BRAZILIAN JOURNAL OF BIOLOGY®

ISSN 1519-6984 (Print)
ISSN 1678-4375 (Online)

Original Article

Antimicrobial finishing of textiles using nanomaterials

Acabamento antimicrobiano de têxteis a partir da utilização de nanomateriais

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Abstract

Metals, such as copper and silver, can be extremely toxic to bacteria at exceptionally low concentrations. Because of this biocidal activity, metals have been widely used as antimicrobial agents in a multitude of applications related with agriculture, healthcare, and the industry in general. A large number of microorganisms live in the human environment. if the balance of these creatures in nature is disturbed, the health of the individual and society will be threatened due to the production and emission of unpleasant odors and the reduction of health standards. The presence of microorganisms on textiles can cause adverse effects such as discoloration or staining on textiles, decomposition of fibrous materials, reduced strength, and eventually decay of textiles. Most fibers and polymers do not show resistance to the effects of microbes and by providing growth factors for microorganisms such as the right temperature and humidity, nutrients from sweat and fat from skin glands, dead skin cells as well as materials used in the stage of finishing the textiles causes the rapid growth and spread of various microbes. With the advent of nanotechnology, various industries and human daily life underwent changes. In recent years, increasing research on nanoparticles has led to the production of textiles with greater efficiency and added value. These modified textiles prevent the spread of unpleasant odors, the spread, and transmission of diseases. This article reviews the basics and principles of antimicrobial tetiles, as well as a brief overview of antimicrobial materials and nanostructures with antimicrobial properties.

Keywords: nanomaterials, antimicrobial, textiles, nanostructures, nanoparticles.

Resumo

Metais como cobre e prata podem ser extremamente tóxicos para bactérias em concentrações excepcionalmente baixas. Devido a esta atividade biocida, os metais têm sido amplamente utilizados como agentes antimicrobianos em uma infinidade de aplicações relacionadas à agricultura, saúde e indústria em geral. Muitos microrganismos vivem no ambiente humano e, se o equilíbrio dessas criaturas na natureza for alterado, a saúde dos indivíduos e da sociedade estará ameaçada devido à produção e emissão de odores desagradáveis e à redução dos padrões de saúde. A presença de microrganismos em têxteis pode causar efeitos adversos, como descoloração ou manchas, decomposição de materiais fibrosos, resistência reduzida e, eventualmente, deterioração. A maioria das fibras e polímeros não apresenta resistência aos efeitos dos micróbios e fornecem fatores de crescimento para os microrganismos, como temperatura e umidade adequadas, nutrientes do suor e gordura das glândulas da pele, células mortas da pele, bem como materiais usados na etapa de acabamento causando crescimento e disseminação de vários micróbios. Com o advento da nanotecnologia, diversas indústrias e o cotidiano humano passaram por mudanças. Nos últimos anos, o aumento da pesquisa em nanopartículas levou à produção de têxteis com maior eficiência e valor agregado. Esses têxteis modificados evitam a propagação de odores desagradáveis, a propagação e a transmissão de doenças. Este artigo analisa os fundamentos e princípios dos têxteis antimicrobianos, bem como uma breve visão geral dos materiais antimicrobianos e nanoestruturas com propriedades antimicrobianas.

Palavras-chave: nanomateriais, antimicrobianos, têxteis, nanoestruturas, nanopartículas.

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Received: June 13, 2022 – Accepted: November 10, 2022

1. Introduction

Non-essential metals, such as silver, can be toxic to bacteria, having biocidal activities at exceptionally low concentrations, while essential metals, such as copper, can also be lethal above some threshold despite their relevance in the biochemistry of organisms (Lemire et al., 2013). Because of this biocidal activity, metals have been widely used for centuries as antimicrobial agents in agriculture, healthcare, and industry in general. Metal, oxide, or salt compounds based on copper and silver are among the most widely applied antimicrobial agents in this context (Gunawan et al., 2011).

A large number of microorganisms live in the human environment. If the balance of these creatures in nature is disturbed, the health of the individual and society will be threatened due to the production and emission of unpleasant odors and the reduction of health standards (Lemire et al., 2013; Gunawan et al., 2011; Damm et al., 2008; Bokov et al., 2022; Zhang et al., 2006; Kumar et al., 2013). The presence of microorganisms on textiles can cause adverse effects such as discoloration or staining on textiles, decomposition of fibrous materials, reduced strength, and eventually decay of textiles (Giglio et al., 2013; Appendini and Hotchkiss, 2002; Jasim et al., 2023; Prabhu and Poulose, 2012; Sintubin et al., 2009; Ruparelia et al., 2008). Most fibers and polymers do not show resistance to the effects of microbes and by providing growth factors for microorganisms such as the right temperature and humidity, nutrients from sweat and fat from skin glands, dead skin cells as well as materials used in the stage of finishing the textiles causes the rapid growth and spread of various microbes (Karlsson et al., 2013; Xia et al., 2006; Sondi and Salopek-SoNdi, 2004; Muñoz-Bonilla and Fernández-García, 2012). Therefore, due to the prevalence of diseases and unwanted damage caused by microorganisms, much effort has been made to control the effects of these organisms (Thomas et al., 2007; Ghasemzadeh and Ghanaat, 2014; Ren et al., 2009; Weickmann et al., 2005; Raya et al., 2022b; Fouda et al., 2013). In addition to providing a suitable environment for the growth of microbes, textiles can cause the transmission of various diseases in health care centers, so the use of antimicrobial textiles in these centers can prevent the spread of drug-resistant diseases and also the risk of disease in employees Reduce these centers and the general public (Anita et al., 2014; Kasthuri et al., 2013; Liu et al., 2013; Viegi et al., 2003). on the other hand, the use of chemicals with antimicrobial properties in textile finishing has many disadvantages due to its toxicity and environmental problems (Yang et al., 2012; Dimapilis et al., 2018; Warheit et al., 2007; Tian et al., 2007). The use of nanoparticles, especially metal and mineral nanoparticles, has provided a new arena in the finishing of antimicrobial textiles (Lemire et al., 2013).

2. Principles of Antimicrobial Modification of Textiles

Microorganisms include fungi, bacteria, viruses, algae, spores, etc., which are often expressed as microbes and are found in the environment (Wijnhoven et al., 2009; Sun et al., 2005; Rai et al., 2009). These microorganisms weigh about 25 times the weight of all animals and in their environment play an effective role in fermentation, production of metabolic compounds, preparation of chemicals (lactic acid and citric acid), finishing off the cycle of returning materials to nature, and adverse effects such as spoilage (Geoprincy et al., 2011; Jia et al., 2012; Ramyadevi et al., 2012). Foods, material degradation, commodity decay, and various diseases occur (Shinde et al., 2013; Paladini et al., 2014; Sundaresan et al., 2011; Al-Obaidi et al., 2023; Kumar et al., 2013). Since textiles, in addition to providing a suitable environment for the growth and multiplication of microbes, can cause the transmission and spread of various diseases, therefore, research has been conducted to produce antimicrobial fibers and textiles with the following objectives (Salimi et al., 2017a, b; Pirouzfar et al., 2014):

- **Prevent the adverse effects of microorganisms on the functional properties of textiles**

Some fibers, especially cellulose fibers, are biodegraded by microbes. This action of microbes can change the color and reduce the mechanical properties (abrasion and tensile strength) of the fibers and cause the fabric to rot. Microorganisms can also reduce the viscosity and degrade materials used in various textile processes (Kianfar et al., 2017).

- **Prevent unpleasant odors**

Microbes need the right nutrients, moisture, and temperature to grow and multiply. Sweat and dead skin cells, moisture, and body temperature provide a good breeding ground for germs in textiles (Kianfar et al., 2018a, b 2019a, b). Under these conditions, microorganisms produce volatile substances with unpleasant odors, including fatty acids (acetic, propionic, butyric, valerian, caproic), methylamines, ammonia, aldehydes, sulfides, mercaptans, lactones, and aromatic compounds (Kianfar et al., 2018a, 2019a, 2020b; Liu and Kianfar, 2021). In order to reduce the unpleasant odor caused by the presence of microbes on the textiles, methods such as clogging the pores of the skin, using micro and Nano capsules, converting odorous compounds into odorless compounds, and reducing the volatility of unpleasant-smelling substances (Kianfar et al., 2018a, b). The use of antimicrobial compounds in the production or finishing of textiles is one of the most effective methods to eliminate unpleasant odors (Damm et al., 2008).

2.1. Cell structure of microorganisms

The bacterial cell is made of a hard wall in which there is a flagellum or lashes that move

covers the cell and contains the material inside the cell (Kianfar et al., 2020a). Bacteria are divided into gram-positive bacteria and gram-negative bacteria in terms of cell walls. Gram-positive bacteria have a relatively thick wall, consisting of a large number of peptidoglycan layers and only one plasma membrane; Gram-negative bacteria, on the other hand, have a thinner layer of peptidoglycans than a more complex cell wall with two cell membranes (Mousavian et al., 2020; Yang et al., 2020). Therefore, gram-negative bacteria are more resistant to many chemical agents than gram-positive bacteria.

2.2. Living conditions of microorganisms

The best way to prevent and minimize microbial damage is to disrupt the growth and reproduction conditions of these organisms (Gao et al., 2021). Due to their close contact with the body, clothing provides the best environment for the growth and multiplication of fungi, bacteria, and yeasts (Kianfar, 2020a, b). The following are suitable conditions for the growth of microorganisms:

- **Nutrients**

Dust, fat and food stains, dead skin cells, body perspiration, fat from skin glands, and some natural substances used in the process of completing textiles can provide the necessary conditions to feed microbes.

- **Water**

All microorganisms need a thin layer of water to grow, which is the amount of moisture on the skin and textiles.

- **Oxygen**

The oxygen required by microbes is easily present in their environment.

- **Heat**

Most fungi and bacteria grow at a temperature of 10-20 degrees Celsius and some microbes prefer a warmer environment than the skin such as clothing and sheets.

2.3. Common definitions and terms in antimicrobials

Antimicrobial modification prevents the rapid growth of bacteria, fungi, and algae on textiles. These antimicrobial textiles are not germ-free or sterile, but they can prevent the growth of microorganisms or kill them by using one or more active ingredients.

Antimicrobials are divided into two main categories:

- **Biostatic or bactericidal inhibitory substances**: These substances bind to DNA chain amino acids in bacteria and prevent DNA replication and thus bacterial proliferation and thus keep the cause constant. The number of bacteria increases.
- **Bactericidal or bactericidal substances**: These substances cause bacterial death by disrupting the metabolism of the bacterium or stopping it completely. These substances inactivate the necessary and vital enzymes in biological reactions (Gunawan et al., 2011).

If a substance has a negative effect on the life of microorganisms, it is known as an antimicrobial agent. The term antibacterial or antimitotic refers to substances that limit the activity of bacteria and fungi (Gunawan et al., 2011).

2.4. Properties of a suitable antimicrobial agent

In order to modify the antimicrobial of textiles, the antimicrobial agent must have suitable properties, some of which are (Kianfar and Gas, 2020; Mehran et al., 2016):

- Ability to use simple in common complementary methods.
- Stability against washing, drying, and durability during use.
- Having antibacterial properties against undesirable microorganisms.
- Ability to transfer moisture properly.
- Compatibility with product color and other complementary materials.
- Non-toxicity for the consumer of goods and the environment.
- Possibility of selective effect on a wide range of bacteria and lack of effect on skin flora (effective skin bacteria) and lack of compatibility against microorganisms.
- Availability and fast performance.
- Lack of effective color and smell on the fabric.

At present, ideal materials with all the mentioned properties are not known and often different antimicrobial substances are used depending on the type and final use of the product (Farshad et al., 2015b; Kianfar, 2019b).

2.5. antimicrobial material affect microorganisms

In general, antimicrobials with effect on the cell wall, inner membrane, or cytoplasm and disrupt protein synthesis, blocking nucleic acids, oxidation of SH-containing groups, reaction with amino groups, accelerating the penetration of low molecular weight substances such as potassium salts and amino acids Inside the cell, swelling and bursting of the cell, etc. (Hajimirzaee et al., 2022; Kianfar, 2021a) cause inactivation and death of germs (Figure 1).

Antimicrobial compounds such as antibiotics, formaldehyde, heavy metal ions such as silver, copper, etc., quaternary ammonium salt (with long hydrocarbon chains), phenols, oxidizing agents such as chlorine, chloramine, hydrogen, ozone, etc., which are by methods Physically or chemically lead to the effect on microbes (Huang et al., 2021; Kianfar, 2021b). Antibiotics have been reported to inactivate bacteria by inactivating cellular enzymes. Quaternary ammonium salts and phenol compounds damage cells and slow down bacterial activity by affecting the membrane properties of microorganisms (Kianfar, 2021a; Syah et al., 2021; Isola et al., 2022). Oxidizing compounds can rapidly inactivate microorganisms through chemical reactions with some vital agents, but most of these compounds are toxic and allergenic. Oxidizing agents, including aldehydes, halogens, and peroxide compounds, act on the cell membranes of microorganisms and, when they enter the cytoplasm, on enzymes within the cell. Radical compounds such as halogens are highly active due to their free electrons and react with organic structures. Chlorine-releasing agents and peroxidation agents are effective against viruses and in some cases primates and a variety of bacteria and fungi. The antimicrobial effect of cationic compounds has been attributed to the reaction of cations with anionic phospholipids in the microbial cell wall, which increases permeability and ultimately cell death (Kianfar, 2021b; Syah et al., 2021). The surface of cationic activities has antibacterial properties due to the strength of the strong electrostatic bond with the anionic wall of the bactericidal cell (Majdi et al., 2021; Bokov et al., 2021; Ansari et al., 2022; Chupradit et al., 2022). The formation of anion/cation bonds leads to the hydrophobicity of the cell wall and prevents the absorption of water (one of the vital factors of the microorganism) and ultimately the multiplication and growth of bacteria. The cell wall may be physically damaged, which will kill the bacteria (Aldeen et al., 2022; Suryatna et al., 2022; Abdelbasset et al., 2022; Zaid et al., 2021). Metallic compounds inhibit the activity of enzymes and disrupt cell fuel (Zaid et al., 2018; Zaid et al., 2018; Kaduim et al., 2021). The antimicrobial action of these compounds lasts several

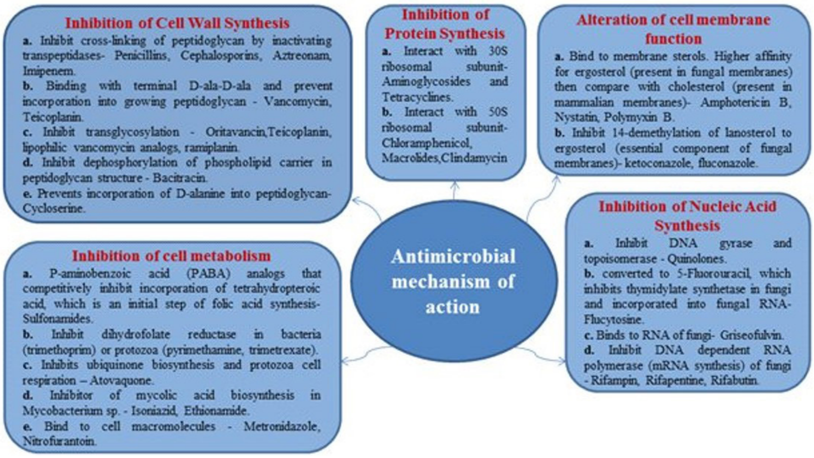

Figure 1. Different functions of antimicrobial agents (Abdelbasset et al., 2022).

minutes. Among metals, the toxicity of cadmium is more than other metals and the antimicrobial properties of silver, brass, copper, mercury, etc. are reduced, respectively. But metals such as platinum, iron, and aluminum have no antimicrobial effect (Salahdin et al., 2022; Isola et al., 2022).

3. Common Compounds Used to Modify Antimicrobial Textiles

3.1. Introduction of antimicrobial materials used for textiles

Antimicrobial active ingredients that have been used for a long time are:

- Minerals such as gallium, silver sulfate, silver nitrate, copper sulfate, zinc sulfate, zinc nitrate;
- Organic materials such as orthochlorophenol, pentachlorophenol;
- Organic-metallic materials that have a direct bond between carbon and metal, such as tetramethyl tin.

The following are some examples of antimicrobials: their fourth type of hexamethylenediamine derivatives in laundry solvents for disinfection of clothing, halogenated gandinium salts such as chlorhexidine for children's clothing, hexapyrimidine for penicillin bandages, elite Amine tetraacetic acid (EDTA) is used to make antibacterial sanitary napkins (Lemire et al., 2013).

Chemical compounds used in antimicrobial modification include metal and organometallic salts, iodine compounds, phenols and thiophenols, ammonium type IV and other cationic salts, antibiotics, heterocyclic compounds, nitro compounds, urea, and most amine-based structures, aldehydes (Al-Madhhachi and Smaisim, 2021; Smaisim et al., 2016; Zaid et al., 2019).

Lactic acid is a good antibacterial against Escherichia coli due to its organic acids.

3.2. Antifungal and antibacterial industrial materials

Antifungal and bacterial industrial materials can be classified as follows (Smaisim, 2017; Zaid et al., 2021):

- Mineral salts;
- Copper fatty acids or naphthalic acid;
- Copper oxycholate;
- Chlorophenols;
- Salicylic anilides;
- Organic compounds of mercury;
- Cationic compounds.

3.3. Classification of emerging antimicrobial agents

Emerging antimicrobial agents can be divided into four groups (Figure 2):

3.3.1. Modified chemical compounds with antimicrobial effect

At least four main antimicrobial agents can be considered for this group (Fatla et al., 2015; Liu et al., 2022; Sallal et al., 2021; Siswanto et al., 2021)

- Inorganic ion exchange materials: Intermediate metal salts such as silver and copper with mineral carriers (zeolites) used in synthetic fibers. By controlling the release of silver ions by a suitable mineral carrier, the antimicrobial properties and possible negative effects on the fiber are controlled. This method prevents discoloration, discoloration, or reduced mechanical strength of the fibers. Mineral substrates such as zeolites, titanium dioxide, zinc oxide, etc. are used for this purpose;
- Mineral hydroperoxides: Manganese acetate tetrahydrate and hydrogen peroxide, which show antimicrobial activity in most fibers, but have higher chemical stability in cotton;
- Ammonium salts type IV: Phosphorus polymer salts have been reported as antimicrobial agents for cotton fibers. These materials have strong cationic properties and react covalently in acrylic fibers with dye site stains, while they are not suitable for polyester and polyamide fibers due to their dissolution in water. This material is widely used in the production of home textiles with anti-allergy and anti-asthma properties;
- Hydroperoxy Acetate and Magnesium Dihydroperoxy: These materials have less pollution and better

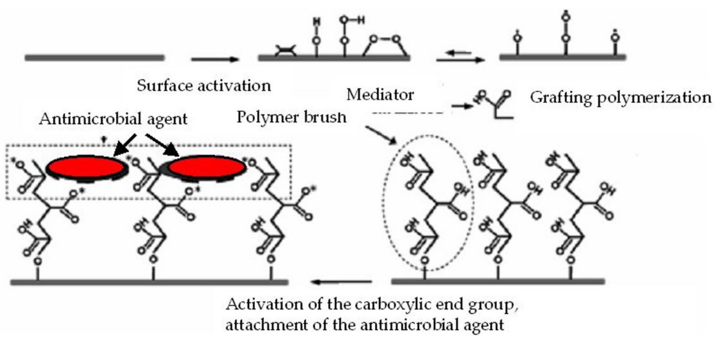

Figure 2. Classification of emerging antimicrobial agents (Ahamad et al., 2022).

biocompatibility compared to mineral peroxides based on zinc and zirconium (Gunawan et al., 2011).

3.3.2. Modified compounds to reduce, prevent microbial growth and biofilm formation

In this method, the formation of biofilms or microbial processes is reduced by changing the surface of the polymer. For this purpose, acrylic acid is bonded to the polyurethane layers by heat or plasma, thus reducing bacterial adhesion from 5% to 1% (Alharbi et al., 2022; Hussien et al., 2018; Zaid, 2019; Jiang et al., 2022). Therefore, by changing the surface energy and creating acidic factors on the surface, the connection of microbes to the surface is prevented.

3.3.3. Materials used to modify the irritated surface through external factors

Intelligent materials that respond reversibly to external stimuli. Dicotetrahydroglyceride (Hydantoin) can show intelligent antimicrobial properties by binding to cotton fibers and being activated by bleach (Mozafarifard et al., 2022; Smaisim et al., 2022a; AbdulHussein et al., 2022; Wang et al., 2022).

3.3.4. Natural antimicrobials

Research has shown that natural antimicrobial agents are a good solution for biocidal bacteria. Chitosan is a natural antimicrobial that is obtained by deacetylating chitin (Cai et al., 2022; Wu et al., 2022). It is a naturally occurring amino acid that is found in abundance. The antimicrobial properties of this substance depend on its molecular weight. The antimicrobial properties of chitosan are due to the amine group, which is converted to ammonium salt in an acidic environment and adheres to the negatively charged microbial cell membrane, causing the cell wall to rupture and the material to escape, eventually killing the microbial cell (Tian et al., 2022a, b; Abed et al., 2022). This polycation can also bind to cell DNA and inhibit protein synthesis by the cell.

4. Antimicrobial Inorganic Nanostructures

Antimicrobial Inorganic nanostructures can be used directly or by loading in carrier systems to modify textiles. Nanostructures can be classified into two groups.

4.1. Inorganic, metal nanostructures and nanocomposites

These include titanium dioxide nanoparticles and nanocomposites, silver and zinc oxide nanostructures, silicon dioxide, copper nanocrystals, aluminum, and iron compounds, metal oxides and hydroxides, carbon nanotubes, and nanotubes (Smaisim et al., 2022b; Abderrahmane et al., 2023; Younis et al., 2022; Xiao and Smaisim, 2022; Mourad et al., 2022).

4.2. Loaded nanostructures in organic carriers

This group includes microcarriers and mineral-carrying nanocapsules in which Inorganic nanostructures are loaded as guests in the organic host bed. In some cases, zeolites are used as carriers, but due to the compatibility of organic-mineral systems with polymer substrates and surfaces and textiles, more organic carriers are used. Polymeric substrates such as nanoparticles, nanoparticles and microcapsules, dendrites and lipid carriers such as nanoparticles and microliposomes, and molecules such as cyclodextrins are used as organic carriers of inorganic nanostructures (Figure 3).

5. Inorganic and Metal Nanostructures and Nanocomposites

5.1. Titanium dioxide nanoparticles

Titanium dioxide nanoparticles have been considered for their stability, safety and health, antimicrobial properties, and self-cleaning.

5.1.1. Performance of titanium dioxide against microbes

Atomic force microscopy (AFM) examinations showed that the photocatalytic degradation of TiO_2 nanoparticles in the outer layer of Escherichia coli caused the death of the bacterium (Figure 4). Cell death of this bacterium occurs after ultraviolet irradiation of a thin layer of titanium dioxide nanoparticles through the destruction of the primary cell wall and subsequent decomposition of the cell membrane wall (Tan et al., 2023; Mir et al., 2023; Ruhani et al., 2022; Li et al., 2022). Damage to cell membranes leads to the leakage of minerals, proteins, and genetics, resulting in cell death.

5.1.2. Photocatalytic performance of titanium dioxide

When light energy greater than or equal to the energy required to separate an electron hits the TiO_2 surface, free electrons and cavities are produced, which can lead to an oxidation and reduction reaction at the TiO_2 surface. This generated cavity can produce highly active OH_o hydroxyl radicals in the presence of H_2O or OH on the surface of TiO_2. Electrons released by oxygen in the air also produce superoxide ions ($O2_o$). In this way, by side reactions, hydroxyl ions HO_{2o} and H_2O_2 and other active species produce oxygen (Abed et al., 2022; Hai et al., 2022; Smaisim et al., 2022a). Finally, these active species can oxidize the organic compounds of the microorganism cell and lead to its death. Among the active groups produced, hydroxyl radicals are more active and therefore have less stability and longevity, while superoxide ions are more stable but cannot penetrate the cell membrane due to their negative charge.

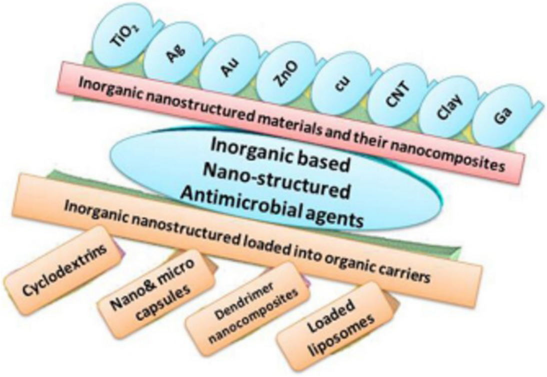

Figure 3. Antimicrobial modification of textiles using Inorganic nanostructures (Abed et al., 2022).

5.1.3. The effect of the crystalline structure of titanium dioxide on photorealistic properties

The crystal structure of TiO_2 has a significant effect on its photocatalytic properties. So that the structure of anatase has stronger photocatalytic properties and wider applications than the structure of rutile. Anatase is a semi-stable form of titanium dioxide at low temperatures and converts to rutile as the temperature rises. In order to increase thermal stability, the addition of silicon and zirconium ions to the crystal structure of anatase is used. The excitation energies of rutile and anatase are 25.3 and 75.3 electron volts, respectively.

It has been reported that the catalytic activity of TiO2 nanoparticles is increased by the following three methods:

- Adding metal ions;
- Mixing with other nanocrystals;
- Application of an electric field on particles: An electric field enhances the photocatalytic properties of TiO_2 by decomposing air and water molecules into positive and negative ions and free radicals.

Research has shown that in the finishing of cotton textiles with titanium dioxide, due to the photocatalytic properties of TiO_2, it is possible to convert the crosslinking acidic groups of succinic acid into active aldehyde groups (Smaisim et al., 2022b; Brontowiyono et al., 2023; Tian et al., 2022a). The aldehyde groups are produced to bind to the hydroxyl group of cotton and bond to free radicals in

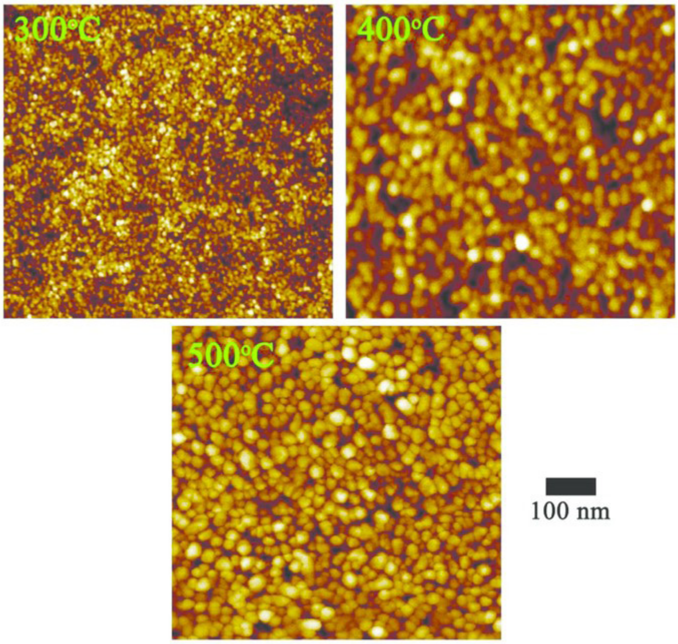

Figure 4. Atomic force microscopy (AFM)/ TiO_2 (Gunawan et al., 2011).

acid and cellulose to form a network bond. The decrease in tensile strength of the product has been attributed to stress concentration due to crosslinking as well as fiber damage due to optical reduction (Gunawan et al., 2011).

5.1.4. Titanium dioxide polymer nanocomposites

Nanocomposites made from 2% by weight of titanium dioxide nanoparticles that were added directly to the molten polypropylene have good mechanical and antimicrobial properties and also have a higher flowability than pure polypropylene. Increased conductivity has been reported due to the degradation of polymer chains by oxidizing TiO_2 nanoparticles.

5.1.5. Titanium dioxide nanocomposites

The synthesis of various titanium dioxide nanocomposites with the addition of metals such as silver, gold, and platinum may improve the photocatalytic activity of TiO_2. The addition of some metals to semiconductors due to the reduction of semiconductor energy distances can affect the photocatalytic properties by changing the reaction products or increasing the reaction rate. It has also been reported that metal nanoparticles are more stable in the TiO_2 substrate. This stability has been attributed to the formation of surface bonds between oxygen TiO_2 and metal nanoparticles.

The core-shell nanocomposite is made of carbon nanotubes and titanium dioxide by activating carbon nanotubes and then coating them by sol-gel process. This nanocomposite has many photocatalytic properties, which is due to the very high specific surface area for photocatalytic reactions and the very common surface area for trapping electrons. Although graphite layers are ideally inactive and neutral, the presence of some structural defects in carbon nanotubes allows them to be functionalized for chemical reaction with titanium dioxide in the sol-gel process (Smaisim et al., 2022a, b; Sharba et al., 2022).

5.2. Carbon nanotubes

Carbon nanotubes are composed of tubular graphite plates with carbon hexagonal structures that are available in single and multi-walled types with different structures. Different types of functionalized carbon nanotubes with the aim of improving compatibility with polymer and fiber substrates, reactivity, adsorption power Different chemicals and ... have been developed. The presence of carbon nanotubes in polymer and fibrous composites has been considered by researchers due to their properties such as good conductivity, dye absorption, increase in hardness and resistance, deceleration properties, UV protection properties, and antimicrobial properties. However, their use on an industrial scale is limited due to their serious safety and health risks. The toxicity and carcinogenicity of carbon nanotubes have been confirmed in various in vivo and in vitro tests. Semiconductor carbon nanotubes with a bandgap energy of 0 to 5 EV have photocatalytic properties similar to titanium dioxide nanoparticles and electron pairs and holes are formed on its surface (Doss et al., 2022)

The antimicrobial properties of single-walled carbon nanotubes were first reported in 2007 against Escherichia coli. Carbon nanotubes damage the cell membrane by direct contact with the bacterium, killing it. The antimicrobial properties of single-walled nanotubes have been reported to be greater than the antimicrobial effect of single-walled carbon nanotubes (Gunawan et al., 2011).

5.3. Silver nanoparticles

Silver nanoparticles have been prepared by various methods such as electrochemical reduction, photocatalytic reduction, ultrasound reduction, biochemical reduction, and biological reduction by microorganisms including bacteria and fungi (Lemire et al., 2013). In the present study, the antibacterial properties of silver nanoparticles in various fields of pharmaceutical, medical, textile, sanitary ceramics, water treatment, color, agriculture, animal husbandry, and polymer composites for industrial applications and household water filters were studied. The re-emergence of MDR microbes is facilitated by drug and/or antibiotic resistance, which is the acquired way of microbes for their survival and multiplication in uncomfortable environments. Therefore, development, modification, or searching the antimicrobial compounds having bactericidal potential against MDR bacteria is a priority area of research. One of the areas of application of Nanobiotechnology use of silver nanoparticles in the treatment of microbial infections is for a new strategy. Microbial properties of silver have been known since ancient times in the form of various compounds used to treat bacterial infections. But recently due to its construction as nanoparticles, surface-enhanced antimicrobial activity of over 99%. Silver nanoparticles new hope for the treatment of human pathogenic bacteria that have developed resistance to antibiotics.

5.4. Mechanism of action of silver nanoparticles against microorganisms

Silver has a strong antimicrobial effect against certain species of microorganisms and acts selectively, so it has little toxic effect against other microorganisms. Different mechanisms have been reported for the antimicrobial action of silver. The three main mechanisms that are most cited are:

- Destruction of the cell membrane of the microorganism.
- Reacting with SH groups on enzymes and disrupting cell metabolism.
- Production of reactive oxygen species.

Silver possibly causes the microbial cell membrane to interact, ultimately stopping the cell from absorbing phosphate, and it can also react with the negative charge on the microbial surface or with enzymes and bind to the -SH groups. Silver ions are involved in the electron transfer process of a chain. These compounds are generally effective against bacteria and have less effect on yeasts and molds (Gunawan et al., 2011). Research has shown that the size of nanoparticles has a significant effect on the antimicrobial properties of silver. In a study examining the sensitivity of rabbit skin cells to silver nanoparticles, these particles are not harmful, and also smaller particles show more compatibility with the skin. As you know, many medical antimicrobials are not able to kill bacterial biofilms.

5.4.1. Silver nanocomposite fibers

Silver nanoparticles are one of the most suitable nanoparticles for use in the process of spinning man-made fibers due to their high thermal resistance. In research, organic/inorganic nanocomposite fibers were designed with two parts of core-shell made of pure polypropylene and a nanocomposite of Nanosilver with different percentages of pure polypropylene for stable antimicrobial properties (Hussein et al., 2021; Bahadoran et al., 2022). The fibers containing silver particles in the core part have no antimicrobial activity, while the fibers containing silver particles in the shell part, even with a very low percentage of silver, have shown excellent antibacterial properties.

5.4.2. Silver / SiO_2 nanocomposite

The use of silver nanoparticles coated on metal oxides and semiconductors is one of the valuable solutions to increase the effective level of silver by consuming less of it. In addition, electronic exchanges can lead to augmentation and increase functional properties. Bonding of this nanocomposite on the surface of wool fibers has led to significant antimicrobial properties (Gunawan et al., 2011).

5.4.3. Zinc oxide nanoparticles

Zinc oxide, like semiconductor titanium dioxide, has similar photocatalytic properties; The difference is that the difference in excitation energy levels of titanium dioxide ev3.2 and zinc oxide ev3.37 is estimated. Among semiconductor metal oxides, only titanium dioxide and zinc oxide are stable in the excited state. When an ultraviolet metal oxide is excited with energy equal to or greater than the particle gap band, the formation of an electron-hole pair reduces the probability of electron transfer to the valence band, resulting in rearrangement of the electron and the empty orbital. This causes stability in the aroused state. These nanoparticles are non-toxic and have significant antimicrobial properties in the absence of light and in neutral conditions. Zinc oxide nanoparticles are superior to silver nanoparticles in terms of price, whiteness, and UV protection. These particles show photocatalytic properties as soon as they are absorbed by light, and for this reason, they are used for antimicrobial modification of textiles and their antimicrobial properties increase due to radiation (Figure 5).

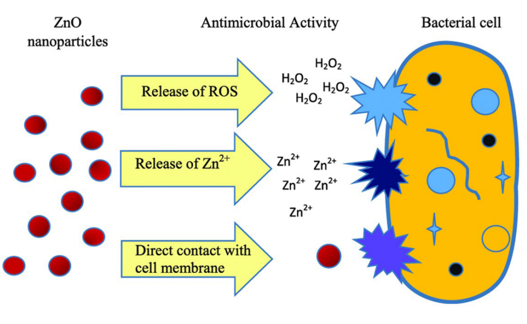

Figure 5. Antimicrobial properties of zinc oxide nanoparticles.

5.5. Copper nanoparticles

Copper nanoparticles have also been considered for their conductivity and antimicrobial properties. However, they have weaker antimicrobial properties than silver. In a study comparing the antimicrobial properties of three different samples of activated carbon fibers with silver, copper, and their combinations, the researchers found that copper-activated fibers showed the lowest antimicrobial properties, even when consumed many times more than silver (Gunawan et al., 2011).

5.6. Zinc/copper oxide composite

Zinc oxide nanoparticles are less excited by visible light due to the high gap band. Thus, in the last decade, carbon / nitrogen-mixed ZnO has been increasingly proposed due to its better photocatalytic activity under visible light. Also, ZnO nanomaterials doped with Fe2O3, WO3, CdS, Cu_2O, CuO create a narrower gap band, so it shows better photocatalytic properties with visible light. CuO / ZnO-functionalized membranes under visible light show better photocatalytic and antimicrobial activity than pure ZnO membranes.

5.7. Clay nanofilms

Clay is a generic name for the family of laminated aluminosilicates. The use of this substance in pharmaceutical applications has been started in 2002. Clay was used as an ointment on the coated infection and a greater rate of healing was observed for clay-coated wounds. These observations may be due to the antimicrobial properties of clay. Of course, the mechanism of action and bactericidal action of this substance are still not completely clear. Studies have shown that in addition to the physical absorption of toxins, mineral clay can kill some bacteria and viruses, possibly through specific chemical reactions, and reduce bacterial colonies. Research suggests that some types of artificial clay soils can have antimicrobial properties similar to metals (Lemire et al., 2013).

In the preparation of antimicrobial composites from clay, the amount required for this material to achieve the desired functional properties is significantly higher than nanostructures such as silver. In a study, silver nanolayers containing silver were prepared by the ion-exchange process by calcination and mechanical operation. Silver-modified clay nanotubes showed good antimicrobial properties against Escherichia coli (Gunawan et al., 2011). Alternatively, the polymer nanocomposite was produced in a silver-chitosan, silver-chitosan-clay and then the silver-chitosan-clay-stepwise method in polydimethylsiloxane with excellent antimicrobial properties and drug release capability for medical use. The antimicrobial properties of this composite were improved compared to silver nitrate as well as chitosan.

6. Use of Nanocapsules Containing Antimicrobials

Ciba Company produces a product called Tinoson CEL, which is prepared in the form of nanocapsules containing antimicrobial substances in the aqueous medium. These nanocapsules have reactive groups with cotton fibers that have good washing stability when bonded with the product.

Silver-polyamidoamine woody compounds such as silver-polyamidoamine nanocomposite solutions show significant antimicrobial properties without reducing solubility and activity in the presence of sulfate and chloride ions (Tahmasebi et al., 2021). with adding silver acetate powder to the pre-prepared tree solution, the polyamide amine tree containing silver can be easily produced. The production process involves the formation of silver carboxylate salts and the formation of complexes with internal nitrogen. Interesting antimicrobial properties are attributed to its very high local concentration (256 groups of carboxylates around a sphere with a diameter of 54 angstroms); Because nanoparticles with a very high specific surface area, silver compounds in the form of + Ag or AgO come into contact with microorganisms.

7. Conclusion

Recently, the use of nanoparticles for antimicrobial modification of textiles and polymers has provided a significant basis for improving public health. Textiles as the second covering of the human body provide the best environment for the growth of microorganisms. Nanoparticles are a good option for textile antimicrobial modification due to their non-toxicity and non-irritating properties compared to chemical compounds that have harmful effects such as toxicity and weak antimicrobial ability. Also, increasing the use of antibiotics in the diet of animals and patients increases the resistance of microbes, which increases the possibility of a serious impact on public health. The use of a mixture of antimicrobial chemicals along with mineral nanostructures has expanded in the industry.

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