ADVANCED TECHNOLOGIES IN THE DEVELOPMENT OF ANTIMICROBIAL TEXTILES: A REVIEW

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ABSTRACT. Textile materials with antimicrobial properties have become increasingly important in various sectors, including healthcare, public transportation, and personal apparel, due to their potential to inhibit the spread of microorganisms. This article reviews the development of antimicrobial textiles, focusing on the integration of advanced technologies such as nanotechnology, plasma treatments, and electrospinning. Specifically, the review explores modern methods including electrospinning, plasma surface functionalization, sol-gel coatings, spray application, microencapsulation, and nanoparticle integration, highlighting their role in improving antimicrobial performance. These methods enhance the antimicrobial efficacy of textiles while maintaining the physical and aesthetic properties of the fabrics. Nanoparticles, particularly silver, have demonstrated significant efficacy against a wide range of pathogens and are used in protective gear and everyday fabrics.
KEYWORDS: textile, antimicrobial, antibacterial, electrospinning, nanoparticles

TEHNOLOGII AVANSATE PENTRU DEZVOLTAREA TEXTILELOR ANTIMICROBIENE: O TRECERE ÎN REVISTĂ

REZUMAT. Materialele textile cu proprietăți antimicrobiene au devenit din ce în ce mai importante în diverse sectoare, inclusiv în domeniul sănătății, transportului public și îmbrăcămintei personale, datorită potențialului lor de a inhiba răspândirea microorganismelor. Acest articol analizează dezvoltarea textilelor antimicrobiene, concentrându-se pe integrarea tehnologiilor avansate, cum ar fi nanotehnologia, tratamentele cu plasmă și electrofilarea. Mai exact, analiza explorează metode moderne, inclusiv electrofilarea, funcționalizarea suprafeței cu plasmă, acoperirile sol-gel, aplicarea prin pulverizare, microîncapsularea și integrarea nanoparticulelor, evidențiind rolul lor în îmbunătățirea performanței antimicrobiene. Aceste metode sporesc eficacitatea antimicrobiană a textilelor, menținând în același timp proprietățile fizice și estetice ale țesăturilor. Nanoparticulele, în special argintul, au demonstrat o eficacitate semnificativă împotriva unei game largi de agenți patogeni și sunt utilizate în echipamente de protecție și țesături de zi cu zi.
CUVINTE CHEIE: textile, antimicrobian, antibacterian, electrofilare, nanoparticule

TECHNOLOGIES AVANCÉES DANS LE DÉVELOPPEMENT DE TEXTILES ANTIMICROBIENS : UNE REVUE

RÉSUMÉ. Les matériaux textiles aux propriétés antimicrobiennes gagnent en importance dans divers secteurs, notamment la santé, les transports publics et l'habillement, en raison de leur potentiel à inhiber la propagation des micro-organismes. Cet article passe en revue le développement de textiles antimicrobiens, en se concentrant sur l'intégration de technologies avancées telles que la nanotechnologie, les traitements plasma et l'électrofilage. Plus précisément, l'analyse explore les méthodes modernes, notamment l'électrofilage, la fonctionnalisation de surface par plasma, les revêtements sol-gel, la pulvérisation, la microencapsulation et l'intégration de nanoparticules, soulignant leur rôle dans l'amélioration des performances antimicrobiennes. Ces méthodes renforcent l'efficacité antimicrobienne des textiles tout en préservant leurs propriétés physiques et esthétiques. Les nanoparticules, en particulier l'argent, ont démontré une efficacité significative contre un large éventail de pathogènes et sont utilisées dans les équipements de protection et les tissus du quotidien.
MOTS-CLÉS : textiles, antimicrobien, antibacterien, électrofilage, nanoparticules

INTRODUCTION

Textiles are ubiquitous and play an essential role in human life, with varied applications ranging from clothing and household products to industrial and medical equipment. Throughout history, textiles have been used not only for protection and comfort, but also as a means of preventing microbial contamination. With the discovery of antibiotics during World War II, antimicrobial textiles began to be used industrially, treated to prevent damage caused by microorganisms and to reduce the risk of infections. This was essential for military equipment, such as tents, tarpaulins, and truck covers, which required protection against microbial attacks caused by humidity and extreme temperatures. At that time, antimicrobial treatments included antimony salts, copper, and chlorinated wax, which, although effective, had adverse effects on human health and the environment [1].

Today, antimicrobial textiles have become essential in sectors such as medicine, the hospitality industry, public transportation, and sportswear, where controlling the spread of microorganisms is crucial. In medical facilities, for example, gowns, masks, bandages, and bed linens can become vectors for transmitting pathogens, facilitating cross-contamination between patients and medical staff. In addition, in public places such as hotels, restaurants, and public transport,

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frequently used textiles, such as carpets, curtains, and upholstered seats, can be significant sources of infections [1].

Interest in antimicrobial textiles has increased even more with the COVID-19 pandemic, which highlighted the importance of materials capable of reducing viral and bacterial loads. Studies have shown that the SARS-CoV-2 virus can survive on textile surfaces for extended periods, necessitating the development of materials with antiviral, antibacterial, and antifungal properties. Furthermore, in the context of the global health crisis, the use of face masks and personal protective equipment has become essential, emphasizing the need for textiles that are safe, effective, and durable.

Thus, the development of antimicrobial materials has become a continuously expanding research field, integrating advanced technologies such as electrospinning, nanotechnologies, plasma treatments, polymerization, and sol-gel techniques. These methods allow for the creation of textiles with innovative properties such as hydrophobia, fire retardancy, and resistance to microorganisms, opening up new opportunities in biomedical, industrial, and consumer applications [2].

ANTIMICROBIAL TEXTILE TREATMENT METHODS

Antimicrobial treatments applied to textile materials must meet several essential criteria, not just effectiveness against microorganisms. They need to be compatible with textile processes, withstand repeated washings, chemical cleaning, and high temperatures during ironing [3]. They also must be safe for both users and the environment, without compromising the aesthetic or functional properties of the material.

Depending on the composition and structure of the textile fibers, as well as the type of antimicrobial agent used, various chemical and physical techniques have been developed to impart antimicrobial properties to fabrics. One method involves integrating antimicrobial agents into the structure of synthetic fibers during the manufacturing process. Alternatively, for natural and synthetic fibers, antimicrobial treatments can be applied in the finishing stage, in the form of coatings or impregnations on the textile material surface [4].

These antimicrobial treatments act through two main mechanisms: direct contact or diffusion. In the first case, the antimicrobial agent remains fixed on the fiber surface and acts only upon direct contact with microorganisms. In the case of diffusion, active substances gradually release from the fiber surface or from the textile matrix, attacking microorganisms in the external environment.

To combat microorganisms, antimicrobial agents act by damaging cellular functions. If the antimicrobial treatment only inhibits the development and reproduction of microbes, it has a biostatic effect. Conversely, if the antimicrobial agent is capable of destroying microorganisms, then its effect is considered biocidal [3, 4].

THE USE OF NANOPARTICLES IN ANTIMICROBIAL TEXTILES

Nanoparticles have gained a prominent role in the development of antimicrobial textiles, being applied to both natural and synthetic fibers. Silver nanoparticles (AgNPs), for example, are valued for their effective toxicity against a broad spectrum of microorganisms while maintaining a low level of toxicity towards human cells. Not only do they enhance the durability and color fastness of textile materials, but they have also proven effective in antiviral activities, including against SARS-CoV-2, as indicated by the study of Thi Ngoc Dung *et al*. (2020) [5].

In addition to silver nanoparticles, other types of metal nanoparticles and metal oxides, such as titanium, tin, zinc, gold, and copper, are used for their antimicrobial properties. Copper oxide nanoparticles (CuONPs), for instance, are effective against both Gram-positive and Gram-negative bacteria, according to the study by Rajendran *et al*. (2020) [6], which highlights the complex mechanisms of action including the release of copper ions and the production of reactive oxygen species.

Furthermore, the use of nanoparticles in medical and textile applications is also extending to the development of targeted drug delivery systems, as described by Zhou *et al*. (2020) [7]. These nanoparticles are also involved in the rapid detection of pathogens and in anticancer therapies using labeled nanoparticles, a field extensively explored by Kennedy *et al*. (2011) [8].

In another study, Liu *et al*. (2019) [9] highlighted the immobilization of silver nanoparticles on textile fabrics through a radiochemical process, resulting in a material with significant antiviral activity. These findings underline the vast potential of nanoparticles in combating viral, bacterial, and fungal infections and in promoting public health through the development of advanced functional textiles [8].

PROCESSING TECHNIQUES FOR ANTIMICROBIAL TEXTILE MATERIALS

Antimicrobial textiles are materials treated to eliminate or prevent the growth of microbes on the fiber surface. To impart antimicrobial properties to fabrics, numerous finishing and functionalization methods have been developed, including both wet chemical processes and physical surface treatments. Advances in the production of synthetic fibers have facilitated the development of new techniques, as presented in Fig. 1 [8].

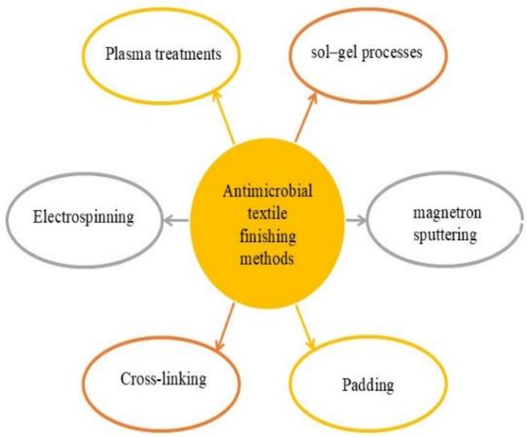

Figure 1. Antimicrobial textile finishing methods

Padding is a conventional textile finishing method where the textile material is uniformly impregnated with an antimicrobial solution, then dried and thermally set (often called the pad-dry-cure process). This technique is particularly suitable for antimicrobial agents in the form of micro/nano particles or polymers with low fiber affinity, requiring a binder or rapid cross-linking at high temperatures (typically 100–150°C for 1–5 minutes) to permanently attach to the material [10]. A successful example of this method is the finishing of cotton with a quaternary ammonium salt-based antimicrobial agent, followed by drying and thermal polymerization. The treated fabric demonstrated excellent bactericidal activity against *Staphylococcus aureus* and *Escherichia coli*, maintaining its effectiveness even after 50 washing cycles [11].

Spray-coating involves using a spray device (airbrush) to deposit a fine layer of antimicrobial solution or suspension; in this case, the composition must have low viscosity. The antimicrobial materials applied by spraying range from biocidal polymer solutions to nanoparticle dispersions. For example, the successful deposition of a luminescent composite based on strontium oxide doped with lanthanides on cotton fabrics has been demonstrated, resulting in a “glow-in-the-dark” material with antibacterial activity against *E. coli*, *S. aureus*, and *Candida albicans* [12]. Hydrophobic nano-layers with antimicrobial properties were also applied to silk by spraying, using a mixture of silica nanoparticles and quaternary ammonium salts (bactericidal agent) to protect the fiber without compromising its fineness.

The sol-gel method is a wet chemical technology used to create thin oxidative or hybrid layers on the surface of textile materials [1]. The process involves obtaining a colloidal solution of organic precursors (usually metal alkoxides or organomodified polymers) that, through polycondensation, forms a three-dimensional network attached to the textile support. A major advantage of the sol-gel method is the ability to obtain multifunctional coatings: for example, antimicrobial agents and components for UV protection or self-cleaning properties can be simultaneously incorporated into the same film matrix. Metals and metal oxides are frequently integrated through sol-gel – recent studies have shown the deposition of TiO_2 and ZnO nanoparticles by this process on fabrics, resulting in materials that prevent the development of nosocomial microbes and also exhibit a photocatalytic self-cleaning effect [2].

Plasma treatments constitute a physical, wet-chemical-free method for the surface modification of textiles for the grafting or fixing of functional agents, including antimicrobials. Plasma obtained in a vacuum or at atmospheric pressure creates a reactive environment (ions, free radicals, electrons) that can clean, activate, or nano-structure the fiber surface. Plasma can be used either as a pre-treatment step to increase the subsequent adherence of antimicrobial finishes or as a direct method of depositing thin antimicrobial films. In the presence of suitable monomers, plasma can initiate polymerization directly on the textile fiber or chemically graft various types of antimicrobial agents: from organic compounds (chlorinated phenols, triclosan derivatives, quaternary ammonium salts, polymers with guanidine groups, chitosan) to inorganic nanoparticles (Ag, Cu, TiO_2, ZnO). For example, it has been reported that plasma jet and sputtering deposition of nanometric layers of silver, titanium, or copper on textile materials resulted in stable and durable antimicrobial coatings [13].

Microencapsulation is a technology by which the antimicrobial agent is enclosed within a capsule, forming microcapsules [10]. The purpose of microencapsulation is to protect the active substance from external factors and to control its gradual release onto the textile fiber surface. A concrete example is microcapsules with lime essential oil obtained by coacervation using alginate and gelatin as materials. These microcapsules, with an average diameter of ~1.5 µm, were applied to cotton fabric using the pad-dry-cure method, using citric acid as a binder for anchoring. The functionalized fabric thus exhibited high antibacterial activity against skin bacteria, and durability tests showed that only ~3% of the microcapsules detached after 15 washing cycles, with the remainder remaining attached to the fiber [14].

Electrospinning is a modern technology for manufacturing nanometric fibers, which has proven extremely useful for obtaining textile materials with intrinsic antimicrobial properties. The process involves using a strong electric field to extract and solidify fine jets from a polymer solution, thus forming a network of nano/microfibers with a very large specific surface area [15]. This method allows for the direct incorporation of antimicrobial agents into the fiber mass during their formation, resulting in non-woven or fibrous membranes with uniformly distributed biocidal activity. For example, it has been demonstrated that electrospun nanofibers from biocompatible polymers loaded with silver nanoparticles or antimicrobial oils can destroy pathogenic bacteria and prevent biofilm formation, highlighting the effectiveness of this strategy for biomedical and environmental applications [15].

Comparative Evaluation of Antimicrobial Finishing Techniques

Electrospinning allows the fabrication of nanofiber webs with extremely high surface area, enabling excellent antimicrobial efficacy due to greater contact with microbes and high loading of biocidal agents. However, electrospinning faces challenges in scalability and mechanical stability – scaling up from lab to industrial production is non-trivial, and electrospun nanofibrous layers can be fragile. Recent studies emphasize that while electrospinning is a promising route for functional textiles, issues of throughput, fiber strength, and cost must be overcome for large-scale use [16].

Plasma treatments, in contrast, are a dry, eco-friendly technology that safely modifies fabric surfaces to enable strong binding of antimicrobial agents without added chemicals. Plasma-based processes create reactive surface functional groups, improving the durability of subsequent antimicrobial finishes by covalently grafting or anchoring biocides onto fibers. The lack of liquid processing chemicals makes plasma a relatively safe and environmentally benign option, although specialized equipment is required and treatment of large fabric rolls at industrial speeds can be a scalability concern [17].

Sol–gel coating techniques offer the benefit of forming inorganic–organic networks on the textile that can entrap antimicrobial compounds in a durable matrix. Finishes applied via sol–gel have demonstrated long-lasting antimicrobial power and wash durability, since biocidal agents (e.g., silver, ZnO) are embedded in a silica or hybrid network that adheres strongly to fiber surfaces. This strong bonding yields controlled release of the antimicrobial and minimizes leaching during laundering, though careful formulation is needed to avoid brittle coatings. In terms of safety, sol–gel matrices can reduce direct exposure of users to nanoparticles or biocides by immobilizing them, but any nanomaterials used must be assessed for cytotoxicity. Each technology thus balances efficacy with other factors: for instance, electrospun nanofibers can achieve rapid and broad-spectrum microbial kill, yet may require reinforcement for wear; plasma treatments excel in improving bonding and avoiding chemical waste, but often must be combined with an antimicrobial agent to be effective; and sol–gel finishes excel in durability and sustained release, albeit with added process complexity [18].

Practical Applications of Antimicrobial Textile Technologies

Recent advancements highlight the practical implementation of antimicrobial textile technologies, particularly in healthcare and public environments. For instance, hospitals have begun using bed linens, patient gowns, and staff uniforms impregnated with metallic nanoparticles (such as silver or copper) to reduce pathogen transmission. A 2023 systematic review reported that textiles treated with copper, silver, zinc oxide, and other agents significantly lowered microbial contamination on fabrics and even reduced healthcare-associated infection rates in clinical use [19]. These antimicrobial healthcare textiles – ranging from privacy curtains to surgical scrubs – provide an added line of defense against resistant bacteria in hospital environments. Another prominent example is the development of reusable antimicrobial face masks for public health protection. Innovative masks coated with antiviral nanoparticles (e.g., nano-silver or ZnO) maintained >99% efficacy against bacteria even after 20 laundry cycles, demonstrating excellent durability for repeated use [11]. Such products not only offer personal protection but also address environmental concerns by being reusable. Likewise, researchers recently introduced antimicrobial nanocomposite uniforms and linens that withstood over 100 wash cycles with no loss of functionality [20]. These fabrics, tested against dangerous pathogens like methicillin-resistant *S. aureus*, remained highly effective after extensive laundering and were verified to be non-irritating to skin. This level of performance suggests that antimicrobial textile innovations are becoming viable for long-term use in hospitals.

CONCLUSIONS

In the context of developing and integrating advanced technologies in textile production, the main goal remains enhancing their functionality in combating microorganisms, a crucial aspect in many sectors of contemporary life. This need has been significantly accelerated by the COVID-19 pandemic, which highlighted the importance of materials capable of reducing viral and bacterial loads. Antimicrobial textiles, through their ability to reduce the spread of infections in medical facilities, public spaces, and even in personal use contexts, represent a promising direction in improving public health standards [16].

The ongoing development of antimicrobial materials integrates techniques such as electrospinning, nanotechnologies, plasma treatments, polymerization, and sol-gel methods. These methods enable the creation of textiles with innovative properties such as hydrophobicity, fire retardancy, and resistance to microorganisms, thereby extending their potential applications in biomedical, industrial, and consumer domains. Additionally, antimicrobial treatments are designed to be compatible with existing textile processes, withstand rigorous maintenance conditions such as repeated washings and high temperatures, and be safe for users and the environment, without compromising the aesthetic or functional properties of the material. A crucial aspect in the use of these technologies is the need for a balance between antimicrobial efficacy and the impact on the environment and human health, avoiding the risk of developing antimicrobial resistance [2, 21].

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