

## REVIEW ARTICLE

# Research progress in applying nanomaterials in the field of functional textiles

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## ABSTRACT

The ways of developing functional textiles based on nanomaterials were introduced, and the latest research achievements of nanomaterials in such aspects as flame retardancy, antibacterial, super-hydrophobic, self-cleaning, UV resistance, and anti-static textiles were reviewed. The main technical obstacles to the large-scale application of nanomaterials in functional textiles were pointed out, the possible solutions were discussed, and the development of functional textiles by nanomaterials has been prospected.

**Keywords:** Nanomaterials; Functional Textiles; Flame Retardancy; Antibacterial; Self-cleaning

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## ARTICLE INFO

Received: 17 December 2021

Accepted: 4 February 2022

Available online: 24 February 2022

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## 1. Introduction

With the continuous improvement of people's living standards and the rapid progress of science and technology, functional textiles have penetrated into every field of the national economy. Using nanomaterials to develop textiles with special functions is helpful to enhance the competitiveness of China's textile industry. The combination of nanomaterials and functional textiles can accelerate the innovation of the textile industry and lead the development of the textile industry.

## 2. Methods of modifying functional fabrics by nanomaterials

There are four methods to modify functional textiles by using nanomaterials<sup>[1]</sup>: one is the blending spinning method, in which the nanomaterials are evenly dispersed in the polymer melt, and then the nanomaterial modified functional fibers are prepared by granulation, melt spinning and other processes. This method has little effect on the finishing process and is mainly used to produce chemical fibers or regenerated fibers modified by nanomaterials. The second is the post-finishing method, which uses physical and chemical methods to treat the surface of the fiber or fabric, and then adds the nanomaterials to the finishing agent, and combines the nanomaterials with the fabric through impregnation, coating and spraying. The third is the graft modification method, which endows the surface of nanomaterials with nanomaterials to the surface of textile materials. The fourth is the *in*

*situ* generation method, in the surface and interior of the fiber *in situ* generation of nanomaterials to achieve specific functions.

### 3. Application of nanomaterials in functional fibers and fabrics

In recent years, the application of plasma technology, self-healing technology and other new technologies is conducive to the composite of nanomaterials with fibers and fabrics, realizing the rapid development of single nanoparticle modification to multiple nanoparticle compounding, multi-functional composite direction, and the development of many nano-modified functional textiles.

#### 3.1 Flame retardancy

Most of the fibers belong to combustible fibers, and the flame retardant finishing of the fabric is helpful to reduce the risk of fire. At present, nano flame retardants used in the textile field include nano phosphorus and nitrogen flame retardants, inorganic nanomaterial flame retardants, organic-inorganic mixed nano flame retardants, biological flame retardants. Compared with halogen flame retardants, phospho-nitrogen flame retardants have lower toxicity and smoke emission and meet environmental requirements<sup>[2]</sup>. Inorganic nano flame retardants include carbon nanomaterials such as carbon nanotubes, graphene<sup>[3]</sup>, and oxides such as TiO<sub>2</sub><sup>[4]</sup>, SiO<sub>2</sub><sup>[5]</sup>, ZnO<sup>[6]</sup>, hydroxyl oxide<sup>[7]</sup>, hydroxide<sup>[8]</sup>, etc. Bio-based flame retardants contain deoxynucleotides, etc.<sup>[9]</sup> Nano flame retardants are usually added into the fibers by means of self-assembly, compounding, surface modification, and microencapsulation to improve the flame retardant property of the fibers.

Wang *et al.*<sup>[3]</sup> applied the impregnation method to finish the PGO on the surface of cotton fabric, which significantly enhanced the flame retardant performance of the cotton fabric. PGO with a large layered structure can effectively insulate oxygen and volatile combustible gases from permeation, thus reducing the heat release rate. At the same time, the presence of phosphorus contributes to catalytic carbonization during combustion, promoting the formation of carbon slag and preventing the infiltra-

tion of oxidation and pyrolysis products. Wang *et al.*<sup>[8]</sup> constructed a safety coating consisting of polydopamine, layered dihydroxide, and polydimethylsiloxane on cotton fabric, which significantly improved the flame retardant performance of the cotton fabric and gave it excellent oil-water separation characteristics. Polydopamine and layered dihydroxide inhibit most smog, while coated polydimethylsiloxane enhances stain resistance and durability. Ortelli *et al.*<sup>[9]</sup> applied the mixture of nano TiO<sub>2</sub> and DNA on the surface of cotton by impregnation curing method, which significantly improved the flame retardant performance of the cotton fabric.

#### 3.2 Antibacterial

The active components of nano-antibacterial materials used in the textile are mainly heavy metal ionic and photocatalytic. Specifically, metal ion type nano antibacterial materials include nanometer-scale Ag<sup>[10]</sup>, Au<sup>[11]</sup>, Cu<sup>[12]</sup>, etc. In the process of use, metal ions dissolve out, destroy the respiration, metabolism, and reproduction pathways of bacteria, to achieve the antibacterial effect. Photocatalytic antibacterial agents mainly use TiO<sub>2</sub><sup>[13]</sup>, ZnO<sup>[14]</sup>, BiVO<sub>4</sub><sup>[15]</sup>, and other semiconductor materials to produce OH<sup>-</sup> with strong oxidation capacity under the action of photocatalysis, which destroys the respiration of bacteria and interferes with the material delivery pathway to achieve the antibacterial purpose. In order to combine antibacterial nanoparticles firmly with fiber surface, the impregnation method, layer deposition method, and *in situ* synthesis method are adopted.

In order to make full use of the surface plasmon resonance effect of silver nanoparticles to present brilliant colors and their efficient and safe antibacterial properties, Wu *et al.*,<sup>[10]</sup> adopted a simple solution impregnation method. A cotton fabric with adjustable color and antibacterial, durable, self-healing, and super-hydrophobic properties was prepared by coating the surface of cotton fabric with F-POSS/AgNPs/PEI. The self-healing super-hydrophobicity of F-POSS/AgNPs/PEI coated cotton fabric significantly improved the color fastness of AgNPs to washing and mechanical wear,

and retained the antibacterial properties of AgNPs. Ran *et al.*<sup>[15]</sup> fixed CuO/BiVO<sub>4</sub> nanocomposite photocatalyst on cotton fabric through the polydopamine template, endowed the fabric with photocatalytic properties, and made it have good antibacterial activity and UV resistance. Ibrahim *et al.*<sup>[13]</sup> prepared Anatase TiO<sub>2</sub> nanoparticles doped with Cu<sub>2</sub>O nanoparticles as nano antibacterial composite materials, and treated them into cotton fabric by impregnation method, endows cotton fabric with self-cleaning, UV resistance and antibacterial functions. The cotton fabric has high antibacterial activity due to the production of reactive oxygen species under sunlight.

### 3.3 Super-hydrophobic

In the field of super-hydrophobicity, fibers and fabrics are treated with nanomaterials to construct micro/nano rough structures. Meanwhile, the fiber was chemically modified with low surface energy materials. Micro/nano rough structure can adsorb gas and form nano-sized air film, so that oil or water cannot penetrate into the fabric, thus showing super-hydrophobic or oil-phobic properties<sup>[16]</sup>. Commonly used nanomaterials include SiO<sub>2</sub><sup>[17]</sup>, TiO<sub>2</sub><sup>[18]</sup>, ZnO<sup>[19]</sup>, Al<sub>2</sub>O<sub>3</sub><sup>[20]</sup>, etc. The commonly used methods include chemical vapor precipitation, layer-by-layer self-assembly, sol-gel and so on. These nanomaterials not only improve the super-hydrophobic properties of the fabric, but also have antibacterial, self-cleaning, flame retardant, UV resistance and other properties.

Yao *et al.*<sup>[17]</sup> combined the bio-based 1 benzoxazine monomer with SiO<sub>2</sub> nanoparticles and prepared a bio-based polybenzoxazine/SiO<sub>2</sub> coating on polyethylene terephzoate (PET) non-woven fabric by spraying and thermal curing, endows the non-woven fabric with super-hydrophobic/superoleophilic function. The surface contact angle between the finished fabric and water is  $(156.2 \pm 1.5)^\circ$ , rolling angle is  $(5.2 + 1.0)^\circ$ , with good adhesion strength, can be used for various types of oil-water separation. The fabric still shows super-hydrophobic stability after severe treatment such as mechanical wear, acid and alkali immersion, and solvent immersion. Guo *et al.*<sup>[18]</sup> deposited su-

per-hydrophobic and flame retardant coatings on cotton fabrics with a simple two-step spraying method, and prepared fabrics with both flame retardant and super-hydrophobic functions. The super-hydrophobic and superoleophilic coatings are composed of layered TiO<sub>2</sub> and PDMS, while the flame retardant coatings are composed of alkylamine sesimiloxane/phytic acid. The finished cotton fabric exhibits high thermal stability, flame retardancy, super-hydrophobicity, self-cleaning and oil-water separation properties. In addition, after 50 wear tests and 5 washing treatments, the cotton fabric still maintained good hydrophobicity and self-extinguishing ability. Xiao *et al.*<sup>[20]</sup> deposited Al<sub>2</sub>O<sub>3</sub> layer and Al<sub>2</sub>O<sub>3</sub> nanoparticles on the surface of the wool fabric by atomic layer deposition technology, effectively increasing the surface roughness of wool fabric, increasing the static contact angle between wool fabric surface and water from 130° to about 160°, and achieving higher durability. Although the fluorine-containing finishing agent has good water-repellent and oil-repellent properties, its high price and bio-cumulative effect limit its further development. In addition, in the actual use process, the modified super-hydrophobic and super-oil-phobic surface structure are vulnerable to mechanical damage and chemical action, resulting in a decrease in durability. In order to solve this problem, Lahiri *et al.*<sup>[21]</sup> deposited the SiO<sub>2</sub>-alkyl silane coating mixed with boric acid on cotton fabric through a simple dip rolling finish, and then modified it with PDMS to prepare fluorine-free super-hydrophobic composite coating on the surface of cotton fabric. The static contact angle between the finished fabric and water reaches  $(157.95 \pm 2)^\circ$ , rolling angle reached  $(3.8 \pm 0.6)^\circ$ , showing excellent super-hydrophobic characteristics. Coated fabrics demonstrate excellent robustness and durability, as well as self-healing and oil-water separation.

### 3.4 Self-cleaning

Self-cleaning fabrics can be divided into super-hydrophobic self-cleaning and photocatalytic self-cleaning according to the way of self-cleaning. Super-hydrophobic self-cleaning mainly refers to the use of bionics principles to treat fabrics with

super-hydrophobic treatment to achieve self-cleaning performance. Commonly used inorganic nanomaterials include layered bimetal hydroxide<sup>[8]</sup>, SiO<sub>2</sub><sup>[21,22]</sup>, etc. Chen *et al.*<sup>[22]</sup> prepared super-hydrophobic fabrics by the sol-gel method by deposition of SiO<sub>2</sub> on the fabric and grafting of the finishing agent. The fabric remains highly oil-repellent and water-repellent under various harsh conditions (such as ultraviolet radiation, alkali (pH 12) or acid (pH 2) solution, water treatment at 2 °C or 95 °C), and has excellent self-cleaning and antifouling performance. Photocatalytic self-cleaning mainly uses nano-semiconductor materials with photocatalytic effects, such as BiOI<sup>[23]</sup>, TiO<sub>2</sub><sup>[24,25]</sup>, ZnO<sup>[26]</sup>, carbon nitride<sup>[27]</sup>, etc., to generate free radicals under the action of light and degrade organic pollutants on the fabric into CO<sub>2</sub> and H<sub>2</sub>O, so as to achieve the purpose of self-cleaning. Zahid *et al.*<sup>[24]</sup> prepared manganese-doped nano TiO<sub>2</sub> by sol-gel method, and applied organosilicon adhesive to finish it on textiles. Using methylene blue dye to simulate pollutants, the fabric showed a good self-cleaning effect under ultraviolet and visible light irradiation. At the same time, the functional fabric has good biocompatibility and shows antibacterial properties in natural sunlight. Jaksik *et al.*<sup>[25]</sup> reported that TiO<sub>2</sub> modified by Ag/Au nanoparticles was deposited on cotton fiber through gel sol process to prepare self-cleaning cotton fabric with photocatalytic properties. TiO<sub>2</sub> coating with Au and Ag nanoparticles endow cotton fabric with self-cleaning and antibacterial properties. Pedrosa *et al.*<sup>[27]</sup> prepared functional fabrics with high antibacterial and self-cleaning properties by treating g-C<sub>3</sub>N<sub>4</sub> and GO on cotton fabric with a simple impregnation method. Using caffeine and rhodamine B as simulated pollutants, the finished cotton fabric effectively degraded the pollutants under visible light irradiation and showed excellent photocatalytic activity, indicating that it has an excellent self-cleaning function.

### 3.5 UV resistance

Adding UV absorbent or blocking agent to fabric can effectively reduce the damage of excessive UV to the human body. However, some organic

anti-UV protective agents are prone to allergic reactions and may be toxic to the human body. Inorganic nanomaterials with non-toxic, stable properties and long-lasting UV resistance are easier to be accepted by the market. Commonly used UV blocking agents of nanomaterials include nano Au<sup>[11]</sup>, BiOI<sup>[23]</sup>, ZnO<sup>[28]</sup>, Ag<sup>[29]</sup>, metal-organic skeleton materials<sup>[30]</sup>, TiO<sub>2</sub><sup>[31]</sup>, graphene<sup>[32]</sup>, etc. These nanomaterials, when combined with the fiber, can enhance the fiber's UV reflection and scattering effect, thus achieving enhanced UV absorption and shielding effect.

Yuan *et al.*<sup>[29]</sup> successfully deposited Ag/ZnO composite films on polyester fabrics with pure silver and zinc targets by DC magnetron sputtering and RF magnetron reactive sputtering techniques. The results show that zinc coating on silver film before RF reactive sputtering can effectively protect the silver film from oxidation. Ag/ZnO composite film can produce structure color on polyester fabric, and give the fabric excellent UV resistance and antistatic properties. Xiao *et al.*<sup>[31]</sup> successfully deposited nano TiO<sub>2</sub> onto silk fiber by atomic layer deposition technology, which enhanced the thermal stability and mechanical properties of silk fiber and endowed the fiber with excellent UV protection characteristics. Li *et al.*<sup>[30]</sup> fixed the InOF-1 nanocrystals generated *in situ* on the surfaces of three kinds of fabrics (cotton, polyester and aramid) based on the solid-phase hot pressing method without adding solvents or adhesives, significantly improving the UV resistance of the fabrics. Cao *et al.*<sup>[32]</sup> prepared a multifunctional silk fabric with conductivity, UV resistance and water repellency by repeatedly impregnating go and chemical reduction methods by finishing RGO onto silk fabric.

### 3.6 Antistatic fiber

Due to the friction electrostatic effect, the fabric is easy to produce spark discharge in the process of use, and the high voltage electrostatic is harmful to health and easy to induce a variety of diseases. In inflammable and explosive places, high voltage static electricity can easily cause hidden dangers, in addition, high voltage static electricity will damage

precision electronic instruments, so it is necessary to develop antistatic fabrics. Compared with antistatic materials such as antistatic agents, metal fibers, carbon fibers and conductive polymers, nano conductive particles are more suitable for preparing permanent antistatic fabrics due to their simple preparation and wide application range. Conductive particles such as carbon nanotubes<sup>[33]</sup>, MXene<sup>[34]</sup>, GO<sup>[35]</sup> and SiO<sub>2</sub>/TiO<sub>2</sub><sup>[36]</sup> are often compounded with fibers by post-finishing method or blending spinning method to improve the antistatic properties of fabrics.

Li Liang *et al.*<sup>[35]</sup> prepared polyester fabrics with good antistatic properties by using dopamine *in situ* polymerization to construct polydopamine films on the surface of polyester fabrics and then loading GO. The antistatic fabric has good washing durability thanks to the super adhesive effect of polydopamine. Kelly *et al.*<sup>[37]</sup> prepared a new type of silver nanoparticles wool composite by chemical reduction method. Silver nanoparticles give the composites excellent antibacterial and antistatic properties.

#### 4. Technical obstacles and solutions of nanomaterials application

At present, the main obstacles in the application of nanomaterials in the textile field are as follows: one is the problem that the nanoparticles are difficult to disperse evenly in spinning and on the fiber surface. The particle size of nanomaterials is small, the surface energy is high, easy to agglomerate; in addition, the polarity difference between some nanomaterials and the spinning solution makes it difficult for the nanoparticles to disperse evenly in the spinning solution, which affects the rheology and spinnability of the spinning solution. The second is to improve the bonding firmness of nanoparticles with fibers and fabrics. The durability and stability of functional textiles can be enhanced by increasing the binding degree of nanomaterials and fibers.

Solutions: (1) *in situ* synthesis of nanomaterials on the surface or inside the fiber. This method takes advantage of the porous structure of the fiber material, effectively solves the agglomeration

problem of the nanomaterial in use, and enhances the binding degree between the nanomaterial and the fiber matrix to a certain extent. (2) The fiber surface is modified, such as plasma treatment, chemical etching, radiation, etc., to improve the roughness of the fiber surface and increase the number of active groups, so as to improve its binding ability with nanomaterials. (3) Surface coating and modification of nanomaterials. Based on graft polymerization reaction, gel-sol method, and so on, use coated modification agents such as surfactants, super-dispersants to achieve the purpose of modifying nanomaterials, so as to enhance the binding ability of nanomaterials and fibers.

#### 5. Conclusion

Using nanomaterials to develop functional textiles has become one of the main trends in the textile industry. However, due to the unpredictability of nanomaterials in nano-toxicology and their own characteristics, as well as the standardization of functional textiles modified by nanomaterials, all these hinder the further development of functional textiles. How to further accelerate the application of nanomaterials in the field of functional textiles can be carried out from the following four aspects.

(1) Develop nano textile standards. Nano-modified functional fabrics are popular in the market because of their excellent properties. Very few businesses take the opportunity to hype nano, shoddy, seriously disrupted the market order. In order to solve the chaos of the nano textile market and further standardize the market, it is necessary to standardize the performance testing of functional textiles and accelerate the formulation and improvement of the standard of nano-modified functional textiles.

(2) Due to the unique nano-size effect of nanomaterials, while benefiting mankind, they may cause harm to the human body and the environment<sup>[38]</sup>. Nanotoxicology has formed new interdisciplinary research on the biological effects of nanomaterials. At present, the research on nano-toxicology is still in its infancy, so it is necessary to establish reasonable, effective, and rapid evaluation methods and establish safety evaluation



systems and detection standards of nanomaterials, so as to promote the rapid development of nanomaterials.

(3) At present, China has made a series of research achievements in the development of nano-modified functional textiles, and occupies a certain market share. But in general, most are still experimental.

(4) The development of new nanomaterials and the application of nanotechnology, micro-electronics, bionic technology, 3D printing technology and textile technology have greatly promoted the development of multi-functional textiles. At present, smart fibers and smart textiles are in the ascendant. Our country should speed up the pace of research and development, and constantly develop functional textiles with multi-function and high added value to form core competitiveness.

## Acknowledgment

This article is supported by the key project of natural science research of universities in Anhui Province “Dilute Soil Doped Pure Silicon MCM-41 Gentle Oxidation and Product Separation of Aromatic Ring Compounds” (KJ2019A0850), and major project of natural science research in Anhui Province “Controllable Preparation and Surface Functionalization Regulation of Highly Dispersed Spherical Porous Silica” (KJ2019ZD62).

## Conflict of interest

The authors declare that they have no conflict of interest.

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