Nano and Medical Materials 2025, 5(1), 3002.
https://doi.org/10.59400/nmm3002

Review

Preparation of antimicrobial polyamide fibers based on surface treatment

Lei Li[1,2,3,*], Donghong Zhu[1,*], Fanmin Kong[1], Ang Xiao[1], Ziling Zhang[1], Haoqi Wang[1], Weizhou Yao[1], Yutian Duan[1,2,*]

[1] SINOPEC Nanjing Research Institute of Chemical Industry Co., Ltd., Nanjing 210048, China
[2] China Petroleum and Chemical Corporation, Beijing 100728, China
[3] Hefei National Laboratory for Physical Sciences at the Microscale, University of Science and Technology of China, Hefei 230026, China
*** Corresponding authors:** Lei Li, leili619@outlook.com; Donghong Zhu, lionel93@sina.com; Yutian Duan, ytduan211@outlook.com

CITATION

Li L, Zhu D, Kong F, et al. Preparation of antimicrobial polyamide fibers based on surface treatment. Nano and Medical Materials. 2025; 5(1): 3002. https://doi.org/10.59400/nmm3002

ARTICLE INFO

Received: 25 March 2025
Accepted: 14 April 2025
Available online: 22 April 2025

Abstract: Antibacterial nylon fiber, a crucial functional material, has demonstrated substantial potential for applications in medical, textile, food packaging, and other fields. While conventional nylon fibers possess excellent mechanical properties, their lack of inherent antimicrobial functionality has spurred research into surface treatment methods, including modification and post-finishing techniques. These approaches enable the integration of antibacterial agents such as silver ions, copper ions, and chitosan while preserving fiber integrity. Despite this progress, challenges persist in durability, biocompatibility, and economic feasibility, driving ongoing innovation. This review focuses on surface treatment methods, including chemical modification, dyeing, and post-finishing, covering antibacterial agents, and antimicrobial performance, providing insights into structure-property relationships and optimization strategies. The advancement of antibacterial nylon fibers not only meets critical healthcare demands but also aligns with global sustainability goals, offering innovative solutions with significant societal and economic impact.

Keywords: polyamide fiber; antibacterial fiber; chemical modification; post-finishing; antibacterial agents

1. Introduction

The escalating global population and rapid urbanization have intensified public health concerns, driving significant demand for advanced antibacterial materials capable of mitigating microbial proliferation in critical sectors such as healthcare, textiles, and food packaging [1–3]. Among synthetic fibers, polyamide (commonly referred to as nylon) has garnered substantial attention due to its exceptional mechanical properties, wear resistance, and processability, making it indispensable across diverse industries including textiles, automotive, and electronics [4,5]. However, the inherent lack of antimicrobial functionality in conventional nylon fibers severely limits their application in environments requiring microbial resistance, particularly in medical textiles where the risk of bacterial and viral transmission necessitates robust antibacterial properties [6]. This limitation has propelled the development of antibacterial nylon fibers as a critical research frontier in materials science.

Recent advancements in nanotechnology, biotechnology, and materials engineering have facilitated the integration of antibacterial agents into nylon fibers through innovative manufacturing processes [7,8]. These agents, encompassing inorganic compounds (e.g., silver, copper, and zinc ions) and organic substances (e.g., chitosan and quaternary ammonium salts), exert antimicrobial effects by disrupting microbial cell membrane integrity [9,10]. The production of functionalized nylon fibers primarily relies on several principal methodologies including melt spinning, electrospinning, fiber surface treatment, dyeing and post-finishing, and so on [11–13]. Wherein, surface treatment methods, including surface chemical modification and post-finishing methods offer distinct advantages, enabling the direct use of commercial fiber materials, eliminating additional preparation steps, and reducing production time and cost [14]. Essentially, they preserve the mechanical properties of fibers, as antibacterial agents are only applied to the surface, leaving the internal structure unaffected. This enables the retention of fiber strength while imparting antibacterial functionality [15]. Moreover, surface treatment methods are simple, easy to operate, and require minimal specialized equipment, unlike melt blending or electrospinning, which demand complex setups and increase production costs. These attributes make surface modification and post-finishing methods highly suitable for large-scale industrial production, offering both economic feasibility and operational efficiency (**Figure 1**) [16,17]. As a result, they represent a promising approach to developing antibacterial nylon fibers, particularly in applications where cost-effectiveness and fiber performance are paramount [18–20].

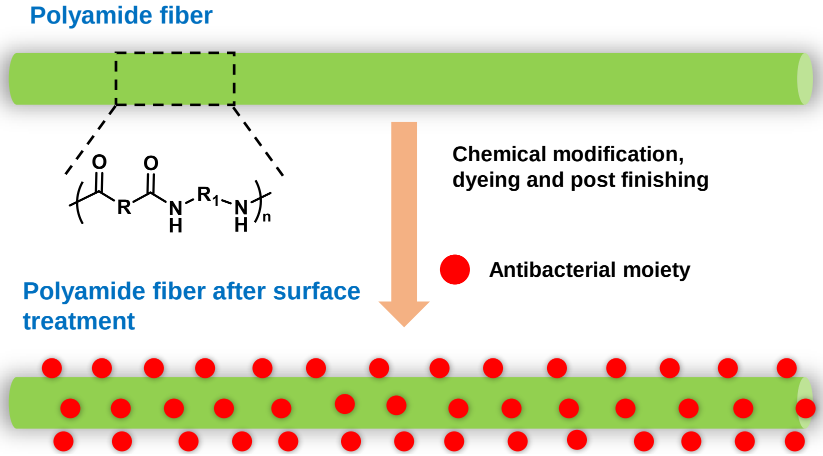


Figure 1. Schematic illustration for the preparation of antimicrobial polyamide fibers based on surface treatment.

The antimicrobial efficacy of functionalized nylon fibers is fundamentally governed by the specific interactions between the incorporated antibacterial agents and the bacterial cellular structures [21]. Silver ions, for instance, exert their bactericidal effect by binding to thiol groups in microbial membranes, inducing structural disorganization and subsequent cellular content leakage [22,23]. Similarly, copper ions demonstrate antimicrobial activity via the generation of reactive oxygen species that inflict oxidative damage on essential microbial biomolecules, including DNA and proteins [24,25]. Chitosan, a naturally derived cationic polysaccharide, interacts electrostatically with anionic components of microbial membranes, compromising their structural integrity and permeability [26–29]. The integration of nanotechnology has revolutionized the field of antibacterial materials, with nano-antibacterial agents offering enhanced performance due to their exceptional surface-to-volume ratio and quantum effects. Notably, silver nanoparticles (AgNPs) exhibit superior antimicrobial activity through synergistic mechanisms involving surface plasmon resonance effects and enhanced membrane penetration capabilities, with studies confirming that particle size optimization significantly influences antimicrobial potency [30–32].

The development of antibacterial nylon fibers represents a significant advancement in sustainable materials technology, aligning with global initiatives to reduce reliance on environmentally persistent heavy metals and toxic organic compounds. The practical implementation and commercialization of antibacterial nylon fibers face several critical challenges that require comprehensive solutions, encompassing durability [33–35], biocompatibility, safety [36–38], and economic feasibility [39,40]. For example, the durability issues with antimicrobial nylon fibers primarily stem from the gradual release or leaching of antimicrobial agents, resulting in insufficient long-term efficacy. In terms of biocompatibility, potential concerns may arise from the cytotoxicity or sensitization induced by certain antimicrobial components, such as silver ions or organic antimicrobial agents. These pending challenges have spurred ongoing technological innovations in the research domain of antimicrobial nylon. This review systematically examines the preparation methods, antibacterial agents, and performance characterization of antibacterial polyamide fibers based on surface treatment. By elucidating structure-property relationships and optimization strategies, this work highlights the progress in developing high-performance antibacterial polyamide fibers with enhanced antimicrobial activity and environmental compatibility. The comprehensive analysis of design principles, fabrication methods, and characterization techniques provides valuable insights for overcoming technical challenges and promoting the development of differentiated functional fibers. As a multidisciplinary field, antibacterial nylon fiber technology offers innovative solutions for critical applications in healthcare, environmental protection, and public health, underscoring its substantial societal and economic value.

2. Agents for antibacterial fiber

Antibacterial agents serve as crucial components in the fabrication and functionalization of antibacterial fibers including polyamide fiber [41]. Based on their chemical composition and antimicrobial mechanisms, these agents can be systematically categorized into four primary classes: (1) organic antibacterial agents, characterized by their specific chemical structures and molecular interactions; (2) inorganic antibacterial agents, typically comprising metal ions or metallic compounds; (3) natural antibacterial agents, derived from biological sources with inherent antimicrobial properties; and (4) composite antibacterial agents, which combine multiple active components to achieve synergistic effects (**Figure 2**). This classification framework provides a comprehensive understanding of the diverse antimicrobial strategies employed in the development of functional nylon fibers.

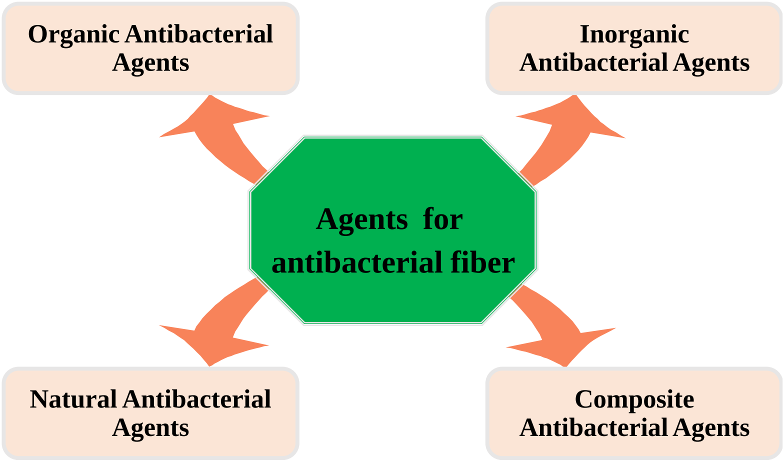


Figure 2. Schematic illustration of the commonly used antimicrobial agents for preparing antimicrobial fibers.

2.1. Organic antibacterial agents

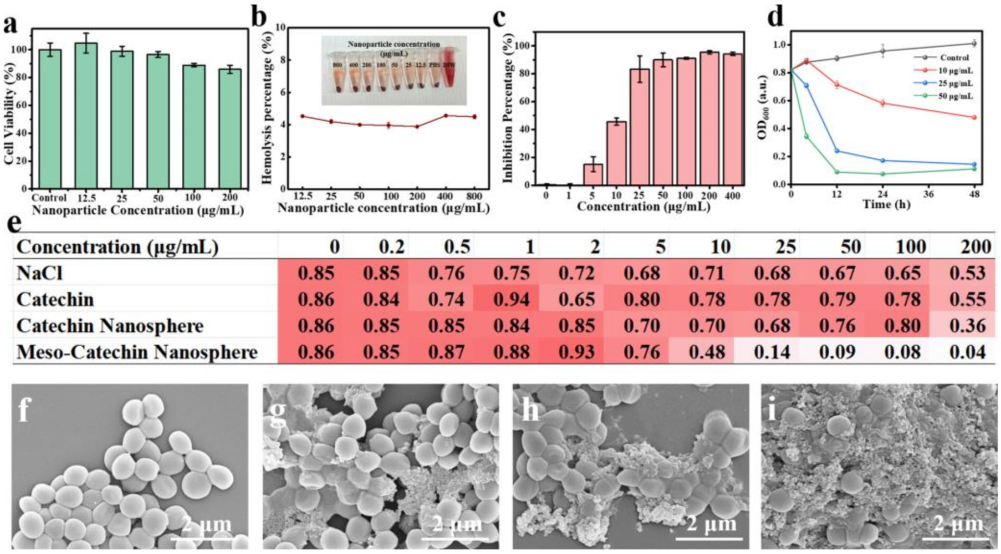
Organic antibacterial agents represent a significant category of antimicrobial compounds that exert their bactericidal effects through molecular interactions with intracellular biomacromolecules, thereby disrupting essential physiological processes in microbial cells [10,42]. This class encompasses various chemical groups, including quaternary ammonium salts, biguanides, alcohols, phenols, and organometallic compounds. The antimicrobial mechanism of these agents varies according to their chemical structure; for instance, quaternary ammonium salts function through their cationic groups, which electrostatically interact with the negatively charged microbial cell surface, subsequently altering membrane permeability and inducing cellular content leakage, ultimately resulting in microbial death [43,44]. Similarly, biguanide compounds primarily target the microbial cell membranes and walls, interfering with critical metabolic pathways [45–47]. These organic agents offer several advantages, such as high antimicrobial efficacy, rapid action kinetics, broad-spectrum activity against various bacteria and fungi, and favorable solubility properties that facilitate their incorporation into fiber processing. However, they are not without limitations: many exhibit poor thermal stability, leading to potential decomposition and loss of efficacy under high-temperature conditions for nylon fiber production [48,49]. Furthermore, prolonged use may contribute to the development of microbial resistance [50,51], and certain compounds raise safety concerns due to their potential impact on human health and environmental safety, necessitating careful consideration in their application [52].

2.2. Inorganic antibacterial agents

Inorganic antibacterial agents constitute a distinct category of antimicrobial materials that leverage the unique physicochemical properties of inorganic compounds to achieve bactericidal effects, primarily encompassing metal ion-based agents and photocatalytic materials [53]. Among metal ion antibacterial agents, silver ions (Ag^+), copper ions (Cu^{2+}), and zinc ions (Zn^{2+}) are widely utilized, with silver ions demonstrating particularly exceptional antimicrobial performance. The mechanism of silver ions involves their strong binding affinity to essential biomacromolecules such as proteins and nucleic acids within microbial cells, thereby disrupting critical cellular functions and inhibiting microbial proliferation [54]. Silver-based agents offer several advantages, including broad-spectrum antimicrobial activity, high efficacy, long-lasting antibacterial effects, and a low propensity for inducing microbial resistance, coupled with relatively favorable safety profiles [55,56]. However, their application is constrained by high material costs and potential discoloration issues, which may compromise the aesthetic quality of fiber products [57]. In the realm of photocatalytic antibacterial agents, titanium dioxide (TiO_2) serves as a prominent example, functioning through the generation of highly reactive oxygen species (ROS) under light irradiation [58,59]. These ROS exhibit strong oxidative capabilities, enabling the degradation of organic components within microbial cells and subsequent microbial inactivation. While photocatalytic agents demonstrate high antibacterial efficiency and environmental compatibility without secondary pollution, their performance is inherently dependent on light availability, resulting in significantly reduced efficacy under dark or low-light conditions [60]. This limitation necessitates careful consideration of the application environments for optimal functionality.

2.3. Natural antibacterial agents

Natural antibacterial agents, derived from biological sources including flora, fauna, and microorganisms, represent a class of bioactive compounds with antimicrobial properties, exemplified by chitosan, tea polyphenols, and plant essential oils [61–63]. Chitosan, a cationic polysaccharide obtained through chitin deacetylation, exhibits antimicrobial activity primarily through electrostatic interactions between its protonated amino groups and anionic components of microbial cell membranes, thereby disrupting membrane integrity and permeability [64]. Additionally, it demonstrates enzyme-inhibitory effects that further contribute to its antimicrobial efficacy. This biopolymer is particularly advantageous for textile applications due to its exceptional biocompatibility, biodegradability, and inherent safety profile, coupled with its beneficial hygroscopic properties [65]. Tea polyphenols, a group of polyphenolic compounds abundant in Camellia sinensis, exert antimicrobial effects through protein binding and subsequent denaturation, effectively inhibiting microbial proliferation while also demonstrating significant antioxidant capacity [66–68]. Plant essential oils, comprising complex mixtures of volatile aromatic compounds including terpenoids and phenolic derivatives, exhibit species-specific antimicrobial activity [69–71]. For instance, Melaleuca alternifolia (tea tree) oil demonstrates pronounced efficacy against both Gram-positive (*Staphylococcus aureus*) and Gram-negative (*Escherichia coli*) pathogens [71,72]. Recently, Lin et al. [73] synthesized novel mesoporous catechin nanoparticles (mesoformulation) through a balanced multivariate interaction approach, optimizing water/ethanol ratios and ionic strength to control hydrogen bonding and π–π stacking (**Figure 3**). The resulting 100 nm spherical particles with 15 nm pores effectively preserve catechin's molecular structure. This drug-free, negatively charged formulation demonstrates exceptional biocompatibility and antibacterial efficacy, completely inhibiting *Staphylococcus aureus* growth at ~25 μg mL^{-1} in vitro. In vivo studies show accelerated wound healing (6–8 days) and effective biofilm resistance. The synthesis method provides insights into polymer nanoparticle formation and antibacterial mechanisms, advancing functional polymer material development [73]. While natural antibacterial agents offer distinct advantages such as renewable sourcing, environmental compatibility, and favorable biocompatibility [74,75], they are constrained by limitations including moderate antimicrobial potency, narrow spectrum of activity, and susceptibility to environmental degradation during storage and application [76–78], necessitating careful consideration in their implementation for functional textile development.



Concentration (µg/mL)	0	0.2	0.5	1	2	5	10	25	50	100	200
NaCl	0.85	0.85	0.76	0.75	0.72	0.68	0.71	0.68	0.67	0.65	0.53
Catechin	0.86	0.84	0.74	0.94	0.65	0.80	0.78	0.78	0.79	0.78	0.55
Catechin Nanosphere	0.86	0.85	0.85	0.84	0.85	0.70	0.70	0.68	0.76	0.80	0.36
Meso-Catechin Nanosphere	0.86	0.85	0.87	0.88	0.93	0.76	0.48	0.14	0.09	0.08	0.04

Figure 3. Biocompatibility and antibacterial activity assay of mesoporous catechin nanoparticles: **(a)** Cell viability of endothelial cells with mesoporous catechin nanoparticles; **(b)** Hemolytic performance assay; The antibacterial activity with **(c)** varied concentrations for 24 h; **(d)** and prolonged time against *Staphylococcus aureus*; **(e)** Antibacterial activity against *Staphylococcus aureus*; **(f–i)** Scanning electron microscopy (SEM) images of *Staphylococcus aureus* cocultured with mesoporous catechin nanoparticles for 24 h. Reprinted with permission from reference [73], copyright American Chemical Society 2024.

2.4. Composite antibacterial agents

Composite antibacterial agents represent an advanced strategy in antimicrobial technology, achieved through the synergistic combination of multiple distinct antibacterial components. This approach enables the integration of complementary functionalities, effectively addressing the limitations inherent in single-component systems [79,80]. For instance, the combination of silver ions with organic antibacterial agents demonstrates enhanced antimicrobial efficacy while simultaneously reducing silver ion concentration, thereby optimizing cost-effectiveness and improving thermal stability and durability of the organic components [22,81,82]. Another exemplary combination involves the integration of photocatalytic antibacterial agents with metal ion-based systems, where photogenerated radicals from the photocatalytic component amplify the antimicrobial activity of metal ions, while metal ions reciprocally enhance the stability and spectral responsiveness of the photocatalytic materials [83]. The strategic design of composite antibacterial systems enables tailored optimization of multiple performance parameters, including antimicrobial spectrum, environmental stability, and biocompatibility, to meet specific application requirements [82,84]. However, the development of these composite systems presents significant technical challenges, particularly regarding the optimization of component compatibility, elucidation of synergistic mechanisms, and maintenance of substrate integrity [85]. These complexities necessitate a comprehensive investigation of interfacial interactions, synergistic kinetics, and potential impacts on the physicochemical properties of the host materials during the formulation process.

3. Surface treatment for preparing functional antimicrobial fibers

Antibacterial functionalization represents a pivotal strategy for expanding the application scope of synthetic polymer fibers, including nylon 6, in the textile industry [86]. Current technological approaches to developing antibacterial nylon 6 fibers based on surface treatment primarily include the following distinct methodologies: chemical modification, dyeing, and post-finishing [87,88]. Chemical modification directly alters the molecular structure of nylon 6, introducing antibacterial moieties at the molecular level. This approach offers long-lasting antibacterial efficacy as the modifications are integral to the fiber. However, it may require complex synthetic procedures and could potentially affect the fiber's original properties. Dyeing incorporates antibacterial agents during the dyeing process. It is relatively straightforward and can simultaneously impart color and antibacterial function. But the antibacterial durability might be limited, as the agents may gradually leach out during use and washing. Post-finishing involves applying antibacterial agents to the fiber surface after production. This is a flexible method that allows for easy adaptation to different antibacterial agents. Nevertheless, its effectiveness may decline over time due to abrasion or washing, and the adhesion of the agents to the surface may not always be optimal. Each method has its own merits and limitations when developing antibacterial nylon 6 fibers. Recently, electrospraying and electrospinning are emerging methods for engineering antibacterial polymer fiber surfaces [89,90]. In electrospraying, a high-voltage electric field is applied to a component solution or melt, causing it to be atomized into fine droplets. Electrospinning, on the other hand, employs the same principle but forms continuous nanofibers. These techniques are crucial as they enable precise control over fiber morphology and antibacterial agent distribution. Their prospects are promising, with potential applications in medical textiles, wound dressings, and air filtration where antibacterial properties are highly desired. Notably, each technique induces unique antibacterial properties and structural characteristics in the resultant fibers, owing to their inherent process-specific mechanisms. Consequently, the selection of an appropriate preparation method necessitates careful consideration of the intended application requirements, including durability, antibacterial efficacy, and mechanical properties, to ensure optimal performance in specific end-use scenarios.

3.1. Chemical modification

Surface chemical modification represents a sophisticated chemical approach to impart antibacterial properties to fibers through the covalent/non-covalent attachment of functional sites, including antibacterial agents, onto the polymer backbone (**Figure**

4) [91–94]. This molecular-level modification confers exceptional stability and durability to antibacterial functionality, as the chemically bonded antibacterial groups demonstrate remarkable resistance to detachment [95]. Such characteristics render graft-modified nylon 6 fibers particularly suitable for demanding industrial applications, including food packaging materials and water treatment filtration systems, where sustained antibacterial efficacy under severe operational conditions is paramount [6]. The permanent integration of antibacterial groups ensures consistent performance, even when subjected to repetitive stress or aggressive chemical environments. However, the implementation of this technique presents significant technical challenges: the process necessitates precise control over critical parameters such as reaction temperature, duration, and stoichiometric ratios, demanding advanced production technologies [96]. Furthermore, the chemical modification process may potentially alter the intrinsic properties of the matrix fibers, often requiring subsequent optimization treatments to restore or enhance desired characteristics [97]. These technical complexities and potential material alterations must be carefully considered in the development and application of graft-modified antibacterial nylon 6 fibers.

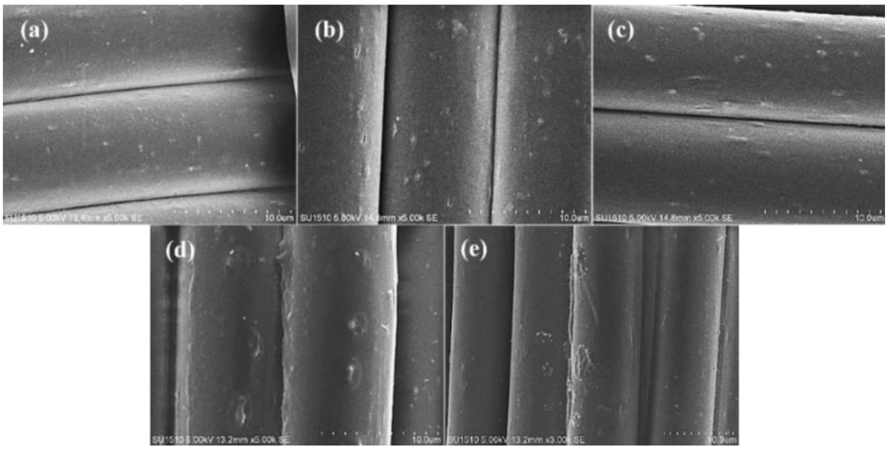


Figure 4. **(a)** Surface morphology analysis of the refined PA fabric; **(b,c)** ethanol@Bromelain modified PA; **(d,e)** and ethanol@Bromelain@Laccase modified PA. Reprinted with permission from reference [94], copyright Springer 2024.

3.2. Dyeing and post-finishing

Dyeing and post-finishing technologies involve surface modification approaches for imparting antibacterial properties to polymer fibers via impregnation or coating of antibacterial agents onto pre-formed fibers or fabrics [98,99]. These methodologies offer distinct advantages in terms of operational simplicity and process flexibility, enabling the customization of antibacterial treatments through the selection of specific antibacterial agents and processing parameters according to the application requirements [100,101]. These techniques demonstrate particular suitability for applications where preservation of the fiber’s intrinsic properties is paramount and transient antibacterial functionality suffices, such as disposable protective equipment or seasonal antimicrobial apparel [102]. However, the surface-bound nature of the antibacterial agents in post-finished fibers presents inherent limitations in durability [103,104]. The physical adhesion mechanism renders the antibacterial components susceptible to gradual depletion through mechanical abrasion and laundering processes, leading to a progressive deterioration of antimicrobial efficacy over time [105]. This surface instability necessitates careful consideration of the intended product lifecycle when selecting post-finishing as the antibacterial treatment method.

4. Recent advances in differentiated antimicrobial polyamide fiber

The advancement of material technology, particularly the emergence of novel functional fiber materials such as antimicrobial nylon, has had a profound impact on the fields of hygiene, health, and environmental protection [106]. By incorporating antimicrobial agents into the fibers, antimicrobial nylon effectively inhibits the growth of bacteria and microorganisms, significantly enhancing the hygienic performance of textiles in medical, athletic, and daily wear applications, thereby reducing the risk of infection. Furthermore, the durability and ease of cleaning associated with these materials decrease the frequency of washing, conserving water resources and minimizing environmental pollution caused by chemical detergents. The innovation of functional fiber materials not only promotes the adoption of healthier lifestyles but also provides new solutions for sustainable development, contributing to a cleaner and healthier future.

4.1. Antimicrobial PA fiber based on surface chemical modification

Surface modification methods are advantageous for imparting antibacterial properties to fibers. By loading antimicrobial agents only on the fiber surface without changing the internal structure, they maintain the fiber’s mechanical integrity. In contrast, melt blending or electrospinning, which incorporate agents into the polymer matrix, can disrupt polymer crystallinity and molecular chain alignment, reducing tensile strength and durability. Thus, surface modification is a better strategy for developing antibacterial fibers, especially for applications needing both mechanical strength and long-term antibacterial performance. Pagnotta et al. [107] developed an innovative approach to create antibacterial polyamide 6,6 (PA 6,6) nanofibers through Ionized Jet Deposition (IJD) of nanostructured silver coatings. The PA 6,6 nanofibers, fabricated via electrospinning with optimized parameters (20% w/v HFP solution, 20 kV voltage, 15 cm needle-to-collector distance, and 0.5 mL/h flow rate), exhibited favorable mechanical properties ($E = 31$ MPa, $\varepsilon_b = 115\%$). The IJD process generated a plasma plume containing silver ions, atoms, and clusters, which coalesced to form a continuous nanostructured metallic silver coating on the fiber surface. The antimicrobial evaluation demonstrated significant efficacy, with silver-coated nanofibers showing clear inhibition zones against both *Escherichia coli* and *Staphylococcus aureus*. Notably, Ag-PA 6,6 exhibited superior antibacterial performance against *Escherichia coli* compared to other polymer substrates, while maintaining consistent efficacy against *Staphylococcus aureus*. This scalable and efficient fabrication method combines the inherent mechanical advantages of PA 6,6 with the potent antimicrobial properties of nanostructured silver, offering promising potential for advanced wound dressing applications that require both structural integrity and effective microbial inhibition.

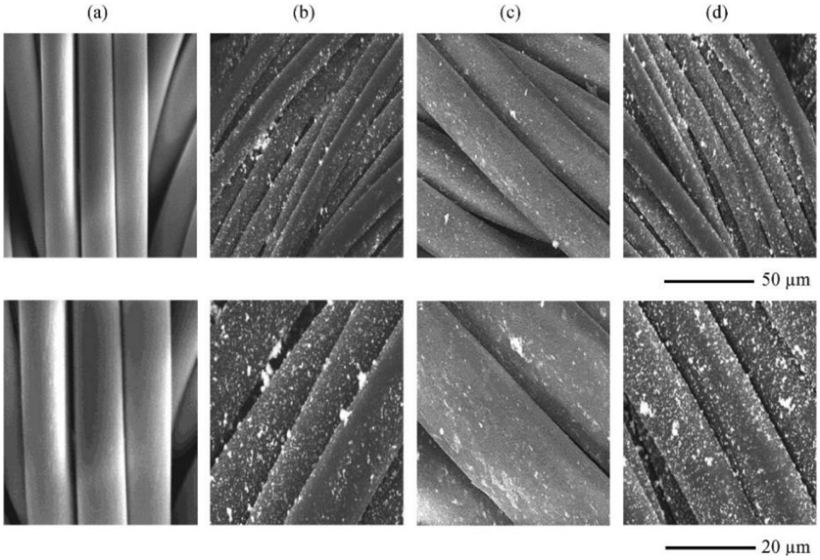


Figure 5. Surface morphology of control and nano-silver-treated nylon fibers: **(a)** C-nylon; **(b)** R-nylon; **(c)** Y-nylon; **(d)** B-nylon, and corresponding higher magnification images at the bottom. Reprinted with permission from reference [108], copyright Elsevier 2024.

Notably, silver nanoparticles demonstrate superior broad-spectrum antimicrobial activity and faster bactericidal effects compared to CuO, particularly exhibiting enhanced efficacy against Gram-negative bacteria. In practical applications, CuO is more suitable for scenarios requiring long-term, stable release of antimicrobial ions, while silver nanoparticles are better suited for situations demanding rapid sterilization. Hasan et al. [108] developed an innovative in-situ synthesis method for creating multifunctional nylon fabrics with simultaneous coloration and antibacterial properties through silver nanoparticle (AgNP) deposition (**Figure 5**). The technique leverages the surface plasmon resonance of AgNPs to generate a spectrum of colors on nylon substrates, with precise color control achieved by modulating precursor concentration and ascorbic acid levels. Surface characterization revealed uniformly distributed spherical AgNPs with a significant impact on the fiber’s surface properties. The deposition mechanism relies on chitosan’s molecular interactions, facilitated by its thin film formation and double network establishment through chemical linkages. Quantitative *X*-ray fluorescence (XRF) analysis confirmed the safety profile of the treated fabrics, with silver release levels within acceptable human toxicity limits. The functionalized nylon exhibited exceptional antibacterial efficacy, maintaining up to 88% microbial reduction in both Gram-positive and Gram-negative bacteria after 20 washing cycles. Additionally, the plasmonic coloration demonstrated superior colorfastness properties, including resistance to light, washing, and rubbing, coupled with excellent color strength. This approach represents a significant advancement over conventional dyeing technologies, offering a sustainable alternative for producing multifunctional textiles with integrated coloration and antimicrobial properties. Montazer et al. [109] developed two distinct methodologies for fabricating antibacterial polyamide 6 nanofibers incorporating silver nanoparticles (Ag NPs). The first approach involved simultaneous reduction of silver nitrate and dissolution of nylon in a formic/acetic acid solvent system, yielding thicker nanofibers with higher silver content. In contrast, the second method employed post-solution silver nitrate reduction, producing thinner nanofibers. Both techniques demonstrated that increasing silver nitrate concentration decreased average fiber diameter due to enhanced solution conductivity, while non-reduced silver nitrate formulations resulted in larger diameter fibers. Antimicrobial evaluation, conducted through standardized bacterial culture techniques using Luria-Bertani (LB) broth and Tryptone Soy Agar, revealed that all Ag NP-incorporated nanofibers exhibited significant antibacterial activity against both *Escherichia coli* and *Staphylococcus aureus*. Notably, fibers with higher silver nitrate concentrations achieved complete (100%) bacterial reduction for both pathogens. These findings demonstrate the effectiveness of silver nanoparticle integration in polyamide 6 nanofibers for antimicrobial applications, with the fabrication method significantly influencing fiber morphology and silver content, thereby affecting antibacterial performance.

Mehmood et al. [110] developed durable antibacterial textiles by modifying commercial nylon and cotton/nylon fabrics with chitosan and silver nanoparticles (AgNPs) using triethyl orthoformate (TEOF) as a crosslinker (**Figure 6**). The AgNPs were synthesized via sodium borohydride reduction of silver nitrate at 0 °C. Structural characterization confirmed successful modification, with FTIR spectra showing characteristic peaks at 1650 cm^{-1} (C=N stretching) and 3375 cm^{-1} (amine stretching), indicating chitosan attachment and silver coordination, respectively. SEM analysis revealed intact fiber surfaces post-modification, while mechanical testing demonstrated enhanced tensile strength from 90 to 100 MPa for nylon and from 91 to 99 MPa for cotton/nylon. The modified fabrics exhibited exceptional antibacterial efficacy, achieving 90% and 89% inhibition against *Escherichia coli* and *Staphylococcus aureus*, respectively, as measured by agar diffusion and broth dilution assays. Remarkably, the antibacterial activity persisted through 50 aggressive washing cycles (10 g/L non-ionic detergent, 100 rpm, 15 min). Practical evaluation using football players' socks demonstrated over 90% bacterial inhibition after 70 min of activity, highlighting the commercial potential of these durable antimicrobial textiles for sportswear and other high-performance applications. Syafiuddin et al. [111] developed an innovative green method for permanent deposition of silver nanoparticles (AgNPs) on nylon fabrics using Muntingia calabura leaf extract. The successful deposition was confirmed by color darkening, with SEM-EDS analysis revealing surface compositions of 42.1% carbon, 27.8% oxygen, 23.4% silver, and 6.7% nitrogen. The modified fabrics exhibited altered physical properties, including a 23.0% reduction in water absorption capacity and a 5.9% increase in textile density. Antibacterial assessment demonstrated significant efficacy, with inhibition zones of 4.33 ± 0.58 mm against *Escherichia coli*, 2.33 ± 0.58 mm against *Chromobacterium haemolyticum*, and 2.00 ± 1.00 mm against *Bacillus cereus*, indicating superior activity against Gram-negative bacteria. The heat treatment process facilitated deep penetration of AgNPs into the fiber structure, ensuring durable antibacterial properties. This environmentally friendly approach presents a promising solution for developing long-lasting medical textiles with enhanced antimicrobial functionality, addressing the critical need for sustainable antibacterial materials in healthcare applications.

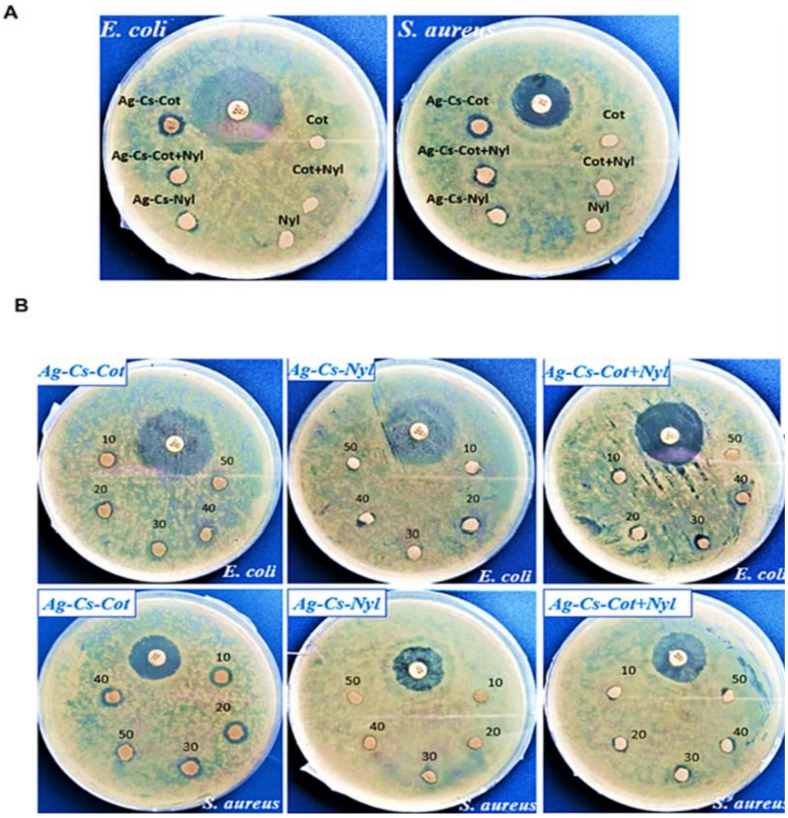


Figure 6. Antibacterial ability characterization of the developed smart fabrics: **(A)** Antibacterial activity before washing; **(B)** Antibacterial durability after 50 wash cycles. Reprinted with permission from reference [110], copyright Elsevier 2024.

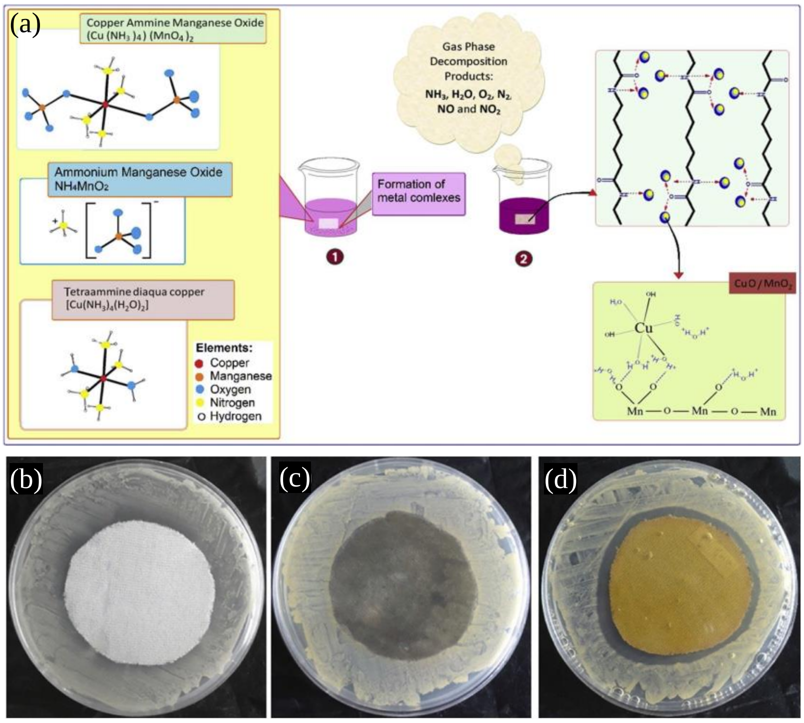


Figure 7. (a) The proposed mechanism for the formation of CuO/MnO$_2$ core/shell nanostructures within polyamide chains; Inhibition zones of *Staphylococcus aureus* growth with **(b)** untreated; **(c)** treated with CuO; **(d)** treated with CuO/MnO$_2$. Reprinted with permission from reference [112], copyright Elsevier 2019.

Notably, copper oxide (CuO) antimicrobial agents exhibit significant differences from silver nanoparticle (Ag) antimicrobial agents in terms of antibacterial performance and application characteristics. Firstly, regarding the antimicrobial mechanism, CuO primarily functions through the release of copper ions (Cu^{2+}) that disrupt bacterial cell membranes and generate reactive oxygen species (ROS), while silver nanoparticles operate by releasing silver ions (Ag^{+}) that bind to bacterial proteins and DNA. Secondly, in terms of cost-effectiveness, CuO antimicrobial agents demonstrate a distinct economic advantage, with raw material costs significantly lower than those of silver nanoparticles. Thirdly, concerning safety, CuO generally exhibits lower cytotoxicity compared to silver nanoparticles, particularly at high concentrations. Fourthly, in terms of environmental friendliness, CuO shows a lower bioaccumulation potential and relatively reduced environmental risks. Zahra et al. [112] developed a multifunctional nylon fabric through in-situ synthesis of CuO/MnO_2 core/shell structures, demonstrating enhanced mechanical and antibacterial properties (**Figure 7**). The synthesis involved forming a tetraamminecopper (II) dipermanganate complex $(Cu(NH_3)_4)(MnO_4)_2$, followed by selective reduction to create CuO cores decorated with MnO_2 shells. Characterization through SEM, FTIR, and EDS confirmed the uniform distribution of nanoparticles on the fabric surface, with characteristic peaks at 880 cm^{-1} verifying successful incorporation. The modified fabric exhibited significant improvements in tensile strength (344.9 MPa) and flexibility, with bending length increases of 27% and 35% for CuO and CuO/MnO_2 treatments, respectively. These enhancements are attributed to the cross-linking action of nanoparticles and the strong chelation between polyamide chains and metal complexes. The treated fabric demonstrated excellent water repellency, self-cleaning properties, and antibacterial efficacy against *Staphylococcus aureus*, as evidenced by clear inhibition zones in antibacterial testing. This innovative approach presents a promising method for developing advanced textiles with combined mechanical, hydrophobic, and antimicrobial functionalities, potentially revolutionizing applications in protective clothing and medical textiles. Polyamide 6 (PA6) fibers exhibit excellent mechanical strength and wear resistance, but face challenges in effectively incorporating inorganic antibacterial agents while maintaining performance. This limitation drives research into innovative strategies for developing multifunctional PA6 fibers with enhanced antimicrobial properties. Wang et al. [113] developed an innovative approach to enhance the functionality of polyamide 6 fibers by integrating cuprous oxide-loaded aminated graphene (Cu_2O-GO-NH_2) through in situ polymerization. The aminosilane coupling agent N-(2-Aminoethyl-3-aminopropyl)trimethoxysilane (AEAPTMS) was employed to modify graphene oxide, improving both the compatibility and thermal stability of the inorganic component within the polymer matrix. This modification strategy resulted in PA6/Cu_2O-GO-NH_2 composite fibers with significantly enhanced mechanical properties, demonstrating a 40% increase in fracture strength (from 3.0 to 4.2 cN/dtex) at 0.2 wt% Cu_2O-GO-NH_2 loading. The composite fibers exhibited exceptional antimicrobial efficacy, achieving complete inactivation of both *Bacillus subtilis* and *Escherichia coli* at 0.6 wt% loading. Remarkably, the fibers maintained high antibacterial activity after 50 washing cycles, with 98.85% and 99.99% reduction rates against *Bacillus subtilis* and *Escherichia coli*, respectively. These improvements are attributed to the synergistic effects of in situ polymerization and chemical modification, which enhance inorganic agent dispersion and interfacial bonding. The study demonstrates a promising strategy for developing high-performance antimicrobial fibers with potential applications in medical textiles and protective materials.

Compared to inorganic antimicrobial materials such as silver nanoparticles, the use of organic antimicrobial agents for modifying nylon fibers to produce antibacterial fibers offers significant advantages. Organic antimicrobial agents (e.g., quaternary ammonium salts, chitosan derivatives) can form strong bonds with fiber surfaces through chemical bonding or physical adsorption, enhancing the durability and wash resistance of antimicrobial components. These agents enable molecular-level functional design, optimizing antimicrobial performance while avoiding nanoparticle aggregation issues. They exhibit superior biocompatibility and environmental friendliness, reducing the risk of metal ion release. Additionally, multifunctional modifications can impart other desirable properties to the fibers, such as hydrophilicity, antistatic characteristics, or flame retardancy. Furthermore, the organic modification process is relatively simple, facilitating scalable production with high cost-effectiveness. This approach provides a versatile and sustainable strategy for developing advanced antibacterial nylon fibers with tailored properties for various applications. Zhang et al. [114] developed a durable antimicrobial nylon 66 fiber through a three-step modification process to address the growing threat of antibiotic-resistant bacteria (**Figure 8**). The fabrication involved gamma radiation-induced graft polymerization (producing PA66-*g*-PDMAEMA), followed by protonation (yielding PA66-HBr) and anion exchange (resulting in PA66-MnO4). A comprehensive characterization using FTIR, SEM, TGA, and XPS confirmed the successful incorporation of 1.48 mmol/g permanganate ions. The modified fibers exhibited enhanced mechanical properties, with breaking forces increasing from 7.37 cN (pristine) to 7.69 cN (PA66-*g*-PDMAEMA) and maintaining 7.57 cN after final modification. SEM analysis revealed controlled diameter growth from 12.3 to 20.5 μm throughout processing. The XPS spectra identified characteristic peaks corresponding to Br 3d, C 1s, O 1s, N 1s, and Mn 2p, confirming chemical modifications. The fibers demonstrated exceptional antimicrobial efficacy, achieving nearly 100% reduction against *Staphylococcus aureus* and *Candida albicans*. The durability tests showed remarkable stability, with maintained antimicrobial activity through 100 laundering cycles and consistent mechanical properties (breaking force ~7.57 cN) after 20 accelerated laundering cycles. This innovative approach presents a significant advancement in durable antimicrobial textiles, offering potential applications in medical and protective clothing where long-lasting antibacterial properties and mechanical integrity are crucial.

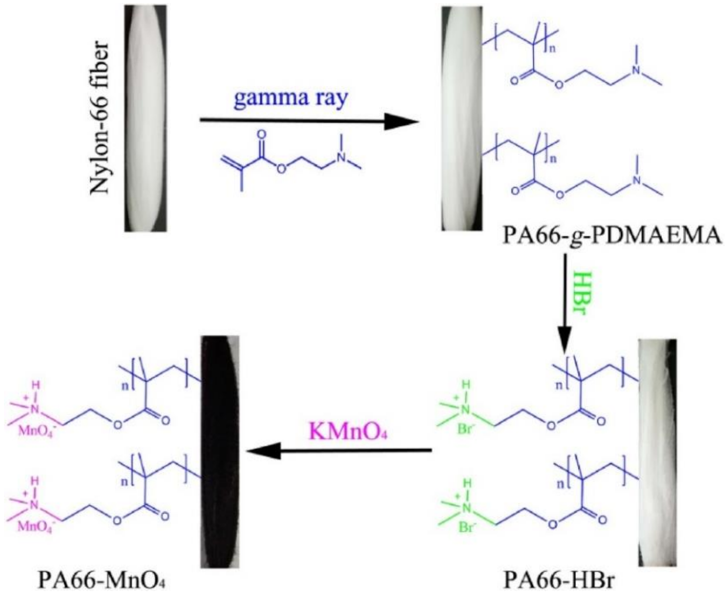


Figure 8. Schematic illustration of the preparation of antimicrobial nylon-66 fibers. Reprinted with permission from reference [114], copyright Elsevier 2017.

The escalating prevalence of pathogenic bacteria, exacerbated by the widespread misuse and overuse of antibiotics, poses a significant threat to public health and socioeconomic stability. This crisis is further compounded by the rapid emergence of antibiotic-resistant bacterial strains, which undermine the efficacy of conventional antimicrobial treatments and necessitate the development of innovative antibacterial strategies. Zhao et al. [115] developed an innovative approach to enhance the durability and functionality of antibacterial textiles through a polydopamine (PDA)-mediated layer-by-layer self-assembly of copper ion-crosslinked sodium alginate-graphene oxide (Cu^{2+}/SA-GO) on nylon 66 fabric. This design addressed the limitations of traditional metal ion coordination by creating a stable crosslinked network that improved Cu^{2+} loading stability and saltwater resistance. The fabric's antibacterial activity against *Staphylococcus aureus* and *Escherichia coli* was evaluated using a standardized bacterial count method. Bacterial suspensions (10^5 CFU/mL in PBS) were incubated with fabric samples for 24 h, then diluted to 10^3 CFU/mL and plated on LB agar. After 24-h incubation at 37 ℃, colony counts provided quantitative antibacterial efficacy data. The modified fabric demonstrated exceptional antibacterial performance, maintaining a 99.9% reduction rate against both *Staphylococcus aureus* and *Escherichia coli* after 30 washing cycles, attributed to the controlled release of Cu^{2+} from the robust crosslinked structure. A comprehensive evaluation using bacterial count methods confirmed the fabric's efficacy, with standardized testing procedures involving PBS buffer dilution and LB agar plate incubation. Additionally, the fabric exhibited enhanced hydrophilicity, hygroscopicity, and durable antistatic properties, maintaining a surface resistivity of approximately 10^8–10^9 Ω·cm even after 10 washing cycles and 6 h of NaCl soaking. These multifunctional properties, combined with the coating's high stability and slow-release mechanism, represent a significant advancement in textile modification technology, offering a promising solution for developing long-lasting antibacterial fabrics with applications in medical textiles and protective clothing.

Overall, surface modification methods have marked advantages in simplicity and cost-effectiveness. They demand little equipment and have uncomplicated operational steps. In comparison, melt blending and electrospinning need specialized gear and strict processing conditions, which heightens production complexity and operational expenses. The simplicity of surface modification makes it appealing for scalable manufacturing, but the technical demands of melt blending and electrospinning restrict their large-scale practical use. This shows the economic and practical merits of surface modification in developing functional textiles, especially for industrial applications and cost-efficiency. Surface modification methods offer significant advantages for the industrial production of antibacterial nylon fibers, combining economic viability with functional precision. This approach enables efficient antimicrobial agent utilization, mechanical property preservation, and flexible multifunctional design while maintaining environmental sustainability. These benefits make surface modification particularly valuable for advanced applications in medical textiles, smart fabrics, and environmental filtration, addressing both performance requirements and eco-friendly manufacturing demands.

4.2. Antimicrobial PA fiber based on dyeing and post-finishing

Compared to surface modification methods using inorganic materials (e.g., silver nanoparticles, copper oxide nanoparticles) or organic antibacterial agents, the direct immersion finishing method presents unique advantages in preparing antibacterial nylon fibers. This approach offers remarkable process flexibility, requiring neither complex reactions nor specialized equipment, while allowing for easy adjustment of antibacterial agent types and concentrations. The method demonstrates superior cost-effectiveness, significantly reducing production investments, and minimally impacting the fiber’s inherent properties, effectively preserving its strength and abrasion resistance. Additionally, it provides rapid antibacterial efficacy and broad compatibility with various antibacterial agents, including inorganic, organic, and natural compounds. However, the method’s primary limitation lies in its relatively poor antibacterial durability, as the agents tend to detach through friction or washing. This characteristic necessitates further development of binding techniques to enhance the longevity of antibacterial effects while maintaining the method’s inherent advantages. Lei et al. [116] developed a multifunctional strategy for nylon fabric using bio-based pale-yellow tannic acid (TA) and phytic acid (PA) to address its inherent flammability and stability limitations while imparting additional functional properties. Through a simple finishing method, the researchers constructed a durable coating that significantly enhanced the fabric’s performance characteristics. The modified fabric exhibited exceptional flame retardancy, with a limiting oxygen index (LOI) increasing to 39% and complete elimination of melt-dripping behavior. To ensure washing durability, polyethyleneimine (PEI) was incorporated by fiber immersion to form robust covalent and ionic bonds with TA, PA, and the nylon substrate, maintaining an LOI above 29% after four washing cycles. The treatment also imparted superior antimicrobial properties, demonstrating > 99% bacterial reduction against both *Escherichia coli* and *Staphylococcus aureus*, and enhanced ultraviolet protection, with the ultraviolet protection factor (UPF) increasing from 12.105 to 264.82. This study presents a sustainable approach to multifunctional textile modification, simultaneously addressing flammability, UV resistance, and antimicrobial requirements while maintaining the fabric's inherent mechanical properties, offering significant potential for protective textile applications.

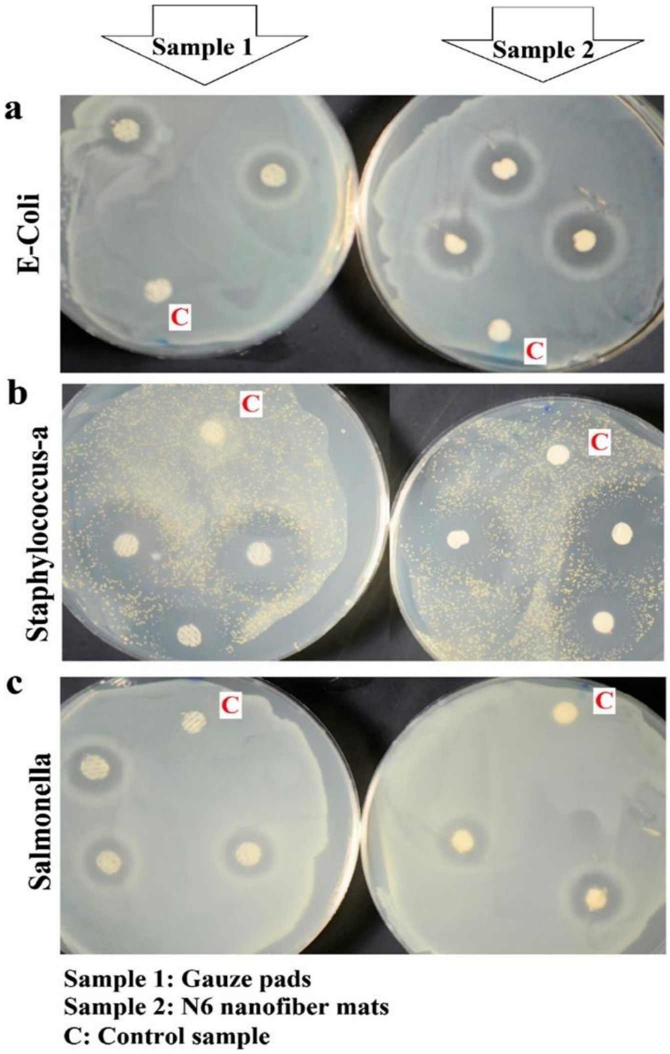


Figure 9. Inhibition zones for gauze pad samples (control and SOJ-coated), on the left side, and nylon 6 nanofiber mats (control and SOJ-coated), on the right side, against different bacteria: **(a)** *Escherichia coli*; **(b)** *Staphylococcus aureus*; **(c)** *Salmonella sp*. Reprinted with permission from reference [117], copyright Elsevier 2019.

Akia et al. [117] developed nylon 6 nanofiber mats through a centrifugal spinning process, producing nonwoven membranes with an average fiber diameter of 209 nm, significantly smaller than the 8.73 µm diameter of commercial gauze fibers (**Figure 9**). The antibacterial efficacy of both materials was systematically evaluated against Gram-positive (*Staphylococcus aureus*) and Gram-negative (*Escherichia coli and Salmonella sp.*) pathogens following functionalization with 100% Texas sour orange juice via a 5-min immersion process. The functionalized nanofiber mats demonstrated superior antibacterial performance, exhibiting inhibition zones of 18.5 mm compared to 16 mm for treated gauze pads, representing enhancements of 336% and 291% over their untreated counterparts (5.5 mm), respectively. This enhanced antimicrobial activity can be attributed to the nanofiber mats' unique structural characteristics: their smaller fiber diameter provides increased surface area for interaction with antibacterial components, while their nanoporous structure facilitates effective moisture retention and distribution of the citrus-based active compounds. Furthermore, the nanofiber membranes demonstrated excellent wettability and moisture absorption capacity, crucial properties for wound healing applications. Notably, these antibacterial effects were achieved without sterilization processes, and the nanofiber mats effectively inhibited bacterial proliferation while maintaining structural integrity. These findings highlight the significant advantages of nanostructured membranes over conventional wound dressing materials, particularly in terms of enhanced antibacterial efficacy, moisture management, and the potential for development as easily removable wound dressings in clinical applications.

Notably, dyes, being molecules that interact with light at specific wavelengths to evoke color perception, have been the subject of extensive research. GÜNSEL et al. [118] investigated the use of water-soluble phthalocyanine compounds as dyes for nylon/elastane fabrics, with a focus on both their dyeing performance and antibacterial capabilities. Four water-soluble phthalocyanine compounds (1–4) with distinct structures were utilized. Compounds 1 and 3 contained copper (Cu), while 2 and 4 contained cobalt (Co), and all had quinoline-5-sulfonic acid groups positioned differently on the phthalocyanine ring. The dyeing process involved a 1/20 dye-to-fiber ratio, using 5 g of nylon/elastane fiber with each compound at a 1% concentration, along with 0.6 g/L acetic acid and 2% leveling agent. After dyeing, the fibers were rinsed and dried. The antibacterial activity against *Escherichia coli* and *Staphylococcus aureus* was assessed via the disk diffusion method. All compounds and the resulting dyed fibers demonstrated antibacterial activity, with inhibition zone diameters ranging from 8–11 mm, and compound 3 showed a marginally superior antibacterial effect. In contrast, the undyed fibers exhibited no antibacterial properties. In terms of dyeing outcomes, as evaluated within the CIELAB color space, non-peripherally substituted dyes (1 and 2) yielded darker colors compared to peripherally substituted ones (3 and 4). Additionally, Cu-containing dyes (1 and 3) were darker and bluer than Co-containing dyes (2 and 4). The dyed fibers had excellent wet fastness and among them, the fiber dyed with phthalocyanine dye 1 had the best lightfastness. In conclusion, water-soluble phthalocyanine compounds can effectively be applied to dye nylon/elastane fibers, presenting good fastness characteristics. The dyed fibers, particularly those with compound 3, displayed significant antibacterial activity, signifying their potential for the development of functional textiles. Shaki [119] investigated the application of azo disperse and cationic dyes on polyamide and acrylic fabrics, demonstrating superior dye uptake and build-up on polyamide substrates compared to acrylic materials. The dyed fabrics exhibited a color range spanning purple, purplish red, and yellowish red hues, with excellent wash and rubbing fastness properties, complemented by moderate to good light fastness characteristics. The antimicrobial evaluation revealed exceptional microbial inhibition, with 97%–99.9% reduction rates against both Gram-positive and Gram-negative bacteria, as well as fungal species. A comprehensive biocompatibility assessment through skin sensitivity tests on rabbit models confirmed the absence of dermal irritation from both the dyes and dyed polyamide fabrics. These findings highlight the dual functionality of the developed dyeing system, which combines effective coloration with significant antimicrobial properties while maintaining biocompatibility, suggesting promising applications in the development of multifunctional textiles for medical and protective applications.

Han et al. [120] developed a novel light-driven antimicrobial nylon/cotton blended fabric (N/C-RB/ZP) through a one-bath loading of Rose Bengal (RB) and tetra[β-(4-sodium sulfonylphenoxy)]-phthalocyanine zinc(II) (ZP) photosensitizers (**Figure 10**). The dual-photosensitizer system exhibited enhanced photodynamic properties, characterized by two strong absorption peaks in the 450-700 nm range and exceptional singlet oxygen ($^1O_2$) generation capability. Under dual-lamp irradiation (red: 15 ± 1 mW/cm^2; green: 77 ± 1 mW/cm^2), N/C-RB/ZP-0.5% demonstrated a DPBF bleaching rate of 92.52% within 180 seconds, surpassing the combined performance of individual photosensitizer systems (86.03%). This synergistic effect was attributed to the Förster resonance energy transfer (FRET) process and electrostatic repulsion between RB and ZP, which improved photon utilization efficiency and reduced molecular aggregation. The fabric exhibited remarkable antimicrobial efficacy, achieving 99.99% and 99.67% reduction rates against *Staphylococcus aureus* and *Escherichia coli*, respectively, following 90 min of daylight flashlight irradiation (14 ± 1 mW/cm^2). Notably, the material maintained substantial antibacterial activity (> 80% against *Staphylococcus aureus* and > 75% against *Escherichia coli*) after three antimicrobial cycles or 20 standard washing cycles. These results demonstrate the potential of this dual-photosensitizer system for developing durable, broad-spectrum photodynamic antimicrobial textiles with applications in health protection and infection control. Shariatinia et al. [121] developed novel nanosized copper(II) complexes incorporating phosphoric triamide ligands ($Cu(NO_3)_2L_2$ (1) and $Cu(CH_3COO)_2L_2$ (2), where L = 4-$NO_2C_6H_4NHP(O)(NC_4H_8O)_2$) through an ultrasonic synthesis method for textile applications. A comprehensive characterization using ^{1}H, ^{13}C, ^{31}P NMR, FT-IR, photoluminescence, UV-Vis spectroscopy, XRD, FE-SEM, and elemental analysis confirmed the formation of spherical nanoparticles with diameters of 17–20 nm. The complexes were successfully applied to nylon and wool fibers, producing yellow and green coloration respectively. Although the dyed fabrics exhibited excellent wash fastness, their lightfastness properties were less satisfactory. Antibacterial evaluation against *Bacillus subtilis* demonstrated concentration-dependent activity, with enhanced efficacy observed at higher dye concentrations (0.1% to 0.5% o.w.f.) for both fiber types. This study presents a promising approach for developing multifunctional textiles combining coloration and antimicrobial properties, though further optimization of lightfastness characteristics is necessary for practical applications.

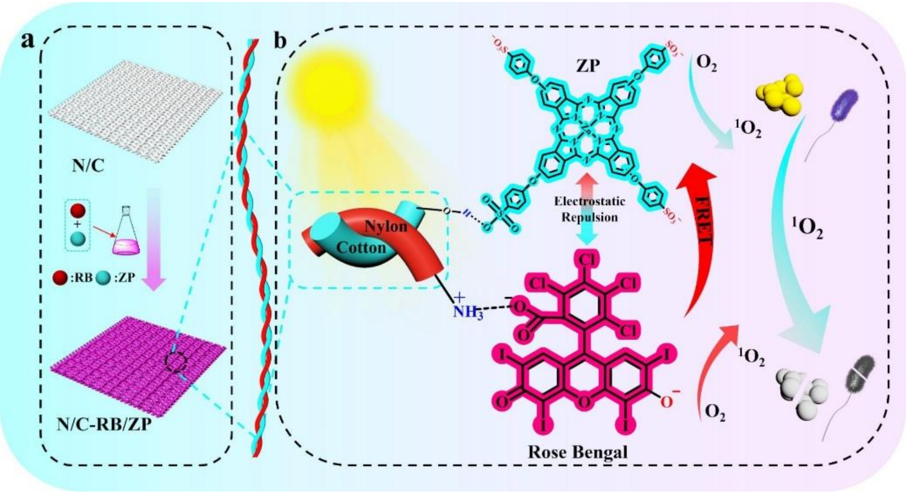


Figure 10. Schematic illustration for: **(a)** the RB and ZP mixed dyeing process for nylon/cotton blended fabric; **(b)** the mechanism of dye-fiber interaction and photodynamic action. Reprinted with permission from reference [120], copyright Elsevier 2024.

5. Future perspectives

5.1. Sustainability benefits of fiber surface treatment method

Surface chemical modification and post-finishing offer significant advantages in the preparation of antibacterial nylon fibers, particularly in maintaining the mechanical properties of fibers, simplifying production processes, and reducing costs. These methods impart antibacterial functionality by loading antibacterial agents onto the fiber surface, thereby preserving the internal structure of the fibers. In contrast, melt blending or electrospinning methods that incorporate antibacterial agents into the polymer matrix may alter the crystallinity and molecular chain arrangement of the polymer, potentially compromising the mechanical properties of the fibers. Furthermore, surface modification and post-finishing methods are characterized by simplicity, ease of operation, and minimal requirement for complex equipment, making them highly suitable for large-scale industrial production with significant cost-effectiveness. Furthermore, these methods allow for direct use of commercially available fiber materials, eliminating the need for additional fiber preparation steps, which further reduces production costs and time.

5.2. Challenges and strategies for fiber surface treatment methods

Despite their numerous advantages, surface modification and post-finishing methods face several challenges that limit their widespread application. One major drawback is the limited durability of antibacterial functionality, as antibacterial agents tend to gradually degrade or leach out due to mechanical friction, washing, or environmental factors such as UV exposure and humidity. To address this issue, strategies such as chemical grafting or cross-linking can be employed to enhance the binding strength of antibacterial agents to the fiber surface. Additionally, the development of multilayer coating technologies and nanoencapsulation techniques can enable controlled release mechanisms, thereby extending the lifespan of antibacterial effects. Another challenge is the uneven distribution of antibacterial agents on the fiber surface, which can lead to inconsistent antibacterial performance. Optimizing coating processes, such as spray coating or dip coating, and utilizing self-assembly technologies can improve the uniformity of antibacterial agent distribution. Furthermore, certain antibacterial agents, such as silver or copper ions, may exhibit toxicity at high concentrations, while some organic agents are susceptible to decomposition under high temperatures or humid conditions. To mitigate these risks, the development of low-toxicity, high-efficiency antibacterial agents, such as natural compounds (e.g., chitosan, tea polyphenols) or composite systems, is crucial. Precise control over the amount of antibacterial agents loaded can ensure effective antibacterial performance while minimizing potential health risks. Finally, ensuring process consistency and product quality stability in large-scale production remains a significant challenge. The introduction of automated coating equipment and online monitoring systems, combined with green production technologies, can enhance production efficiency and reduce environmental impact.

5.3. Future directions for technological development

Surface modification and post-finishing methods hold immense potential for the preparation of antibacterial nylon fibers, with promising prospects for future advancements. As nanotechnology, green chemistry, and automated production technologies continue to advance, these methods are expected to achieve breakthroughs in several areas. Firstly, the development of novel antibacterial agents and advanced coating technologies will enable surface modification and post-finishing methods to deliver more durable and stable antibacterial performance, meeting the demands of high-end medical and hygiene applications. Secondly, by integrating multiple functionalities such as antibacterial, hydrophobic, and conductive properties, these methods will drive the development of multifunctional nylon fibers, expanding their applications in smart textiles, medical devices, and environmental filtration systems. Lastly, with the maturation of automated production lines and green manufacturing processes, surface modification and post-finishing methods will make large-scale production more efficient and cost-effective, further promoting the commercialization of antibacterial nylon fibers. In conclusion, through continuous technological innovation and process optimization, surface modification, and post-finishing methods are poised to overcome existing limitations, paving the way for widespread application of antibacterial nylon fibers in healthcare, textiles, and environmental protection, ultimately contributing to human health and sustainable development.

6. Conclusions

The development of antibacterial polyamide (nylon) fibers has emerged as a crucial advancement in functional materials, responding to the growing demand for antimicrobial solutions across the medical, textile, and packaging industries. This review comprehensively explored various aspects of antibacterial nylon fibers based on surface treatment, including preparation methods, antibacterial agents, and performance characteristics. The preparation methods for antibacterial nylon fibers, such as surface modification, dyeing, and post-finishing, each have their own characteristics. Surface modification offers stable antibacterial functionality but involves complex chemical processes; dyeing and post-finishing is simple and flexible yet has durability issues. A variety of antibacterial agents, including inorganic, organic, natural, and composite agents, have been integrated into nylon fibers. These agents act through different mechanisms, like disrupting microbial cell membranes or generating reactive oxygen species, to inhibit or kill microorganisms. The integration of nanotechnology and composite systems has further enhanced the performance of antibacterial nylon fibers, especially in applications that require long-term durability and broad-spectrum antibacterial activity. In summary, antibacterial nylon fibers have great potential in addressing public health concerns and promoting sustainable materials technology. Continued advancements in design, fabrication, and characterization will enhance performance and expand applications, contributing to a healthier and more sustainable future.

Funding: We are grateful for the financial support from the SINOPEC Major scientific and technological projects (223334).

Conflict of interest: The authors declare no conflict of interest.

References

1. Moore M, Gould P, Keary BS. Global urbanization and impact on health. International Journal of Hygiene and Environmental Health. 2003; 206(4-5): 269-278. doi: 10.1078/1438-4639-00223
2. Capon A. Harnessing urbanisation for human wellbeing and planetary health. The Lancet Planetary Health. 2017; 1(1): e6-e7. doi: 10.1016/S2542-5196(17)30005-0
3. Kadakia KT, Galea S. Urbanization and the Future of Population Health. The Milbank Quarterly. 2023; 101(S1): 153-175. doi: 10.1111/1468-0009.12624
4. Duan Y, Li L, Shen Z, et al. Engineering Metal-Organic-Framework (MOF)-Based Membranes for Gas and Liquid Separation. Membranes. 2023; 13(5): 480. doi: 10.3390/membranes13050480
5. Li L, Duan Y. Engineering Polymer-Based Porous Membrane for Sustainable Lithium-Ion Battery Separators. Polymers. 2023; 15(18): 3690. doi: 10.3390/polym15183690
6. Ryšánek P, Malý M, Čapková P, et al. Antibacterial modification of nylon-6 nanofibers: structure, properties and antibacterial activity. Journal of Polymer Research. 2017; 24(11). doi: 10.1007/s10965-017-1365-6
7. Kang W, Ju J, Zhao H, et al. Characterization and antibacterial properties of Ag NPs doped nylon 6 tree-like nanofiber membrane prepared by one-step electrospinning. Fibers and Polymers. 2016; 17(12): 2006-2013. doi: 10.1007/s12221-016-6821-0
8. Lin J, Winkelman C, Worley SD, et al. Antimicrobial treatment of nylon. Journal of Applied Polymer Science. 2001; 81(4): 943-947. doi: 10.1002/app.1515
9. Li Y, Miao Y, Yang L, et al. Recent Advances in the Development and Antimicrobial Applications of Metal-Phenolic Networks. Advanced Science. 2022; 9(27). doi: 10.1002/advs.202202684
10. Saidin S, Jumat MA, Mohd Amin NAA, et al. Organic and inorganic antibacterial approaches in combating bacterial infection for biomedical application. Materials Science and Engineering: C. 2021; 118: 111382. doi: 10.1016/j.msec.2020.111382
11. Xu F, Cudmore E, Walji S, et al. In Situ-Gelling Antimicrobial Poly(oligoethylene glycol methacrylate)-Based Hydrogels Integrating Bound Quaternary Ammonia Compounds and Antibiotic Functionalities for Effective Infected Wound Healing. Advanced Healthcare Materials; 2025. doi: 10.1002/adhm.202403800
12. Kanerva M, Puolakka A, Takala TM, et al. Antibacterial polymer fibres by rosin compounding and melt-spinning. Materials Today Communications. 2019; 20: 100527. doi: 10.1016/j.mtcomm.2019.05.003
13. Hou X, Fan M, Zheng S, et al. Washing Resistant Antibacterial PET Composite Fibers Fabricated by Melt Spinning. Fibers

and Polymers. 2024; 25(12): 4689-4698. doi: 10.1007/s12221-024-00787-y
14. Singh S, Kumar S, Khanna V. A review on surface modification techniques. Materials Today: Proceedings; 2023. doi: 10.1016/j.matpr.2023.01.010
15. Hwang MY, Yoon SH, Kim M. Ultraviolet Irradiation Surface Treatment to Enhance the Bonding Strength of Polyamide-Based Carbon Fiber-Reinforced Thermoplastic Polymers. Polymers. 2024; 16(20): 2864. doi: 10.3390/polym16202864
16. Ansari MS, Zafar S, Pathak H. A comprehensive review of surface modification techniques for carbon fibers for enhanced performance of resulting composites. Results in Surfaces and Interfaces. 2023; 12: 100141. doi: 10.1016/j.rsurfi.2023.100141
17. Liu Y, Liu X, Lu J, et al. Post-treatment technologies for high-speed additive manufacturing：Status, challenge and tendency. Journal of Materials Research and Technology. 2024; 30: 1057-1082. doi: 10.1016/j.jmrt.2024.03.110
18. Wang CG, Surat’man NEB, Mah JJQ, et al. Surface antimicrobial functionalization with polymers: fabrication, mechanisms and applications. Journal of Materials Chemistry B. 2022; 10(45): 9349-9368. doi: 10.1039/d2tb01555b
19. Huang L, Liu CJ. Progress for the development of antibacterial surface based on surface modification technology. Supramolecular Materials. 2022; 1: 100008. doi: 10.1016/j.supmat.2022.100008
20. Saito S, Matsuno S, Saito A, et al. Modification of Antibacterial Copolymers on the Surface of PVA-Based Microfibers via Thermal Cross-Linking and Their Antibacterial Properties. ACS Omega. 2024; 9(46): 45961-45969. doi: 10.1021/acsomega.4c05637
21. Gulati R, Sharma S, Sharma RK. Antimicrobial textile: recent developments and functional perspective. Polymer Bulletin. 2021; 79(8): 5747-5771. doi: 10.1007/s00289-021-03826-3
22. Anees Ahmad S, Sachi Das S, Khatoon A, et al. Bactericidal activity of silver nanoparticles: A mechanistic review. Materials Science for Energy Technologies. 2020; 3: 756-769. doi: 10.1016/j.mset.2020.09.002
23. Liao C, Li Y, Tjong SC. Bactericidal and Cytotoxic Properties of Silver Nanoparticles. International Journal of Molecular Sciences. 2019; 20(2): 449. doi: 10.3390/ijms20020449
24. Salah I, Parkin IP, Allan E. Copper as an antimicrobial agent: recent advances. RSC Advances. 2021; 11(30): 18179-18186. doi: 10.1039/d1ra02149d
25. Portelinha J, Duay SS, Yu SI, et al. Antimicrobial Peptides and Copper(II) Ions: Novel Therapeutic Opportunities. Chemical Reviews. 2021; 121(4): 2648-2712. doi: 10.1021/acs.chemrev.0c00921
26. Edo GI, Yousif E, Al-Mashhadani MH. Chitosan: An overview of biological activities, derivatives, properties, and current advancements in biomedical applications. Carbohydrate Research. 2024; 542: 109199. doi: 10.1016/j.carres.2024.109199
27. Harugade A, Sherje AP, Pethe A. Chitosan: A review on properties, biological activities and recent progress in biomedical applications. Reactive and Functional Polymers. 2023; 191: 105634. doi: 10.1016/j.reactfunctpolym.2023.105634
28. Jiménez-Gómez CP, Cecilia JA. Chitosan: A Natural Biopolymer with a Wide and Varied Range of Applications. Molecules. 2020; 25(17): 3981. doi: 10.3390/molecules25173981
29. Aranaz I, Alcántara AR, Civera MC, et al. Chitosan: An Overview of Its Properties and Applications. Polymers. 2021; 13(19): 3256. doi: 10.3390/polym13193256
30. Iwuji C, Saha H, Ghann W, et al. Synthesis and characterization of silver nanoparticles and their promising antimicrobial effects. Chemical Physics Impact. 2024; 9: 100758. doi: 10.1016/j.chphi.2024.100758
31. Prabhu S, Poulose EK. Silver nanoparticles: mechanism of antimicrobial action, synthesis, medical applications, and toxicity effects. International Nano Letters. 2012; 2(1). doi: 10.1186/2228-5326-2-32
32. Urnukhsaikhan E, Bold BE, Gunbileg A, et al. Antibacterial activity and characteristics of silver nanoparticles biosynthesized from Carduus crispus. Scientific Reports. 2021; 11(1). doi: 10.1038/s41598-021-00520-2
33. Habibullah G, Viktorova J, Ulbrich P, et al. Effect of the physicochemical changes in the antimicrobial durability of green synthesized silver nanoparticles during their long-term storage. RSC Advances. 2022; 12(47): 30386-30403. doi: 10.1039/d2ra04667a
34. Xue W, Zhang M, Zhao F, et al. Long-term durability antibacterial microcapsules with plant-derived Chinese nutgall and their applications in wound dressing. e-Polymers. 2019; 19(1): 268-276. doi: 10.1515/epoly-2019-0027
35. Gerges B, Rosenblatt J, Jiang Y, et al. Comparative Effectiveness and Persistence of Antimicrobial Durability in Dry and Wet States of a Novel Antimicrobial Surface Disinfectant. Applied Microbiology. 2023; 3(2): 549-561. doi: 10.3390/applmicrobiol3020039
36. Liu Y, Gao Z, Chen T, et al. Versatile Fabrication of Biocompatible Antimicrobial Materials Enabled by Cationic Peptide

Bundles. ACS Applied Materials & Interfaces. 2024; 16(33): 43918-43932. doi: 10.1021/acsami.4c06381

37. Zhu C, Diao Z, Yang Y, et al. Recent advances and challenges in metal-based antimicrobial materials: a review of strategies to combat antibiotic resistance. Journal of Nanobiotechnology. 2025; 23(1). doi: 10.1186/s12951-025-03249-6
38. Rosa V, Silikas N, Yu B, et al. Guidance on the assessment of biocompatibility of biomaterials: Fundamentals and testing considerations. Dental Materials. 2024; 40(11): 1773-1785. doi: 10.1016/j.dental.2024.07.020
39. McNulty MJ, Gleba Y, Tusé D, et al. Techno-economic analysis of a plant-based platform for manufacturing antimicrobial proteins for food safety. Biotechnology Progress. 2019; 36(1). doi: 10.1002/btpr.2896
40. Putnik G, Sluga A, ElMaraghy H, et al. Scalability in manufacturing systems design and operation: State-of-the-art and future developments roadmap. CIRP Annals. 2013; 62(2): 751-774. doi: 10.1016/j.cirp.2013.05.002
41. Kong Q, Yang Y. Recent advances in antibacterial agents. Bioorganic & Medicinal Chemistry Letters. 2021; 35: 127799. doi: 10.1016/j.bmcl.2021.127799
42. Kwaśniewska D, Chen YL, Wieczorek D. Biological Activity of Quaternary Ammonium Salts and Their Derivatives. Pathogens. 2020; 9(6): 459. doi: 10.3390/pathogens9060459
43. Wang S, Qiu B, Shi J, et al. Quaternary ammonium antimicrobial agents and their application in antifouling coatings: a review. Journal of Coatings Technology and Research. 2023; 21(1): 87-103. doi: 10.1007/s11998-023-00825-z
44. Nadagouda MN, Vijayasarathy P, Sin A, et al. Antimicrobial activity of quaternary ammonium salts: structure-activity relationship. Medicinal Chemistry Research. 2022; 31(10): 1663-1678. doi: 10.1007/s00044-022-02924-9
45. Jones IA, Joshi LT. Biocide Use in the Antimicrobial Era: A Review. Molecules. 2021; 26(8): 2276. doi: 10.3390/molecules26082276
46. Chen F, Moat J, McFeely D, et al. Biguanide Iridium(III) Complexes with Potent Antimicrobial Activity. Journal of Medicinal Chemistry. 2018; 61(16): 7330-7344. doi: 10.1021/acs.jmedchem.8b00906
47. Kathuria D, Raul AD, Wanjari P, et al. Biguanides: Species with versatile therapeutic applications. European Journal of Medicinal Chemistry. 2021; 219: 113378. doi: 10.1016/j.ejmech.2021.113378
48. Samara E, Moriarty TF, Decosterd LA, et al. Antibiotic stability over six weeks in aqueous solution at body temperature with and without heat treatment that mimics the curing of bone cement. Bone & Joint Research. 2017; 6(5): 296-306. doi: 10.1302/2046-3758.65.bjr-2017-0276.r1
49. Traub WH, Leonhard B. Heat stability of the antimicrobial activity of sixty-two antibacterial agents. Journal of Antimicrobial Chemotherapy. 1995; 35(1): 149-154. doi: 10.1093/jac/35.1.149
50. Ho CS, Wong CTH, Aung TT, et al. Antimicrobial resistance: a concise update. The Lancet Microbe. 2025; 6(1): 100947. doi: 10.1016/j.lanmic.2024.07.010
51. Ahmad M, Aduru SV, Smith RP, et al. The role of bacterial metabolism in antimicrobial resistance. Nature Reviews Microbiology; 2025. doi: 10.1038/s41579-025-01155-0
52. Wanda CR. An overview of the antimicrobial resistance mechanisms of bacteria. AIMS Microbiology. 2018; 4(3): 482-501. doi: 10.3934/microbiol.2018.3.482
53. Wang C, Makvandi P, Zare EN, et al. Advances in Antimicrobial Organic and Inorganic Nanocompounds in Biomedicine. Advanced Therapeutics. 2020; 3(8). doi: 10.1002/adtp.202000024
54. Vukomanovicć M, Kurtjak M, Aničić N. Inorganic Nanoparticles: Innovative Tools for Antimicrobial Agents. Antibacterial Agents; 2017. doi: 10.5772/67904
55. Chernousova S, Epple M. Silver as Antibacterial Agent: Ion, Nanoparticle, and Metal. Angewandte Chemie International Edition. 2012; 52(6): 1636-1653. doi: 10.1002/anie.201205923
56. Bonilla-Gameros L, Chevallier P, Sarkissian A, et al. Silver-based antibacterial strategies for healthcare-associated infections: Processes, challenges, and regulations. An integrated review. Nanomedicine: Nanotechnology, Biology and Medicine. 2020; 24: 102142. doi: 10.1016/j.nano.2019.102142
57. Hamad A, Khashan KS, Hadi A. Silver Nanoparticles and Silver Ions as Potential Antibacterial Agents. Journal of Inorganic and Organometallic Polymers and Materials. 2020; 30(12): 4811-4828. doi: 10.1007/s10904-020-01744-x
58. Hosseini F, Assadi AA, Nguyen-Tri P, et al. Titanium-based photocatalytic coatings for bacterial disinfection: The shift from suspended powders to catalytic interfaces. Surfaces and Interfaces. 2022; 32: 102078. doi: 10.1016/j.surfin.2022.102078
59. Nagaraj K, Radha S, Deepa CG, et al. Photocatalytic advancements and applications of titanium dioxide (TiO_2): Progress in biomedical, environmental, and energy sustainability. Next Research. 2025; 2(1): 100180. doi: 10.1016/j.nexres.2025.100180
60. Haque F, Blanchard A, Laipply B, et al. Visible-Light-Activated TiO2-Based Photocatalysts for the Inactivation of

Pathogenic Bacteria. Catalysts. 2024; 14(12): 855. doi: 10.3390/catal14120855

61. Li S, Jiang S, Jia W, et al. Natural antimicrobials from plants: Recent advances and future prospects. Food Chemistry. 2024; 432: 137231. doi: 10.1016/j.foodchem.2023.137231
62. Stan D, Enciu AM, Mateescu AL, et al. Natural Compounds With Antimicrobial and Antiviral Effect and Nanocarriers Used for Their Transportation. Frontiers in Pharmacology. 2021; 12. doi: 10.3389/fphar.2021.723233
63. Mantil E, Daly G, Avis TJ. Effect of tea tree (Melaleuca alternifolia) oil as a natural antimicrobial agent in lipophilic formulations. Canadian Journal of Microbiology. 2015; 61(1): 82-88. doi: 10.1139/cjm-2014-0667
64. Yilmaz Atay H. Antibacterial Activity of Chitosan-Based Systems. In: Functional Chitosan: Drug Delivery and Biomedical Applications. Springer Singapore: Singapore; 2019.
65. Ke CL, Deng FS, Chuang CY, et al. Antimicrobial Actions and Applications of Chitosan. Polymers. 2021; 13(6): 904. doi: 10.3390/polym13060904
66. Manso T, Lores M, de Miguel T. Antimicrobial Activity of Polyphenols and Natural Polyphenolic Extracts on Clinical Isolates. Antibiotics. 2021; 11(1): 46. doi: 10.3390/antibiotics11010046
67. Bansal S, Choudhary S, Sharma M, et al. Tea: A native source of antimicrobial agents. Food Research International. 2013; 53(2): 568-584. doi: 10.1016/j.foodres.2013.01.032
68. Zhang Q, Zhang J, Zhang J, et al. Antimicrobial Effect of Tea Polyphenols against Foodborne Pathogens: A Review. Journal of Food Protection. 2021; 84(10): 1801-1808. doi: 10.4315/jfp-21-043
69. Álvarez-Martínez FJ, Barrajón-Catalán E, Herranz-López M, et al. Antibacterial plant compounds, extracts and essential oils: An updated review on their effects and putative mechanisms of action. Phytomedicine. 2021; 90: 153626. doi: 10.1016/j.phymed.2021.153626
70. Seow YX, Yeo CR, Chung HL, et al. Plant Essential Oils as Active Antimicrobial Agents. Critical Reviews in Food Science and Nutrition. 2013; 54(5): 625-644. doi: 10.1080/10408398.2011.599504
71. Carson CF, Hammer KA, Riley TV. Melaleuca alternifolia(Tea Tree) Oil: a Review of Antimicrobial and Other Medicinal Properties. Clinical Microbiology Reviews. 2006; 19(1): 50-62. doi: 10.1128/cmr.19.1.50-62.2006
72. Cox SD, Mann CM, Markham JL, et al. Determining the Antimicrobial Actions of Tea Tree Oil. Molecules. 2001; 6(2): 87-91. doi: 10.3390/60100087
73. Lin R, Li G, He Q, et al. Synthesis of Mesoporous Catechin Nanoparticles as Biocompatible Drug-Free Antibacterial Mesoformulation. Journal of the American Chemical Society. 2024; 146(39): 26983-26993. doi: 10.1021/jacs.4c08336
74. Mahady GB, Huang Y, Doyle BJ, et al. Natural Products as Antibacterial Agents. In: Studies in Natural Products Chemistry. Elsevier. 2008; 35: 423-444. doi: 10.1016/S1572-5995(08)80011-7
75. Pancu DF, Scurtu A, Macasoi IG, et al. Antibiotics: Conventional Therapy and Natural Compounds with Antibacterial Activity—A Pharmaco-Toxicological Screening. Antibiotics. 2021; 10(4): 401. doi: 10.3390/antibiotics10040401
76. Zouine N, Ghachtouli NE, Abed SE, et al. A comprehensive review on medicinal plant extracts as antibacterial agents: Factors, mechanism insights and future prospects. Scientific African. 2024; 26: e02395. doi: 10.1016/j.sciaf.2024.e02395
77. Pormohammad A, Hansen D, Turner RJ. Antibacterial, Antibiofilm, and Antioxidant Activity of 15 Different Plant-Based Natural Compounds in Comparison with Ciprofloxacin and Gentamicin. Antibiotics. 2022; 11(8): 1099. doi: 10.3390/antibiotics11081099
78. Franco CM, Vázquez BI. Natural Compounds as Antimicrobial Agents. Antibiotics. 2020; 9(5): 217. doi: 10.3390/antibiotics9050217
79. Ippili S, Jung JS, Thomas AM, et al. An Overview of Polymer Composite Films for Antibacterial Display Coatings and Sensor Applications. Polymers. 2023; 15(18): 3791. doi: 10.3390/polym15183791
80. Jamiri F, Nayeri Fasaei B, Joghataei SM, et al. Synergistic antibacterial activity of chitosan-polyethylene glycol nanocomposites films containing ZIF-8 and doxycycline. BMC Biotechnology. 2025; 25(1). doi: 10.1186/s12896-025-00953-x
81. Prasitnok O, Paupun T, Wiseskuembong P, et al. Synthesis, characterization and antibacterial activity of silver-loaded ZIF-8 and ZIF-67: One-pot and chemical deposition methods. Materials Chemistry and Physics. 2025; 333: 130363. doi: 10.1016/j.matchemphys.2025.130363
82. Hu C, Yang Y, Lin Y, et al. GO-based antibacterial composites: Application and design strategies. Advanced Drug Delivery Reviews. 2021; 178: 113967. doi: 10.1016/j.addr.2021.113967
83. Kench T, Sultana Chowdhury N, Rahman KM, et al. Discovery of Phototoxic Metal Complexes with Antibacterial Properties

via a Combinatorial Approach. Inorganic Chemistry. 2025; 64(10): 5113-5121. doi: 10.1021/acs.inorgchem.4c05414

84. Si Z, Zheng W, Prananty D, et al. Polymers as advanced antibacterial and antibiofilm agents for direct and combination therapies. Chemical Science. 2022; 13(2): 345-364. doi: 10.1039/d1sc05835e
85. Han D, Liu X, Wu S. Metal organic framework-based antibacterial agents and their underlying mechanisms. Chemical Society Reviews. 2022; 51(16): 7138-7169. doi: 10.1039/d2cs00460g
86. More A, Maurya P, Ubhale Y. Nylon fiber: composites and applications. Synthetic and Mineral Fibers, Their Composites and Applications; 2024. doi: 10.1016/b978-0-443-13623-8.00004-6
87. Oxenham W. Integrated composite spinning (ICS). Advances in Filament Yarn Spinning of Textiles and Polymers; 2014. doi: 10.1533/9780857099174.2.149
88. Mahmoudi MR. Blending and composite yarn spinning. Advances in Yarn Spinning Technology; 2010. doi: 10.1533/9780857090218.1.102
89. Chen S, Wu X, Ding X. One-step side-by-side electrospraying of Janus particles for durable multifunctional coatings on cotton textiles. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2025; 710: 136227. doi: 10.1016/j.colsurfa.2025.136227
90. Deng W, Liu Y, He C, et al. Synergistic improvements of properties of cellulose acetate based curcumin@TiO2 nanofibers via triaxial electrospinning. Chemical Engineering Journal. 2025; 506: 160117. doi: 10.1016/j.cej.2025.160117
91. Ghosh J, Rupanty NS, Khan F, et al. Grafting modification for textile functionalization: innovations and applications. Discover Applied Sciences. 2025; 7(1). doi: 10.1007/s42452-024-06364-5
92. Shalaby SE, AL-Balakocy NG, Abdel-Fatah OM, et al. Antimicrobial finishing of regular and modified nylon-6 fabrics. Journal of Applied Polymer Science. 2008; 110(2): 738-746. doi: 10.1002/app.28628
93. Pappas D, Bujanda A, Demaree JD, et al. Surface modification of polyamide fibers and films using atmospheric plasmas. Surface and Coatings Technology. 2006; 201(7): 4384-4388. doi: 10.1016/j.surfcoat.2006.08.068
94. Wang H, Feng J, Lu J, et al. Surface modification of polyamide fabric based on a multi-enzyme system. Fibers and Polymers. 2024; 25(7): 2585-2596. doi: 10.1007/s12221-024-00591-8
95. Abdelmoula S, Mzid K, Achari AE, et al. Modification of Nylon and Polyesters via Graft Copolymerization. Journal of Macromolecular Science, Part C: Polymer Reviews. 1997; 37(4): 649-686. doi: 10.1080/15321799708009652
96. Dong C, Qian LY, Zhao GL, et al. Preparation of antimicrobial cellulose fibers by grafting β-cyclodextrin and inclusion with antibiotics. Materials Letters. 2014; 124: 181-183. doi: 10.1016/j.matlet.2014.03.091
97. Verma A, Kumar S, Tiwari A, et al. Surface Modification of Kosa Silk Fiber by Graft Copolymerization with Vinyl Benzyl Trimethylammonium Chloride (VBT) and Its Antibacterial Study. Russian Journal of Applied Chemistry. 2024; 97(5): 515-525. doi: 10.1134/s1070427224030054
98. Zhou B, Wang X, Wang Z, et al. Enhancement of antimicrobial and UV resistant properties of aramid III fiber through surface coating. Progress in Organic Coatings. 2024; 189: 108317. doi: 10.1016/j.porgcoat.2024.108317
99. Zhou CE, Liu C, Kan C wai, et al. Antimicrobial Finishing of Cotton Fabric with N-MA Based on Plasma-Induced Grafting. Fibers and Polymers. 2024; 25(10): 3741-3749. doi: 10.1007/s12221-024-00676-4
100. Ranjbar Mohammadi M, Naghashzargar E, Kamali Moghaddam M, et al. Production of PLA fibers with surface modifications and silver nanoparticle coating to impart antibacterial activity. Polymer Bulletin. 2023; 81(7): 6055-6072. doi: 10.1007/s00289-023-04989-x
101. Jin H, Xu W. The Preparation and Properties of Fluoroacrylate-Modified Polysiloxane as a Fabric Coating Agent. Coatings. 2018; 8(1): 31. doi: 10.3390/coatings8010031
102. Raza ZA, Habib S, Khan A, et al. Nanosilver finishing of cellulosic fabric with antibacterial performance: A thematic review. Cellulose. 2025; 32(3): 1423-1446. doi: 10.1007/s10570-025-06370-9
103. Dewri SP, Gnanamoorthy R. Surface Modification of Coconut Fibers: Latex Coating. In: Processing and Fabrication of Advanced Materials. Springer Nature Singapore: Singapore; 2024.
104. Sun D, Stylios GK. Cotton fabric mechanical properties affected by post-finishing processes. Fibers and Polymers. 2012; 13(8): 1050-1057. doi: 10.1007/s12221-012-1050-7
105. Granados A, Pleixats R, Vallribera A. Recent Advances on Antimicrobial and Anti-Inflammatory Cotton Fabrics Containing Nanostructures. Molecules. 2021; 26(10): 3008. doi: 10.3390/molecules26103008
106. Li L, Kong F, Xiao A, et al. Preparation of nascent disentangled ultra-high molecular weight polyethylene based on Ziegler-Natta catalyst. Materials Technology Reports. 2025; 3(1): 2305. doi: 10.59400/mtr2305

107. Pagnotta G, Graziani G, Baldini N, et al. Nanodecoration of electrospun polymeric fibers with nanostructured silver coatings by ionized jet deposition for antibacterial tissues. Materials Science and Engineering: C. 2020; 113: 110998. doi: 10.1016/j.msec.2020.110998
108. Hasan KMF, Wang H, Mahmud S, et al. Colorful and antibacterial nylon fabric via in-situ biosynthesis of chitosan mediated nanosilver. Journal of Materials Research and Technology. 2020; 9(6): 16135-16145. doi: 10.1016/j.jmrt.2020.11.056
109. Montazer M, Malekzadeh SB. Electrospun antibacterial nylon nanofibers through in situ synthesis of nanosilver: preparation and characteristics. Journal of Polymer Research. 2012; 19(10). doi: 10.1007/s10965-012-9980-8
110. Mehmood S, Akhtar N, Arshad M, et al. A novel methodology for stabilization of silver nanoparticles on cotton, nylon and cotton/nylon fabrics using chitosan and triethyl orthoformate for enhanced and elongated antibacterial performance. International Journal of Biological Macromolecules. 2024; 267: 129256. doi: 10.1016/j.ijbiomac.2024.129256
111. Syafiuddin A, Fulazzaky MA, Salmiati S, et al. Sticky silver nanoparticles and surface coatings of different textile fabrics stabilised by Muntingia calabura leaf extract. SN Applied Sciences. 2020; 2(4). doi: 10.1007/s42452-020-2534-5
112. Komeily-Nia Z, Montazer M, Aye S seint seint, et al. A practical approach to load CuO/MnO_2 core/shell nanostructures on textiles through in situ wet chemical synthesis. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2019; 583: 123998. doi: 10.1016/j.colsurfa.2019.123998
113. Wang R, Zhou J, Xiang H, et al. In Situ Growth of Highly Compatible Cu2O-GO Hybrids Via Amino-Modification for Melt-Spun Efficient Antibacterial Polyamide 6 Fibers. Macromolecular Rapid Communications; 2024. doi: 10.1002/marc.202400302
114. Zhang M, Gao Q, Yang C, et al. Preparation of antimicrobial MnO4−-doped nylon-66 fibers with excellent laundering durability. Applied Surface Science. 2017; 422: 1067-1074. doi: 10.1016/j.apsusc.2017.06.070
115. Zhao Y, Hu J, Hu X, et al. A novel strategy for fabrication of antistatic and antibacterial fabric via layer-by-layer self-assembly. Surface and Coatings Technology. 2023; 453: 129143. doi: 10.1016/j.surfcoat.2022.129143
116. Lei C, Fang Y, Liu X. Durable Multifunctional Modification of Nylon Fabric with Excellent Flame Retardancy, Antibacterial and UV-Resistant Properties. Fibers and Polymers. 2023; 25(2): 515-523. doi: 10.1007/s12221-023-00442-y
117. Akia M, Rodriguez C, Materon L, et al. Antibacterial activity of polymeric nanofiber membranes impregnated with Texas sour orange juice. European Polymer Journal. 2019; 115: 1-5. doi: 10.1016/j.eurpolymj.2019.03.019
118. Günsel A, Usluoğlu A, Bilgiçli AT, et al. The use of water-soluble phthalocyanines as textile dyes in nylon/elastane fabric: fastness and antibacterial effectiveness. Turkish journal of chemistry. 2020; 44(4): 923-931. doi: 10.3906/kim-1912-11
119. Shaki H. Color, Fastness, Antibacterial, and Skin Sensitivity Properties of High Lightfastness Azo Disperse Dyes Incorporating Sulfamide Groups. Fibers and Polymers. 2020; 21(11): 2530-2538. doi: 10.1007/s12221-020-1148-2
120. Han H, Hu L, Wang F, et al. Daylight-driven antimicrobial fabrics: Design strategy for enhancing efficiency based on electrostatic repulsion-FRET synergistic effects of dual photosensitizers. Chemical Engineering Journal. 2024; 501: 157753. doi: 10.1016/j.cej.2024.157753
121. Shariatinia Z, Shekarriz S, Mirhosseini Mousavi HS, et al. Disperse dyeing and antibacterial properties of nylon and wool fibers using two novel nanosized copper(II) complexes bearing phosphoramide ligands. Arabian Journal of Chemistry. 2017; 10(7): 944-955. doi: 10.1016/j.arabjc.2015.03.005