textiles

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Review

Highly Specialized Textiles with Antimicrobial Functionality—Advances and Challenges

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Abstract: Textiles with antimicrobial functionality have been intensively and extensively investigated in the recent decades, mostly because they are present in everyday life in various applications: medicine and healthcare, sportswear, clothing and footwear, furniture and upholstery, air and water purification systems, food packaging etc. Their ability to kill or limit the growth of the microbial population in a certain context defines their activity against bacteria, fungi, and viruses, and even against the initial formation of the biofilm prior to microorganisms' proliferation. Various classes of antimicrobials have been employed for these highly specialized textiles, namely, organic synthetic reagents and polymers, metals and metal oxides (micro- and nanoparticles), and natural and naturally derived compounds, and their activity and range of applications are critically assessed. At the same time, different modern processing techniques are reviewed in relation to their applications. This paper focuses on some advances and challenges in the field of antimicrobial textiles given their practical importance as it appears from the most recent reports in the literature.

Keywords: antimicrobial textiles; synthetic antimicrobial reagents; polymers; natural antimicrobial compounds; applications

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1. Introduction

1.1. General Background

Health risks management has been constantly considered in recent decades in all relevant domains in daily life due to the spectacular worldwide increase in number and variety of microbial infestation and proliferation, ranging from local to global, and from aggressive to violent and nonresponsive epidemics/pandemics (plague, SARS, West Nile, SARS-CoV-2, COVID-19, cholera, smallpox, scarlet rash, HIV-AIDS, Marburg, Ebola, Spanish flu, MERS) [1–3]. Thus, the employ of textiles with antimicrobial functionality has expanded up to unexpected rates. This market was estimated at USD 10.7 billion in 2021 and was projected to reach a 50% increase by 2026 at a compound annual growth rate (CAGR) of 6.5% in the same interval [4].

Subsequently, the scientific literature recorded an increase in the number of articles reporting on antimicrobial textiles and their specific finishing, reagents, and processing. A bibliometric analysis indicated in 2021 a number of publications of 534 articles per year [5], but the domain is very active and the rapid progress is abundantly documented by the most recent literature reports, which also illustrate the variety of new features connected to the subject [6–25].

Furthermore, recent surveys confirmed this trend. For example, data from the Web of Science Core Collection confirmed a number of 50 review articles published in the interval 2018–2023 on topics considered relevant for this manuscript. Moreover, a significant number

of patents—245—has been reported in the interval 2018–2023 (https://patents.google.com; accessed on 26 April 2023). Some of these data are illustrated in Figures 1 and 2, where the selection criteria are given in the legend.

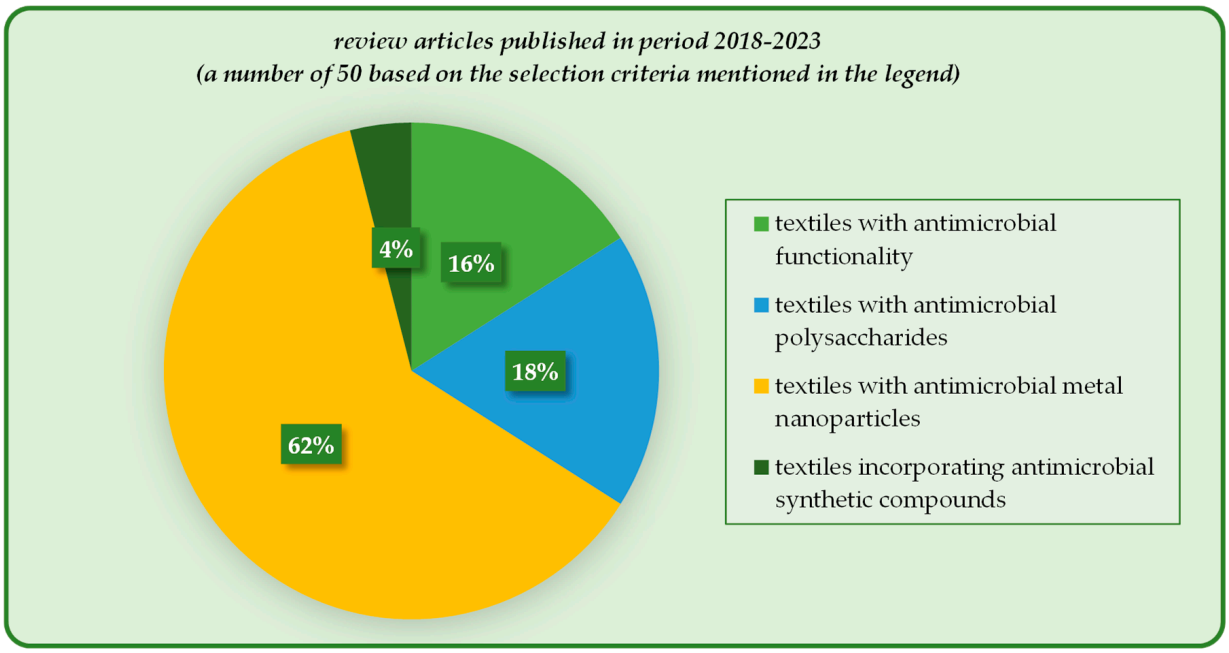


Figure 1. Review articles published in 2018–2023 (data from Web of Science Core Collection).

First and foremost, textiles with antimicrobial finishing have to comply with several requirements: prevent, control, and/or eliminate microbial infestation, growth, and cross-infection over a wide spectrum; reduce odor, prevent staining, and maintain freshness for long intervals; must be stable, safe, durable, and reusable (in certain applications) [26]. Considering their antimicrobial effectiveness and the mechanism of action, as well as their toxicity versus tolerance, nature of fibers, and durability, textiles with antimicrobial functionality may be divided into several classes [18]:

- biostats, biocides (antibacterial, antifungal, antiviral), barriers, and antibiofilm;
- textiles with bound or leaching antimicrobial finishing;
- textiles made of natural (cotton, wool, silk, linen) or synthetic fibers (PP, PE, PES) or blends (cotton/elastane, cotton/PES, wool/acrylic);
- textiles able to release compounds with biologic activity;
- wearable and washing resistant.

Commonly, microorganisms are divided into different classes: bacteria, archaea, protozoa, algae, fungi, viruses, and multicellular animal parasites [27]. They have distinct features; most of them do not negatively interfere with human biota, but some can be or become pathogenic when certain favorable conditions are met. Bacteria are mainly divided into Gram-positive (*Staphylococcus aureus*) and Gram-negative (*Escherichia coli*). Other pathogenic bacteria (*Plasmodium malariae*, *Mycobacterium tuberculosis*, *Clostridium tetani*, *Corynebacterium diphtheriae*, *Treponema pallidum*), fungi (*Cryptococcus neoformans*, *Candida auris*, *Aspergillus fumigatus*, *Candida albicans*, *Candida glabrata*), and viruses (Ebola, herpes, hantavirus, papillomavirus, HIV, COVID-19) of particular concern have been used to evaluate the level of performance of antimicrobial textiles.

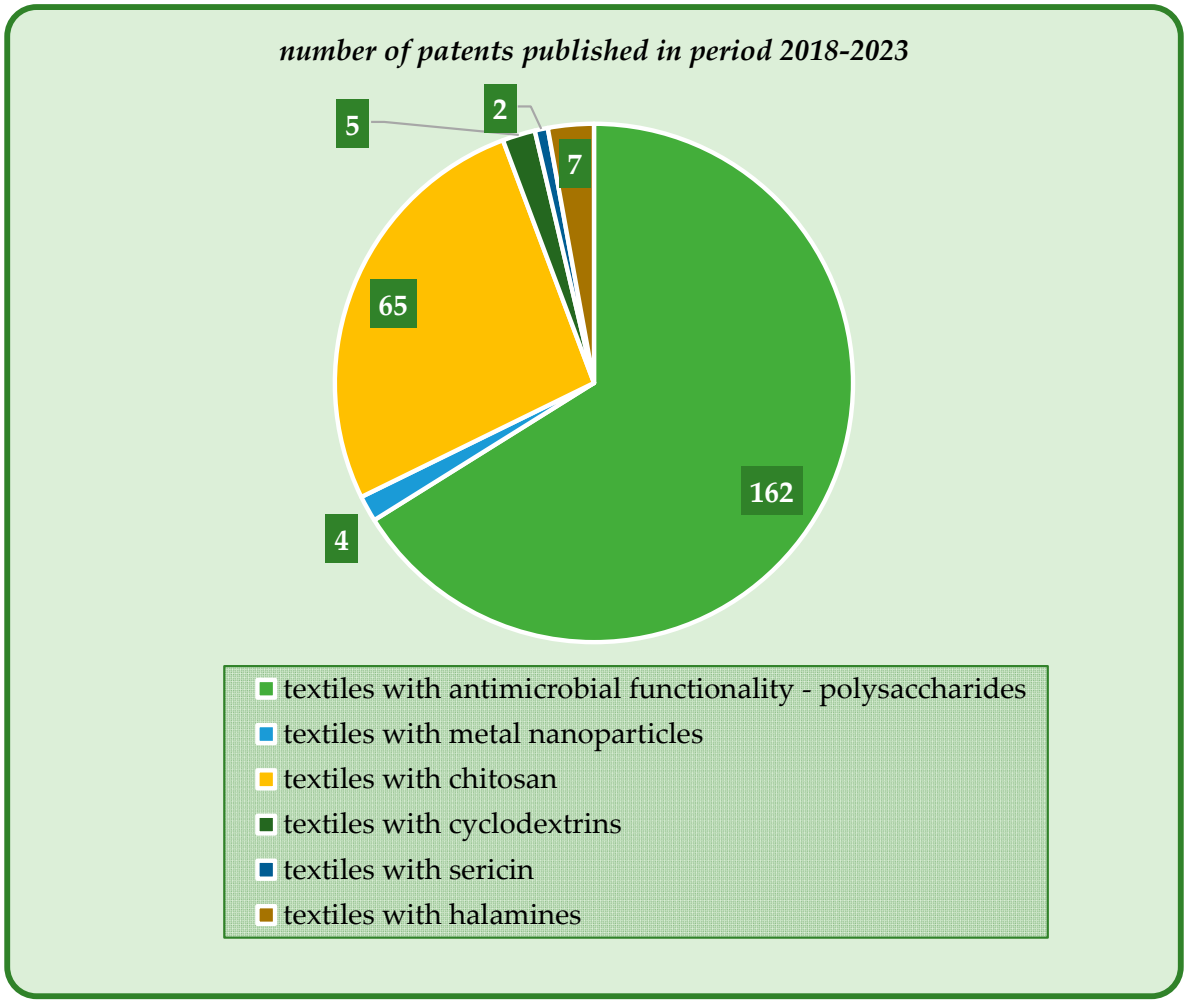


Figure 2. Patents published in the interval 2018–2023 (data acquired from https://patents.google.com; accessed on 26 April 2023).

The present review surveyed some of the most recent and relevant papers in the field of highly specialized textiles with acquired antimicrobial functionality. This allowed the identification not only of new trends and advances, but also of challenges in the field, mainly when it came to the use of high-tech processing methods, variety of applications, employ of complex formulations which include several antimicrobial agents that act in synergy, manufacture of multitask antimicrobial textiles, safety, and environmental risks.

1.2. Processing Techniques

Textiles with antimicrobial functionality are materials of high interest; therefore, their processing is a key factor in their activity and stability. Padding, spraying, grafting, and cross-linking are some of the most relevant techniques. However, the development of biocide/biostatic textiles made of synthetic fibers has allowed new methods, such as compounding extrusion and melt blending [28,29]. At the same time, the employ of colloidal solutions, plasma treatments, magnetron sputtering, sol–gel processes, microencapsulation techniques, or even *in situ* formation/growth of different antimicrobials onto textile supports are modern processing methods that grant textiles enhanced activity and stability [28].

Coating is one of the most popular procedures and is suitable for both yarns and fabrics, natural and synthetic fibers, knitted, woven, and nonwoven textiles. Direct coating can be achieved by knife, roller, or calendaring, and the finishing must be viscous in order to form a satisfactory coating. The spray-coating technique uses an airbrush and the finishing

solution must be less viscous. The method may be applied to nanoparticles deposition as well [30].

The exhaust method was "imported" from dyeing processing and comprises the transfer of the active reagent from a batch to the textile substrate, sometimes in the presence of a binder, and a curing stage is required to stabilize the coating. Thiazole-derived reagents have been successfully applied by this method to textiles which subsequently exhibited high effectiveness against Gram-positive and Gram-negative bacteria [31].

The pad–dry–cure approach, also known as the mechanical thermal fixation or padding, is suitable for micro- and nanoparticulate coating materials with low or no affinity toward the textile substrate. The thermal treatment must be short (1–5 min) and at high temperatures (100–150 °C) in order to reach an appropriate cross-linking degree (thermal fixation). The method is simple and effective [28].

Textile substrates may be submitted to different methods of surface modification in order to achieve better compatibility with the antimicrobial finishing reagents. Plasma techniques, microencapsulation and ultrasound methods are among the most employed.

Plasma treatments are highly effective and environmentally friendly, despite their drawbacks (high-energy-consuming process, expensive equipment), and are used to clean/etch or create new functional groups onto textile surfaces, to deposit thin films of nanometric thickness, or even grow nanoparticles *in situ*. The possibility to limit the in-depth alteration of the support is considered the main advantage of this method because it prevents the alteration of the bulk properties of the textile [21,32]. Plasma grafting and polymerization can be applied to a wide range of antimicrobial finishing reagents (quaternary ammonium salts derivatives, dichlorophenol, triclosan, chitosan, guanidine-based compounds, metal and metal oxides nanoparticles) when natural, synthetic, or blended textiles are used as support [21]. Plasma and magnetron sputtering were preferred for metals and metal oxides nanoparticles deposition (Ag, Ti, Cu) onto different substrates when stable coatings were obtained [9,33,34]. Moreover, it was recently reported that the emergence of highly effective antiviral textiles for personal protective equipment was favored by the employ of plasma processing [35,36].

The microencapsulation technique is a modern method used to manufacture antimicrobial textiles, having the advantage that the core is protected and thus the degradation under the action of external factors is prevented. Moreover, the microcapsules are stable and safe to handle and apply to the textile support [37,38]. The approach is preferred when natural and naturally derived compounds are used as antimicrobial finishing reagents. It can be achieved by chemical (*in situ* polymerization in oil-in-water emulsion; interfacial polymerization) and physico–chemical (coacervation, molecular inclusion complexes) methods, and the obtained coatings are resistant to friction, sunlight, washing, and wet/dry cleaning [39].

Nanotechnology is also employed in the manufacture of antimicrobial textiles in various manners. The sol–gel method is a wet chemical procedure and uses colloidal solutions of monomers as precursor to form an interpenetrated network with the textile support or to deposit particles onto the textile surface [28,40]. Metals and metal oxides can also be applied onto textiles by this method, as in the case of titanium dioxide and zinc oxide nanoparticles used for coating fabrics able to prevent the spreading of nosocomial infections [41] or for textiles with antibacterial activity and self-cleaning properties [42]. Cotton, wool, and silk fabrics are suitable for this method and a wise selection of reagents for the sol phase can impart in the end a multiple functionality to the textiles, alongside their biocide activity [28].

In situ synthesis of nanoparticles has the advantage of nanoparticles deposited directly onto the textile support, rather homogeneously, without binders or stabilizers, thus significantly reducing the waste and pollution (and the safety and environmental risks, respectively) and increasing the stability of deposition. Metals and metal oxides (Ag, ZnO, Fe, Au) are mostly used for this technique applied to natural or synthetic textiles [1,28,43].

Highly specialized fibers with antimicrobial activity have been successfully obtained by electrospinning, a modern technique that allows materials made of biopolymers or synthetic polymers, with fibrous/porous morphology, and having tailored biocide properties [44,45].

In the following, some new trends and advances in the field of highly specialized textiles with antimicrobial functionality are presented, as illustrated by recent reports.

2. Synthetic Antimicrobial Agents for Textile Finishing

Antimicrobials encompass a large variety of chemical compounds and physical agents that act on microbes (bacteria, fungi, viruses, protozoa) in general. They are used to kill bacteria or to prevent their development. However, many of them exhibit some serious drawbacks that restrict or prohibit their use, such as the emergence of resistance developed shortly after their introduction, and undesired side effects. At the same time, chemical biocides are potentially harmful substances for the environment and human health if not handled or processed properly.

N-halamine compounds are organic biocides capable of killing microorganisms without releasing free oxidative halogen until they come into contact with microorganisms. They present efficiency against a broad spectrum of microorganisms, long-term stability, non–toxicity to humans, regenerability upon exposure to aqueous free chlorine solutions, and excellent biocompatibility. In addition, microorganisms do not develop resistance to this class of antimicrobials. The surface of the materials influences the antibacterial mechanism of *N*-halamines and has an important role in their antibacterial effectiveness. A large number of places of contact with bacteria increases the inactivation rate and is favored by a larger surface area.

N-halamine biocides have been used in different applications such as water filtration systems, disinfectants in pools, textiles, and medical devices [46]. *N*-halamines and some other synthetic compounds, such as quaternary ammonium compounds, polyhexamethylene biguanide, and triclosan, have been applied for antimicrobial treatment of textiles. Antimicrobial fabrics have found different applications in pharmaceutical, medical, engineering, agricultural, and food industries [47,48]. The *N*-halamine-treated fabrics can be rendered as having excellent antimicrobial activity through a bleaching process and can inactivate a broad spectrum of microorganisms, including Gram-negative and Gram-positive bacteria, in relatively short contact times. When the oxidative halogen is consumed, textiles modified with *N*-halamines regain their antimicrobial properties by exposing them to diluted household bleach. However, the practical application of *N*-halamines involves some disadvantages. For example, the cost of the treatment increases in the case of the use of organic solvents necessary to dissolve some *N*-halamine derivatives, which also presents safety risks.

As surfactants, quaternary ammonium compounds concentrate at the interface between the lipid-containing bacterial cell membrane and the surrounding aqueous environment. There are two types of interaction between quaternary ammonium salts and microbes: a polar interaction, occurring by cationic nitrogen, and a non–polar one, attributed to the hydrophobic chain. The cationic ammonium group can interact with the negatively charged cell membrane of bacteria. This attraction force induces the generation of a surfactant–microbe complex which can interrupt the activity of proteins, including all of the important functions in the cell membrane and even bacterial DNA. Furthermore, hydrophobic groups can penetrate into the microorganism and cancel all of the key cell functions. Increasing the length of the alkyl chain results in increasing the antibacterial activity of quaternary ammonium salts [49].

Quaternary ammonium compounds have no effectiveness against difficult-to-kill non–enveloped viruses. Among the extremely effective disinfectants with a wide spectrum and short contact times (3–5 min), we can count the formulations with low alcohol content used against bacteria, enveloped viruses, pathogenic fungi, and mycobacteria. Disinfectants based on quaternary ammonium salts with the addition of alcohol or solvents bring about a much faster drying of the products on the applied surface, which results in an ineffective

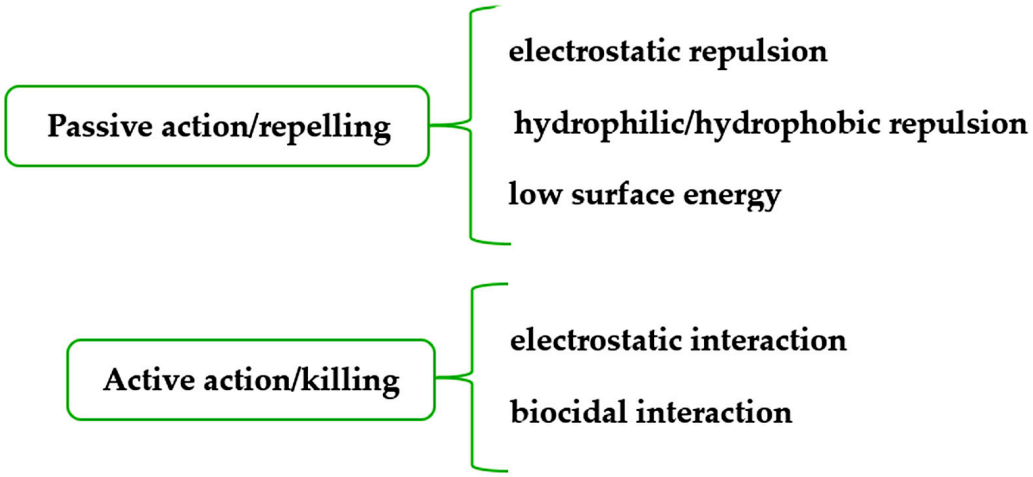
or incomplete disinfection. In addition, quaternary ammonium compounds kill algae and are used in industrial water systems to counteract unwanted biological growth. Cetrimide (alkyltrimethylammonium bromide) and benzalkonium chloride have antibacterial, antifungal, and antiviral (enveloped viruses) properties and can be applied to the skin or mucous membranes to avoid or minimize the risk of infection. Hard water, anionic detergents, and organic matter reduce the activity of these disinfectants based on quaternary ammonium salts, which is a disadvantage. Moreover, *Pseudomonas* can metabolize cetrimide, using it as a carbon, nitrogen, and energy source.

Triclosan has antiseptic and disinfectant properties and a significant action against Gram-negative and Gram-positive bacteria. The acaricide benzyl benzoate in its structure accounts for protection against mites and it is used in acaricide (spray or powder) formulas, and for the treatment of scabies as a solution (25% concentration). Triclosan has been widely used in a large number of consumer products, such as cosmetics, toothpastes, deodorants, soaps, toys, and surgical cleaning treatments, based on its non-toxicity and antibacterial properties. Although triclosan is not considered to be as toxic as other pollutants, its occurrence in wastewaters, biosolids, and aquatic and terrestrial environments remains a concern. Furthermore, triclosan exhibits certain physicochemical characteristics that make it difficult to remove from the environment. There are studies that attribute some harmful health effects to triclosan, such as skin irritation, hormonal disruption, interference with muscle function, and contribution to antibacterial resistance [50].

Chlorhexidine has a cationic molecular component that attaches to negatively charged cell membrane area and causes cell lysis. As an antiseptic, chlorhexidine is used as a mouth rinse and endodontic irrigant due to long-lasting antimicrobial effect attributed to its binding to hydroxyapatite. It is commonly held that chlorhexidine would be less caustic than sodium hypochlorite. Similar to sodium hypochlorite, heating chlorhexidine in low concentration increases its local efficacy in the root canal system and maintains low systemic toxicity. Chlorhexidine presents drawbacks, such as its incapacity to dissolve necrotic tissue remnants and chemically clean the canal system, and lower effectiveness on Gram-negative than on Gram-positive bacteria [51].

Common antimicrobial agents are prepared from natural or low-molecular-weight compounds. Due to biocidal diffusion, they present toxicity to the human body. In addition, they are easily susceptible to resistance and can lead to environmental contamination. Antimicrobial polymeric materials can overcome these problems by promoting antimicrobial efficiency and reducing residual toxicity. Moreover, antimicrobial polymers exhibit chemical stability, non–volatility, and long-term activity. Polymers containing covalently linked antimicrobial moieties avoid the penetration of low-molecular-weight biocides from the polymer matrices, unlike antimicrobial polymers obtained by physical methods (trapping or coating of organic and/or inorganic active agents during or after processing). These antimicrobial polymers are environmentally friendly and show durability over time. The most studied antimicrobial polymeric materials, and probably the most used, are those based on quaternary ammonium and/or phosphonium salts [52]. In addition, polymeric *N*-halamines with or without reactive functional groups were used to coat different fabrics by various approaches [49].

During the last two decades, synthetic (co)polymers have been designed to mimic the prominent physio–chemical characteristics of host defense peptides. Although these polymers have revealed a broad-spectrum antimicrobial activity, rapid bactericidal kinetics, and a very low propensity to induce resistance, none of them has been currently in clinical trials [53]. The schematic reaction mechanism of passive and active action of the antimicrobial polymers is presented in Scheme 1.



Scheme 1. The mechanism of action of antimicrobial polymers.

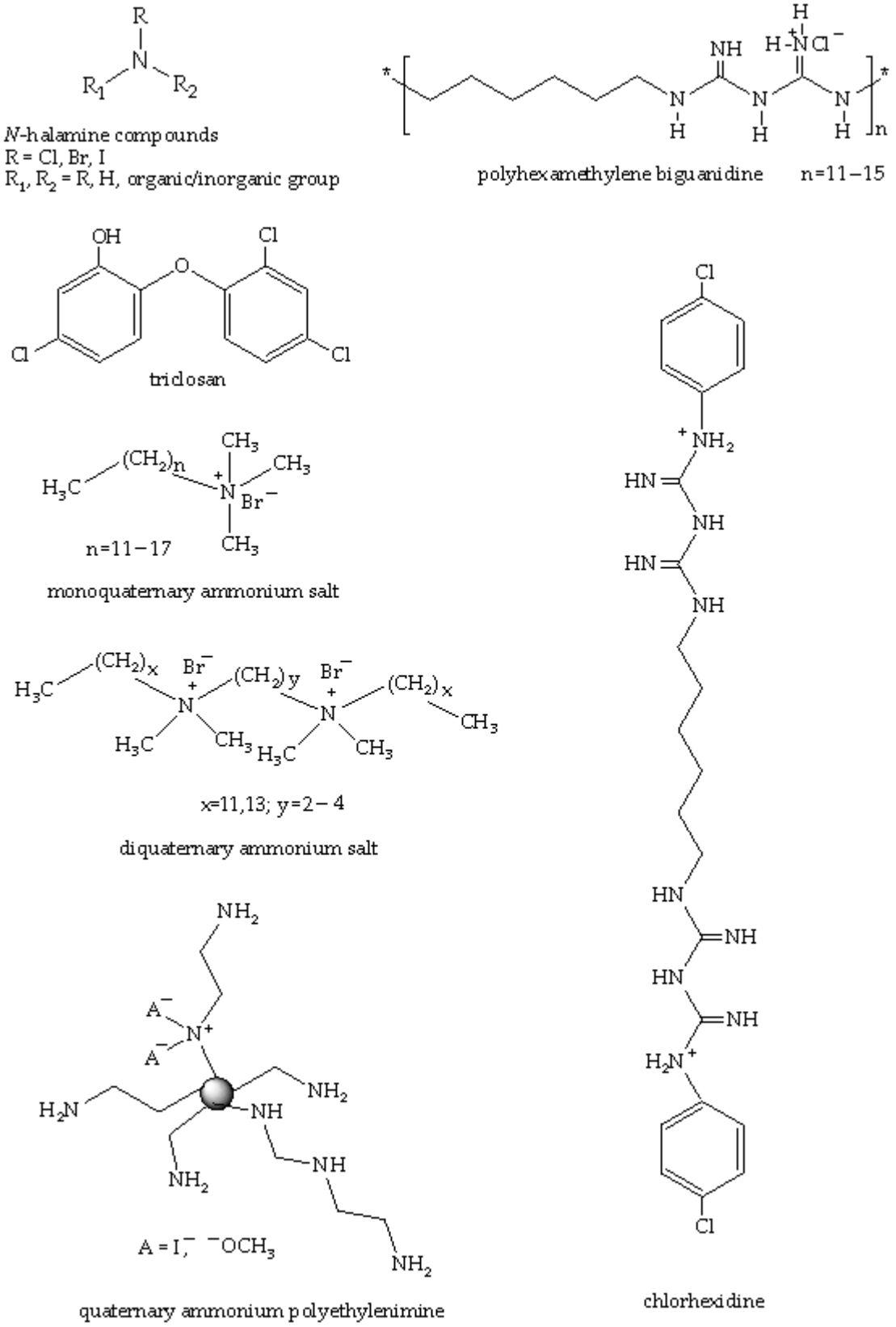
Concerning the conducting polymers, namely, polyaniline, polypyrrole, and polythiophene, their biomedical applications have not been well studied even though they have good antimicrobial activity. This limitation may be dampered by the preparation of polymer blends and nanocomposites with different (bio)polymers and nanomaterials, respectively, to achieve the desirable biocompatibility and physicochemical properties [54]. Table 1 summarizes the most relevant antimicrobial agents presented above, their applications, and mechanism of action, and Scheme 2 illustrates the chemical structures of the most important antibacterial compounds.

Table 1. Synthetic antimicrobial products, their applications, and mode of action.

Antimicrobial Agent	Properties and Applications	Antimicrobial Mechanism	Ref.
Quaternary ammonium compounds Polymeric materials having onium salts (quaternary ammonium and/or phosphonium salts) Quaternary ammonium polyethylenimine	- Healthcare, household products, surface preservation, food industry, pharmaceutical/cosmetic (preservation) - Highly effective as antimicrobial agents in orthodontic cements to introduce antibacterial activity toward *S. mutants* and *L. casei*	The long, lipophilic alkyl chain of the quaternary ammonium compounds perforates cell membranes, and produces the release of cytoplasmic components, autolysis and cell death of the microbial strain	[52,55–59]
Halogenated phenols Triclosan	- Antiseptic, disinfectant, fungicide, pesticide, antimicrobial, antiseptic, preservative - Antimicrobial activity against many types of Gram-positive and Gram-negative non-spore-forming bacteria, some fungi - Clinical settings, consumer products (cosmetics, cleaning products, paint, plastic materials, toys) - Durable antifungal finishing of cotton fabrics	Inhibits the active site of enoyl-acyl carrier protein reductase enzyme, which is essential to the fatty acids synthesis of bacteria and the building of the cell membrane	[10,58,60,61]

Table 1. *Cont.*

Antimicrobial Agent	Properties and Applications	Antimicrobial Mechanism	Ref.
Chlorhexidine Hexametaphosphate salt of chlorhexidine (as nanoparticles) Polyhexamethylene biguanide (PHMB)	- Preoperative skin cleansing preparations, hand disinfectants, and oral mouth rinses - Efficient antimicrobial agent against gram-negative and -positive bacteria and yeasts. - Biomedical materials and consumer products - Antimicrobial efficacy against MRSA and *P. aeruginosa*, in both planktonic and biofilm growth conditions - Healthcare uniforms - Nonspecific antimicrobial properties and remained efficient (>99% against *S. aureus* and *K. pneumoniae*) after use for 5 months	Chlorhexidine inhibits membrane-bound ATPase, based on cell membrane disruption and leakage of intracellular constituents, a rapid process with most damage occurring within 20 s of exposure The positively charged biguanidines bind to negatively charged phosphate group of the bacterial cell wall or virus envelope, breaking the membrane integrity, which leads to cell lysis and subsequent cell death	[25,62–64]
N-halamines	- Antimicrobial activity against a broad spectrum of microorganisms, rechargeability, nontoxicity to humans - Medical devices, water purification, hospitals, antibacterial modification of cotton fabrics - Antimicrobial activity against aerosolized bacteria - Air filtration technology - Biocidal properties against *S. aureus* and *E. coli* - Food packaging and biomedical applications	The direct transfer of oxidative halogens to a cell after contact resulting in oxidation of the amino acids in the cell membrane and inactivation the microorganism	[46,49,65–68]
5,5-dimethylhydantoin	Cotton fabric with regenerable antibacterial properties against *S. aureus*	Coating dimethylhydantoin on cotton fabric (by pad–dry–plasma–cure process) followed by chlorination inhibits the bacteria	[69]
Cinnamic acid derivatives	Pharmacological, antifungal, and antibacterial action	Plasma membrane disruption, nucleic acid and protein damage, and the induction of intracellular reactive oxygen species	[70–72]
Polyaniline and its derivatives	- Bacteria-resistant surfaces against *S. aureus* and *E. coli* - Wall and room-door coatings in hospitals	Different oxidation states of polyaniline and presence of functional groups	[73]
Polypyrrole (nanoparticles)	Antimicrobial treatment against *S. aureus* and *E. coli* of polyester fabrics	The positive charges (=NH+) in the polypyrrole backbone that are created by dopant compounds	[74,75]
Polythiophenes	Antimicrobial compounds able to kill bacteria selectively by damaging negatively charged cell envelopes	Cationic charges with capacity to create huge amounts of singlet oxygen that interact with organism	[76]



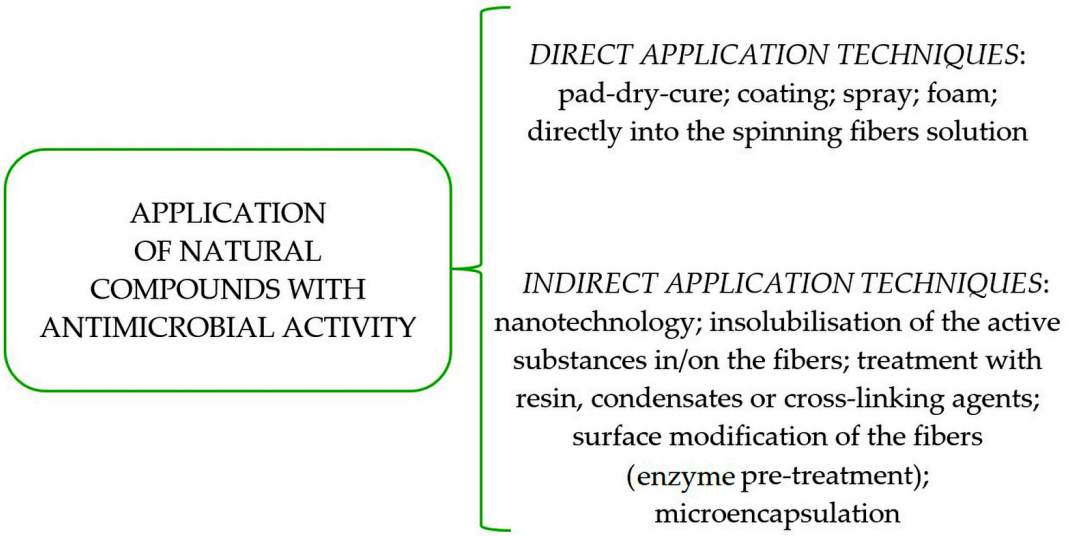
Scheme 2. Chemical structures of some conventionally used synthetic antimicrobial agents.

3. Natural Compounds with Biocide Activity Applied to Antimicrobial Textiles

Natural compounds are best suited to meet the biocidal activity requirements of textile-based materials and present important specific characteristics, being non–harmful

in relation to the toxicity issues, environmentally friendly, and renewable. This biocidal property is manifested towards microorganisms' inherent presence, namely, bacteria and fungi, which may cause microbiological destruction of the textile materials. Such issue is of real significance when applications relying on the use of textile materials derived from natural fibers are considered. The most sensitive components of the textile materials to the microbiological action are the cellulose fibers. Some effective biocidal formulations applied to impart antimicrobial properties to textile materials were recently reviewed [77], with focus mainly on the natural compounds such as pectin and lignin, which exhibit important biocidal peculiarities, and the methods which can be employed in order to confer increased resistance as biocidal effect in relation to textile materials' applications. Methods employed in order to apply natural compounds having antimicrobial activity on textile materials are presented in Scheme 3.

Natural compounds with biocide activity applied for textiles protection are referred to as biopolymer matrices (such as chitosan, lignin, starch, cyclodextrins, zein, gelatin) and biological active components extracted from plants (such as essential oils) [18,78–81]. Cellulose-based fibrous scaffolds produced by electrospinning have effectively encapsulated cinnamon, lemongrass, and peppermint essential oils and could be very useful for topical treatments even at low concentration levels due to their significant biocidal resistance against a Gram-negative bacilli, namely *Escherichia coli* [82].



Scheme 3. Some of the usual methods employed for application of natural compounds with antimicrobial activity to textile materials [83].

Natural-fibers-based fabrics present valuable enhanced properties through application of natural compounds for their functional finishing, including [18,77,82,84]:

- UV protection properties (conferred by using lignin extracts, natural dye extracts);
- Antioxidant properties (conferred by using natural dye extracts);
- Antimicrobial properties (conferred by using chitosan, lignin, cyclodextrins, essential oils).

Generally, the natural compounds, polysaccharides and oligosaccharides, employed for the antimicrobial finishing of textiles (chitosan, starch, cyclodextrins), as well as lignin, are largely abundant as environmentally friendly waste products [85].

Chitosan modified with hinokitiol (a natural monoterpenoid, namely, a tropolone derivative, found in the wood of trees in the family *Cupressaceae*) is a natural product with very good prospective as antibacterial agent for textiles. The treated cotton fabric exhibited good antibacterial properties while maintaining its initial properties such as hydrophilicity, handle, and strength [86]. Significant antibacterial properties were also conferred to cotton

fabrics when using *Aloe vera* gel for finishing, with the bacterial growth being strongly inhibited [87].

In the following, aspects referring to some biopolymer matrices usually applied for textiles finishing and protection are considered.

3.1. Chitosan

Chitosan, a cationic polysaccharide originating from crustaceans and fungi, is obtained by alkaline deacetylation of chitin. Its valuable advantages for adding functionalities to the textile surfaces finishing include biocompatibility, biodegradability, and properties such as antimicrobial, antistatic, nontoxicity, chelating ability, deodorizing, film-forming ability, reactivity in chemical media, presence of ionizable groups, dyeing enhancement, efficacy of cost, thickening ability, and wound alleviation [85,88]. Application of chitosan under hydrogel form on cellulosic fabric conferred antibacterial resistance against bacteria strains such as *Staphylococcus aureus*, *Escherichia coli*, and *Listeria monocytogenes* [89].

The poor binding ability of chitosan with the fibers from textile materials is usually addressed by employment of various cross-linking agents which grant an improved antimicrobial activity. Mostly used and safer agents are:

- 1,2,3,4-butanetetracarboxylic acid (BTCA) and citric acid (CA), when cellulose fibers are considered;
- organic anhydrides, such as succinic and phthalic ones, for grafting chitosan on wool fabrics;
- citric acid in combination with oxidizing agents having reduced toxicity, such as potassium permanganate and sodium hypophosphite, for an effective cross-linking between chitosan and textile substrates—cotton cellulose, wool fabrics).

The application of chitosan on textiles by UV radical curing is also a feasible innocuous methodology for yielding fabrics with finishes having lasting microbial resistance [90].

3.2. Lignin

Lignin, a dark-colored phenolic compound provides resistance against microbial attack in lignocellulose resources (plants and trees). It is generally separated during the processing (delignification or pulping process) when cellulose fibers are obtained. Lignocellulose resources mainly comprise biopolymers with resistance against microorganisms, cellulose and lignin; therefore, these materials can have antimicrobial potential [91].

A coating formulation using lignin extracts derived from sugarcane bagasse was proved to impart good antibacterial activity against *Staphylococcus epidermidis* to the textile support, and the effect was manifest by the reduction of the inherent formation of bacteria onto the textile sample [92,93].

3.3. Cyclodextrins

Cyclodextrins (CDs) are a family of water-soluble cyclic oligosaccharides having two components, one hydrophilic (outer surface) and one lipophilic (central cavity). They are produced during enzymatic conversion of the starch by the enzyme, namely cyclodextrin glycosyltransferase. CDs are composed of alpha-1,4-linked glucopyranosides subunits, and the most commonly available types are α-CD (6 moieties), β-CD (8 moieties)—the most used in research studies, and γ-CD (10 moieties).

The main advantages of using CDs in different applications [85] include eco-friendly character, ability to form inclusion complexes, insecticides carrier ability, fragrances slow-releasing ability, solubilization ability, facile production, efficacy of cost, ability for chelation, and drug-delivery ability. Application of cyclodextrins in textile functional finishing can effectively aid properties such as antimicrobial, fragrance, and dyeing (CDs act as encapsulating, dispersing, and leveling agents) [94].

Feasible interactions between β-CD and some textile fibers include ionic interactions (for wool fibers), covalent bonds, cross-linking agents, and graft polymerization (for both cotton and wool fibers). CDs can impart better UV protection and odor reduction through

complexing and controlled releasing of different fragrances (perfumes, aromas), substances with therapeutical effects or "skincare-active" compounds (vitamins, caffeine, menthol), as well as bioactive agents (biocides, insecticides—mosquito repellents).

A significant application of CDs for various textile materials finishing is represented by water and soil remediation and catalysis (e.g., adsorption of small pollutants from waste waters and polluted soil) when such fabrics act as effective selective filters—so-called "preparation of textile nanosponges" [95]. Last, but not the least, CDs have an essential contribution as guest molecules employed in antimicrobial textile modifications by grafting using citric acid as cross-linker in the presence of sodium hypophosphite when a most efficient, lasting antibacterial textile having a pleasurable fragrance was obtained [96].

Improvement in the grafting yield of the cyclodextrin derivative monochlorotriazinyl-β-cyclodextrin (MCT-β-CD) on organic cotton was attained by previously applying a biopolishing procedure, a cellulase enzyme treatment of the textile substrate [97]. An enhanced antibacterial activity and improved durability (upon repeated washing process) for the MCT-β-CD grafted enzymatic treated organic cotton were imparted through incorporation of thymol.

A recent report [98] presented the ability of β-CDs to form complexes with essential oils, and the application of β-CD nano/microcapsules to produce aromatic textiles with focus on the various assembly methods of these aromatic β-CD nano/microcapsules by incorporation of essential oils, as well as on the large range of methodologies employed for the production of such textiles with aromatic character.

3.4. Sericin

Sericin is a natural protein derived from silk worm, *Bombyx mori*, with important characteristics being biocompatible, biodegradable, UV-resistant, oxidative-resistant, good moisture retention receptor, antibacterial, prone to gelling, and adherent [85]. The action against microbes in testing resistance of cotton fabric against bacterial strains, namely *Escherichia coli* and *Staphylococcus aureus*, was enhanced after applying a sericin-based coating [99].

4. Metal and Metal Oxide Nanoparticles

The associations of fibers and textile materials with metal stripes, wires, or plates made of gold, silver, copper, or their alloys have been used in artworks and luxury objects since ancient times [100]. Later on, the progress in both metal and textile processing also led to practical uses, starting with protective/strengthened items and, more recently, to multilayered and composite textiles with an extended range of engineered functionalities, from stimuli-responsive clothes and devices to medicine and electronics [101–103].

This evolution was highly enhanced in the last decades by the significant advances made in the field of nanotechnologies, polymer nanocomposites, and nanosized inorganic particles. In this regard, a major breakthrough in healthcare and medical tools was the successful integration of metal and metal oxide nanoparticles within a large spectrum of natural and synthetic fibers, yarns, and fabrics, otherwise prone to microbial colonization and conveyance, to impart their antibiotic and even antiviral properties. Additional benefits consist of increased resilience at discoloration, decay, and odor formation [104–107]. Unlike other inorganics, such as clays, graphene, or carbon nanotubes, which, rather, passivate the textile host, metal-based nanoparticles also act as biocides through the active release of metal ions that compromise the cell membrane and subsequently the cytoplasmic metabolism in a cascade of events driven by enhanced free radical formation and biomolecule conjugation [108]. A generally accepted mechanism of action is depicted in Figure 3.

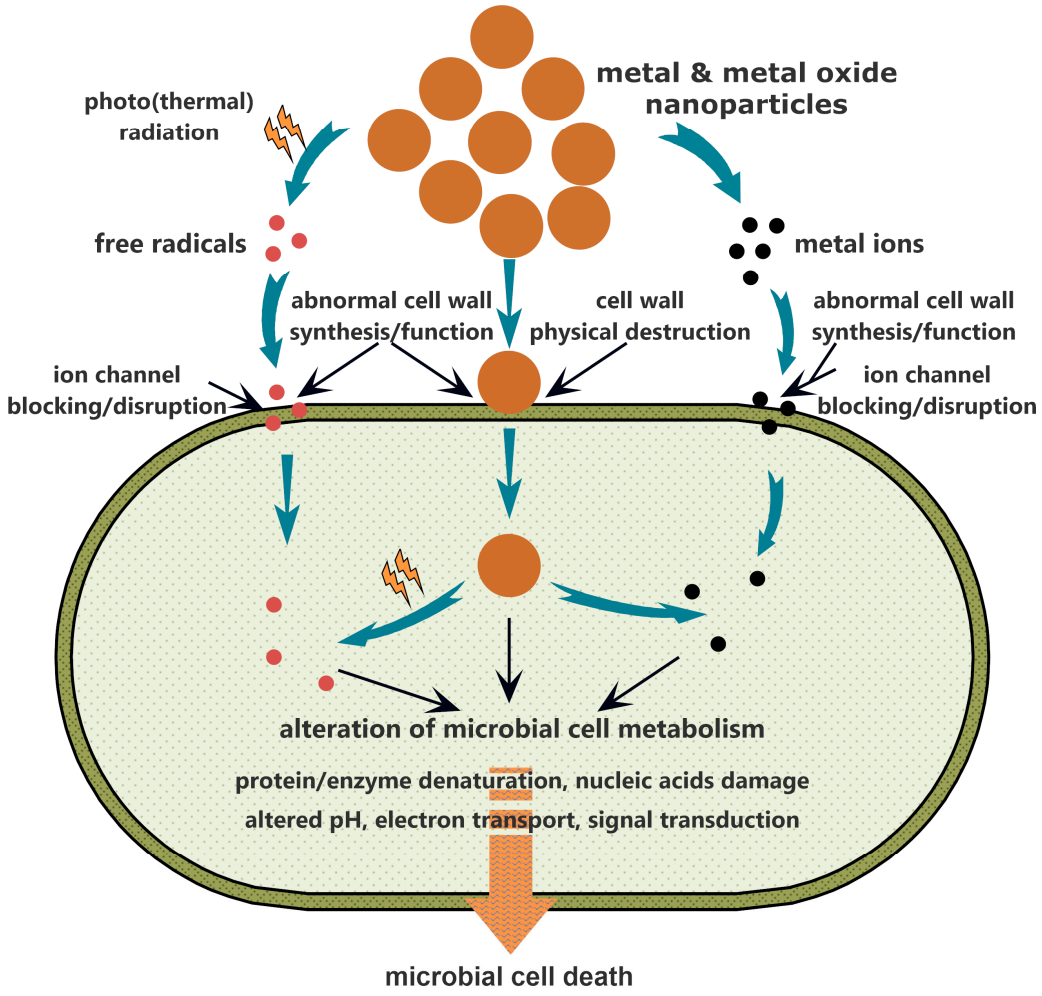


Figure 3. The main mechanisms of action exhibited by metal and metal oxide nanoparticles as antimicrobial active agents.

However, despite the fact that various effects against a plethora of microbial and viral types and strains are frequently reported and reviewed, specific mechanisms, targets, and taxonomies are still far from a complete elucidation [109–116].

The most studied and used to date for textile modification are silver and copper oxide nanoparticles, which are considered to be the most effective antimicrobial agents, followed by zinc oxide and titanium dioxide (Tables 2–5). Other metals and metal oxides are also applied; however, to a lesser extent [117]. The application of other potential metal-based nanoparticles may be limited either by price (gold) or facile surface oxidation (copper), or is prohibited due to their higher toxicity to humans and environment, as in the case of chromium and nickel. It must be mentioned that a high number of heavy metal species, including copper, zinc, and titanium salts and complexes, could be present in traces to sizeable amounts within the unmodified textile materials, originating from raw materials and processing, but especially from the dyeing steps, which may interfere with the further added nanoparticles [118,119].

Table 2. Examples of textile modification with silver nanoparticles (AgNPs).

Fiber/Textile Type	Preparation	Morphology/Content	Microbial Strains	Applicative Characteristics	Refs.
Plain weave 100% bleached organic cotton fabric	Dip and dry coating	49.23 mg/kg, 73.28 mg/kg; eventually embedded in alginate matrix	Gram-positive *Staphylococcus aureus* ATCC 6538/Gram-negative *Escherichia coli* ATCC 873937	Antibacterial and UV protection; superior coloration effect; leakage of about 2.04 mg/kg/cycle during first fifteenth washing cycle	[120]
Brown cotton fiber	*In situ* one-step process under heating	8−21 nm spherical particles; 12.8 μg/kg weight fraction formation of Ag NPs	Gram-positive *Staphylococcus aureus* ATCC 6538/Gram-negative *Pseudomonas aeruginosa* ATCC 9027	Stable antibacterial activity for 50 cycles of laundering; good dispersion; potential applications in sportswear, underwear, and medical textiles	[121]
Commercial polyamide 6,6 fabric	PVP-AgNP dispersions deposited on PA66 with/without DBD plasma pretreatment	20 nm PVP-AgNP colloids	Gram-positive *Staphylococcus aureus* ATCC 6538/Gram-negative *Escherichia coli* ATCC 25922	Plasma-treated polyamide fabric maintains antimicrobial activity even at very low Ag concentration after five washing cycles	[122]
Cellulosic/cotton fabrics	Photochemical reduction in Na–CMC solutions	2–8 nm/5–35 nm spherical polydisperse/monodisperse nanoparticles	*Staphylococcus epidermidis*/*Candida albicans*	Antifungal effect; prevents odor formation	[123]
Polyamide 6 fibers	Electroless plating method; fibers pretreated with a dopamine/$CuSO_4$/H_2O_2 system	Average particle size of 223 nm; surface continuous and compact silver layer	*Escherichia coli* AATCC 11229/*Staphylococcus aureus* AATCC 6538	Antimicrobial efficiency of 99.9% and 100% against *E. coli* and *S. aureus* decrease to 83.5% and 87.9%, respectively after 1 h/2 h of ultrasonic washing; potential use as antibacterial/conductive textiles	[124]
Commercial prewashed PES fabric	Spray coating of PES with layers of chitosan or HMDSO before and after AgNP deposition	Quasi-spherical particles of 20–30 nm with relative uniform distribution	*Staphylococcus aureus*/*Escherichia coli*	Fast and cost-effective method; controlled release of silver; antimicrobial effect reduced by washing; applications in medical textiles	[23]
Reusable and single use face masks	Testing of commercial face masks from a safe-by-design perspective	Silver detected in both the external and the internal layer under both ionic and nanoparticulate form; mostly near-spherical particles of 13 to 155 nm	viral pathogens	Evaluation of content, type and *in situ* localization of silver-based biocides face; safety of silver-containing masks	[125]

Table 2. *Cont.*

Fiber/Textile Type	Preparation	Morphology/Content	Microbial Strains	Applicative Characteristics	Refs.
Scoured and bleached 100% cotton fabric of plain weave structure	*In situ* deposition of Ag nanoparticles on cotton fabrics premodified with dopamine	Medium size of 33–43 nm	*Staphylococcus aureus*/*Escherichia coli*	Dopamine is effective in nanoparticles immobilization; ~98% remanent activity after twenty wash cycles	[126]

Na–CMC: sodium–carboxymethylcellulose. DBD: dielectric barrier discharge. PVP: poly(N-vinylpyrrolidone).

Table 3. Examples of textile modification with copper oxides nanoparticles (CuO NPs).

Fiber/Textile Type	Preparation	Morphology/Content	Microbial Strains	Applicative Characteristics	Refs.
Bleached and mercerized cotton fabric (100%)	Pure and hybrid CuO/colloidal chitosan nanosol sonochemically prepared; cotton coating by pad–dry–cure method	Spherical morphology with irregular formation; medium size of 58 nm	*Staphylococcus aureus*/*Escherichia coli*	Improved antibacterial activity for hybrid coatings after ten wash cycles	[127]
Fine–medium-weight 100% cotton woven fabric	*Ex situ* by wet chemical method/ pad–dry–cure method	Spherical shape; size of 60–75 nm	*Staphylococcus aureus*/*Escherichia coli*	Antimicrobial activity decreases at laundering (*S. aureus*: 74.36%/12.05% after 10/20 cycles; *E. coli*: 69.54%/9.85% after 10/20 cycles washes; potential healthcare and hygiene uses	[128]
Cotton fabrics	Green synthesis with *R. tuberosa* leaf extract	Polydisperse nanorods ranging from 20 to 100 nm	*Staphylococcus aureus*; *Escherichia coli*; *Klebsiella pneumoniae*	Prevention of fabrics microbial damage; bioremediation of industrial dyes	[129]
Polyester/cotton 65/35 blend fabric (PES/CO)	*In situ* impregnation by the pad–dry/pad–dry/pad–thermofix process	Sizes of about 3 nm and 20 nm	antiviral species: SARS-CoV-2_COV2019 ITALY/INMI1 and Human Corona Virus 229E strain ATCC VR-740; *Escherichia coli* ATCC 25922 strains	99.93%; 99.96% inactivation efficiency (30; 60 min exposure) against SARS-CoV-2; 99% efficiency on *E. coli* growth after 20 wash cycles; reusable face masks with antiviral/antibacterial properties and reduced environmental contamination	[130]
70% cotton and 30% polyester mixed textiles	*In situ* and *ex situ* green and chemical syntheses	Green route: spherical morphology with sizes of 2.4 ± 0.5 nm; chemical route: no defined geometry with average size of 75 ± 28 nm	*E. coli* ATCC No. 8739/*S. aureus* ATCC No. 6538 bacteria; *Aspergillus brasiliensis* ATCC No. 16 404 fungus	*In situ* method and 734 ppm Cu_2O gives better antifungal effects; high potential against aspergillosis	[131]

Table 3. *Cont.*

Fiber/Textile Type	Preparation	Morphology/Content	Microbial Strains	Applicative Characteristics	Refs.
Rolls of cotton, plain unbleached woven cotton	*In situ* sonochemical method; "throwing the stones" (TTS) technology with preformed colloids and ultrasound impregnation	Homogeneous layer of ~40 nm nanoparticles on cotton fibers (0.9% *w*/*w* CuO)	HDF/HepG2 cells	Low toxicity (>95% HDF cell viability); nanoparticles do not penetrate the skin barrier; potential uses as antimicrobial fabrics for bed sheets, curtains, and laboratory coats	[132]
100% cotton fabric	*In situ* by exhaust dyeing method	Small nanoparticles of different sizes and shapes randomly distributed on fiber surfaces	*Escherichia coli*	Still efficient after 20 washes, could be an economic alternative for antimicrobial textiles	[133]
Fabric samples	CuO biosynthesis with *Aspergillus terreus* strain AF-1; *ex situ* pad–dry–cure method	Homogeneous distributions of spherical, 11–47 nm nanoparticles; 6.1% elemental composition	*Bacillus subtilis ATCC 6633*, *Staphylococcus aureus ATCC 6538*, *Escherichia coli ATCC 8739*, and *Pseudomonas aeruginosa ATCC 9027*	Green synthesis; potential uses in healthcare and hygiene products	[134]
Cotton fabric	Plasma pretreated cotton fabric; *ex situ* coating by pad–dry–cure method	Fabric roughness gradually rises with increases in plasma treatment time; 40 nm sized CuO nanoparticles	*Bacillus subtilis*, *Staphylococcus aureus*, *Salmonella typhimurium*, *Klebsiella pneumoniae*	Potential uses in various biomedical applications	[135]

Table 4. Examples of textile modification with zinc oxide nanoparticles (ZnONPs).

Fiber/Textile Type	Preparation	Morphology/Content	Microbial Strains	Applicative Characteristics	Refs.
Bleached woven cotton fabric (100%; 144 g/m^2)	Single-step sonoenzymatic process	30–120 nm Zn nanoparticles	*Staphylococcus aureus*; *Escherichia coli*	Nanoparticles agglomeration regardless the enzyme used; 33.4% Zn retained on fabrics after ten washing cycles; potential antibacterial medical textiles	[136]
100% plain woven cotton fabrics	Plasma pretreated cotton woven fabric; *in situ*, sonochemically	Spherical shape with 20–90 nm diameter	*Staphylococcus aureus*	Stability improves by cotton fabric prefunctionalization with plasma; Zn content goes from 5.63% to 5.41% after five washing cycles	[137]
Polyamide 6 (PA), polyethylene terephthalate (PET) and polypropylene (PP) textiles	Chemical bath deposition; washing; thermal stabilization; hydrothermal formation of nano/microrods	Irregular needles, flower-like agglomerates and nano/microrods	*Escherichia coli*; *Staphylococcus aureus*	Significant antibacterial activity, particularly in the case of PA/ZnO and Gram-negative bacteria; potential uses in everyday life applications	[138]

Table 4. *Cont.*

Fiber/Textile Type	Preparation	Morphology/Content	Microbial Strains	Applicative Characteristics	Refs.
100% cotton yarns and polyester/cotton (67/33) blend yarns	Exhaust–dry–cure method	Sizes ranging between 30 and 90 nm	*Staphylococcus aureus*; *Escherichia coli*	Antimicrobial efficacy of samples increases at blends, higher yarn twists and lower particle sizes	[139]
100% cellulose cotton	Pad–dry–cure method assisted by open-air plasma modification; green sonochemically nanoparticle synthesis with *Psidium guajava Linn* (guava) plant extract	Hexagonal nanoparticles of about 41 nm agglomerated into larger clusters	*Staphylococcus aureus*; *Escherichia coli*	Open-air plasma treatment enhances nanoparticle adsorption; self-cleaning activity of 94% after five washing cycles	[140]
Gray cotton fabric (100% cotton) of plain weave structure	Pad–dry–cure method and thermo-fixation with sonochemically synthesized ZnO nanoparticles	Nearly spherical nanoparticles with an average size of 40–100 nm; 0.5%, 1%, and 2% ZnO content	*Staphylococcus aureus*; *Escherichia coli*	86% reduction of microorganisms after 15 washes; uses as multifunctional textiles with antimicrobial, self-cleaning, and UV protective properties	[141]

Table 5. Examples of textile modification with titanium dioxide nanoparticles (TiO_2NPs).

Fiber/Textile Type	Preparation	Morphology/Content	Microbial Strains	Applicative Characteristics	Refs.
Polyamide 66 cloth in plain weave	Pad–dry–cure process	700 nm particles	*Aspergillus niger* NRRL-A326 (fungus)/*Staphylococcus aureus* ATCC 6538-P (G+)/*Escherichia coli* ATCC 25933 (G)/*Candida albicans* ATCC 10231 (yeast)	Hydrophobic; photocatalytic self-cleaning activity; UV protection activity; potential applications in air filters, outdoor textiles, furniture, and medical textiles	[142]
Nylon 66 knitted fabrics	Synthesized by sol–gel method; subsequently applied by layer by layer (LBL) technique	Medium size of 40–60 nm; tendency to aggregation	*Staphylococcus aureus* (NCTC 3750)/*Escherichia coli* (AATCC-10148)	Potential applications in optics, biosensing, separation membranes and technical textile	[143]
Cotton–polyester twill fabric (70–30%)	*In situ* coating	Average diameter size of 98 nm	-	UV protective properties	[144]
Cotton fabric	Immersion in a mixture of perfluorodecyl triethoxysilane and TiO_2NPs solution	Medium size of 50 nm; uniform coating	*E. coli*	Water repellency; self-cleaning; oil–water separation; stain resistance; antibacterial properties	[145]

Table 5. *Cont.*

Fiber/Textile Type	Preparation	Morphology/Content	Microbial Strains	Applicative Characteristics	Refs.
Plain woven cotton mercerized fabric	Pad–dry–cure method; functionalization with trimethyl[3-trimethoxysilyl) propyl] ammonium chloride to enhance the affinity	Particles of 30 nm; 4% dried TiO_2 NPs by weight	*S. aureus*/*E. coli*	Dye degradation; antibacterial properties; multifunctional cotton fabric for outdoor, industrial and medical applications	[146]
Cotton fabrics lab coat and indiolino fabrics	*In situ* impregnation; sonochemically, hydrothermal and solvothermal synthesis of TiO_2 particles	Homogeneous distribution on the cotton fabric surface	*Escherichia coli*/*Bacillus pumilus*	Sonosynthesis with Ti isopropoxide as precursor enhances the bactericidal activity; self-cleaning properties; potential use for face masks	[147]

Despite their proven efficiency and specific advantages, the application of metallic and metal oxide nanoparticles as antimicrobial additives for textile materials should always take into account their toxicity and environmental impact by leaching and disposal [148–150]. Leaching, furthermore, limits the type and number of uses for a given item, but also exhibits higher biocidal activity [18,151].

There are basically two methods of producing antimicrobial textiles based on metal and metal oxides: *ex situ* and *in situ* [13,152–154]. *Ex situ* methods are related to the incorporation of previously synthesized nanoparticles through direct application to the targeted textile matrix, commonly by the pad–dry–cure technique, which involves a chain sequence of immersion into the nanoparticulate colloidal solution followed by pressurization, drying, and curing. The main drawback of this simple technique, given by the poor adhesion to the constitutive fibers, which favors nanoparticle leaks, agglomeration, and inhomogeneity, could be addressed by the addition of carboxylic acids, thiols, or generation of reactive and negatively charged groups onto the initial fabric surface through chemical or physical means, cross-linking, as well as by incorporating macromolecular stabilizing agents in either one or both raw media.

In situ methods suppose the initial adsorption of metal ions at the level of fiber surfaces followed by their conversion to nanoparticles by chemical reduction or radiation, which improves the stability and distribution. Before, during, or after nanoparticles formation, the surface of textile scaffold may be modified in similar ways. As an alternative, nanoparticles could be also synthesized during polymerization or fiber spinning, followed by processing into final textile products.

5. Challenges in Antimicrobial Textiles Manufacturing

Antimicrobial textiles have to meet a series of requirements due to their wide range of applications (hydrophilic/hydrophobic, breathable, safe, nontoxic, resistance to cleaning cycles, etc.) and one of the most relevant for their purpose is the antimicrobial activity.

Tests for antimicrobial activity are standardized by international organizations and can be divided into two classes [7,14,155]:

a. qualitative tests—AATCC TM147, AATCC TM30 (American Association of Textile Chemists and Colorists Test Method), ISO 20645, ISO 11721 (International Organization for Standardization) and SN 195920, SN 195921 (Swiss standard);
b. quantitative tests—AATCC TM100, ISO 20743, SN 195924, JIS L 1902 (Japanese industry standards) and ASTM E 2149 (or its modification) [156].

Qualitative evaluation is fast and simple, based on the formation of an inhibition area around the tested sample. This does not necessarily mean the sample is biocide, but that it is only biostatic. Therefore, it is not possible to compare the activity of different

antimicrobial agents or textiles. Quantitative assessment provides information on the level of performance, but it can be also used as criterion for the optimization of the finishing reagent and/or method. It requires more time and is more specific as it relies on the count of microorganisms. The main drawback of these tests is their high susceptibility to be contaminated and compromised. Therefore, they are performed under strictly controlled conditions. At the same time, the lack of a unitary standard, the poor reproducibility, and the effectiveness of the microbial extraction from samples are factors that affect the tests accuracy in a negative way. Complementary tests, such as viability tests, colorimetric analysis, staining, and microscopy, are useful and their results can be corroborated.

Another issue that has to be addressed is the environmental impact of antimicrobial textiles waste. On one hand, there is the problem of the non-biodegradable textile support (synthetic polymers), and the most eloquent example is the massive accumulation of protective masks discarded in nature in the last years. On the other hand, some antimicrobial reagents used as textile finishing may end up in water biotopes and their accumulation will negatively affect the natural balance, as in the case of quaternary ammonium salts and derivatives, and triclosan (half-life in lake water is approximately 10 days and the degradation products, such as methyl triclosan, are more toxic) [7].

Associated with this issue is the problem of nanoparticles released from the antimicrobial textile and which migrate into the human body, where they can accumulate within various tissues as they can easily penetrate the cell wall barrier. This concern arose along with the development of nanotechnology and its applications in medicine, healthcare, pharmaceutics, and cosmetics. For example, clinical studies on the accumulation of silver nanoparticles in living tissues confirmed its toxicity [157].

Other challenges in antimicrobial textiles that have been already tackled are:

- the use of natural plant fibers with intrinsic antimicrobial activity, raw or modified [158];
- employ of biopolymers with intrinsic antimicrobial activity (i.e., chitosan) as both support and antimicrobial finishing, and with multiple functionality [159];
- combining various antimicrobial compounds in order to enhance the effect in the final product; for example, plant extracts and plant-derived molecules with biologic activity have been encapsulated in chitosan particles that were subsequently used as antimicrobial finishing for cotton fabrics [160];
- use of complex antimicrobial formulations including metals, metal oxides, and other nanoparticles (Ag, TiO_2, silica), natural compounds (curcumin, *Aloe vera*), and binders;
- increasing the compatibility between the textile substrate and the antimicrobial finishing in order to achieve materials with enhance stability and wearability;
- a constant concern to maintain the production cost of most of these materials in the affordable range for the public—this can be achieved through an increased funding of research, both from public and private funds, and a more active involvement of the business community in healthcare and environmental protection.

6. Conclusions and Future Trends

The domain of highly specialized textiles with antimicrobial functionality is, without a doubt, a very active field of research, both theoretically and practically, and a continuously expanding market as a result of the societal demand. The multivalent nature of the textile substrate (natural fibers, synthetic fibers, blends of natural and synthetic fibers, biopolymers, natural plant fibers with intrinsic biocide/biostatic activity), the wide variety of antimicrobial finishing materials (organic synthetic compounds, synthetic polymers, natural and naturally-derived compounds, metals and metal oxides, raw or functionalized silica micro- and nanoparticles), the broad range of processing techniques (coating, microencapsulation, grafting and copolymerization, plasma processing, electrospinning, sol–gel methods, etc.) and applications (biocides/biostatics, antibacterial, antifungal, antiviral, water and air filtration media, protective personal clothing and masks, sports- and footwear, upholstery, hospital beddings, wound dressings, etc.) are factors that clearly illustrate the complexity of this domain. At the same time, each and every one of them can become a

driving force orienting the research toward new frontiers, as presented in this paper using some of the most recent advances reported in the literature.

New trends have already emerged. One major advance is represented by the highly specialized textiles with antiviral activity which are even more relevant given the viruses' natural ability to evolve by mutations, as substantiated by studies on aggressive epidemics/pandemics (SARS-CoV, MERS-CoV, SARS-CoV-2, Ebola, West Nile, etc.). The development of up-to-date antiviral drugs and vaccines is time-consuming, so antiviral textiles are a realistic alternative and can contribute to significantly limit, or even control, the viruses' proliferation and spreading (textile biosensors). Even more, computational modeling can be considered a valuable tool in order to assess the virus–receptor interaction and factors affecting the binding affinity, and then to model the corresponding counterparts designed to bind and neutralize the virus. Modern processing techniques, such as plasma-assisted methods, are helpful as well.

Combining green processing, such as sonochemical methods, plasma-assisted procedures, sol–gel techniques, *in situ* growth of nanoparticles (i.e., green synthesis of Ag nanoparticles is nontoxic, cost-effective, and accurate), and green antimicrobial reagents (natural and naturally-derived compounds) for textile finishing represent another trend that has already confirmed most expectations. By this approach, antimicrobial textiles with multiple functionality (anti-inflammatory, antibacterial, antifungal, anti-odor, etc.) can be manufactured.

Last, but not least, the increasing awareness of the environmental risk associated with the careless disposal of textiles with antimicrobial finishing must be considered. Medical waste is disposed of in a controlled manner, but the reckless discharge of some antimicrobial textiles from domestic applications has become rapidly a source of concern (i.e., the massive accumulation in nature of personal masks after the SARS-CoV-2 pandemics). The management of non-biodegradable plastic waste, as well as the monitoring and neutralization of toxic reagents accumulated in various biotopes, are valid solutions that must be considered in a general plan for the coherent elimination of antimicrobial textiles, or even the partial recycling of some of them, at least those designed to be wearable and resistant to multiple cycles of washing and wet/dry cleaning.

Highly specialized textiles with antimicrobial functionality are becoming more and more part of our everyday lives. Therefore, regardless of how much we appreciate the advantages, we must not minimize the risks and disadvantages of their use. In order to control and limit them, we need a very active research–development–innovation flow, which has been shown, and the commitment to transfer the solutions offered by research to practice.

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