrasonic device. Table 1 lists different nanostructure types synthesized using mechanical methods and their diverse applications[32]

Physical Synthesis Methods

Evaporation, condensation, and laser ablation are some of these techniques. To obtain the correct size distribution, rapidly controlled condensation is followed by molecule evaporation. In contrast to chemical approaches, thin films created utilizing physical methods do not contain solvent contaminants, and nanoparticle distribution is even. However, a sizable area and a lot of energy are needed to raise the surrounding temperature of the starting material when employing a tube furnace at atmospheric pressure for the synthesis of nanoparticles. Furthermore, achieving thermal stability takes time. [32].

Inorganic and some organic materials can be deposited in vacuum conditions using physical vapor deposition (PVD). PVD is essentially an evaporative deposition technique that transfers material at the atomic level. This process is similar to CVD, except that the starting materials/precursors (i.e., the material to be deposited) are initially solid rather than gaseous. PVD methods include sputtering, electrophoretic deposition, electron beam PVD, pulsed laser deposition, atomic layer deposition, and molecular beam epitaxy. [32]. (table 2)

PVD thin films are primarily used in optical, optoelectronic, microelectronic, and magnetic applications. They're also good for thermal insulation, corrosion protection, and decorative coatings. PVD can create a uniform and visible nanoscale coating on the substrate surface. PVD coatings are tough, and resistant to wear, and oxidation. Spray techniques such as spray drying, freeze drying, plasma spraying, and hot spraying are used to create a diverse range of functional, simple, and multicomponent materials in a single step. [32].

Table 1. Mechanical methods used to fabricate different nanoparticle and nanostructure types

Method	Nanoparticles	Size and Shape	Features/Applications
Ball milling	Al nanoparticles	~30 nm, spherical	Quick combustion at a flame temperature of over 1100 °C
Grinding	NiCoFe–OH Nanoparticles	~15 nm, Nanosheets	Improved electrical conductivity for asymmetric supercapacitor
High-energy ball milling	P nanoparticles in a carbon matrix	100–300 nm, Carbon fringe	Suitable for large-scale production and better performance in the phosphorus-based anode material
Mechanical alloying	Al–Y_2O_3 Nanocomposites	50–70 nm, spherical Y_2O_3	Improved mechanical properties suitable for automotive industries
Mechanical compaction	TiO_2 Nanoparticles	~10 nm, Spherical	Improved blending and film forming properties for gas sensing, energy storage, and production

Table 2. Physical methods used to synthesize nanoparticles and nanostructures[32].

Method	Nanoparticles	Size and Shape	Features/Applications
Physical vapor deposition	Magnesium alanate and lithium borohydride	20–40 nm, nanorods 10–40 nm, nanobelts	Improved hydrogen storage
Pulsed laser ablation	CuO_x/GrO nanosheets	~60 nm, Spherical (CuO_x)/nanosheets (GrO)	Enhanced dye removal than graphene oxide
Spray drying	SiO_2 nanoparticles modified with alginate	890 nm, smooth doughnut	Drug carrier for cancer treatment
Solution electrospinning	Chitosan/poly(ethylene oxide)	270 nm, nanofibers	Good mechanical properties with improved properties for drug delivery
3D printing	Polymethyl methacrylate modified with cellulose nanocrystal-coated Ag nanoparticles	80 nm in width, elongated rods	Antimicrobial biomaterials for functional dental restoration and other biomedical applications

Bottom-Up Approaches

Bottom-up methods, as opposed to top-down methods, permit the creation of NMs with fewer faults. Atoms, molecules, and nanoparticles are used as starting materials in such approaches to create complex nanostructures. Ionic and molecular self-assembly is a bottom-up approach in which noncovalent bonds, such as hydrogen and ionic bonds, van der Waals forces, and water-mediated hydrogen bonding, are used to gather individual blocks/molecules into larger structures. Bottom-up approaches enable the individual blocks' properties and composition to be controlled. The size of the building blocks is determined by the desired properties. Bottom-up approaches include wet chemical techniques (e.g., sol-gel, microemulsion) and co-precipitation.[32] .

Chemical and Physicochemical Synthesis Methods

Chemical vapor deposition, sol-gel, solvothermal processes, polymerization, and other chemical precipitation techniques are examples of bottom-up chemical techniques for the synthesis of NMs. Laser deposition and electrochemical deposition methods are hybrid systems that combine chemical and physical techniques. Electrochemical methods are an example of physicochemical approaches to producing metal nanoparticles in which a metal anode is dissolved in an aprotic solvent. Physicochemical methods include hydrothermal and solvothermal processes, CVD templating, microwave irradiation, combustion, thermal degradation, and pulsed laser deposition. Wet chemical synthesis can be used to obtain nanoparticles with specific surface morphologies, phases, shapes, and sizes and thus specific properties. Wet chemical synthesis allows fine-tuning the reaction conditions (e.g., temperature, substrate concentration, additives, pH) to obtain the desired nanomaterials[32]. (Table 3)

Synthesis via Conventional Sol-Gel Method

During the sol-gel synthesis, a colloidal suspension is formed as a result of the precursors' hydrolysis and polymerization reactions, which leads to the transition from liquid sol to solid gel phase upon complete polymerization and solvent loss.

This method is used to create nano silver, nano ZnO, and nano TiO2 nanoparticles, among other oxide materials. The significance of this technique includes high purity of the precursors, molecular scale mixing, and product homogeneity with high purity of chemical, physical, and morphological properties. It is also referred to as the multipurpose method. [33].

Synthesis via Microwave Method

Various nanomaterials have been synthesized by microwave radiation. The microwave technique use of high-temperature calcination for extended periods and allows for fast the synthesis of crystalline TiO2 nanomaterials. Preparing colloidal TiO2 nanoparticle suspensions within 5 min using microwave radiation [33].

Innovations in Nanotechnology-Based Textile Industry Applications

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

Nanofibers

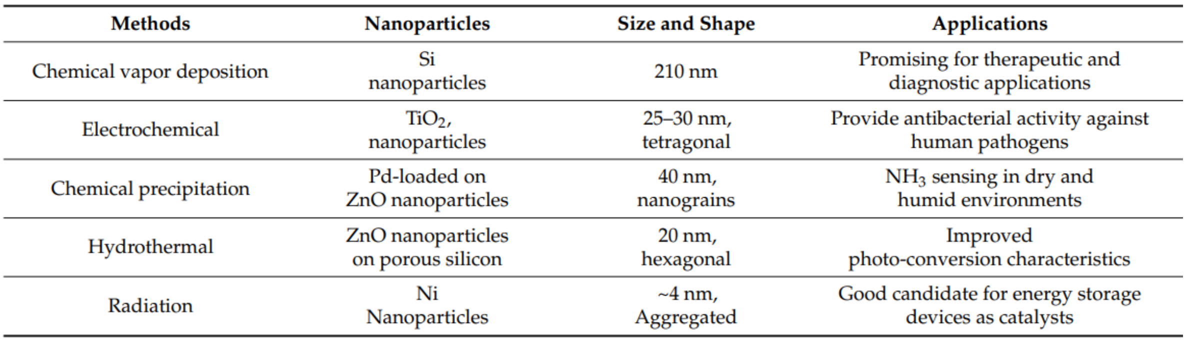
Nanofiber is a continuous fiber that has a diameter in the range of billionths of a meter. The smallest nano-fibers made today are between 1.5 and 1.75 nanometers.

At the right, a human hair (80,000 nanometers) is placed on a mat of nano-fibers [34].

Unique Properties of Nanofibers

1. Nanofibers are very small which gives them unique physical and chemical properties and allows them to be used in very small places.
2. Nano-fibers have a huge surface area compared to their volume
3. Low basis weight
4. High porosity

Table 3. Chemical and physiochemical techniques for the production of nanoparticles and nanostructures[32].



Methods	Nanoparticles	Size and Shape	Applications
Chemical vapor deposition	Si nanoparticles	210 nm	Promising for therapeutic and diagnostic applications
Electrochemical	TiO_2, nanoparticles	25–30 nm, tetragonal	Provide antibacterial activity against human pathogens
Chemical precipitation	Pd-loaded on ZnO nanoparticles	40 nm, nanograins	NH_3 sensing in dry and humid environments
Hydrothermal	ZnO nanoparticles on porous silicon	20 nm, hexagonal	Improved photo-conversion characteristics
Radiation	Ni Nanoparticles	~4 nm, Aggregated	Good candidate for energy storage devices as catalysts

Synthesis of nanofibers

For the fabrication of nanofibers, different techniques are used, like electrospinning (Figure 2), self-assembly, force spinning, melt blowing, and island-in-sea (bicomponent nanofiber)[34].

Electrospinning is the most convenient of these techniques due to its low cost, higher rate of production, higher porosity, and ability to control nanofiber morphology and diameter. A stretchable piezo-resistive carbon nanotube-incorporated nanofiber sensing yarn (Figure 3) was created first using a simple electrospinning technique[34].

Electro-spinning is the most important method in the synthesis of nanofibers. [17, 26, 35] In the electro-spinning process, a high voltage creates electricity for the deposition or melt, or streaming of polymer solution (Figure 4). The electric field between the tip of the capillary and a grounded collector is very high and formed at the tip of the capillary producing sub-micron diameter fibers. Different types of material were processed into nanofibers in the range of 50 to 1000 nm. Recently, electrospinning has also been extended to making nanofibres from polymer nanocomposites, incorporating nano clays, [30, 36] CNTs, and other nanoparticles, and adding a new dimension to nanofibres. In addition to producing fabrics, antistatic materials, electromagnetic shielding materials, high-performance separation mediums, reinforcing materials, electrical and thermal conductivity materials, wave absorbing materials, etc., these nanocomposite fibers can also be used to deposit over textile substrates.

Additionally, the nanofibers are remarkable and highly effective as active layers in face masks that shield users from infections like the coronavirus. [34].

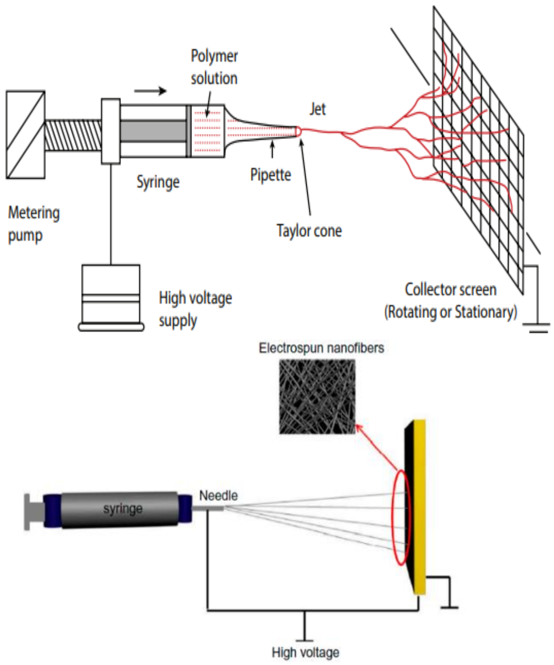


figure 2-3: Electrospinning design[34]

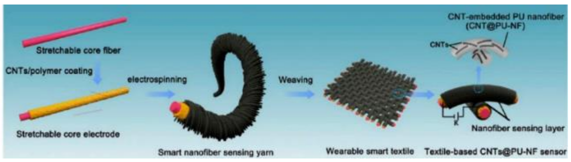


Figure 4. Schematic of the fabrication processes of carbon nanotube-incorporated nanofiber sensing yarn[34].

Nanocomposites

It is possible to create nanocomposite fibers by dispersing nanosized fillers within a fiber matrix. Nanosilicates, metal oxide nanoparticles, graphite nanofibers (GNFs), single-wall and multi-wall carbon nanotubes, and other fillers can be used to create nanocomposite fibers with excellent electrical conductivity, exceptional strength, toughness, and lightweight properties (CNTs) [4].

Metal Nanoparticles (MNPs)

Metal nanoparticles (MNPs) are the most common and versatile nanomaterials. Numerous types of nanoparticles (NPs) have been integrated into various textile materials due to their diverse functional properties. [15, 16, 18, 19, 22, 23, 37-53] Because of their ability to withstand high temperatures both thermally and chemically, permanent stability under ultraviolet rays, and non-toxicity, 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. Their ability to adhere to fibers is also influenced significantly by their size. The largest particle cluster should be easily removed from the fiber surface, but the smallest particles will penetrate deeper and adhere more firmly to the fabric. The properties of the material change as the particle size is reduced. The creation of these metallic nanoparticles requires the presence of a reducing and stabilizing agent. The reduction of metal salt solutions produces metal nanoparticles. [1]. (figure 5)

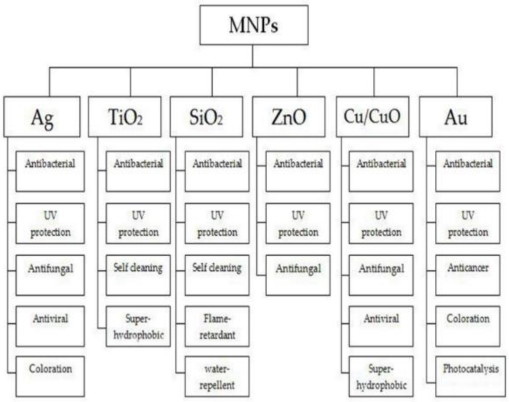


figure 5: Metal nanoparticles and their functions used in textiles[1]

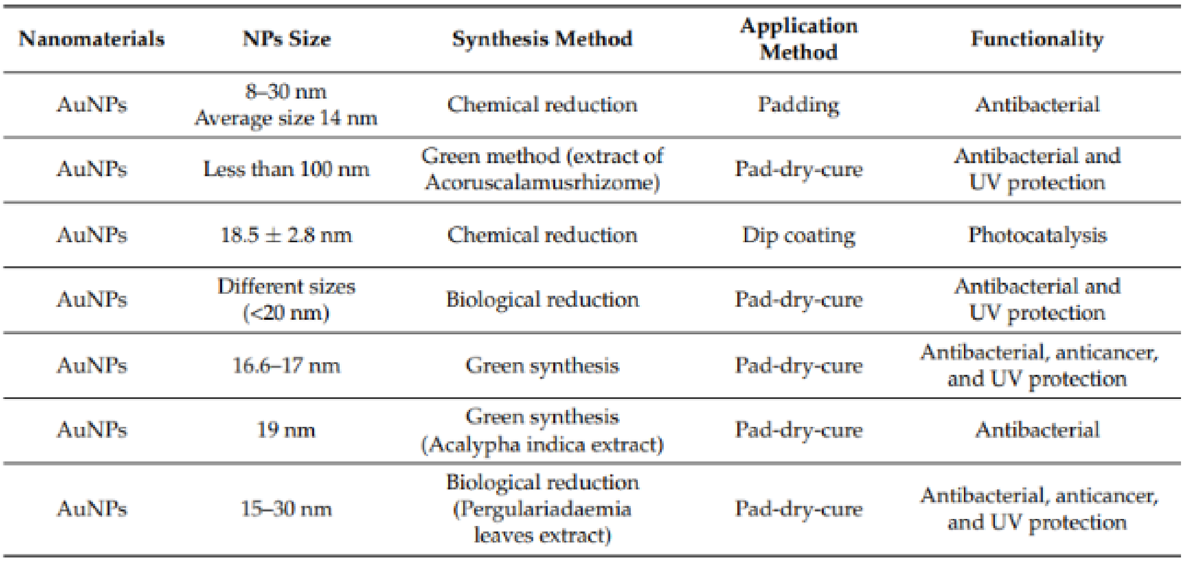
Applications of Metal Nanoparticles Synthesis.

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[1, 54-58].

- Shanmugasundaram and Ramkumar's study attempted to improve the antibacterial property of cotton fabric by padding it with keratin protein and AuNPs. A chemical reduction method was used to produce AuNPs.
- 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[1].
- A study by Ganesan and Prabu 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[1].
- A study by Baruah et al. 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 [1].
- The photocatalytic dye degradation and recycling properties of the composite materials were excellent. By immersing cotton fabrics in colloidal solutions, Boomi et al. synthesized AuNPs by reducing HAuCl4 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[1].
- A study by Boomi et al. 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. 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, inhibition[1].
- Similarly, Dakineni et al. 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[1]. Table(4)

Table 4 summarizes the functionalization of cotton fabrics with AuNPs[1].



Nanomaterials	NPs Size	Synthesis Method	Application Method	Functionality
AuNPs	8–30 nm Average size 14 nm	Chemical reduction	Padding	Antibacterial
AuNPs	Less than 100 nm	Green method (extract of Acoruscalamusrhizome)	Pad-dry-cure	Antibacterial and UV protection
AuNPs	18.5 ± 2.8 nm	Chemical reduction	Dip coating	Photocatalysis
AuNPs	Different sizes (<20 nm)	Biological reduction	Pad-dry-cure	Antibacterial and UV protection
AuNPs	16.6–17 nm	Green synthesis	Pad-dry-cure	Antibacterial, anticancer, and UV protection
AuNPs	19 nm	Green synthesis (Acalypha indica extract)	Pad-dry-cure	Antibacterial
AuNPs	15–30 nm	Biological reduction (Pergulariadaemia leaves extract)	Pad-dry-cure	Antibacterial, anticancer, and UV protection

Silver Nanoparticles (AgNPs)

Silver is one of the most popular antimicrobial nanoparticles. It acts as a doping antimicrobial agent and exhibits antimicrobial activity without affecting mechanical properties. AgNPs have strong antiviral properties. Furthermore, AgNPs interactions with viruses can be improved by adjusting their physicochemical properties such as size, shape, surface charge, dispersion, and protein corona effects. AgNPs may be applied to the surface of the textile as part of a finishing process to functionalize them, such as spraying, or producing AgNPs directly on the surface of the fiber and inside it[1].

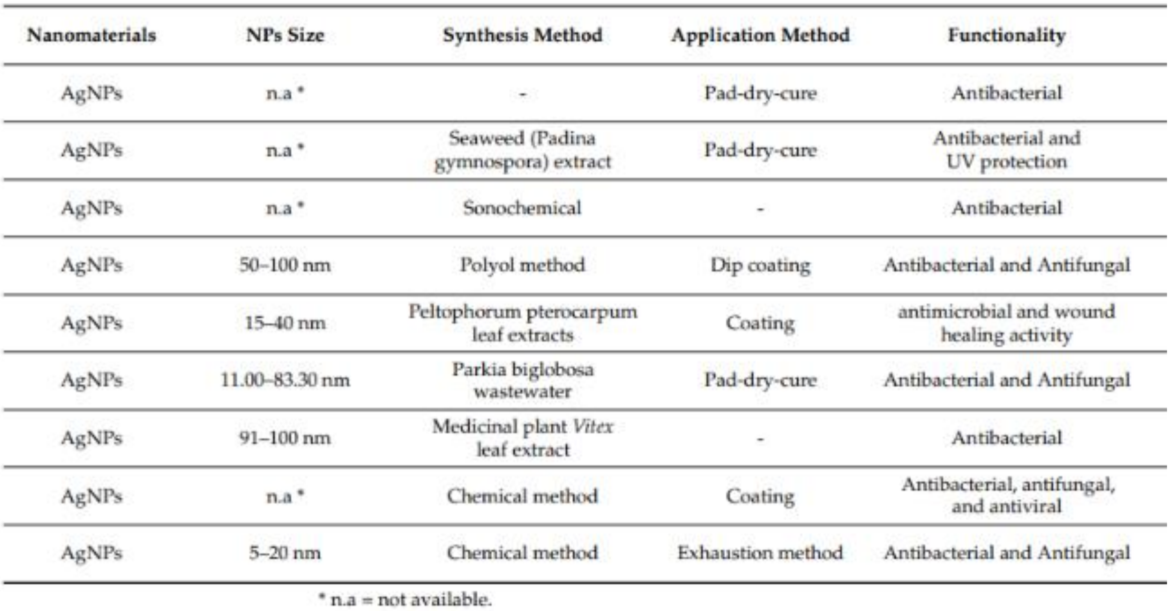
- Cotton fabrics have been coated with AgNPs using a variety of techniques. The functionalization of cotton fabrics incorporating AgNPs is summarized in Table 5.
- A study by Xu et al., 2018 created durable antimicrobial cotton fabrics using AgNPs that were applied to cotton fabric using the pad-dry-cure 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.
- A study by (Rajaboopathi and Thambidura) 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.
- Sonochemistry and deposition to create AgNPs-coated cotton fabrics with antimicrobial properties. It is 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.
- A cotton textile coated with antimicrobial activity inhibited the growth of S. aureus, E. coli, and Candida albicans. In 2020, Maghimaa et al. 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 E. coli, S. aureus, P. aeruginosa, Klebsiella pneumoniae, Klebsiella oxytoca, and Proteus mirabilis, and antifungal activities against Aspergillus niger were reported by Aguda and Lateef.
- 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. developed antibacterial cotton fabrics with AgNPs using the medicinal plant Vitex leaf extract. The fabrics showed 100% antifungal potency against A. niger.
- 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. 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. Table(5)[1]

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. ZnO nanoparticles have been deposited or incorporated into cotton using various chemical/ physical techniques to develop antibacterial, antifungal, and UV-protective nanotextiles. Table (6). [1]

- Using ZnONPs, Fouda et al. 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 [1].

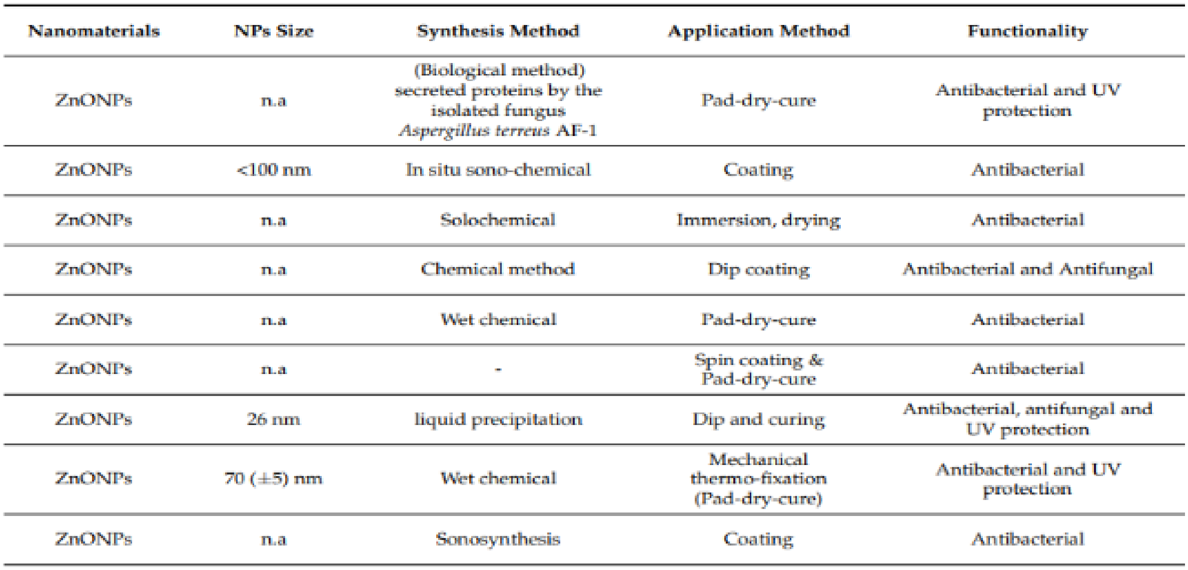
Table 5 summarizes the functionalization of cotton fabrics with AgNPs[1]



Nanomaterials	NPs Size	Synthesis Method	Application Method	Functionality
AgNPs	n.a *	-	Pad-dry-cure	Antibacterial
AgNPs	n.a *	Seaweed (Padina gymnospora) extract	Pad-dry-cure	Antibacterial and UV protection
AgNPs	n.a *	Sonochemical	-	Antibacterial
AgNPs	50–100 nm	Polyol method	Dip coating	Antibacterial and Antifungal
AgNPs	15–40 nm	Peltophorum pterocarpum leaf extracts	Coating	antimicrobial and wound healing activity
AgNPs	11.00–83.30 nm	Parkia biglobosa wastewater	Pad-dry-cure	Antibacterial and Antifungal
AgNPs	91–100 nm	Medicinal plant *Vitex* leaf extract	-	Antibacterial
AgNPs	n.a *	Chemical method	Coating	Antibacterial, antifungal, and antiviral
AgNPs	5–20 nm	Chemical method	Exhaustion method	Antibacterial and Antifungal

* n.a = not available.

Table 6. summarizes the functionalization of cotton fabrics treated with ZnONPs [1].



Nanomaterials	NPs Size	Synthesis Method	Application Method	Functionality
ZnONPs	n.a	(Biological method) secreted proteins by the isolated fungus *Aspergillus terreus* AF-1	Pad-dry-cure	Antibacterial and UV protection
ZnONPs	<100 nm	In situ sono-chemical	Coating	Antibacterial
ZnONPs	n.a	Solochemical	Immersion, drying	Antibacterial
ZnONPs	n.a	Chemical method	Dip coating	Antibacterial and Antifungal
ZnONPs	n.a	Wet chemical	Pad-dry-cure	Antibacterial
ZnONPs	n.a	-	Spin coating & Pad-dry-cure	Antibacterial
ZnONPs	26 nm	liquid precipitation	Dip and curing	Antibacterial, antifungal and UV protection
ZnONPs	70 (±5) nm	Wet chemical	Mechanical thermo-fixation (Pad-dry-cure)	Antibacterial and UV protection
ZnONPs	n.a	Sonosynthesis	Coating	Antibacterial

- The ZnONPs have an excellent ability to block UV rays, increasing the UPF value of the cotton fabric treated with them [1].
- A study by Salat et al. 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% [1].
- To obtain antibacterial fabrics, Souza et al. used the solochemical process for ZnONPs on cotton fabrics. The antibacterial activity of cotton fabrics against S. aureus and P. aeruginosa were tested. The antibacterial activity of the treated cotton was higher against S. aureus than against P. aeruginosa [1].
- In another study, Roy et al. 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 [1].

- Mulchandani et al. 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) [1],
- Momotaz et al. 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 [1].
- In the next study, Mousa and Khairy 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 into 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 [1].
- Tania and Ali 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 [1].
- Patil et al. prepared ZnONPs using sono synthesis and applied them to cotton fabrics in 2021. Finished fabrics with ZnONPs have better flexural rigidity because following the deposition of ZnONPs, the stiffness of the cloth increases. An analysis of the cotton fabric’s tensile strength after ZnONPs was deposited revealed a 5.43% reduction in the tensile strength. On the other hand, the contact angle increased from 38◦ to 110◦. However, the air permeability values after the deposition of ZnONPs on cotton fabric decreased approximately by 4.85%. Against E. coli and S. aureus bacteria, they showed excellent antibacterial activities [1]

Nanocoating

In a nanocoating process, a thin layer approximately less than 100 nm thickness is deposited on the substrate to improve some properties or to add new functionality such as enhanced color fastness, flame retardance, water or oil repellency, wrinkle resistance, and antimicrobial properties[34] Traditional coatings possess certain disadvantages such as

- less durability, (ii) poor abrasion resistance, (iii) strength loss, (iv) less flexibility, and (v) improper adhesion between the substrate and coating layer[34].
- The aforementioned problems of traditional coatings could be solved by the utilization of nanocoatings [34].
- The nanomaterial coating on fabrics will not influence their breathability or hand feel [34].

Nano finishing

The process of Nano finishing involves applying colloidal solutions or ultrafine dispersions of nanomaterials to fabrics to improve some of their functionalities. In the case of Nano finishing, a smaller quantity of nanomaterials is required in comparison to the bulk materials used in traditional finishing achieving a similar effect. These nano finishings 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 [34].

By using nano finishing, existing processes can be improved, or new functional properties can be achieved that are not possible with traditional finishes[34].

Applications of nanocoating and nano finishing

- **Self-cleaning textiles**

There is a novel concept of textiles called self-cleaning textiles that can be cleaned without any laundering action or even can be easily washed and maintained improving their performance in terms of energy and resource consumption[12, 16, 19, 20, 41, 59-67].

Nano-structured surfaces can reduce the contact area between textile and dirt particles which enables overcoming the problems of user comfort and product value reduction[59].

Nanocrystalline TiO_2 photo catalytic was found to be able to destroy organic materials by solar irradiation, also it reduces the maintenance cost of textile products including water, detergents consumption, and temperature required to remove persistent stains. However; recent research work studied the use of silver-titania nanoparticles which were found to enhance fabrics’ self-cleaning and anti-bacterial actions[59].

Moreover; cotton polyester blended fabric treated with the nominated dialdehyde polysaccharide (DAPS, 10 g/l) along with the reactant resin

(DMDHEU, 50 g/l), Ag- or TiO2- NPs as active ingredients (20 g/l) and ammonium persulfate catalyst (5 g/l) using the padding method demonstrated a remarkable improvement in their antibacterial efficacy, UV-blocking ability, self-cleaning capacity, and surface roughness functionality without adversely affecting fabrics resiliency. [59]

"Self-cleaning" properties in textiles can be achieved by three different processes.

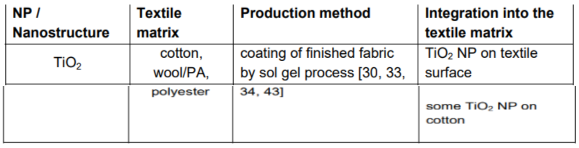
One is the integration of NP that act as a photocatalyst and can degrade organic dirt and stains (Section A)[68].

The second method is the production of superhydrophobic surfaces which provide stain and grime repellency and are "self-cleaned" by the rolling water drops that collect dust and other debris (Section B)[68].

Furthermore, antiadhesive surfaces with repellent properties towards specific compounds or substances, for example, proteins, can be designed through nanoengineering (Section C)[68].

A) Photocatalytic coatings In the examined research papers, stain-degrading properties in textiles were achieved by coating the fabric with nanoparticulate TiO_2. TiO_2 nano sol was produced and applied to the fabric by the dip-pad-dry-cure technique. The textile fabrics were comprised of cotton, wool-polyamide, and polyester fibers. When exposed to light, the electrons of TiO_2 are lifted into an excited state and electron/hole pairs in the valence band region are formed which leads to the formation of superoxide and hydroxyl radicals. These radicals are then able to oxidize organic material adsorbed at the surface and lead to the degradation of stains. As the formed radicals also attack the membranes of microorganisms, textiles that are coated with TiO2 also show antibacterial effects[68].

Table 7: NP, textile matrices, and production methods reported in the examined research papers for stain-degrading textiles. The last column shows the form in which the NP occurs in the finished fabric



NP / Nanostructure	**Textile matrix**	**Production method**	**Integration into the textile matrix**
TiO_2	cotton, wool/PA, polyester	coating of finished fabric by sol gel process [30, 33, 34, 43]	TiO_2 NP on textile surface some TiO_2 NP on cotton

B) Hydrophobic surfaces Attempts to produce superhydrophobic textile surfaces have been made by research groups through the integration of CNT, silica-NP (Si-NP), and fluoro-containing polymer-**NP** [68].

In all three cases, the NP was applied to the textile fabric in form of a coating: produced an emulsion containing fluoro acrylate copolymer NP which was then applied as a coating to nylon and polyester fabrics. Si-NP was applied to cotton fabrics by the production of a nano sol and a subsequent dip-pad-dry-cure-process[68]. In the third case, hydrophobic properties could be achieved by producing artificial lotus leaf structures on cotton fiber surfaces through the application of modified CNT using a common dip-dry-cure method[68].

C) Surfaces with antiadhesive properties report the production of antiadhesive wound dressings by coating viscose fabrics with a modified SiO2 coating. Table 8: NP, textile matrices, and production methods reported in the examined research papers for antiadhesive textiles. The last column shows the form in which the NP occurs in the finished fabric[68].

UV resistant Textiles

UV-resistant textiles made with nanotechnology have inspired many scientists to work in other fields such as architecture. Light scattering predominates at approximately one-tenth of the scattered light wavelength. According to Rayleigh's theory, light scattering is inversely proportional to wavelength, so a particle size of about 20-40 nm is required to effectively scatter UV radiation with wavelengths ranging from 200-400 nm[5].

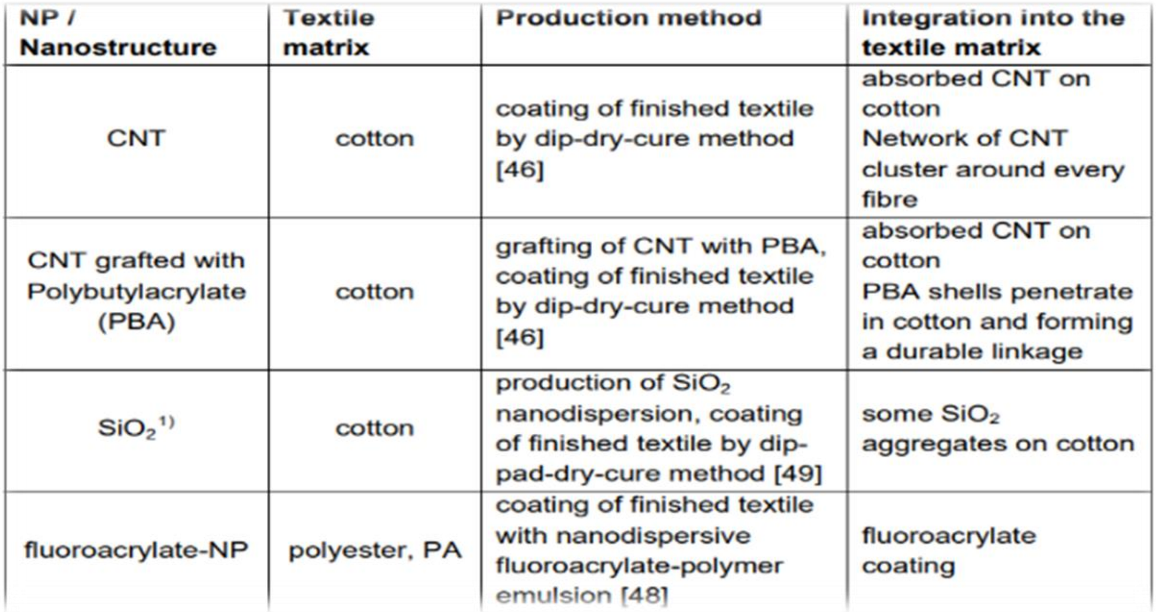
Zinc oxide has been discovered to have very unique photocatalytic, electrical (as a semiconductor and piezoelectric), electronic, optical, dermatological, and anti-bacterial properties due to its bio-safe and biocompatible nature[5].

ZnO nanoparticles with particle sizes ranging from 1045 nm to 1045 nm demonstrated good UV protection with a reasonable increase in UVA and UVB blocking values[5].

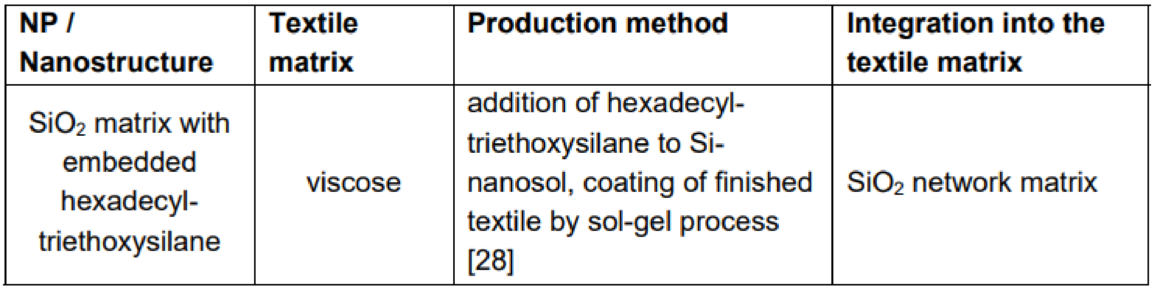
Furthermore, nano-sized zinc oxide, titanium dioxide, and a portion of titanium dioxide and zinc oxide nanorods of 10- 50 nm in length are more effective in scattering and absorbing UV radiation, and thus provide better UV protection when applied to cotton fabrics[5].

This protection is due to the larger surface area per unit mass and volume of nanoparticles which enables such treatments to penetrates into yarn and fabric interstices. However, TiO_2 and ZnO nanoparticles were found to provide textiles several unique properties as UV protection, stain resistance and water repellency as shown in Figure (6)[59].

Table 8: NP, textile matrices and production methods reported in the examined research papers for hydrophobic textiles. The last column shows the form in which the NP occur in the finished fabric[68].



NP / Nanostructure	Textile matrix	Production method	Integration into the textile matrix
CNT	cotton	coating of finished textile by dip-dry-cure method [46]	absorbed CNT on cotton Network of CNT cluster around every fibre
CNT grafted with Polybutylacrylate (PBA)	cotton	grafting of CNT with PBA, coating of finished textile by dip-dry-cure method [46]	absorbed CNT on cotton PBA shells penetrate in cotton and forming a durable linkage
SiO_2 $^{1)}$	cotton	production of SiO_2 nanodispersion, coating of finished textile by dip-pad-dry-cure method [49]	some SiO_2 aggregates on cotton
fluoroacrylate-NP	polyester, PA	coating of finished textile with nanodispersive fluoroacrylate-polymer emulsion [48]	fluoroacrylate coating



NP / Nanostructure	Textile matrix	Production method	Integration into the textile matrix
SiO_2 matrix with embedded hexadecyl-triethoxysilane	viscose	addition of hexadecyl-triethoxysilane to Si-nanosol, coating of finished textile by sol-gel process [28]	SiO_2 network matrix

Photocatalytic Textiles

The band gap of textile material especially the formed free radicals is the key to photocatalytic activity. Different semiconductors such as TiO_2, WO_3, CeO_2, CdS, and ZnS have been widely used for the photocatalytic oxidation of chemicals[59, 63, 69-71].

TiO_2 nanoparticles because of their non-toxicity, chemical, and photostability lower cost, and higher efficiency were known as the reliable choice to achieve the photocatalytic activity of textile materials[59].

It was found that the band gap energy of N-TiO2 reduction to 2.98 eV increases its photocatalytic activity induced by visible light besides its high surface wetting and visible light absorption properties that provides an effective self-cleaning action[59].

Moreover, using nanocrystalline titaniazicronia (TiO_2 – ZrO) composite has been found to have an effective photocatalytic action for textile materials treatments. Thanks to multi-walled carbon nanotubes (MWNTs); the color degradation of textile materials was enhanced. ZnO/NiO coated (MWNTs) showed enhanced efficiency of photodegradation activity in both UV and visible light regions[59].

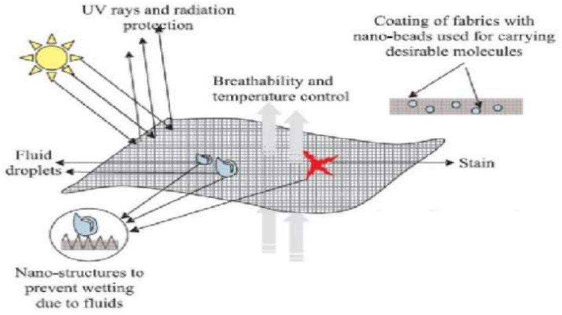


Figure (6) several unique properties are provided by TiO_2 and ZnO nanoparticles[59].

Another application of wearable textiles is using nanocoating and nano finishing in stretchable textiles and wearable solar textiles. [20, 72-79]
stretchable textiles (STs) that have great energy storage capacity and excellent conductivity. The new NiCoP nanoparticles coated spandex textiles are providing perfect conductive and electrochemical performance. A wearable ultra-lightweight polymer solar textile is obtained. It is based on transparent

electronic fabrics (e-fabrics) with a structure of polyester/Ag nanowires/graphene core-shell that have been used as anodes as shown in Figure (7). The e-fabrics are blade-coated by the anode buffer layer and the heterojunction layer[59].

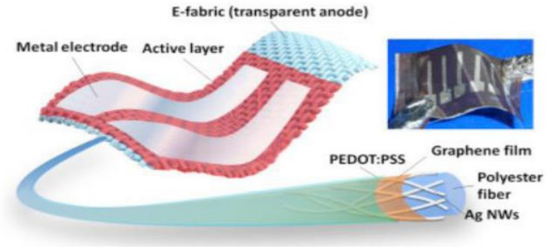


Figure (7) shows Wearable Solar Textiles

These solar textiles show a high degree of compatibility with clothing, a power conversion efficiency of around 2.27%, a low areal density of about 5.0 mg/cm^2, and good resistance to mechanical deformations.

One of the uses of nanotechnology in smart textiles is the triboelectric nano-generator, which is a self-powered, workable way to transform mechanical energy into electricity. In modern triboelectric nanogenerators, a composited fabric with adaptable functional elastomer layers is used as a negative tribomaterial [5].

As seen in Figure (8), this technology is used in power gloves that can make contact with a variety of commonly used objects to gather human motion energy. Even in difficult and complicated circumstances, they exhibit exceptional stability[5].

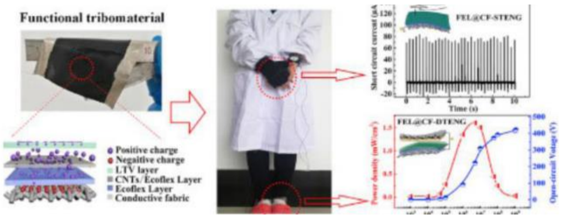


Figure (8) shows FESL@CF TENGs.

Recent research has developed the direct printing of e-textile composed of core-sheath fibers using carbon nanotubes (CNTs) as a conductive core, silk fibroin (SF) as a dielectric sheath and a fabricated CNTs@SF core-sheath fiber-based smart pattern by employing a 3D printer that is equipped with coaxial spinneret which enables printing on textiles for various purposes. The fabricated CNTs@SF core-sheath fiber-based smart pattern is used as a triboelectricity nanogenerator textile. This smart textile can harvest biomechanical energy and achieve power density as high as 18 mW/m^2. This technology may lead to the large production of self-sustainable e-textiles with integrated electronics. CNTs@SF core-sheath fiber-based smart pattern is shown in Figure (9)[59]

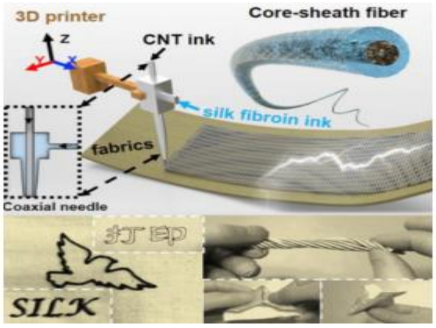


Figure (9) CNTs@SF core-sheath fiber-based smart pattern[59].

Another application of nanotechnology in smart textiles is the one-piece self-power/self-charging power textiles (SCPT). This novel SCPT consists of a fabric triboelectric nano-generator (FTENG) and a woven supercapacitor (WSC). The SCPT is shown in Figure (10)[59]

Figure (10) shows the novel SCPT[59].

Conclusion

Nanotechnology has introduced profitable functions, especially in the textile field. Through increasing comfortability, hygienic properties, durability, and intelligence; the value of textiles has been economically increased especially when applying nanotechnology in smart textiles which imparted unique functions to textile materials. The previously mentioned applications and many other ones of nanotechnology in textiles permit overcoming limitations of the conventional techniques, as a result; smart wearable textiles have been invented and are being developed. Moreover, the combination of nanotechnology and smart textiles would be a global trend in the next few years.

Conflict of Interest

There is no conflict of interest in the publication of this article.

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