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Review

Advancements in Antimicrobial Textiles: Fabrication, Mechanisms of Action, and Applications

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ABSTRACT: Within the past decade, much attention has been drawn to antimicrobial textiles due to their vast potential for reducing the spread of infectious diseases and improving hygiene standards in various environments. This review paper discusses recent studies on preparation methods, modes of action, effectiveness against different microorganisms, and applications of antimicrobial textiles in diverse industries. It examines further challenges, including durability, environmental impact, and regulatory considerations, and looks at prospects for developing and integrating these novel materials. This paper intends to provide a broad-based understanding of state-of-the-art technologies and emerging trends in antimicrobial textiles by integrating existing knowledge and highlighting recent advances in this field that contribute much to improved public health and safety.

1. INTRODUCTION

Antimicrobial textiles now represent one of the essential technologies that can meet the demand for infection prevention and hygienic management from various sectors such as healthcare, basic apparel, air treatment, and food packaging/covering, among others.[1−3] Therefore, incorporating antimicrobial agents into textiles opens a promising avenue for defense against microbial menace, reduces the rate of infection spread, and generally improves public health.[4] With the increase in demand for antimicrobial textiles due to growing awareness of hygiene standards and persistent challenges related to resistance to antimicrobial agents, there is an emerging need to explore and consolidate the state-of-the-art advances and insights within this rapidly expanding field.[4,5]

The present review distinguishes itself from previous literature, such as the work by Naebe et al.:[6] work majorly covered plasma-assisted antimicrobial textiles; or the article by Chatha et al.:[7] study mainly covered antibug textiles; or Pllangutt et al.:[8] where the focus was mainly on face masks by providing a comprehensive and updated synthesis of the diverse strategies, mechanisms, and applications of antimicrobial textiles. While previous reviews have narrowly focused either on a single antimicrobial agent or textile application, this review broadly encompasses different technologies of antimicrobials and their integration into the textile substrates. Recent research and technological advances are critically integrated to develop a unique view of incorporating various antimicrobial agents into textile materials and their successful functionalities in specific applications. The paper not only assesses the current state of the art but also anticipates future trends, such as incorporating innovative technologies and developing eco-friendly antimicrobial solutions, setting a new agenda for research and industry alike.

Conventionally, antimicrobial textiles have been exclusively related to healthcare settings where the prevention of infection is so important.[9,10] With new developments, such material applications have been extended to general consumer products, such as garments, bedding, and upholstery, and even specialized industries like food packaging and filtration systems.[9] This shows how versatile antimicrobial textiles are and how vast their potential is, from personal hygiene to industrial processes and environmental safety.

Antimicrobial agents, most of the time derived from nature or synthesized, include all modes of action against microbial cells.[9,11,12] Antimicrobials, at the heart of all the efficacy in antimicrobial textiles, act either by disrupting the cell membrane or interfering with a metabolic pathway or a cellular communication system.[9] Regarding the optimization of performances in practical applications- antimicrobial performances, safety, and durability- one needs to know better the interactions of these agents with textile substrates. Table 1 presents different species of microorganisms on textiles, usually classified according to type bacteria by Gram staining

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Table 1. Diverse Microorganisms Typically Found on Textiles, with Their Species Categorized by Gram Staining (Positive or Negative), Type (Bacteria, Virus, Fungus), the Diseases They Cause, and the Eliminations Approaches Used

Microorganism	Species	Disease caused	Elimination approach (antimicrobial agent(s) or drug)	Ref.
		Fungus		
Candida albicans	Fungus	Fungal infections, thrush	Tea tree oil, quaternary ammonium compounds (QACs)	13
Penicillium citrinum	Fungus	Rotting	Clotrimazole, miconazole, terbinafine, ketoconazole, terbinafine, itraconazole, and fluconazole	9, 13
Trichophyton interdigitale	Fungus	Athlete's foot	Clotrimazole, miconazole, terbinafine, etoconazole, terbinafine, itraconazole, and fluconazole	9, 13
Chaetomium globosum	Fungus	Rotting	Amphotericin B, nystatin, fluconazole, itraconazole, ketoconazole, terbinafine, and naftifine	9, 13
Aspergillus niger	Fungus	Allergic reactions, respiratory issues	Graphene oxide, high-temperature treatment	13
		Gram-(−ve)		
Escherichia coli (*E. coli*)	Gram-(−ve))	Gastrointestinal infections	Chlorine-based compounds, steam treatment	8−10
Klebsiella pneumoniae (*K. pneumoniae*)	Gram-(−ve))	Pneumonia, urinary tract infections	Antimicrobial peptides, photocatalytic coating	8−10
Pseudomonas aeruginosa	Gram-(−ve))	Respiratory infections, sepsis	Copper (Cu) nanoparticles (NPs), ozone treatment	9, 10
Proteus mirabilis	Gram-(−ve))	Urinary infection	Tea tree oil, TiO_2 NPs	14, 15
Epidermophyton floccosum	Gram-(−ve))	Infection of skin	Acetaminophen-diazobenzothiazole derivatives	16
		Gram-(+ve)		
Methicillin-resistant *Staphylococcus aureus* (MRSA)	Gram-(+ve)	Skin and soft tissue infections	Ionic silver, plasma treatment	9, 10, 13
Clostridium difficile	Gram-(+ve)	Diarrhea, colitis	Peracetic acid, biocidal finishing agents	9, 10, 13
Staphylococcus aureus (*S. aureus*)	Gram-(+ve)	Skin infections, food poisoning	Silver NPs (nAg), UV-C light	8−10
Corynebacterium diphtheroides	Gram-(+ve)	Body odor	Erythromycin, azithromycin, or clarithromycin	9
Brevibacterium ammoniagenes	Gram-(+ve)	Diaper rash	Quinolones, tetracyclines, macrolides, cephalosporins, and penicillin	9
		Virus		
Norovirus	Virus	Gastroenteritis	Hydrogen peroxide, photocatalytic oxidation	17, 18
Influenza A virus	Virus	Influenza, respiratory infections	Titanium dioxide (TiO_2) NPs, UV-A light	18
COVID-19 virus	Virus	Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2)	Hydrogen peroxide, photocatalytic oxidation	17
Dengue virus	Virus (Four distinct serotypes, known as DENV-1, DENV-2, DENV-3, and DENV-4)	Dengue hemorrhagic fever (DHF) and dengue shock syndrome (DSS)	Balapiravir, Celgosivir, Chloroquine, Favipiravir, Ribavirin, rDENΔ30 vaccines	19, 20

(positive/negative), caused diseases, and the methods used to eliminate them. The table serves as a brief overview of exclusive microorganisms and the practices that could be implemented to eliminate contamination from the textile surface.

In addition, the ecological footprint of antimicrobial textiles has gained increasingly greater relevance. Such extensive use of antimicrobial agents raises a lot of concerns about their presence, effect on the microbial community, and contribution to the ecological system.[8−10,13] It denotes that solving all these challenges is possible only within the framework of an integrated approach that would be directed not just at enhancing antimicrobial efficacy in textile materials but also at enhancing research in the field of the environmental impacts connected with the processes of textile production and disposal.[8−10,13] Based on these considerations, this review outlines technological advancements in antimicrobial textiles, including nanotechnology, bioactive treatments, and functionalized fiber materials. These advancements aim to enhance coating efficiency and expand applications in various industries. Smart textiles with data transmission, physical sensation, and self-cleaning have high potential for next-generation textiles. Besides, it highlights market adoption, commercialization barriers, and trends to increase antimicrobial textile use across various industries.

This work aims to provide an all-inclusive resource for policymakers, practitioners, and researchers interested in advancing the field of antimicrobial textiles. By fusing current knowledge as well as identifying areas for future exploration, this review seeks to catalyze further innovation and collaboration in the pursuit of safer, more resilient, and more sustainable antimicrobial textiles.

1.1. The Need for Antimicrobial Textiles. The global rise of antimicrobial resistance (AMR) has been increasing globally, and it is one of the biggest threats to public health today.[19] The prevention of infection from microbes and multidrug-resistant organisms is a challenge for hospitals and healthcare facilities in general.[10,21,22] The emergence of antimicrobial textiles is, therefore, of critical need in healthcare, consumer goods, and industrial applications.[11,23] These materials inhibit the growth of microorganisms or reduce their spread by satisfying various pressing needs, including preventing hospital-acquired infections, enhancing hygiene in everyday life, reducing odors and bacteria buildup in clothing, ensuring public safety in high-touch environments, and prolonging the life of textile materials by preventing microbial degradation.

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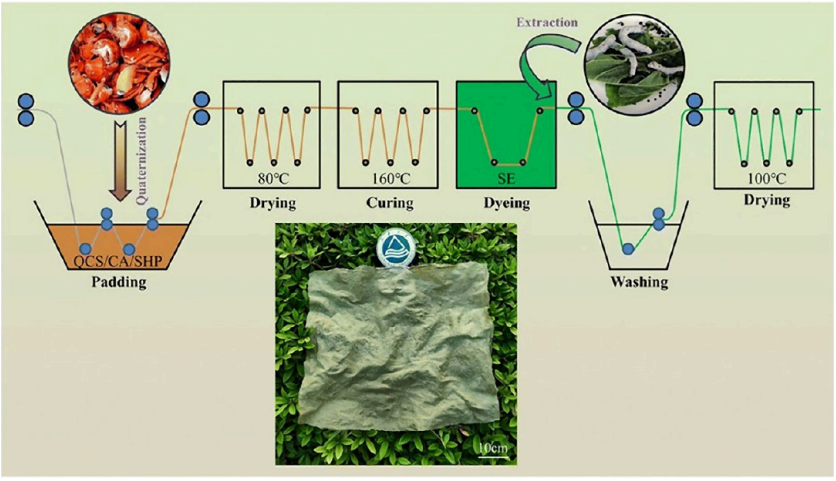

Figure 1. Preparation of fully bio-based photodynamic eco-textiles. Reproduced with permission from Lv et al.[26] Copyright 2024, Royal Society of Chemistry.

Antimicrobial textiles offer an additional layer of defense on surfaces such as bedding, curtains, uniforms, and patient gowns, reducing the transmission of pathogens and enhancing patient safety.[10,21,22] In everyday life, antimicrobial textiles are crucial in maintaining hygiene standards. Products like antimicrobial clothing, towels, and home textiles help reduce the presence of harmful microbes, limiting the risk of infections and promoting overall cleanliness in homes and public spaces.[10,21,22]

Industries such as food processing, agriculture, healthcare, and veterinary medicine benefit from antimicrobial textiles to maintain sanitary conditions and prevent contamination.[8,10,21,22,24−27] For example, antimicrobial coatings on packaging materials can extend shelf life by inhibiting microbial growth, ensuring food safety, and reducing waste.[28−30] Antimicrobial textiles, by incorporating agents that target specific pathogens, offer a proactive approach to minimize the use of traditional antimicrobial agents in direct contact with humans or animals, thereby reducing selective pressure for resistance development.[8,10,22]

Innovations in antimicrobial textiles also strive to meet public health and safety considerations and address environmental, sustainability, and life-cycle concerns associated with traditional antimicrobial treatments. Efforts are made to develop biodegradable antimicrobial agents or to improve the recyclability of textile materials, ensuring that the benefits of antimicrobial functionality do not compromise environmental sustainability. Increasing consumer awareness and demand for hygienic products have also driven the development of antimicrobial textiles across various markets[5,9−12,29,30] Manufacturers are making antimicrobial technologies more applicable by incorporating them in a wider range while avoiding any health hazards by meeting strict industry guidelines. When research and development in this field progresses even further, new possibilities arising from antimicrobial textiles are expected to appear, providing solutions to current and future global health threats.

2. METHODOLOGY

An efficient method was adopted to undertake a thorough analysis of the existing state and prospects for antimicrobial fabrics. The literature search included a variety of databases, including PubMed, Web of Science, and Scopus, and a mix of keywords such as “antimicrobial textiles”, “antimicrobial textile coatings”, “biocidal fabrics”, and “textile-based infection control”, among others. To ensure relevance and recency, the search focused more on English-language papers published in recent decades.

About ≥532 literature was found, though upon screening, only ≤208 of these articles were related to our work. Upon reading through them, further screening was applied to select the articles included in our work. Criteria for the article selection were established to consider only the peer-reviewed articles of journals, conferences, and patents dedicated to antimicrobial textiles’ development, application, and performance. The following papers were excluded: nonempirical research, review papers, and articles unrelated to the study topic.

Data extraction involved the classification of all the features extracted from each of the selected articles based on the type of antimicrobial agent, textile material, fabrication technique, efficacy testing method, challenges highlighted, and suggestions for future work and application area. Data extraction was done using a checklist to minimize bias and improve interstudy comparison. The systematic review of the literature was carried out with the following fold: the antimicrobial technology based on the classification of the agent used and the method of incorporation, the performance of the different technologies in the various applications, and probably the gaps in the current literature. This approach allowed for a convergence of results that underscore the advantages and disadvantages of currently available antimicrobial textiles and trends for future research.

3. FABRICATION METHODS FOR ANTIMICROBIAL TEXTILES

The progress of antimicrobial textiles involves various fabrication techniques aimed at integrating antimicrobial agents onto/into textile substrates. These methods ensure that the antimicrobial properties are effectively imparted to the fabrics, enhancing their ability to inhibit microbial growth and proliferation. The primary fabrication methods include surface modification, coating, incorporation during fiber production, and embedding NPs.

3.1. Coating. Coating involves applying a thin layer of antimicrobial agents on the textile surface. This can be

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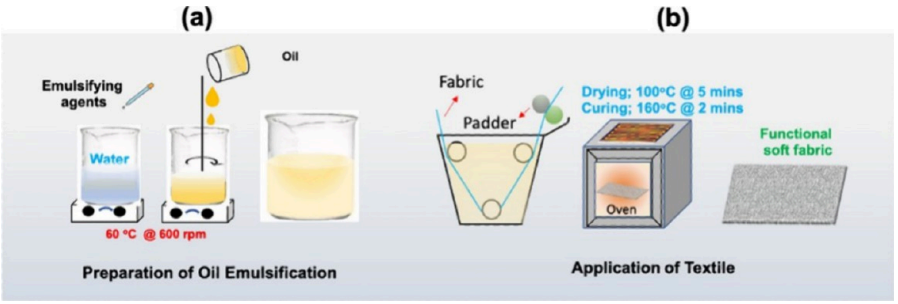

Figure 2. Schematic of (a) the emulsification process of oil and (b) application of a natural soft finish to textile. Reproduced with permission from Noor et al.[11] Copyright 2024, Springer Nature.

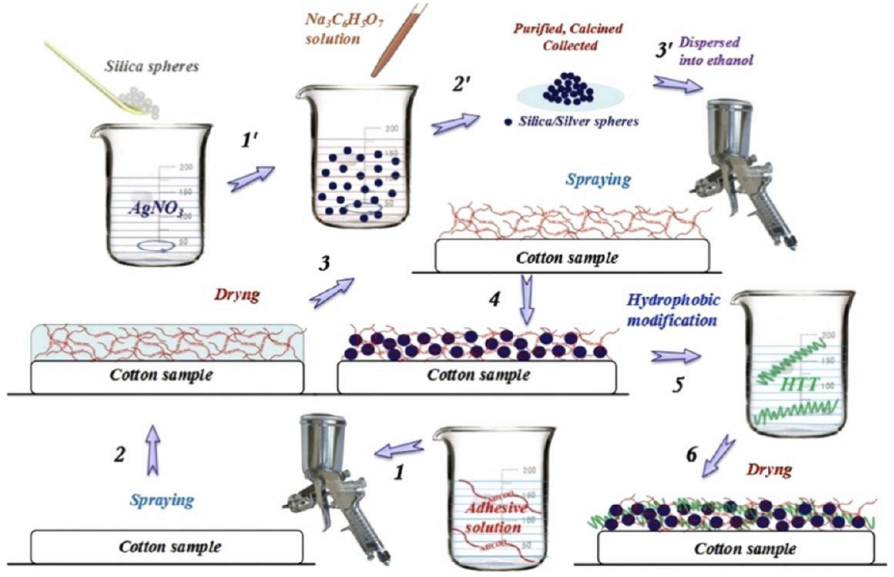

Figure 3. Specific strategy to prepare antibacterial superhydrophobic textiles. Reproduced with permission from Zhang et al.[31] Copyright 2017, Elsevier Science Ltd.

achieved through various techniques such as padding (pad-dry-cure), spraying, and dip-coating.

3.1.1. Padding (Pad-Dry-Cure). In the padding process, textiles are passed through a solution containing antimicrobial agents, followed by squeezing through rollers to ensure even distribution. The treated fabrics are then dried and cured to fix the antimicrobial coating.[11,26] The process begins with preparing a concentrated solution of the antimicrobial agent, which is then applied to the textile material using a padding machine. This machine passes the fabric through rollers immersed in the solution, ensuring uniform distribution and penetration of the antimicrobial substance into the fabric fibers. Following padding, the fabric undergoes drying to remove excess moisture and, if necessary, curing to activate or fix the antimicrobial properties. This technique is highly effective for embedding antimicrobial agents deeply into the textile structure, enhancing durability and efficacy against bacteria, fungi, and other microorganisms. The finished textiles are then tested for antimicrobial activity to confirm compliance with safety and performance standards.[11,26]

Quaternized chitosan (QCTS) has been reportedly applied to cotton fabric (CF) using the following padding method in a specific study.[26] To summarize, 50 mL of 1% acetic acid solution was mixed with 1 g chitosan for 4 h, and then 2.68 g glycidyl-trimethylammonium chloride (GTMAC) (molar ratio 3:1) was added. For 24 h, the mixture was agitated at 100 rpm and 80 °C. Following the reaction, the mixture was added to ethanol that had been allowed to cool, and the precipitate was separated using centrifugation and then redistributed into deionized water. After dialyzing the mixture for 3 days to eliminate any unreacted GTMAC, it was freeze-dried to produce Quaternized chitosan.[26] In a liquid ratio of 1:10, the nonwoven CF (NCF) was submerged in a solution containing 1% QCTS, 4% citric acid, and 4% Sodium hypophosphite, 90% dip ratio, 3 min of drying at 80 °C, and 100 s of curing at 160 °C. Following washing (80 °C, 30 min) and drying (100 °C, 30 min), the Quaternized chitosan-modified NCF (QCF) was produced. In addition, an infrared dyeing machine was used to load pigment made from silkworm excrement (SE, 1% o.w.f.) onto QCF, as shown in Figure 1. The liquor temperature was elevated to 80 °C from room temperature (RT) at a rate of 2 °C/min, dyed for 30 min at 80 °C, and then cooled at a rate of 3 °C/min to 30 °C. After 30 min of soaping (0.5% sodium dodecyl sulfate), 80 °C washing, and 100 °C drying, the QCF-silkworm excrement pigment (SE-QCF) was achieved. Notably, the dyeing exhaustion rate and the loaded amount of SE were determined by gathering the staining solution and measuring its absorbance before and later staining, using a standard curve.[26]

A different study used 130 mL water poured into a beaker, 10 g/L of tween-80, and 15 g/L of the emulsifier (lecithin).[11] The mixture was stirred constantly at 600 rpm for 40 min, and

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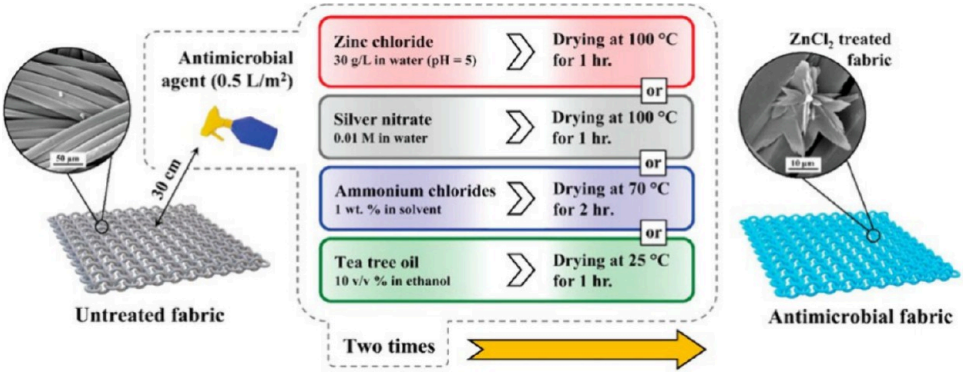

Figure 4. Schematic presentation of the general procedure for antimicrobial fabric preparation. Reproduced with permission from Vojnits et al.[3] Copyright 2024, MDPI.

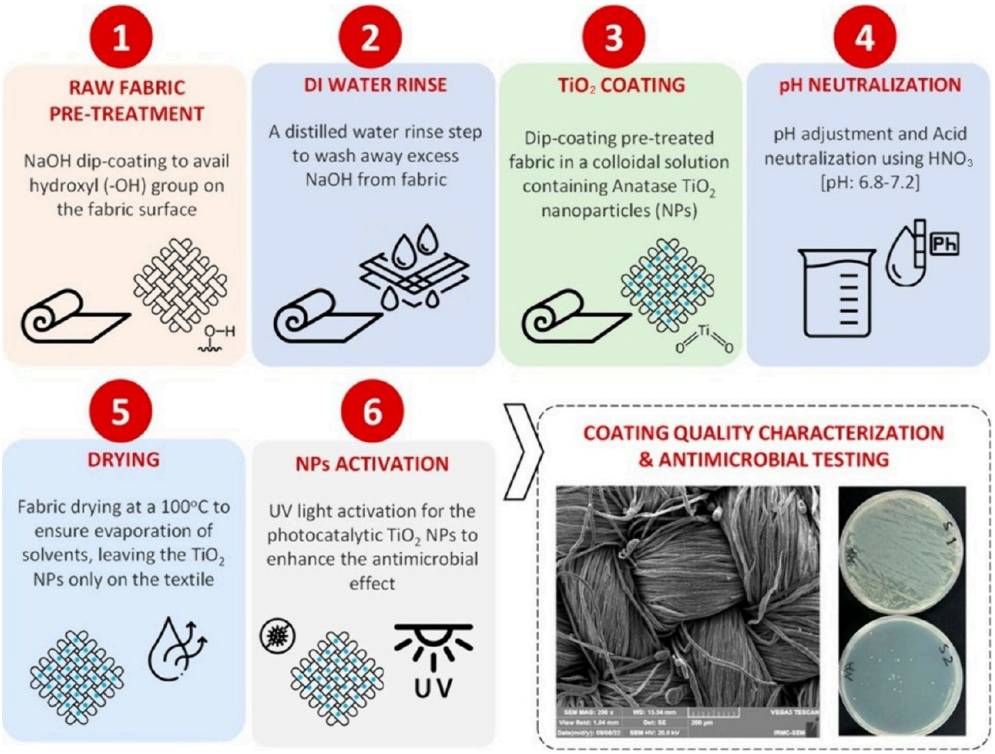

Figure 5. Preparation steps for TiO_2 NPs coated antibacterial cotton textile. (1) The surface of the CF is first modified with an inorganic base solution to obtain the hydroxyl (-OH) group on the fabric, which helps the TiO_2 NPs adhesion to the fabric through hydrogen bonding. (2) A distilled water rinse step to wash away excess NaOH from the fabric. (3) A colloidal solution containing Anatase TiO_2 NPs was prepared using glacial acetic acid and methanol as carrier solutions mixed in distilled water. The fabric is dip-coated in the solution and sonicated to reduce agglomerates and introduce the NPs to the pretreated fabric. (4) pH adjustment and Acid neutralization using HNO_3 [pH: 6.8−7.2]. (5) Fabric drying at 100 °C to ensure evaporation of solvents, leaving the TiO_2 NPs only on the textile. (6) UV activation of the photocatalytic TiO_2 NPs (to maximize antimicrobial effect). Reproduced with permission from Salama et al.[25] Copyright 2024, Sage Journals.

the temperature was maintained at 60 °C. The study aimed to create a stable oil/water emulsion for padding. Upon reaching the desired temperature, 50 mL of *Citrullus colocynthis* seed oil was gradually added to the water-emulsifying agent solution. If required, acetic acid was used to bring the solution's pH down to neutral. The use of the ready combination as the textile soft finish required padding the fabric with the solution at an 80% wet pick-up using a padding mangle. Before being applied, deionized water was used to dilute the padding solution until the ultimate combination had 10% of the oil component, by industry standards. Figure 2 presents the schematic illustration of the entire procedure.[11]

The padding system permits the active/functional liquor to penetrate the fabric structure, not just the surface. During the squeezing of the dipped fabric between the padding roller(s), the liquor/solution is further forced into the interfiber spacing within the fabric at a uniform rate, ensuring that the applied roller pressure is uniform across the treated fabric width.

3.1.2. Spray Coating (SPC). This technique allows for the application of antimicrobial agents in a controlled and uniform manner, even on complex textile structures or three-dimensional surfaces.[3] The antimicrobial solution, often containing active ingredients like nAg or organic compounds, is atomized into tiny droplets and sprayed onto the fabric using specialized equipment, as exemplified in Figure 3.[31]

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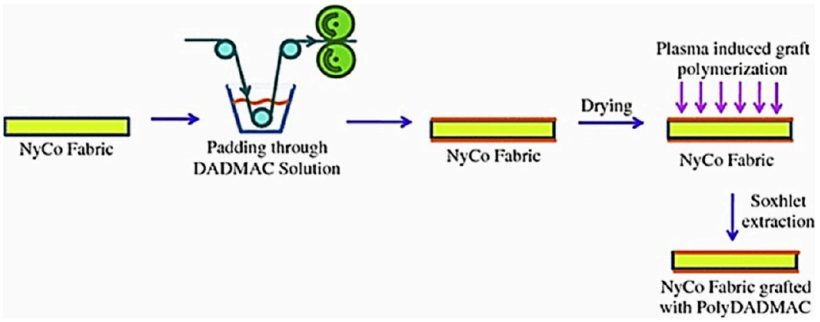

Figure 6. Process flow for plasma induced graft polymerization of DADMAC on NyCo fabric. Reproduced with permission from Malshe et al.[32] Copyright 2012, Springer.

After coating, the fabric is typically dried and, if necessary, cured to ensure the antimicrobial properties are fixed and durable. This technique is advantageous for its flexibility and the ability to treat textiles with varying compositions and structures, making it suitable for diverse antimicrobial textile applications comprising medical fabrics, protective clothing, and consumer products. For example, Vojnits et al.[3] spray-coated 4 cm diameter circular textile swatches. The swatches were rinsed twice at 50 °C to remove any remaining impurities after being bathed in a 1 wt % commercially available cleansing agent bath for 30 min. Using a scalable and controlled spraying technique, different classes of antimicrobial agents, such as metal-based, quaternary ammonium compounds (QACs), and plant-based alternatives, were administered to the washed cloth swatches. Zinc chloride ($ZnCl_2$) spray was made by dissolving $ZnCl_2$ in 30 g/L of water and adding acetic vinegar to get the pH down to 5. A 0.01 M silver nitrate ($AgNO_3$) solution was used for the coating made of Ag. The manufacturer's instructions were followed while diluting the QACs, trimethoxysilylpropyl octadecyldimethylammonium chloride (HM4072) and trihydroxysilylpropyldimethyl octadecyl ammonium chloride (HM4005) to 1 wt % in methanol in addition to water, respectively. Prior to the application, tea tree oil was diluted in 10% v/v ethanol. With a consistent spray application of 0.5 L/m^2, the antimicrobial liquors were then applied to the substrates using a power hand-sprayer. To guarantee that the textiles were completely covered, the coating and drying procedures were repeated two times with the sprayer nozzle held 30 cm away from the target, as shown in Figure 4.[3]

3.1.3. Dip-Coating. Dip-coating is a straightforward and effective technique used in the processing of antimicrobial textiles.[25,32−40] The technique encompasses immersing the textile material into a solution containing an antimicrobial agent, allowing it to absorb the solution uniformly, as earlier shown in Figure 5.[32] The process begins with preparing a concentrated antimicrobial solution, which may include nAg, organic compounds, or other antimicrobial substances. The textile is then submerged in this solution, ensuring complete coverage and penetration of the antimicrobial agent into the fabric fibers. After a specified period, the fabric is removed from the solution, and excess liquid is removed. The textile is then subjected to a drying process to evaporate the remaining solvent and fix the antimicrobial agent onto or within the fabric.[25,32−40]

In the work by Salama et al.,[25] dip-coating has been demonstrated for the adequate preparation of TiO_2-coated antimicrobial fabrics, as per Figure 5. In their work, TiO_2 NPs were able to adhere directly to the substrate (CF) without the need for applying binding agent(s). Higher concentrations of these stabilizing and fixative substances can be added to an organic matrix to increase the adsorption rate of TiO_2 on the fabric surface since TiO_2 NPs have a strong affinity for organic acids, hydroxyl (-OH) functionalities, and alcohols. It was claimed that the internal -OH group found in the cotton's chemical formula and the acid-alcohol medium was the reason for the TiO_2 NPs' suitable attachment mechanism to the chosen CF. The CF was subjected to a cleaning process using a commercial detergent for 15 min at a temperature of 100 °C, aimed at eliminating any pollutants or organic residues that might interfere with the adhesion of the NPs. Following this, the fabric was rinsed twice in distilled water at approximately 25 °C over 30 min. Fabric samples, each weighing 5 ± 0.1 g, were then prepared for the coating process. The pretreatment involved immersing the fabric in a 4 M NaOH solution for 20 min at RT, designed to chemically modify the surface. This pretreatment aimed to introduce hydroxyl groups onto the cotton, thereby enhancing the bonding of TiO_2 NPs to the fabric. The application of NaOH also caused the cellulose fibers in the cotton to swell, increasing their susceptibility to chemical reactions. Subsequently, a brief 10 s rinse with distilled water was performed to eliminate any residual NaOH that might obstruct the surface and diminish the quality of the NPs coating.[25] After that, the primary coating process used a mixture of 300 ppm by wt % Anatase TiO_2 NPs diluted in 1000 mL colloidal solution to add the TiO_2 NPs to the pretreated fabric. In a 3:1 by-volume ratio, the solution comprises deionized water and methanol, which is glacial acetic acid. The solution was mixed for 15 min in an ultrasonication water bath to ensure adequate mixing. To eliminate agglomerates and introduce the NPs to the pretreated fabric, the cloth is dip-coated in the solution and sonicated for 10 min. In the neutralization phase, HNO_3 raised the pH to 6.8−7.2. The fabric was then dried in a dry oven at a temperature between 100 and 110 °C to guarantee complete solvent evaporation and the removal of all TiO_2 NPs from the fabric. To activate the photocatalytic TiO_2 NPs and increase the antibacterial action, the samples were finally exposed to ultraviolet light (UV light; λ = 365−405 nm (UV-A); I = 5000 mW/cm^2) for 15 min at a distance of 10 cm from the textile.

A good instance illustrating the use of the dip-coating process for the fabrication of antimicrobial textiles has been reported by Malshe et al.[32] In their work, the cloth was initially padded with a 4 wt % solution of DADMAC and a 5 mol % cross-linker, pentaerythritol tetraacrylate. Plasma-induced graft polymerization of DADMAC on 60/40 cotton-nylon blend

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(NyCo) was carried out at 800 W for 120 s of plasma exposure. Plasma creates free radicals, which start the plasma-induced free-radical graft polymerization of DADMAC on both the fabric surface and the bulk. To verify that all DADMAC homopolymers were removed, the treated fabric was extracted with water for 12 h. Figure 6 depicts the technique.[32]

Several other instances, as per the literature, have also been presented in Table 2.[25,33−36] Dip-coating is particularly useful for treating textiles with complex structures or those that are difficult to process using other methods. It offers flexibility in controlling the amount of antimicrobial agent absorbed by adjusting the concentration of the solution, immersion time, and drying conditions. This technique is widely used in the production of antimicrobial textiles for various applications, including medical textiles, protective clothing, and household fabrics, providing durable and effective antimicrobial protection.[25,32−40]

3.1.4. Screen Printing. Screen printing is a technique used in the processing of antimicrobial textiles, where a stencil-based method is employed to apply precise and patterned antimicrobial coatings onto the fabric surface.[41−44] This process involves creating a stencil on a fine mesh screen, which allows the passage of an antimicrobial ink or paste through the open areas of the stencil. The antimicrobial ink, containing active ingredients like nAg or other antimicrobial compounds, is then pushed through the screen onto the fabric using a squeegee. This results in the deposition of the antimicrobial agent in a controlled and patterned manner, according to the design of the stencil.

After printing, the fabric undergoes a drying and curing process to ensure the antimicrobial properties are fixed and durable. Screen printing allows for the application of antimicrobial coatings in specific areas or patterns, making it ideal for textiles requiring localized protection or decorative antimicrobial features.[41−44]

In their research, Haripriya et al.,[41] used the screen-printing process to create rhamnolipid (RL)-CuO NPs that were integrated into cotton and polypropylene fabrics, as depicted in Figure 7. Making the stock paste was the first step in their screen-printing procedure. The required viscosity was obtained by adding thinner and carbon ink. After 10 min of constant stirring, a homogeneous stock paste was achieved. After that, a mesh was used to print it on the fabric. Similarly, RL-CuO NPs pigment, carbon ink, and thinner were combined evenly in a ratio of 40:60 to create the pigment paste, which was then printed on the fabric surface using a 1.7 cm-wide mesh. The coated materials were dried for 10 min at 120 °C. When the coated fabrics' antimicrobial activity was assessed later, it was discovered that the RL-CuO NPs coated fabrics had exceptional antibacterial qualities against both gram-(+ve) and gram-(−ve) microorganisms.[41]

This technique is beneficial for creating antimicrobial effects on textiles with complex designs or for applications where visual appeal and antimicrobial functionality are important, such as in fashion textiles, sportswear, and medical bandages.

3.2. Surface Modification. Surface modification techniques involve the chemical or physical alteration of the textile surface to introduce antimicrobial properties.[45] This method ensures that the antimicrobial agents are primarily present on the fabric surface, where they can interact with microorganisms effectively.[45]

Table 2. Comparison of Various Fabrication Methods, Their Mechanisms of Action, and Applications for Antimicrobial Textiles

Fabrication method	Mechanism	Advantages	Limitations	Applications	Ref.
Padding (Pad-Dry-Cure)	The fabric is impregnated with an antimicrobial solution and then dried and cured to fix the agent.	Simple and scalable; uniform treatment; inexpensive	Limited to certain chemicals; can be uneven if not optimized	Home textiles, medical uniforms, and industrial fabrics	11, 26
Spray coating (SPC)	Antimicrobial agents are sprayed onto fabric to impregnate a surface coating.	Easy application; low material waste; flexible for various fabrics	Surface only; less durable after washing	Face masks, disposable medical textiles, and curtains	3, 31
Dip-coating	Fabric is dipped in an antimicrobial solution and wrung out for excess liquid.	Uniform coating, suitable for a wide range of antimicrobial agents	High post-treatment dry time: large volumes of solution are required	Protective clothing, filter materials, and bedding products	25, 32−40
Screen printing	Patterned mesh screen application of antimicrobials to achieve a particular design	Allows for precision , and pattern application; highly reproducible	Surface treatment only, possibly requiring chemical binders for durability	Decorative antimicrobial textiles and custom-designed fabrics	41−44
Chemical grafting	Covalent bonding of antimicrobial agents directly to fabric fibers	High durability; resistance to washing; long-lasting performance	Complex process; may alter fabric texture and properties	High-performance clothing, hospital linens, and military textiles	46−50
Plasma treatment	Plasma modifies fabric surfaces to enable the binding of antimicrobial agents.	Eco-friendly; avoids chemical solvents; can improve fabric functionality	High initial cost; limited to surface treatment	Medical textiles, sportswear, and antibacterial filters	6, 32, 45
Melt spinning (MSP)	Antimicrobials are incorporated into fibers during spinning by mixing with a polymer melt.	Long-lasting effect; creates inherently antimicrobial fibers	Limited to synthetic fibers; requires high-temperature processing	Medical devices like wound dressings, sports textiles, and carpets	53−55, 57, 58
Electrospinning (ES)	Produces nanofibers by electrostatic forces with embedded antimicrobial agents	High surface area; allows the integration of diverse antimicrobial agents	Limited scalability; requires specialized setup; expensive	Face masks, wound dressings, and filtration membranes	58−62
Sol-gel process	Forms a thin, durable coating through hydrolysis and condensation reactions	Versatile; enables functional coatings with multiproperties	Time-consuming; can be brittle; durability challenges in harsh conditions	Antibacterial coatings for outdoor fabrics, electronics, and optical textiles	64−66
Layer-by-Layer (LbL)	Alternating deposition of oppositely charged antimicrobial layers on fabric surfaces	Precise control of composition; customizable multilayer systems	Labor-intensive; low scalability; may require multiple processing steps	Advanced medical textiles, high-end filtration systems, and biosensors	68−73

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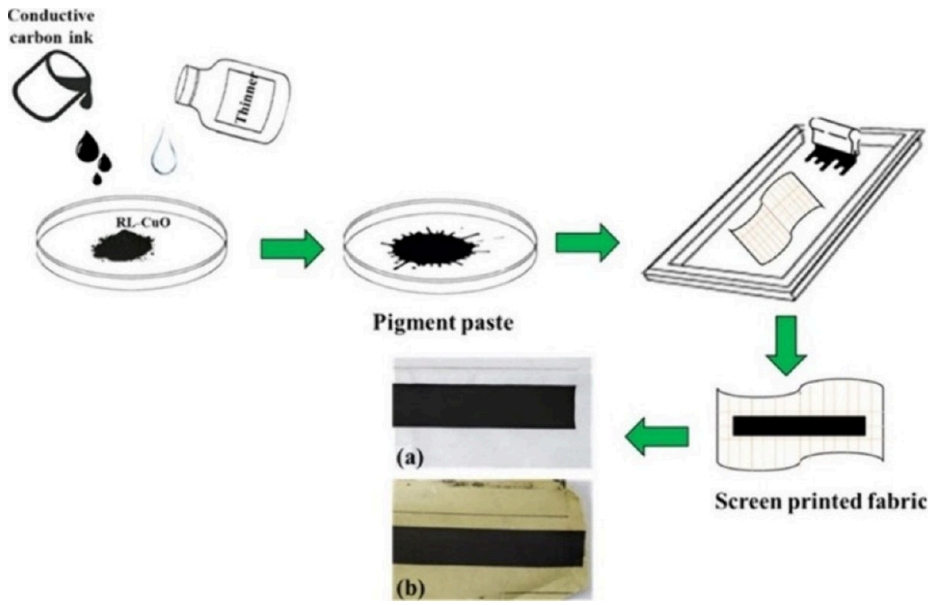

Figure 7. Schematic representation of screen printing of RL-CuO NPs onto the fabric. Photographs of screen-printed (a) polypropylene and (b) CFs. Reproduced with permission from Haripriya et al.[41] Copyright 2024, IOPSCIENCE.

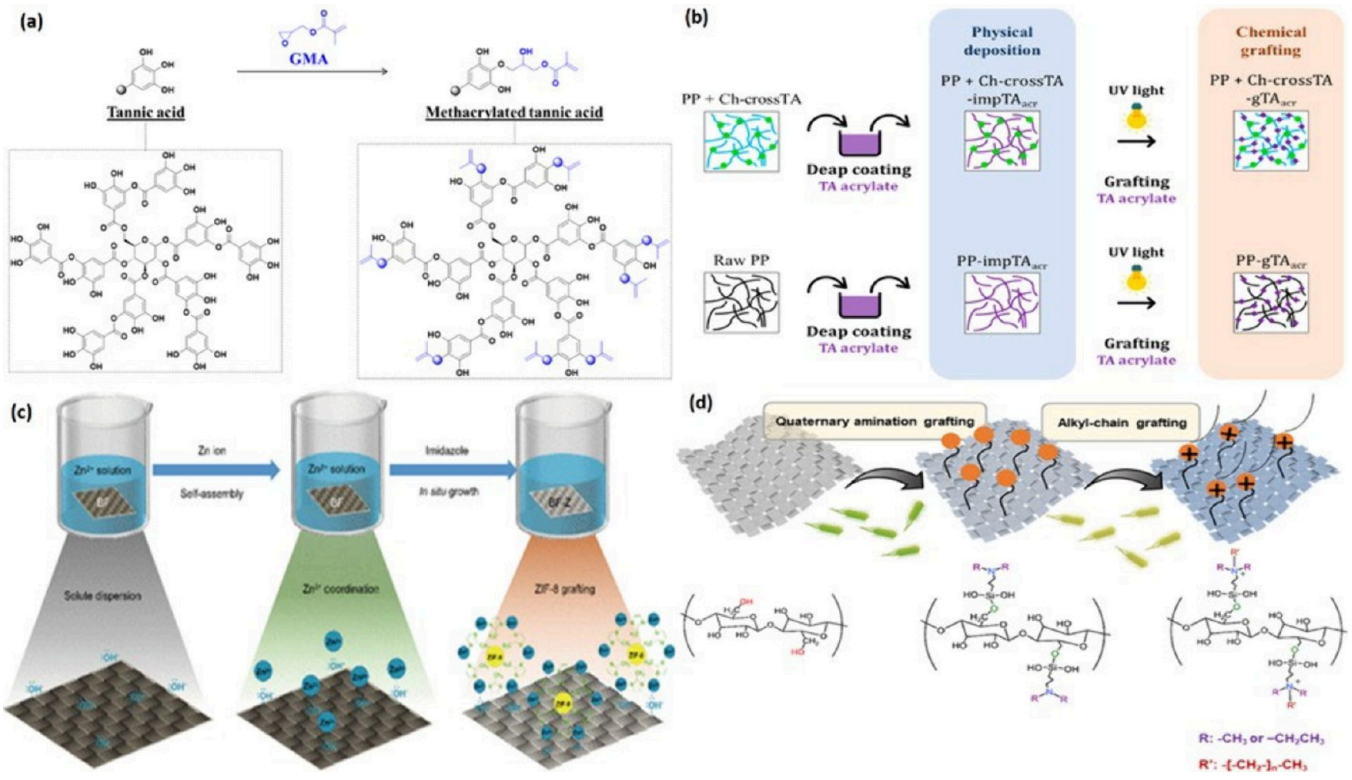

Figure 8. (a) Grafting reaction of methacrylate functions on tannic acid, (b) Schematic representation of the two-step process to functionalize fabrics with methacrylated tannic acid. Reproduced with permission from Fouilloux et al.[46] Copyright 2024, MDPI. (c) Schematic illustration of the preparation process of BF-Z textile. Reproduced with permission from Fang et al.[47] Copyright 2024, ACS Publications. (d) Illustration of the fabrication of antibacterial cotton textiles. Reproduced with permission from Li et al.[48] Copyright 2024, Elsevier Science Ltd.

3.2.1. Chemical Grafting. Chemical grafting-based surface modification is a sophisticated technique used in the processing of antimicrobial textiles, where specific antimicrobial molecules are chemically bonded to the textile surface.[46] This method involves the use of reactive groups on the textile fibers that can form covalent bonds with antimicrobial agents, such as quaternary ammonium compounds, tannic acid, or Ag-containing molecules. The process typically begins with activating the textile surface through plasma treatment or other methods to introduce reactive sites. These sites are then allowed to react with the antimicrobial molecules, forming strong and durable bonds. The covalent attachment ensures that the antimicrobial properties are firmly anchored to the textile, resisting wash-off and providing long-lasting efficacy.[46]

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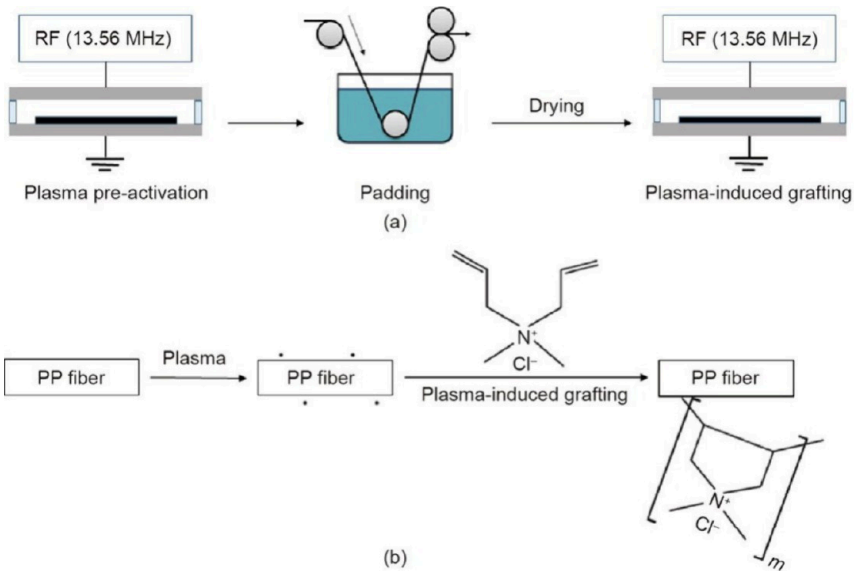

Figure 9. Schematic presentation of plasma-induced graft polymerization: (a) process and (b) mechanism of attachment of Diallyldimethylammonium chloride (DADMAC) on polypropylene (PP) nonwoven by plasma activation. Reproduced with permission from Naebe et al.[6] Copyright 2022, Elsevier Science Ltd.

An instance of this process adoption for the fabrication of antimicrobial textile surfaces has been reported in the work by Fouilloux et al.[46] First, methacrylate functionalities were grafted onto tannic acid as depicted in Figures 8a and b. The fabric samples were then immersed in the modified tannic acid solution followed by UV-irradiation assisted grafted as illustrated in Figure 8b.

A simple in situ generated zeolite imidazole framework 8 (ZIF-8) crystal particle on basalt fibers (BF) using the solution impregnation method was investigated in another case, where ZIF-8 was heavily grafted with a large number of hydroxyl groups on the surface of basalt fibers as per Figure 8c.[47] When it came to *P. aeruginosa*, *E. coli*, and *S. aureus*, the ZIF-8 in situ basalt fiber demonstrated outstanding antibacterial qualities. Moreover, basalt fibers' steady and consistent ZIF-8 distribution gives the initially hydrophilic BF exceptional hydrophobicity. The exceptional air/water retainability and amazing mechanical toughness of ZIF-8 in situ generated basalt fiber simultaneously satisfy the demands of frequent use and numerous launderings, thanks to the strong cooperation between ZIF-8 and BF. Textiles made from ZIF-8 in situ generated basalt, which can be used extensively in harsh conditions, show promise when created via a highly scalable and affordable process.[47]

As shown in Figure 8d by Li et al.,[48] molecular brush assemblies have also been produced on CFs for effective and long-lasting broad-spectrum antibacterial performances through the cooperation of alkyl-chain and QA sites. Their findings demonstrated that the control of quaternary ammonium sites and alkyl chain length could result in effective antibacterial performances. Using cetyl modification, the optimized molecular brush structure of [3-(N,N-Dimethylamino) propyl] trimethoxysilane demonstrated ≥99% antibacterial activity against *S. aureus* and *E. coli* on cotton textiles (CT-DM-16). When (N,N-Diethyl-3-aminopropyl) trimethoxysilane was modified on cotton textiles (CT-DE) based materials, alkyl-chain grafting showed a considerable increase in antibacterial performance against *S. aureus*. In the antibacterial process, alkyl chains and positive N sites were crucial components.[48] The enhanced puncture capacity with alkyl-chain grafting is confirmed by proteomic analysis, which shows that the cytoskeleton, as well as the enclosed membrane lumen in differentially expressed proteins, was increased for the *S. aureus* antibacterial procedure. Theoretical calculations suggest that alkyl-chain grafting can improve the +ve charge on N sites and that the brush structure may be distorted during application, which could further raise the +ve charge on N sites. Finding the regulating mechanism is thought to be crucial information for creating cutting-edge and useful antibacterial materials.[48]

Chemical grafting offers several advantages, including the ability to tailor the antimicrobial properties to specific needs, minimal leaching of the antimicrobial agent, and compatibility with various textile materials. This technique is particularly useful for applications requiring elevated levels of antimicrobial protection and durability, such as in medical textiles and protective gear.[48−50]

3.2.2. Plasma Treatment. Plasma treatment is an advanced technique used in the processing of antimicrobial textiles, which involves the use of low-temperature plasma to modify the surface properties of the fabric.[32,51] The plasma can be tailored to introduce specific functional groups or deposit thin layers of antimicrobial materials onto the fabric. In some cases, plasma treatment is adopted in synergy with other approaches or by itself for the preparation of antimicrobial textile materials, as depicted in Figures 9a and b.[6]

This method permits the fabrication of a durable antimicrobial effect by modifying the surface chemistry of the textile, making it resistant to microbial growth. Plasma treatment also enhances other properties of the fabric, such as wettability, dyeability, and biocompatibility. The process is particularly beneficial for its ability to treat delicate fabrics without damaging the underlying structure and for its eco-friendly nature, as it typically uses nontoxic gases and requires minimal chemical inputs.[6,32,45] Plasma-treated antimicrobial textiles are utilized in various applications, including healthcare, hygiene products, and outdoor gear, where long-lasting antimicrobial protection is essential.[6,32,45]

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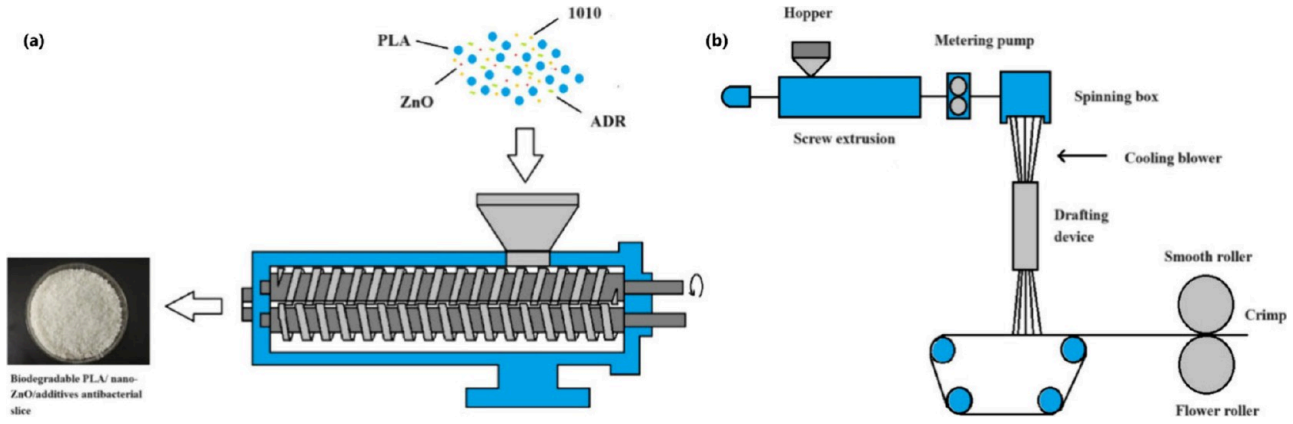

Figure 10. (a) Schematic diagram of twin-screw extrusion melt blending method and (b) Spunbond nonwoven fabric production process diagram. Reproduced with permission from Zhang et al.[53] Copyright 2024, Elsevier Science Ltd.

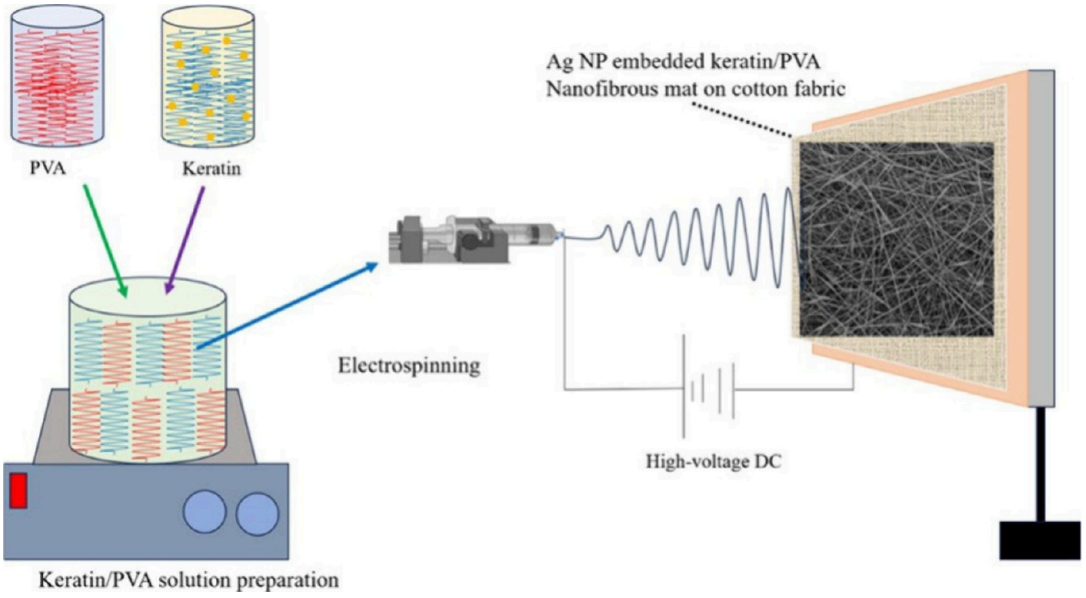

Figure 11. Schematic diagram of fabrication of Silver NPs (nAg)- (wool keratin/poly(vinyl alcohol) (PVA)) WK/PVA nanofibrous membrane on CF by ES. Reproduced with permission from Hassan et al.[62] Copyright 2024, American Chemical Society.

3.3. Incorporation during Fiber Production. Antimicrobial agents can be incorporated into the fibers during the production process, ensuring that the antimicrobial properties are embedded throughout the textile.[45]

3.3.1. Melt Spinning. Melt spinning (MSP) is a widely used technique in the processing of antimicrobial textiles, offering efficient production of synthetic fibers with integrated antimicrobial properties.[52,53] This method involves melting a polymer, often mixed with antimicrobial agents, and extruding it through small orifices to form continuous filaments that solidify upon cooling.[54,55]

In antimicrobial textile production, MSP allows for the incorporation of various antimicrobial agents directly into the fiber structure. Common additives include nAg, zinc oxide (ZnO), and organic antimicrobials like triclosan.[45] The process parameters, such as extrusion temperature, cooling rate, and draw ratio, significantly influence the final fiber properties and the distribution of antimicrobial agents.[45,56] One of many interesting facts about MSP is that it can be synergized with other approaches like nonwoven technologies to directly fabricate textile fabrics ready for the market, as depicted in Figure 10.[53]

Zhang et al.[53] exemplified this approach in their study thus: The slices were first put through the hopper, and then screw extrusion was used to melt them completely. Before being used, the slices produced by the melt-blending process were dried for 12 h at 60 °C. A spinning fabric integrated machine was used to manufacture the nonwoven textiles, as shown in Figure 10a. Subsequently, the metering pump acted to extrude the melted slices into the fiber, which originated from the head. Second, the extruded fiber got finer after drafting, and the drafting device was switched on. Ultimately, following drafting, the fiber was arranged into a network and compressed using a smooth roller followed by a flower roller. This resulted in the antibacterial nonwoven fabrics made of PLA, nano-ZnO, and additives, as depicted in Figure 10b.

MSP technology has also been adopted by Zheng et al.,[57] for the fabrication of ZnO/Ag@SiO_2 incorporated PET fibers aimed at the creation of antimicrobial textiles. nAg particles have reportedly been incorporated into polypropylene (PP) fibers for the fabrication of antimicrobial textiles active against

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E. coli and *S. aureus* in the work by Demirhan et al.[58] Melt-spun antimicrobial fibers find applications in medical textiles, sportswear, and personal protective equipment.[53] Recent advancements include the development of bicomponent fibers with enhanced antimicrobial efficacy and the use of biodegradable polymers for more sustainable antimicrobial textiles.

3.3.2. Electrospinning. Electrospinning (ES) is an advanced technique used in the processing of antimicrobial textiles, which involves the creation of nanofibers containing antimicrobial agents.[58−61] ES process begins with the preparation of the solution via solution mixing/blending or solution intercalation, followed by loading the same into the syringe. This process uses an electrical force to draw a polymer solution into a fine jet, which is then stretched and solidified to form nanofibers, as depicted in Figure 11.[58−60]

A good instance of the adoption of ES to fabricate antimicrobial textiles fibrous mats is presented in the work by Mahmud et al.:[59] In summary, a solution-mixing approach was used to generate solutions containing 10% (w/v) PVA powder and different concentrations of powdered curcumin in 20% (v/v) acetic acid solvent. For 4 h, the solutions were prepared at 80 °C. An in-house electrospinning setup was used to electrospin the solutions as they were prepared. The process's voltage was 15 kV, and its operating gap was set at 10 cm. A 2 mL solution was electrospun at 1 mL/h flow rate. On aluminum foil, the electrospun fiber mats were gathered. Every experiment was carried out with controlled humidity and RT.[59]

ES allows for the production of highly porous and lightweight antimicrobial fabrics, which are suitable for various applications, including medical dressings, filtration materials, and protective clothing.[58−60] The technique offers control over fiber diameter, porosity, and the amount of antimicrobial agent incorporated, enabling the customization of antimicrobial textiles for specific needs.

3.4. Embedding NPs. NPs, particularly metal-based NPs like nAg, ZnO, and TiO_2, are known for their strong antimicrobial properties.[63] These can be embedded into/onto textiles through various methods.

3.4.1. Sol-Gel Process. The sol-gel process is a versatile technique used in the processing of antimicrobial textiles, which involves the conversion of a liquid "sol" into a solid "gel" through a series of chemical reactions, as shown in Figure 12.[64−66] This method allows for the incorporation of antimicrobial agents, such as nAg or TiO_2, onto the textile fibers by forming a thin, durable coating. The process typically begins with the preparation of a sol, which is a colloidal suspension of particles in a liquid.[63,66] Hydrolysis and condensation reactions transform this sol into a colloidal suspension. Antimicrobial agents are added to this sol, which is then applied to the textile surface through methods such as dipping, spraying, or padding.[66] The sol penetrates the textile fibers and undergoes a series of reactions, leading to the formation of a gel-like network that bonds with the fibers. Drying removes the solvent, converting the sol- into a gel. High-temperature curing crystallizes the metal oxide, enhancing antimicrobial properties. Post-treatment and finishing ensure the coating's effectiveness and the textile's usability.[63]

Mahltig and colleagues have documented the synthesis of antimicrobial textiles via sol-gel coatings that have embedded biocidal chemicals.[65] Using a sol-gel technique, they began their work with both pure silica sols and 3-glycidyloxypropyltriethoxysilane (GLYEO)-containing silica sols. These sols

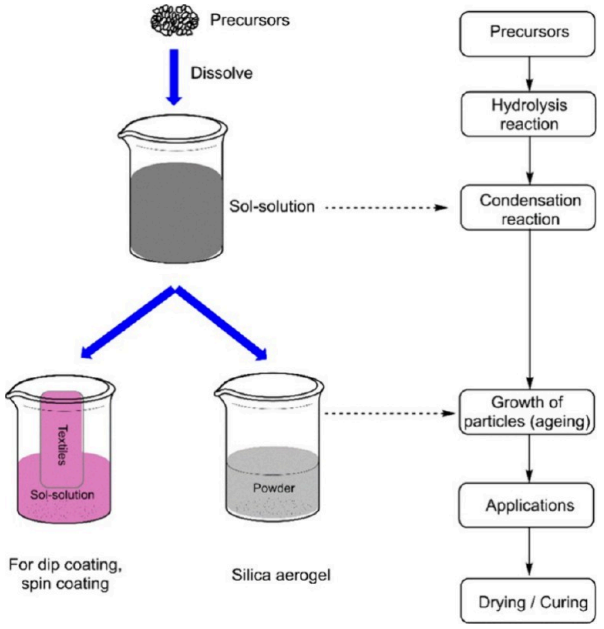

Figure 12. Steps involved in a sol-gel process. Reproduced with permission from Periyasamy et al.[66] Copyright 2024, the Authors.

were treated with two distinct types of Ag compounds: copper compounds and hexadecyltrimethylammonium-p-toluolsulfonat (HTAT). The effects of the concentration of biocidal chemicals and the thermal treatment of the textile following dip-coating between 80 and 180 °C were investigated in viscose fabrics. The application of modified silica coatings inhibits the growth of bacteria (*Bacillus subtilis* and *Pseudomonas putida*) and fungi (*Aspergillus niger*) as the amount of biocide incorporated in the coating increases. GLYEO is added to the coating solutions to improve their stability and to promote the coatings' biocidal activity. Biocides like Ag, Cu, or HTAT can be employed alone to prepare antimicrobial silica coatings, but their combination produces better results against bacteria and fungus. Thus, in some real-world applications, silica sols containing a blend of various biocides could be utilized to modify textile antimicrobials. They suggested that because the solvent in the coating solutions contained 90% water, they were particularly beneficial for industrial applications.[65]

The sol-gel process offers several advantages, including the ability to create uniform and highly adherent coatings, as well as the potential for tailoring the properties of the coating by varying the composition of the sol.[63] This technique is particularly useful for producing antimicrobial textiles with long-lasting efficacy and resistance to washing, making it suitable for various applications, including medical textiles, protective clothing, and home furnishings.[63]

3.4.2. Layer-by-Layer (LbL) Assembly. LbL assembly is an innovative technique that makes possible the sequential deposition of alternating layers of polymers or NPs onto a textile substrate in a controlled manner.[67]

The LbL process typically begins with the textile substrate immersion into a solution containing the first type of polymer or NPs, as shown in Figures 13a and b.[68,69] After rinsing, the textile is then immersed in a solution containing the second type of material, which may include antimicrobial agents such as nAg or QA ammonium compounds. This alternating

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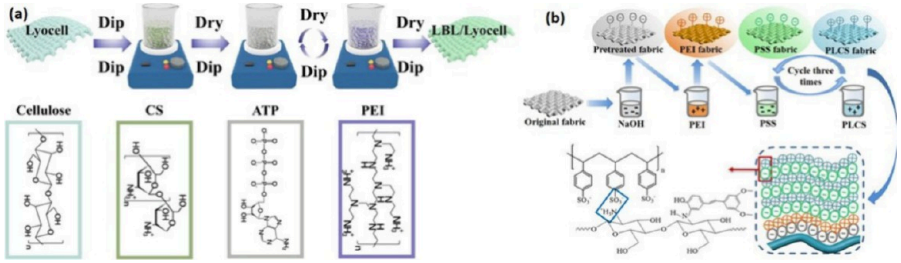

Figure 13. (a) The preparation process of LbL/Lyocell fabrics. Reproduced with permission from Wang et al.[68] Copyright 2024, Elsevier Science Ltd. (b) Schematic diagram of the fabrication process of the PLCS CF. Reproduced with permission from Wang et al.[69] Copyright 2024, Springer Nature.

deposition process is repeated multiple times to achieve the desired thickness and functionality.

To create outstanding antibacterial lyocell fabrics (LbL/Lyocell), a group of researchers successfully deposited layers of adenosine triphosphate (ATP), chitosan (CTS), and polyethylenimine (PEI) in a bio-based coating, as shown in Figure 13a.[68] Furthermore, LbL/Lyocell demonstrated remarkable antimicrobial capabilities, exhibiting 99.99% antibacterial rates against both *E. coli* and *S. aureus*. This bio-based coating showed great promise as an effective flame-retardant (FR) cellulose fiber with superior antibacterial properties.[68]

Natural antibacterial compounds have a great deal of potential for creating long-lasting antibacterial fabrics using the LbL assembly approach, as Wang et al.'s,[69] study illustrates (Figure 13b). In their investigation, they created PLCS with strong antibacterial activity by grafting natural pterostilbene (PL) onto chitosan (CS) via a Mannich reaction. Additionally, a LbL constructed coating containing PLCS as the antibacterial agent was used to create the long-lasting antibacterial CF. According to the findings, PLCS with a grafting ratio of 17.3% obtained the lowest minimum inhibitory concentrations of 33.2 and 16.6 μg/mL against *S. aureus* and *E. coli*, respectively, at a molar ratio of PL to CS of 0.2:1 and a temperature of 80 °C. The antibacterial activity of PLCS against *S. aureus* increased by 67.0% and 58.5% when compared to that of CS and PL alone, whereas the activity against *E. coli* improved by 94.8% and 44.7%, respectively. After three assembled layers, the PLCS CF's antibacterial rate against *S. aureus* and *E. coli* was up to 99.9%, and it remained above 80% after 20 washings. The antibacterial materials made by PLCS showed good wearing performances and safety.[69]

LbL Assembly offers several advantages, including the capability to shape the characteristics of the coating by varying the types and concentrations of the materials used, as well as the number of layers. This technique is particularly useful for creating durable antimicrobial coatings that can withstand washing and abrasion, making it suitable for various textile applications, including medical textiles, sportswear, and filtration materials.[70−73]

The two widely used methods for immobilizing NPs on antimicrobial textiles are LbL assembly and the sol-gel process; both techniques have their pros and cons. LbL assembly also provides special advantages in terms of NPs deposition control for multilayer fabric construction improvement of antimicrobial performance and functions new to textile materials. However, it may take longer and be costly with regard to the use of resources. On the other hand, the sol-gel process allows the uniform dispersion of NPs, and the process can be easily scaled up, which increases the prospects of cost optimization. Nevertheless, it may have several drawbacks associated mainly with the permanency and stability of incorporated NPs to achieve desired effects on the textiles without influencing the reliability of the final products in the long run.

4. MECHANISMS OF ANTIMICROBIAL ACTION AND TYPES OF ANTIMICROBIAL AGENTS

4.1. Mechanisms of Antimicrobial Textiles. *4.1.1. Contact Killing (Physical Killing).* Contact or physical killing (PK) is a critical mechanism in antimicrobial textiles, where physical interactions between the textile surface and microorganisms lead to microbial inactivation. Unlike chemical-based antimicrobial strategies, PK relies on physical attributes and interactions, making it a potent method to reduce microbial load. This section explores the primary physical mechanisms involved in PK, supported by relevant literature citations.[70−74]

Textiles can be engineered to have surfaces that physically disrupt microbial cell membranes upon contact. This rupture may lead to cellular contents to flow out as can be clearly seen in Figure 14 ("**5**"), eventually leading to cell death. Surfaces designed with nanoscale spikes or pillars can also puncture microbial cell membranes, leading to cell lysis. It has been established that NPs adhere to the bacterial membrane through a variety of interactions, including electrostatic interactions, van der Waals forces, receptor-ligand bindings, or hydrophobic associations.[75] Upon attachment, NPs, particularly metal NPs, can penetrate the bacterial membrane, disrupt metabolic processes, and alter the membrane's structure and functionality, as shown in Figure 14 (ROS "**4**"). Inside the cell, these metal NPs can suppress enzyme activity, denature proteins, trigger oxidative stress, and influence gene expression. The concentration of metal within the microorganism is viewed as a critical component of metal-induced harm. Additionally, the metal ions applied can hinder the absorption of necessary ions by compromising the bacterial metal transport systems or by creating reactive oxygen species (ROS "**4**") outside the cell, as depicted in Figure 14. It is essential to recognize that the mechanisms described are not isolated; antibacterial efficacy is the multifaceted effect of numerous, frequently interwoven processes operating in tandem. Consequently, it is arduous to pinpoint their discrete impacts within a complex biological framework, as shown in Figure 14.[75]

This mechanism is inspired by natural antimicrobial surfaces such as insect wings.[76] For instance, synthetic fabrics coated with nanopillars have shown significant antimicrobial activity against bacteria by mechanically damaging their cell walls.[77] Electrostatic forces between the textile surface and microbial cells can lead to cell membrane destabilization and rupture.

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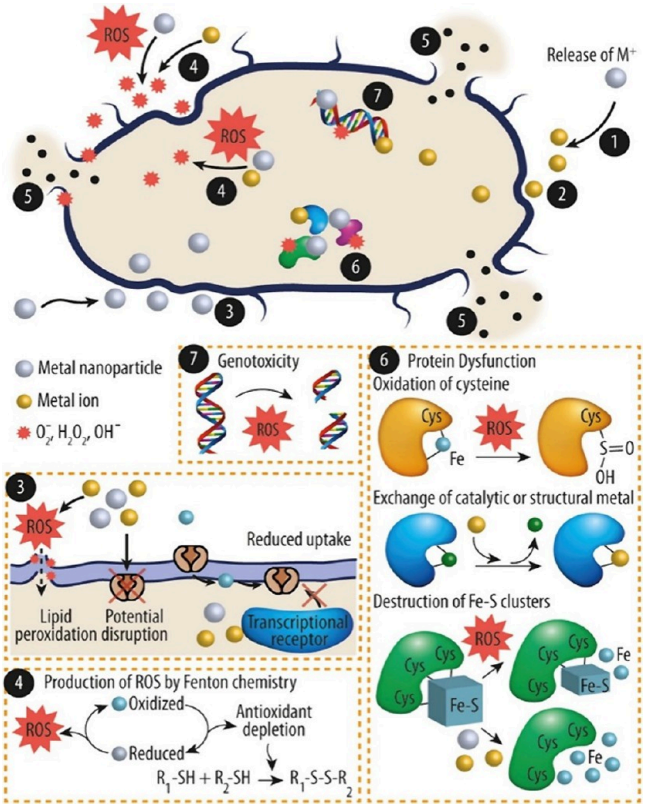

Figure 14. Antibacterial mechanisms of metal ions and NPs. The central modes of action are (1) release of metal ions from the metal NPs and (2) direct interaction of the metal ions and/or (3) metal NPs with the cell wall through electrostatic interactions, leading to impaired membrane function and impaired nutrient assimilation; (4) formation of extracellular and intracellular reactive oxygen species (ROS), and damage of lipids, proteins, and DNA by oxidative stress; (5) high-levels of metal-binding to the cell envelope and high ROS levels can cause damage to the plasma membrane and thus lead to the leakage of the cell content; (6, 7) upon metal uptake, metal NPs, and metal ions can directly interfere with both proteins and DNA, impairing their function and disturbing the cellular metabolism in addition to metal-mediated ROS production. Reproduced with permission from Godoy-Gallardo et al.[75] Copyright 2021, Elsevier Science Ltd.

Materials with high surface charges can attract and disrupt the negatively charged bacterial membranes. Also, textiles functionalized with QACs can induce electrostatic interactions that disrupt bacterial cell membranes. QACs are cationic surfactants that attract negatively charged bacterial membranes, causing structural disintegration and cell death.[78] Some antimicrobial textiles incorporate photosensitive compounds that generate ROS upon exposure to light. These ROS can cause oxidative damage to microbial cells, leading to cell death. Textiles embedded with photosensitizers such as porphyrins or phenothiazinium dyes can produce ROS when activated by light. ROS attacks biological components, including lipids, proteins, and nucleic acids, resulting in microbial cell death.[78] Certain antimicrobial textiles are designed to generate localized heat upon contact, which can kill microorganisms by denaturing their proteins and disrupting cellular functions. The incorporation of materials that can convert light or electrical energy into heat, such as carbon-based materials, can also create antimicrobial surfaces. These materials generate heat upon activation, effectively killing bacteria through thermal disruption.[37]

Textiles with hydrophobic surfaces can interact with microbial cell membranes, leading to membrane destabilization and increased permeability. This interaction can result in cell lysis and death. Textiles coated with hydrophobic compounds such as silicones or fluoropolymers create surfaces that repel water and microbial cells, leading to membrane stress and disruption upon contact.[9,10,14]

4.1.2. Release of Antimicrobial Agents (Chemical). Chemical mechanisms for antimicrobial activity in textiles involve the release of antimicrobial agents that interact with microbial cells to inhibit their growth or kill them.[9,10,14,22] These mechanisms rely on the diffusion of active compounds from the textile to the surrounding environment, providing a sustained antimicrobial effect.

Antimicrobial textiles are designed to release active agents slowly over time, ensuring prolonged antimicrobial activity, as presented in some of the instances in Table 2.[9,10,14,22,79] Moreover, active antimicrobial agents are encapsulated within microcapsules, which are then incorporated into the textile fibers.[34,79] The microcapsules break down gradually, releasing the antimicrobial agents in a controlled manner. This technique is effective for agents such as triclosan, essential oils, and nAg.[14,34] Also, cyclodextrins can form inclusion complexes with antimicrobial agents, protecting them and controlling their release.[80] When incorporated into textiles, these complexes release antimicrobial agents in response to environmental triggers such as moisture or friction.[80] Antimicrobial agents can be covalently bonded (grafted) to the textile fibers, providing a durable and long-lasting antimicrobial effect while minimizing leaching.[46] Textiles grafted with QACs have also been established to provide effective antimicrobial activity.[81] The QACs are chemically bonded to the fibers, allowing them to interact with microbial cell membranes and cause cell death while remaining firmly attached to the textile.[81]

As per the literature, polymers embedded with nAg can be applied as coatings on textiles.[82] The Ag ions are slowly released from the polymer matrix, providing sustained antimicrobial activity. This method is effective against a broad spectrum of bacteria and fungi.[82]

NPs with antimicrobial activity, such as Cu and ZnO, can be incorporated into textile fibers or coatings, which release antimicrobial ions. However, nAg is commonly used due to its superior antimicrobial activity.[22] They can be embedded in textile fibers, where they release Ag ions that interact with microbial cells, disrupting their cell membranes, interfering with enzyme functions, and causing oxidative stress.[22]

4.1.3. Disruption of Microbial Cell Membranes (Biological). The disruption of microbial cell membranes is a crucial biological mechanism by which antimicrobial textiles exert their effects.[6,8,9,14,22,24,78] This method involves the integration of antimicrobial agents into textiles that interact with and compromise the integrity of microbial cell membranes, leading to cell death.[6,78]

4.1.3.1. Cationic Antimicrobial Agents. Cationic antimicrobial agents are positively charged molecules that interact with the negatively charged components of microbial cell membranes.[6,10,14,44,78] This interaction leads to membrane disruption and increased permeability.

QACs are commonly used in antimicrobial textiles for their ability to disrupt microbial cell membranes.[78] The positively

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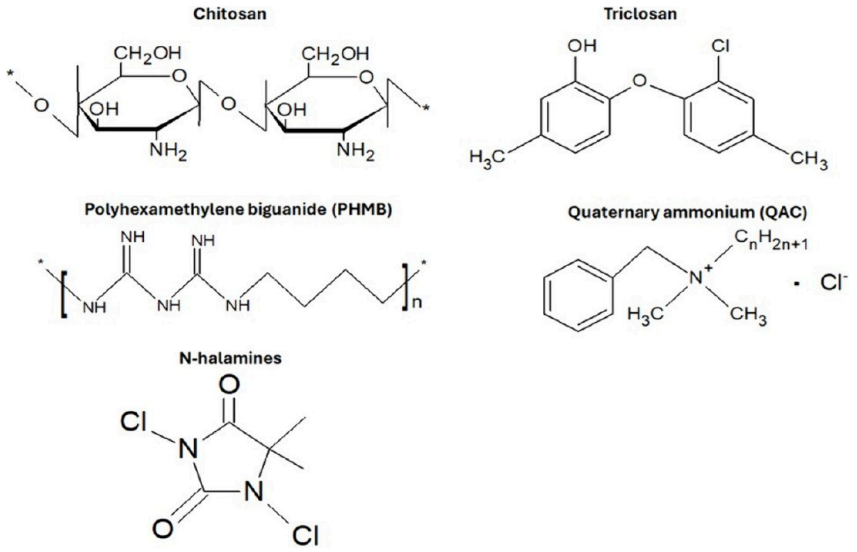

Figure 15. Structural presentation of selected antimicrobial agents for textiles.

charged QACs interact with the negatively charged phospholipids in bacterial membranes, causing membrane destabilization and leakage of cellular contents.[78]

CTS, a natural polysaccharide with cationic properties, can interact with microbial cell membranes, leading to membrane disruption and cell death. It is effective against a broad range of bacteria and fungi.[6,10,14,44,73]

Antimicrobial peptides (AMPs) are short peptides that can insert into microbial cell membranes, forming pores and disrupting membrane integrity.[83] They are a crucial component of the innate immune system and are used in antimicrobial textiles for their potent activity.[83] AMPs such as defensins and cathelicidins bind to microbial membranes due to their amphipathic nature.[83] They integrate into the lipid bilayer, forming transmembrane pores that lead to cell lysis.[83] Incorporating AMPs into textile fibers or coatings can provide effective antimicrobial activity. For example, textiles treated with AMPs have demonstrated significant reductions in microbial load on their surfaces.[83]

Silver NPs (nAg) are widely used in antimicrobial textiles for their ability to disrupt microbial cell membranes.[6,14,22,73,82] They release Ag ions, which interact with membrane proteins and lipids, leading to structural damage. Ag ions released from nAg bind to thiol groups in membrane proteins, disrupting their function and leading to increased membrane permeability and cell death.[82] Additionally, nAg can generate ROS that cause oxidative damage to membrane lipids.[82] Textiles embedded with nAg show prolonged antimicrobial activity due to the sustained release of Ag ions, effectively reducing bacterial and fungal contamination.[6,14,22,73,82]

4.1.3.2. Enzymes. Enzymes play a crucial role in disrupting microbial cell membranes, offering a biological approach to antimicrobial action.[84] This process primarily involves hydrolytic enzymes such as lysozyme, phospholipases, proteases, α-amylase, alkaline pectinase, as well as laccase enzymes.[84,85] Lysozyme, for instance, targets the peptidoglycan layer in bacterial cell walls, hydrolyzing the glycosidic bonds and compromising structural integrity. Phospholipases attack phospholipids in the cell membrane, altering membrane fluidity and permeability. Proteases degrade membrane proteins, further destabilizing the membrane structure.[84,85] The enzymatic disruption of microbial membranes leads to cell lysis, leakage of cellular contents, and, ultimately, microbial death. This mechanism is particularly effective because it targets fundamental components of microbial cells, making it difficult for microorganisms to develop resistance. Furthermore, enzymes can often act synergistically, enhancing their overall antimicrobial efficacy. The specificity of enzymes also allows for targeted antimicrobial action, potentially reducing harm to beneficial microorganisms.

In textile applications, enzyme-based antimicrobial treatments offer a promising eco-friendly alternative to traditional chemical agents, aligning with the growing demand for sustainable and biocompatible solutions.[85]

4.1.3.3. Plant-Derived Antimicrobials. Natural compounds from plants, such as essential oils and phytochemicals such *as Conocarpus erectus L. Leaf*, can disrupt microbial cell membranes.[12] These compounds are gaining popularity for their biocompatibility and eco-friendliness.

Essential oils like tea tree oil, oregano oil, *Citrullus colocynthis* seed oil,[11] and eucalyptus oil contains compounds such as terpenes and phenolics that disrupt microbial cell membranes by interacting with membrane lipids and proteins.[11] This leads to increased membrane permeability and leakage of cellular contents. Textiles treated with essential oils or their active components exhibit antimicrobial activity, making them suitable for applications where natural and nontoxic antimicrobials are preferred.[11]

4.2. Antimicrobial Agents for Textiles. *4.2.1. Natural/Bioderived Antimicrobial Agents.* Natural antimicrobial agents are increasingly used in antimicrobial textiles due to their biocompatibility, environmental friendliness, and broad-spectrum activity against various pathogens.[86,87] These agents are derived from plants, animals, and microorganisms, offering a safe and effective alternative to synthetic antimicrobial chemicals. Below, we explore some of the most commonly used natural antimicrobial agents in textiles as per literature.

4.2.1.1. Chitosan. CTS, structurally depicted in Figure 15, is a linear polysaccharide composed of randomly distributed β-(1 → 4)-linked D-glucosamine (deacetylated unit) and N-acetyl-D-glucosamine (acetylated unit). Its structure is derived from chitin, which is found in the exoskeletons of crustaceans (like

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shrimp and crab) and insects, as well as in the cell walls of fungi.[88] CTS molecular weight can vary widely, typically ranging from 50,000 to over 2,000 000 Da. The presence of free amino groups in the deacetylated units gives chitosan its cationic nature and is responsible for many of its unique properties, including its antimicrobial activity, mucoadhesiveness, and ability to chelate metal ions. It possesses antimicrobial properties against different bacteria and fungi. Chitosan interacts with the negatively charged microbial cell membranes, leading to leakage of cellular contents and cell death.[88] It also inhibits mRNA and protein synthesis by binding to microbial DNA.[88] It is widely applied to textiles through methods such as coating, blending with fibers, or incorporating into nanofibers. It is used in medical textiles, wound dressings, and hygiene products.[88] Section 7.5 presents diverse instances of CTS applications as antimicrobial agents in textiles as per literature. Some challenges are, however, encountered when incorporating CTS-based antimicrobial agents into antimicrobial textiles.[89] this, they have a major drawback in that they are sensitive to the environment, for example, moisture and temperature, which make them less effective with time. Also, CTS has inherent characteristics that cause variation in the antimicrobial effect due to the textile substrate, which may affect even the distribution of protection. Moreover, the mechanical properties of the textile material that has been coated with CTS may be altered depending on the kind of modification given to the CTS-based antimicrobial agent as well as the mode the antimicrobial agent is applied to the textile, especially where long-lasting antibacterial treatment is administered.[90] This causes questions about the durability and softness of the treated textile. Such challenges warrant more studies aimed at improving the stability of chitosan in textiles and broadening the possibilities of its application in the textile industry. Also, the antimicrobial activity of CTS-based agents depends on pH, and most of these agents are also dependent on pH to dissolve.[91]

4.2.1.2. Essential Oils. Essential oils are volatile, fragrant chemicals derived from plants. Essential oils have emerged as promising natural and bioderived antimicrobial agents for textiles, offering an eco-friendly alternative to synthetic antimicrobials.[3,30,34] These volatile, aromatic compounds extracted from various plant parts have demonstrated broad-spectrum antimicrobial activity against bacteria, fungi, and even some viruses.[3,14,30,34,92]

The antimicrobial efficacy of essential oils is attributed to their complex composition of terpenes, terpenoids, phenylpropanoids, phenols, aldehydes, and other aromatic compounds.[14] These components can disrupt microbial cell membranes, interfere with cellular processes, and inhibit microbial growth.[3,14,30,34,92] Popular essential oils used in textile applications include tea tree, eucalyptus, lavender, peppermint, and thyme, each with unique antimicrobial profiles.[3,14,30,34,92]

Recent studies have explored various methods to incorporate essential oils into textiles. Microencapsulation has gained significant attention, as it protects the volatile oils and allows for controlled release.[14,92] For instance, Szadkowski et al.[34] developed CTS microcapsules containing Lavender and cinnamon essential oil for CFs, achieving excellent antimicrobial activity and wash durability. Another approach involves the use of cyclodextrins to form inclusion complexes with essential oils. Farouk et al.,[80] reported enhanced antimicrobial performance and durability of CFs treated with β-cyclodextrin/cinnamon essential oil complexes (EOs/βCD). This study found that the EOs/βCD inclusion-complex-deposited CF has the potential for medicinal and hospital applications. The study found that β-CD improved the fragrance stability of oils without significantly affecting cotton's tensile strength or permeability. Lavender oil exhibited the highest fragrance stability, with a rating of 3.25, even after 30 days. EOS/βCD-impregnated fabrics for method 1 had an inhibition zone ranging from 33 to 23 mm. In contrast, the inhibition zone for method 2 varied from 39 mm to 29 mm, showing that our treatment was able to control the growth of bacteria, even after five washing cycles.[80]

Nanotechnology has also been employed to improve the efficacy and durability of essential oil treatments. Shaheen et al.[93] used nAg as carriers for clove essential oil, resulting in synergistic antimicrobial effects on CFs. Moreover, the combination of essential oils with bio-based polymers has also shown promise in creating sustainable antimicrobial finishes.

While essential oils offer numerous advantages as natural antimicrobial agents for textiles, challenges remain regarding their volatility, potential for skin sensitization, and long-term stability. Ongoing research focuses on addressing these issues and optimizing formulations for specific textile applications.

4.2.1.3. Aloe vera. *Aloe vera* is derived as gel from the leafy parts of the *Aloe* plant. It possesses antibacterial, anti-inflammatory, as well as healing features for the wound(s).[94,95] It is a succulent plant with medicinal qualities that has drawn much interest as a natural textile antibacterial. This sustainable and environmentally safe substitute for synthetic antimicrobials is a viable way to create usable textiles with built-in antimicrobial properties. Aloe's rich phytochemical composition, which includes anthraquinones, saponins, acemannan, and other phenolic compounds, is responsible for its antibacterial properties.[94,95] These bioactive compounds exhibit broad-spectrum antimicrobial activity against both gram-(+) and gram-(−ve) bacteria, as well as certain fungi.[94,95] Several procedures, including pad-dry-cure, microencapsulation, and grafting, can be used to incorporate aloe vera extracts into textiles.[14] Recent studies have demonstrated the efficacy of *Aloe vera*-treated textiles in inhibiting the growth of common pathogens such as *Staphylococcus aureus*, *Escherichia coli*, and *Candida albicans*.[14,95] Such an instance is reported by the work by Fernando et al.,[95] where CF-coated aloe vera (*Aloe barbadensis* (*A. barbadensis*) demonstrated excellent antimicrobial resistance. Effective antifungal activity against *C. albicans*-caused *vulvovaginal candidiasis* was also demonstrated in vitro by the *A. barbadensis* Miller ethanol extract and ethanolic gel treated cloth. These results were concentration-dependent.[95]

In another study, Rimika et al.[96] developed a novel microencapsulation technique to incorporate *Aloe vera* extract, lavender, and eucalyptus onto CFs, resulting in enhanced antimicrobial performance and controlled release of the active compounds.[96] By using a bacterial test, it was determined that all cloth samples had significantly good bacterial suppression. Because of the high concentration (6 mL) of aloe vera and lavender, fabric sample C7 has a very high inhibitory effect for Enterococcus (gram-(+ve)) bacteria. The concentration (8 mL) of all essential oils in fabric C8 results in a very high inhibition against gram-(−ve) bacteria, such as *Escherichia coli*. Similarly, C7 and C8 sample antioxidant activity was dramatically enhanced in the 70−85% range. This can be

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attributed to increased oil bend concentration-induced free radical scavenging activity.[96]

The application of *Aloe vera*, especially in antimicrobial textiles, is not limited to apparel textiles but also to medical textiles and wound dressing. Hence, the future of using *Aloe vera* as an antimicrobial agent in textiles is bright, but more research has to be conducted to improve the application techniques with fabrics, the stability of *Aloe vera*, and the standardization of the extract used. This research should be carried out to emphasize the above-mentioned problems and study the interaction effects of fabric matrix composite and other natural antimicrobial substances.

4.2.1.4. Neem. Neem (*Azadirachta indica*) is a tree inherent to the Indian subcontinent. Neem's extracts from leaves, seeds, and bark have been used for centuries for their antimicrobial properties.[97] Neem contains bioactive chemical functionalities like salannin nimbin, and, azadirachtin, which display antimicrobial properties via disruption of microbial cell walls/membranes and inhibition of enzyme function.[86] Neem extracts can be incorporated into textiles through methods like coating, embedding in fibers, or using neem oil or neem dye, as illustrated in Figure 16.[97] A typical scenario is the extraction of

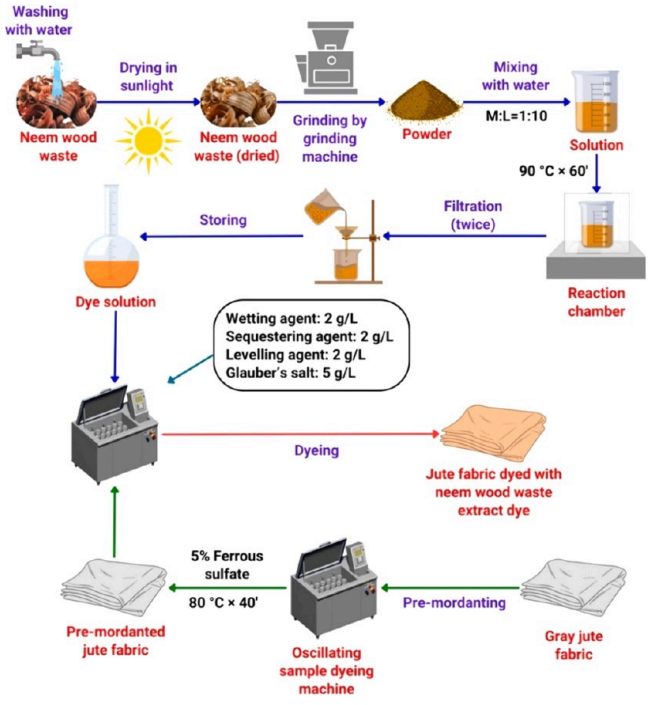

Figure 16. Schematic presentation of the dye extractions and jute fabric dyeing with neem wood waste powder. Reproduced with permission from Mia et al.[97] Copyright 2024, Elsevier Science Ltd.

neem dye from neem wood presented in the work with Mia et al.[97] Thus, to get rid of the dust, the leftover neem wood was rinsed with water. The exposure to the sunlight that followed helped to dry them out. A grinding machine was then used to turn the discarded dried wood into powder. The wood waste was turned into powder in about a minute. In a beaker, the powder and water were combined with a liquor ratio of 1:10. Next, for 60 min, the extraction procedure was carried out in a reaction chamber at 90 °C. After that, a liquid dye solution was obtained by filtering the mixture twice through fine filter sheets. In preparation for the next dyeing step, the recovered dye solution was kept in storage. Figure 16 displays a schematic diagram of the dye extraction procedure. Neem-treated textiles are used in healthcare, personal hygiene products, and insect-repellent fabrics.[97]

Even as the textile industry maintains efforts to find organic substitutes for synthetic antimicrobial compounds, neem can be more desirable, fulfilling both the customer tendency toward organic products and the current trend of the ecological approach to textile production.[97]

There are a few shortcomings that have limited the use of neem as an antimicrobial agent for textiles. Some of these are successful extraction procedures to obtain a constant concentration of bioactive compounds needed for application, according to the texture of the textile and differences in color changes in the fabrics after the application. Current work is directed toward overcoming these threats, as well as investigating possible interactions of neem with other natural antimicrobial compounds to boost their efficiency and stability.[14]

4.2.1.5. Honey and Its Derivatives. Honey is a natural substance produced by bees and has been used for its antimicrobial properties in wound care for centuries.[98−101] Honey and its derivatives have been utilized for their antimicrobial properties in various applications, including textiles. Honey contains several components, such as hydrogen peroxide, gluconic acid, and flavonoids, contributing to its antimicrobial activity. Honey's antimicrobial attributes are ascribed to its high osmolarity, and low pH, as well as the presence of H_2O_2 and other bioactive chemical components. These factors disrupt microbial cell membranes and inhibit microbial growth.[98,102] The antimicrobial mechanism of honey involves the release of hydrogen peroxide and an acidic pH, which create an unfavorable environment for microbial growth[102] Additionally, honey's high viscosity and stickiness can physically entrap microorganisms on the textile surface. The use of honey in textiles provides a natural and sustainable antimicrobial treatment option, although its effectiveness and durability may differ depending on the type of honey and application method.

Honey can be incorporated into wound dressings and medical textiles to promote healing and prevent infection. Manuka honey, in particular, is renowned for its potent antimicrobial properties.[102,103] When applied to textiles, honey can be used in its raw form or as a derivative, such as honeycomb or honey extract. The application of honey in textiles can be achieved through methods like padding, coating, or blending with fibers during manufacturing. In padding, the textile is passed through a honey solution, allowing it to absorb the antimicrobial agent. Coating involves applying a honey-based solution directly onto the fabric surface, while blending involves incorporating honey or its derivatives into the fiber matrix.

An instance of the utilization of honey for the fabrication of antimicrobial textiles has been explored by Dehdast et al. for the fabrication of poly(diallyldimethylammonium chloride) (PDDA)/honey nanofiber.[104] The effect of the processing parameters on the shape of the spun nanofiber blend was first examined. Honey is a naturally occurring, biocompatible, and antibacterial substance that may be added to PDDA solutions in varying ratios. At a honey/PDDA concentration ratio of 40/60%, a 0.8 mL/h flow rate, and 17 kV high-voltage, the results demonstrated a uniform diameter bead-free nanofibers morphology. Different cross-linking times were used to link the sample with the best morphology using glutaraldehyde. 4.9

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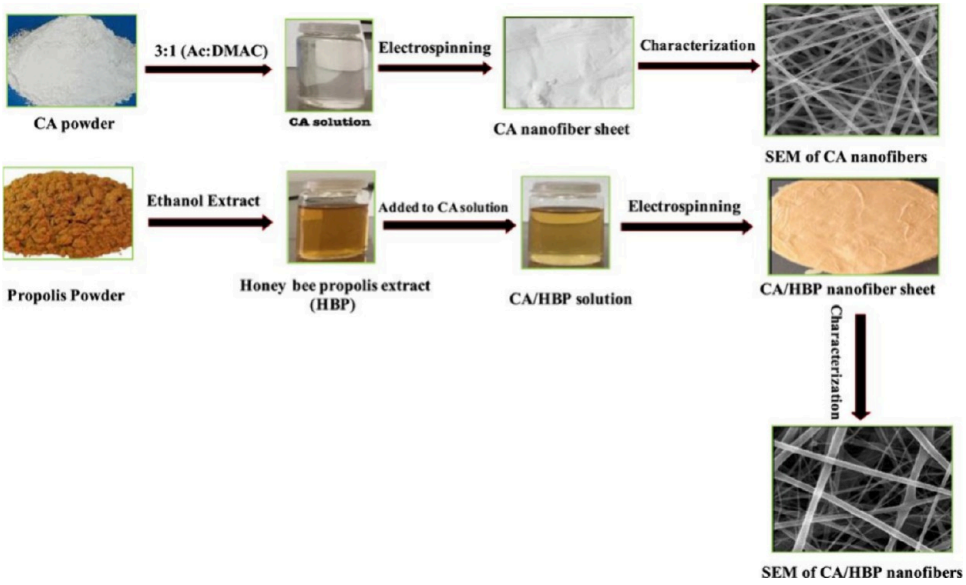

Figure 17. Steps for the formation of nanofibers based on CA and CA/HBP composites. Reproduced with permission from Sharaf et al.[99] Copyright 2018, Springer Nature.

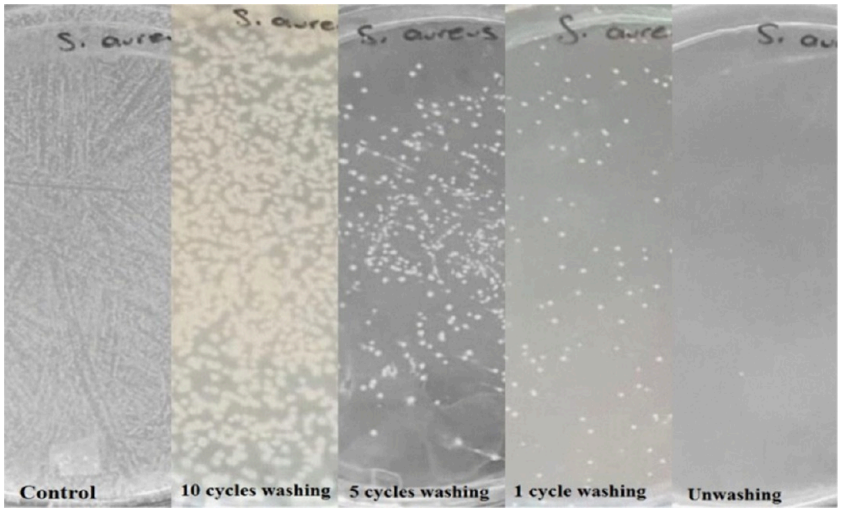

Figure 18. Effectiveness of the fabric coded F-P6 against *S. aureus* after washing (A: 10 cycles washing, B: 5 cycles washing, C: 1 cycle washing, D: unwashing) since it has a lower bacterial concentration than the one, we first set. Reproduced with permission from Yaman Turan and Aydin.[106] Copyright 2024, Springer Nature (under Creative Commons CC BY license).

g/g of water could be absorbed by nanofibers, according to an evaluation of their water absorption properties. After that, the gram-(+ve) and gram-(−ve) strains of *S. aureus* and *E. coli* were tested for the antibacterial activity of nanofiber in vitro. After that, pathogenic *P. aeruginosa* was examined concerning new nanofiber antibacterial activity. The 40/60% PDDA/honey nanofiber ratio caused around 99.9% of the bacteria in both strains to die, according to the minimum inhibitory concentration (MIC) values. Furthermore, against pathogenic *P. aeruginosa*, the new PDDA/honey nanofibers demonstrated an appropriate antibacterial efficacy of 98.89%. Furthermore, the outcomes demonstrated unique nanofibers as new antibacterial agents and showed a significant decrease in the quantity of germs.[104]

In a different study, polyamide 6 (PA6) nanoscale fiber mats were successfully integrated with efficient organic (honey) and inorganic (boric acid) substances linked to the healing of burns, scars, and wounds by the simultaneous use of electrospinning and electrospraying.[105] In the networks of nanofibers, honey was uniformly dispersed. The diameter of the fiber was slightly impacted by the boric acid content. The hybrid fibers' average diameter rose as the amount of boric acid in them increased. When it came to thermal deterioration, fibers loaded with honey and boric acid were generally less stable than clean fibers. All the fibers' wettability and thermal stability seem to make them favorable for wound healing. Additionally, against *S. aureus* and *E. coli*, all fibers exhibited antibacterial activity.[105] The largest inhibitory zone, however, was seen in the fibers containing both honey and 5−10 wt % boric acid. The newly created nanofibrous scaffolds with antibacterial activity could be tested for treating cutaneous bacterial infections or wound healing. To solidify the findings, more research on the fibers' cytotoxicity *in vitro* and *in vivo* as well as wound scratch testing will be required.[105]

Sharaf et al.,[99] in their work, synthesized honey bee propolis (HBP) extract from propolis powder followed by its

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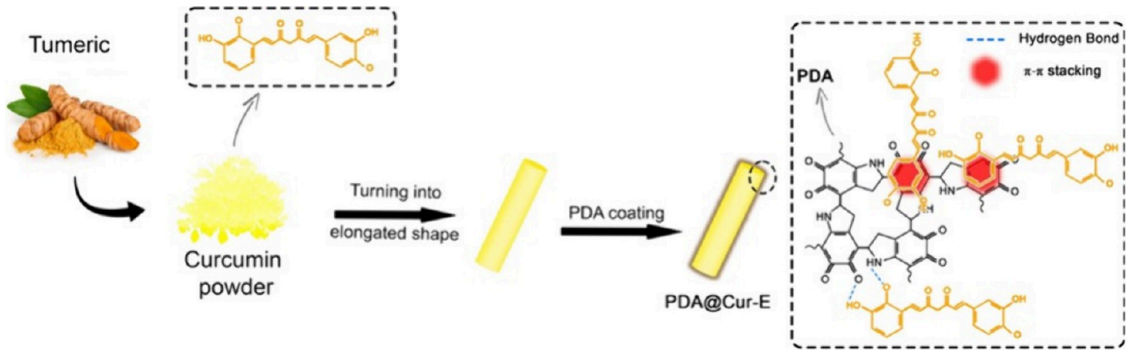

Figure 19. Schematic of synthesizing core-shell structures of PDA@Cur. Reproduced with permission from Azizi et al.[112] Copyright 2023, Springer Nature.

incorporation into cellulose acetate (CA) via electrospinning as depicted in Figure 17. They demonstrated the effective antibacterial qualities of the as-synthesized CA/HBP mats against both gram-(+ve) and gram-(−ve) bacteria. The data also showed that neutral pH is preferred over alkaline and acidic pH for the prolonged and controlled in vitro release of HBP from CA nanofibers.[99]

In their research, Turan and Aydin investigated the antibacterial qualities and laundry endurance of cotton textiles coated with hydrogel doped with propolis.[106]

More precisely, we examined for the first time the antibacterial qualities of propolis and the hygienic qualities of $AgNO_3$, a typical antimicrobial agent in textile materials. Because PVA and sodium carboxymethylcellulose (NaCMC) are nontoxic and biocompatible, they were utilized in the hydrogel synthesis process. Additionally, they examined the efficacy of propolis or $AgNO_3$-doped hydrogel-coated cotton textiles against gram-(+ve) and gram-(−ve) bacteria as well as the fungus *C. albicans, and the propolis-treated samples presented a better result in comparison to nAg samples*, as shown in Figure 18. As a natural antibacterial substitute for $AgNO_3$, their findings suggested that propolis might be useful. Antibacterial and washing resistance increased with the amount of active ingredients present. To determine how much Ag was contained in the layers that were doped with Ag, scientists once more used scanning electron microscopy (SEM) images of the hydrogel coating and SEM with Energy Dispersive X-ray (SEM-EDX) images. Phenol and flavonoids in the propolis's structural makeup were also supported by Attenuated total reflectance-Fourier transform infrared (ATR-FTIR) data. Adjustments to the items' fundamental comfort features were within reasonable bounds.[106]

A variety of industrial and medicinal applications may benefit from the usage of bee products such as honey, pollen, propolis, royal jelly, venom, wax, and bread as antimicrobial or antibiofilm agents.[107] These products have great potential as effective antibiotic substitutes in the realm of medicine, despite several limitations such as their complicated and variable makeup.

4.2.1.6. Turmeric. Turmeric, a spice derived from the Curcuma longa plant, has been conventionally employed for its antimicrobial properties.[108−111] In the context of textiles, turmeric can be applied as an antimicrobial agent through various methods, such as dyeing, printing, or coating.[108] The active component in turmeric, curcumin, is responsible for its antimicrobial activity against a range of microorganisms, comprising bacteria and fungi.[109,111] Turmeric, derived from the root of the *Curcuma longa* plant, as illustrated in Figure 19, contains curcumin, which has strong antimicrobial properties. When used in textile applications, turmeric can be incorporated into the fabric through natural dyeing processes, where the fabric is soaked in a turmeric solution, allowing the curcumin to bind to the fibers. Alternatively, turmeric can be used in printing pastes for screen printing or in formulations for coating the fabric surface.[109] An excellent instance of the application of curcumin in antibacterial textiles is presented in the work by Azizi et al.[112] Their research reduced environmental damage while producing protective clothing textiles incorporated with antiviral, antibacterial, antioxidant, and UV-shielding properties by integrating polydopamine-coated curcumin structures (PDA@Cur). A substantial antibacterial activity against *Escherichia coli* and *Bacillus subtilis*, 95.02% antiviral activity against the human coronavirus NL63, an amazing UV protection factor of 153.21 for sun protection, and an almost 89% increase in antioxidant activity were all reported for the modified cotton samples. By using a novel design approach that combines biocompatible and environmentally benign ingredients like PDA and curcumin, this study marks a substantial leap in the development of multifunctional protective cotton textiles. This breakthrough addresses the limitations of traditional clothing materials, providing total protection by integrating antiviral, antibacterial, antioxidant, and UV protection capabilities in one textile product using plant-based and bioinspired PDA@Cur structures.[112]

The antimicrobial mechanism of turmeric involves the interaction of curcumin with the cell membranes of microorganisms, leading to their disruption and eventual death. The use of turmeric in textiles not only imparts antimicrobial properties but also offers the potential for natural and eco-friendly textile treatments. However, the durability of the antimicrobial effect may be limited compared to synthetic agents, and further research is needed to optimize its application and efficacy in textile products. Other bioderived antimicrobials that have been used for antimicrobial textiles but may not have been covered in this section are onionskin and pulp, tulsi leaves, oregano, azuki beans, peppermint, stinging nettle leaf, amla juice, prickly chaff flower, citrus fruit peels, etc.[14]

4.2.2. Synthetic Antimicrobial Agents. Synthetic antimicrobial agents play an important role in the advancement of antimicrobial textiles due to their high efficacy, stability, and versatility.[22] These agents are designed to inhibit microbial growth or kill microorganisms through various chemical and physical interactions. Below, we explore some of the most used

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synthetic antimicrobial agents in textiles, supported by relevant literature citations. The study by Sharif et al.[113] demonstrates the facile synthesis of diammonium phosphate octadecyl citrate (DAPOC), as depicted in Figure 20.[113]

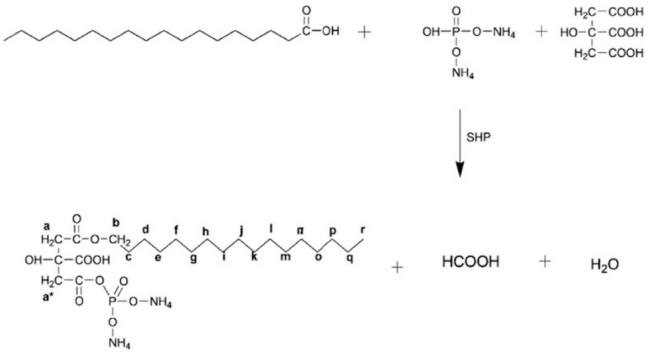

Figure 20. Synthesis of diammonium phosphate octadecyl citrate (DAPOC). Reproduced with permission from Sharif et al.[113] Copyright 2024, RSC (open access article licensed under a Creative Commons license).

It was unearthed by these investigators that CF was treated with a unique fluorine-free finishing agent that possessed hydrophobic and FR qualities.[113] The water contact angle (WCA) of the treated CFs was 151.9°, indicating that the finishing agent had made the CFs superhydrophobic. Remarkably, the WCA maintained its stability at 148.5° even after 20 laundering cycles (LCs). During the vertical flame burning test, the CFs that were finished showed an elevated LOI value of 27.0%. This number was higher than the original LOI of 18% for pure cotton, staying at 26.4% even after 20 wash cycles. Additionally, after 20 wash cycles, the treated CF's char length remained at 40 mm, measuring 48 mm. Furthermore, results from the TGA test showed that the CFs' completed state had FR characteristics. Additionally, because citric acid has strong antibacterial characteristics, the treated CF also demonstrated a sizable zone of inhibition for *S. aureus* and *E. coli*.[113] By adding FR and antibacterial abilities to CFs, the innovative finishing chemical DAPOC provided an environmentally responsible and sustainable solution.

4.2.2.1. Quaternary Ammonium Compounds (QACs). QACs ($R_4N^+X^-$) are widely employed in antimicrobial textiles due to their strong cationic properties and wide-spectrum performance against viruses, fungi, and bacteria,.[14,22,78,114] These compounds consist of an NH_4^+ atom covalently bonded to four alkyl and/or aryl functionalities as per Figure 15, resulting in a structure with both hydrophilic and hydrophobic properties. The amphiphilic nature of QACs allows them to interact effectively with microbial cell membranes, making them potent antimicrobial agents.[14,22,78] In textile applications, QACs are favored for their broad-spectrum antimicrobial activity against bacteria, fungi, and some viruses.[14,22,78] Their mechanism of action primarily involves disrupting the microbial cell membrane, leading to cell lysis plus death. The positively charged nitrogen atom interacts with the negatively charged parts of the microbial cell membrane, causing structural damage and leakage of cellular contents.[14,22,78]

Recent studies have focused on improving the durability and efficacy of QAC-based antimicrobial treatments for textiles. For instance, Kim et al.[81] developed a novel QAC (3-(trimethoxysilyl)propyl-octadecyldimethylammonium chloride (TSA))/sodium alginate (SA) hybrid coating that demonstrated outstanding resistance to washing as well as long-term antimicrobial performance on CFs. *E. coli*, and *S. aureus*, were treated with CFs containing 70 ppm concentration of the SA-TSA NPs (schematically shown in Figure 21), which showed

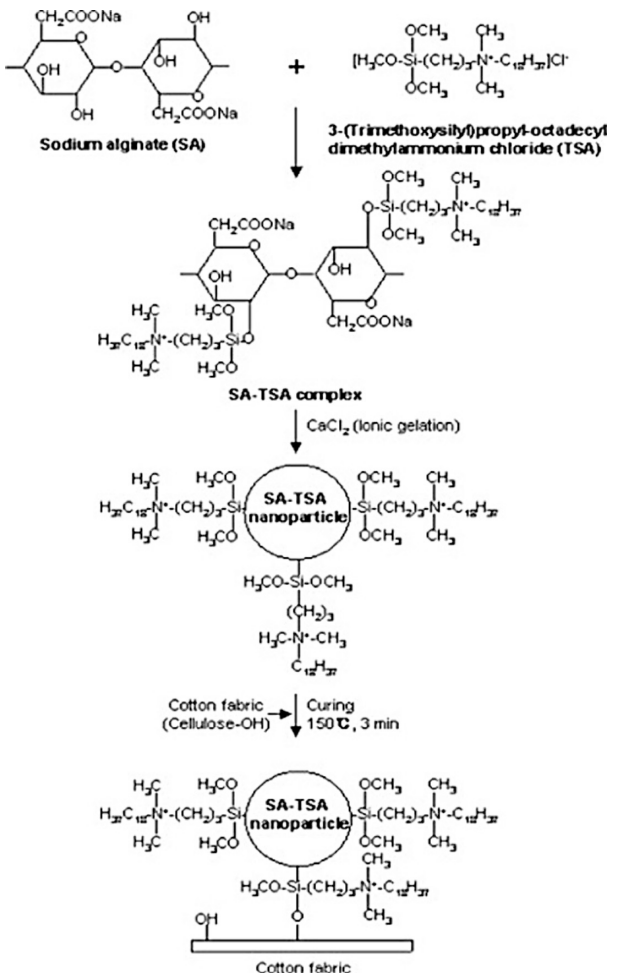

Figure 21. Schematic diagram of reaction between CF and SA-TSA NPs. Reproduced with permission from Kim et al.[81] Copyright 2010, Elsevier Science Ltd.

effective antimicrobial activity of >99.99% decline in the cell counts. After 30 laundry cycles, the antibacterial activity remained intact. According to the findings, SA-TSA NPs could prove themselves effective as a nonleaching agent that gives cotton textiles long-lasting antibacterial qualities.[81]

Another area of research involves the development of eco-friendly, metal-free QACs derived from Meier et al.[115] Hospital curtains were coated homogeneously and noncovalently with a metal-free QAC-based coating by Meier et al.[115] The modified cloth performance was essentially unchanged after age, abrasion, and durability testing. Furthermore, *S. aureus*, *P. aeruginosa*, and *Acinetobacter baumanii* were subjected to qualitative and quantitative antibacterial testing, which demonstrated exceptional antibacterial activity with a colony forming units (CFU) decrease of 98 to 100% in just 4 h of exposure. Prior to testing, the treated curtain was aged for 6 months. In a similar vein, the functionalized curtain demonstrated >99% viral reduction in the antiviral activity

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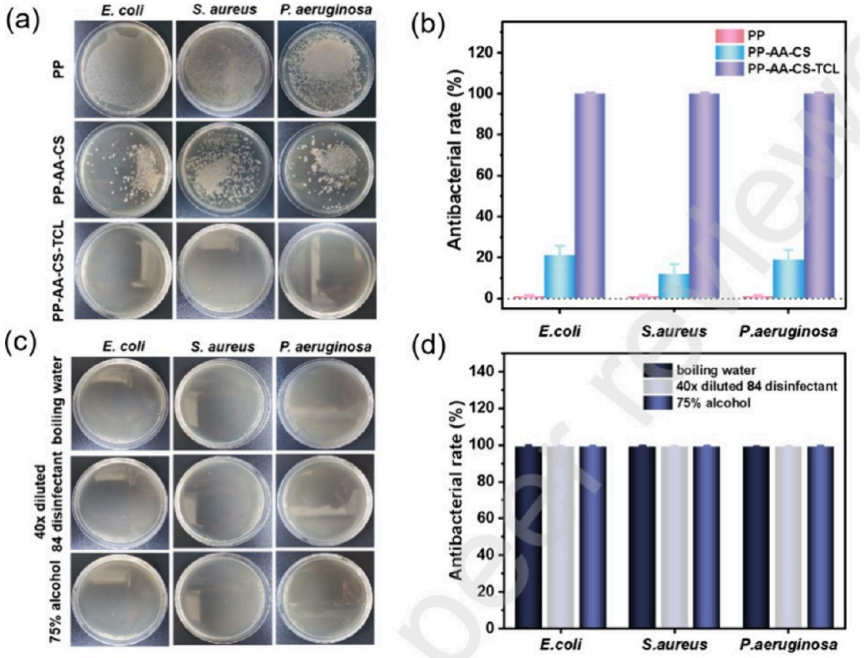

Figure 22. (a) The optical images of *E. coli*, *S. aureus*, and *P. aeruginosa* on agar plates of different samples. (b) The quantitative analysis of bactericidal activity for different samples against *E. coli*, *S. aureus*, and *P. aeruginosa*. (c) The antibacterial effect of PP-AA-CS-TCL nonwoven against *E. coli*, *S. aureus*, and *P. aeruginosa* after disinfection 3 times with boiling water, 75% alcohol and 40x diluted 84 disinfectants for 5 min each. (d) The quantitative analysis of the bactericidal activity of PP-AA-CS-TCL nonwoven against *E. coli*, *S. aureus*, and *P. aeruginosa* after 3x disinfection. Reproduced with permission from Hu et al.[117] Copyright 2024, Elsevier Science Ltd.

test conducted following ISO-18184 using the murine hepatitis virus (MHV).[115]

Furthermore, microorganisms on CF have been found to have a substantial impact on the comfort of wearing it as well as the possibility of health risks. The primary reason for this is that CF is porous and hygroscopic, readily absorbing proteins, fatty materials, and mineral salts to provide an environment that is conducive to the growth of microorganisms. Stains that stick around for a long time are caused by bacteria that are hard to remove with regular washing. Motivated by this problem, Yuan et al.[116] created reactive Gemini quaternary ammonium salt (CGQ) and sulfopropylbetaine (CGB) that bonded to CF covalently, enabling the building of a specialized antibacterial and antifouling coating on CF while maintaining its physical and chemical characteristics. Additionally, the process of bacterial inactivation was observed in real time. Following 50 washes, the antibacterial efficacy of CF completed with CGQ and CGQ/CGB, using only 5.0 mg/mL antimicrobial concentration, exceeded 95% against *Escherichia coli* and 100% against *Staphylococcus aureus*. With standard washing, the loosely adherent germs on CGQ/CGB-finished CF can be readily removed, leaving a long-lasting antimicrobial and antifouling surface. As such, we have devised a simple protocol for the large-scale synthesis of superior antibacterial and antifouling CF, offering a flexible solution with a broad range of uses. This approach also delivers a successful way to track the inactivation of microorganisms in real time.[116]

Despite their effectiveness, concerns about potential environmental impacts and the development of microbial resistance have led to ongoing research into optimizing QAC formulations and application methods. Current trends include the development of controlled-release systems, the use of nanoencapsulation techniques, and the exploration of structure-activity relationships to design more efficient and targeted QACs for textile applications.[74]

4.2.2.2. Triclosan. Triclosan is a synthetic antimicrobial and antifungal agent commonly used in consumer products and textiles.[6,10,14,117] Triclosan is a synthetic, extensive-spectrum antimicrobial compound commonly exploited for various consumer products, including textiles. Its chemical structure, 2,4,4′-trichloro-2′-hydroxydiphenyl ether, as depicted in Figure 15, allows it to target and disrupt bacterial cell membranes effectively.[6,10,14] In textile applications, triclosan is prized for its ability to inhibit the growth of both gram-(+ve) and gram-(−ve) bacteria, as well as some fungi, providing long-lasting protection against odor-causing microorganisms and potential pathogens.[117] The antimicrobial mechanism of triclosan primarily involves inhibiting the enzyme enoyl-acyl carrier protein reductase (ENR), which is crucial for bacterial fatty acid synthesis.[6,10,14,117] This action leads to the disruption of cell membrane integrity and, ultimately, cell death. In textiles, triclosan can be incorporated through various methods, including padding, exhaustion, or directly into synthetic fibers during extrusion.[6,10,14,117]

To safeguard healthcare professionals against contagious diseases like COVID-19, Hu, and colleagues engineered a robust antimicrobial and antifungal postdisinfection polypropylene nonwoven fabric through the combined grafting of triclosan and chitosan.[117] The antibacterial efficacy tests revealed that the newly developed cografted polypropylene nonwoven demonstrated over 99.9% effectiveness in hindering *E. coli*, *S. aureus*, and *P. aeruginosa*, growth which is resistant to multiple drugs, as well as superior antifungal capabilities against *C. albicans* and *A. niger* as illustrated in Figure 22a–d.[117] Notably, this material maintained its exceptional antimicrobial and antifungal characteristics even after being subjected to three rounds of disinfection using boiling water, a

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40-fold diluted solution of 84 disinfectant, and 75% alcohol for 5 min each. This research opens up new avenues for creating more efficient and durable personal protective equipment, aiming to minimize the ecological footprint associated with medical masks and personal protective equipment, particularly in terms of energy use, carbon output, and waste production.[117]

However, the utilization of triclosan in textiles has drawn some controversy due to the threats posed by the compound if it is released into the environment, together with worry over bacterial resistance and potential health risks.[118] Its use in some jurisdictions has been banned, leading to the textile industry searching for other antimicrobial agents. However, triclosan can still be considered a preferred antimicrobial in numerous disciplines of textiles with respect to sportswear, medical textiles, and home textiles.

4.2.2.3. Polyhexamethylene Biguanide (PHMB). PHMB is a widely used synthetic antimicrobial agent in the textile manufacturing sector, known for its wide-spectrum efficacy against some viruses, fungi, and bacteria,.[119,120] This cationic polymer consists of repeating biguanide units connected by hexamethylene chains, as shown in Figure 15, giving it a unique structure that enables strong antimicrobial activity (chemically represented as $(C_8H_{17}N_5)$n. xHCl, where $n \leq 40$).[121] PHMB's mechanism of action primarily involves disrupting the microbial cell membranes.[6,119,120] Being positively charged, the biguanide groups comprising the cationic polymer, therefore, react with the negatively charged phospholipids membrane of microbial cells, hence leading to lysis of the infected cells. This mechanism poses some complexity to the development of the immune system of microbes to PHMB.[119,120]

In textile applications, PHMB can be applied through various methods, including padding, exhaustion, and spray techniques.[6] It forms strong bonds with textile fibers, particularly cellulosic materials, resulting in durable antimicrobial protection that can withstand multiple washing cycles.

Textiles treated with PHMB are used in technical textiles, sportswear, home textiles, and healthcare environments. The polymer is a desirable option for long-lasting antimicrobial protection in textiles because of its minimal toxicity to people and animals as well as its stability in the environment.[6] However, concerns about potential environmental impacts and bioaccumulation have led to ongoing research into its long-term effects and alternatives.

A polyacrylonitrile nanofiber membrane amidoximated (P-Oxime) was produced by Le et al.[119] The P-Oxime-RG19 membrane was then created by grafting reactive green 19 (RG19) dye onto its surface. Poly(hexamethylene biguanide) hydrochloride (PHMB) was physically attached to the P-Oxime-RG19 membrane in order to generate the P-Oxime-RG19-PHMB membrane, which further enhanced the system. Numerous physical and mechanical characteristics, including functional group content, shape, and thermostability, were the subject of in-depth evaluation of the nanofiber membranes. Superior antibacterial activity in P-Oxime-RG19-PHMB nanofiber membranes was mostly attained through the optimization of several modification conditions, such as initial dye and PHMB concentrations, time, temperature, and nitrile group conversion to oxime concentrations. To fully understand the processes modifying RG19 dye and PHMB in the nanofiber membranes, in-depth analyses applied equilibrium and kinetic thermodynamic models. Nearly 100% *E. coli* disinfection was achieved by the P-Oxime-RG19-PHMB nanofibrous film under carefully calibrated optimal modification conditions, demonstrating exceptional antibacterial activity, as depicted in Figure 23. They investigated the antibacterial properties of the

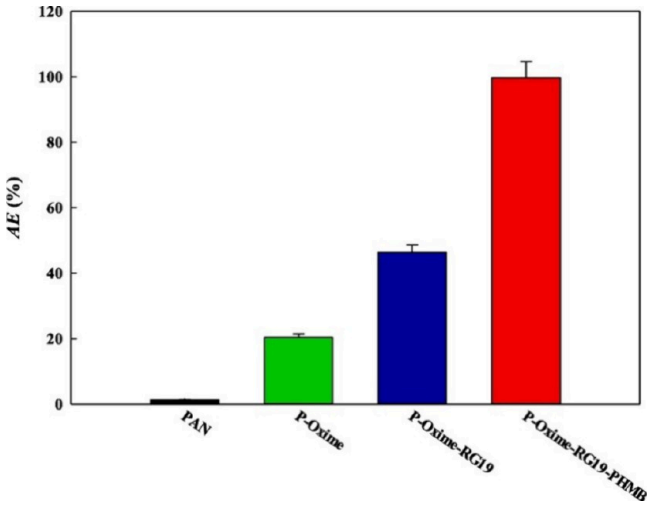

Figure 23. AE values of PAN, P-Oxime, P-Oxime-RG19, P-Oxime-RG19-PHMB nanofiber membranes against *E. coli*. Reproduced with permission from Le et al.[119] Copyright 2024, Elsevier Science Ltd.

nanofiber film in detail, as well as their repeatability and biocompatibility. Because of its remarkable performance and applicability, the P-Oxime-RG19-PHMB nanofibrous film was shown to possess high promise for an antibacterial system. The results also demonstrated the membrane's potential for a variety of applications, particularly in the food and textile fabrication industries.[119]

4.2.2.4. N-Halamine Compounds. Synthetic chemicals known as N-halamines have potent antibacterial activity because they react with microbes to release active halogen species, such as chlorine or bromine. Figure 15 shows the overall structural appearance of N-halamine. N-halamines release halogen species that oxidize and disrupt microbial cell membranes, proteins, and nucleic acids, leading to cell death.[6,50] N-halamine compounds can be incorporated into textile fibers or applied as coatings, padding, and or plasm treatment, as depicted in Figures 24a and b.[50] They are utilized in reusable gowns, hospital textiles, and other items linked to healthcare.[50] Ma et al.'s,[50] work involved the synthesis of (E)-1-(4-(allyloxy)phenyl)-N-(2-(piperazin-1-yl)ethyl)-methanimine (APPEM), a water-soluble N-halamines raw material, as illustrated in Figure 24a. Figure 24b shows the process of grafting this precursor onto CF using an argon plasma-assisted grafting-polymerization. The grafted CF was then treated with a diluted solution of sodium hypochlorite to convert the N-H bond to an N-Cl bond, yielding the antibacterial CF (CF-APPEM-Cl). The CF that was treated showed significant biocidal efficacy and stability when subjected to UV light, washing, and storage. In under 60 min, *E. coli* and *S. aureus* could be effectively inactivated. Furthermore, following 24 h of UV irradiation as well as 50 cycles of washing, the fabric's oxidative chlorine recovered by over 76.9% and 81.5%, respectively. After being stored for 30 days, the oxidative chlorine content stayed at 85%. However, this antibacterial treatment barely had any effect on the mechanical characteristics of CF.

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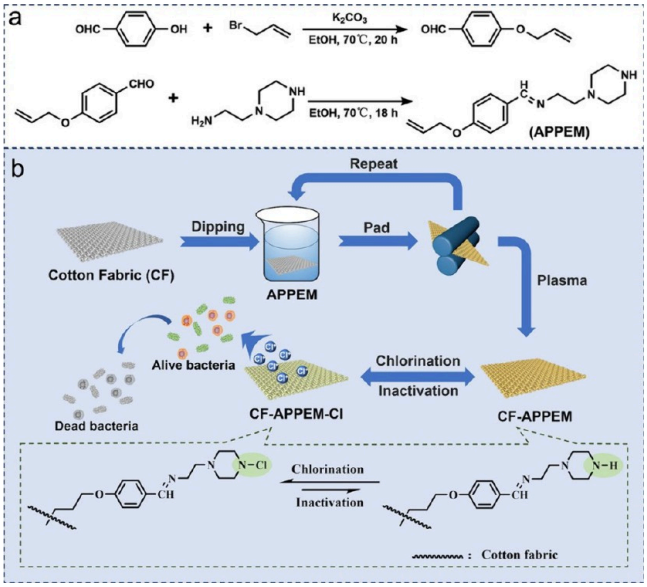

Figure 24. Synthetic route of APPEM (a) and the preparation process of antibacterial CF (b). Reproduced with permission from Ma et al.[50] Copyright 2024, Springer Nature.

A team of researchers combined natural thymol through a hydrophilic poly[2 (Dimethylamino)ethyl Methacrylate] (PDMAEMA) block to create the potent antibacterial agent thymol-poly(N,N-dimethylethyl methacrylate) (TP), which effectively reduces the drug-resistant threat of/from bacteria.[35] Thymol's limited water solubility was compensated for by the synergistic effect of PDMAEMA and TPs, which demonstrated high antibacterial activity via electrostatic interactions and membrane disruption mechanisms. The minimal inhibitory concentration of TPs against pathogenic bacteria and drug-resistant bacteria (MRSA) is 31.25 μg/mL, outperforming the commonly used isothiazolinone and its derivatives. TP might be connected to CFs to create robust, nonleaching fabrics (TP@CF) capable of successfully eradicating dangerous microorganisms, including drug-resistant MRSA. Compared to AAA (a group of enzymes present in bacteria, archaea, and eukaryotes that are considered targets for antibacterial medicines)-class antibacterial CFs, TP@CF fabric has a substantially greater kill percentage of 98% against common Gram-(−ve) and Gram-(+ve) bacteria. These practical cotton textiles also maintain their superior antimicrobial qualities even after 70 washings. This fabric has many possible uses in medical environments, including face masks, jackets, and apparel.[35]

4.2.3. Metal-Based Antimicrobial Agents. Among the available antimicrobial agents, metal-based antimicrobial agents are reputedly efficient as they act differently and last longer against different microbial species. These agents are often incorporated into textiles to provide durable antimicrobial properties.[6,10,14,22]

Ag is one of the most widely used metal-based antimicrobial agents owing to its wide-spectrum action and effectiveness at low concentrations.[6,9,10,14,22,57] Ag ions "Ag^+" interact with microbial cell membranes, triggering damage to the structural plus increasing its permeability. They also bind to microbial proteins and DNA, disrupting cellular functions and replication.[6,9,10,14,22,57] Additionally, Ag^+ can generate ROS, resulting in oxidative stress and cell death.[6,9,10,14,22,57] NAg and Ag salts are commonly incorporated into textile fibers or applied as coatings. nAg and Ag salts can also be embedded in textile fibers or applied as coatings: these textiles are used in medical dressings, sporting wear, and daily apparel to reduce microbial development and odor.[6,10,14,22,24,122] Diverse studies have documented the use of nAg as an efficient antibacterial agent in textiles, as shown in Table 2.

Cu has been used for its antimicrobial properties for centuries and is effective against bacteria, fungi, and viruses.[6,9,10,14,22] Cu^{2+} causes damage to microbes' cell membranes and intracellular components via oxidative stress. Cu can catalyze the production of ROS, leading to lipid peroxidation, protein oxidation, and DNA damage.[6,9,10,14,22] Cu NPs or copper salts can be embedded into textile fibers or used as surface coatings. Cu-treated textiles are used in healthcare settings, socks, and sportswear to reduce microbial contamination and odor.[6,9,10,14,22]

ZnO is known for its antimicrobial, UV-protective, and photocatalytic properties, making it suitable for textile applications.[6,9,10,14,22] ZnO NPs can disrupt microbial cell membranes and generate ROS under UV light, leading to oxidative damage of microbial cells. ZnO also interferes with microbial enzyme systems and protein synthesis.[6,9,10,14,22,88,123,124] ZnO NPs can be incorporated into textile fibers or applied as coatings. They are used in healthcare textiles, protective clothing, and UV-protective fabrics.[6,9,10,14,22,88,123,124]

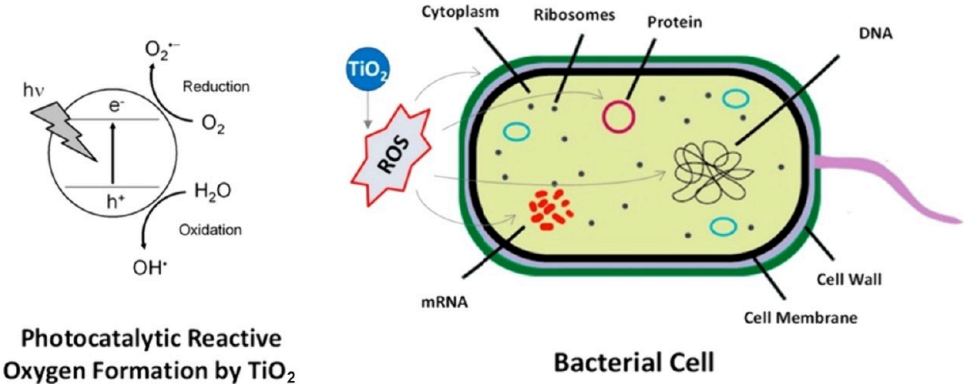

Figure 25. Illustration of the UV effect on photocatalytic TiO_2 NPs, forming reactive oxygen species that act against microbial cells and lead to cell death. Reproduced with permission from Salama et al.[25] Copyright 2024, Sage Journals.

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TiO_2 is a photocatalyst that exhibits strong antimicrobial properties under UV light. Under UV light, TiO_2 NPs generate ROS, which causes oxidative damage to microbial cell membranes, proteins, and DNA, as depicted in Figure 25. This photocatalytic activity leads to the inactivation and death of microorganisms.[25] TiO_2 NPs are used in textiles for self-cleaning and antimicrobial properties. They are applied as coatings or embedded in fibers for applications in healthcare and protective clothing.[6,9,10,14,22,25,88,123,124]

Again, Gold NPs (nAu) have gained attention for their antimicrobial properties and potential applications in textiles. nAu can disrupt microbial cell membranes and interfere with cellular functions by binding to proteins and DNA. The exact antimicrobial mechanisms are still under investigation but may involve oxidative stress and interaction with sulfur-containing biomolecules.[125] nAu can be incorporated into textile fibers or used as coatings. These textiles are used in high-end medical applications and luxury antimicrobial fabrics.[125] Synthetic antimicrobial agents, as powerful as they seem to be in tackling infections, present some tremendous disadvantages. The main disadvantages of synthetic antibacterial agents are that they are primarily nondegradable, not sustainable, highly cytotoxic, and many more, thus posing an ecological concern.[126] One unexpected consequence is the emergence of resistant forms of pathogenic microorganisms, to which these agents can be lethal, thereby decreasing the efficiency of these remedies. Further, synthetic antimicrobials may cause the alteration of the inherent bacteriology, thus leading to the formation of pathologic microbiota by causing disequilibrium; this will cause the formation of secondary infections or other related diseases. Therefore, although synthetic antimicrobials are effective, the various disadvantages related to their use should be sufficient to warrant careful use of these products.[30,43,44,72,79,91,122,127,128]

It is important to remember that section 3.1.1 focuses on the contact killing mechanism of antimicrobial agents, whereas section 4.2.3 is distinctly focused on metal-based antimicrobial agents and their mode of action.

4.3. Biodegradability and Toxicity Aspect of Commonly Used Antimicrobial Agents. Synthetic and natural/biodeived antimicrobial agents have widespread uses in virtue of their potency to suppress microbial growth. However, they are widely different with regard to their biodegradability and toxicity, and therefore their impacts on the environment and human health.[129] Chitosan/alginate/pectin,[130] essential oils,[34,131] aloe vera,[94,95] neem,[86,97] honey,[98−103] and turmeric,[108−111] are some of the natural antimicrobial agents that are biodegradable and of low toxicity. For example, chitosan, a polysaccharide, is obtained from chitin;[130] it is nontoxic and biodegradable, hence potentially suited for biomedical applications. Again, thyme oil and oregano oil are biodegradable but could show toxic effects at high concentrations, as they contain highly active bioactive compounds.[131,132] Similarly, neem and turmeric derivatives are low-toxicity, environmentally friendly antimicrobial agents, but their activity is compromised by stability issues.[86,97,108−111] In contrast, the highly effective synthetic antimicrobial agents comprising QACs, triclosan, and PHMB remain active in the environment because they break down very slowly:[133,134] The aquatic environment accumulates QACs that create harmful conditions for oceanic wildlife.

During and after the COVID-19 epidemic, the use of commercial antibacterial and personal cleaning solutions has been steadily rising: QACs are present in a significant portion of most of these antimicrobial products.[135] Some of these substances get into wastewater treatment plants (WWTPs) through the sewage collecting system. QACs, however, can enter the aquatic environment after passing through WWTPs. According to a study, 25% of QACs are released directly into the environment each year, with the remaining 75% going into WWTPs.[136,137] The two primary methods for eliminating QACs are active sludge adsorption and biodegradation.[135] Even though QACs often degrade on sludge solids, sorption to solids occurs far more quickly than biodegradation. Hence, biodegradation only makes up a minor portion of QAC degradation. Therefore, surface flooding or sewage discharge are the final ways these substances enter the ecosystem. The amount of QACs found in surface water and wastewater effluent around the world ranges from less than 1 μg/L to around 100 μg/L, and their concentration in raw wastewater may be ten times greater (1200 μg/L).[135]

As for PHMB, we know that it is an antiseptic with antiviral and antibacterial qualities that are utilized in pool cleansers, contact lens cleaning solutions, wound care dressings, and perioperative cleansing products. Concerns about human safety are raised by regulations, particularly when it comes to water treatment. The safety of this compound in Sprague-Dawley rats was evaluated by Asiedu-Gyekye et al.[138] A single dose of PHMB, ranging from 2 mg/kg to 40 mg/kg, was given by gavage through a stomach tube in accordance with the manufacturer's instructions. The hematological, biochemical, and histological results of the main organs were evaluated, and subchronic toxicity investigations were also carried out at doses of 2 mg/kg, 8 mg/kg, and 32 mg/kg body weight. The death rate was 50% when a dose of 25.6 mg/kg, or 1.6 mL of 0.4% PHMB solution (6.4× 103 mg/L of 0.1% solution), was administered. In the acute toxicity studies, histopathological analysis revealed no histopathological lesions in the kidney and heart samples, but 30% of the animals had mild hydropic changes in zone 1 of their liver samples. In the subchronic toxicity studies, 50% of the animals displayed feathery degeneration and mild hepatocyte cytolysis with or without lymphocyte infiltration at a dosage of 32 mg/kg. One heart sample reportedly revealed lymphocyte infiltration for the first time, while another kidney sample had minor tubular injury. According to the acute trials, the median fatal dose (LD50) is 25.6 mg/kg, with an LC50 of 1.6 mL of 0.4% PHMB. A few detrimental effects on the internal organs under investigation were also found in subchronic toxicological investigations.[138] Their report confirmed that PHMB possesses lethal effects on animals when leached or released into the environment.

Though triclosan demonstrates good effectiveness as an antimicrobial agent, scientists have established that it can trigger endocrine disruption effects and create antibiotic resistance.[133,134] Thus, it may be concluded that a significant portion of triclosan gets released into the environment through rivers.[133] Triclosan concentrations (>1.4 ng/L) in US streams have been reportedly found to be higher than those of any other chemical in wastewater samples from these streams.[133,139] Triclosan was found in high quantity (944 ng/L) in the surface waters of the Tamraparni River, even in India. According to the study, the main source of triclosan in this river is the industries that surround it.[133,140]

Inorganic antimicrobial agents such as nAg, TiO_2, and ZnO present effectiveness in antimicrobial protection but create safety problems because of their toxic impact in their NPs form

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Table 3. Biodegradability and Toxicity of Selected Antimicrobial Agents

Antimicrobial Agent	Type	Biodegradability	Toxicity	Ref.
Chitosan/alginate/pectin	Natural/Bioderived	High	Low toxicity, biocompatible	130
Essential oils	Natural/Bioderived	High	Low to moderate toxicity at high concentrations	34, 131, 132
Aloe vera	Natural/Bioderived	High	Low toxicity, safe for topical use	94, 95
Neem	Natural/Bioderived	High	Low toxicity, eco-friendly	86, 97
Honey	Natural/Bioderived	High	Low toxicity, safe for consumption	98−103
Turmeric	Natural/Bioderived	High	Low toxicity, widely used in food and medicine	108−111
QACs	Synthetic	Low/poor	Moderate to high toxicity, environmental persistence	136, 137
Triclosan	Synthetic	Low	High toxicity, endocrine disruptor	133, 134
PHMB	Synthetic	Low	Moderate toxicity, used in medical applications	138
N-Halamine compounds	Synthetic	Moderate	Low to moderate toxicity, effective against broad-spectrum microbes	144
nAg	Metal-based	Low	High toxicity at nanoparticle level, environmental accumulation	141, 143
ZnO NPs	Metal-based	Low	Moderate toxicity, potential nanoparticle risks	142
TiO_2 NPs	Metal-based	Low	Low toxicity, but nanoparticle form raises concerns	143

alongside their capacity to remain in the environment.[141−143] Researchers must strike a balance between product effectiveness and environmental protection by developing safer chemical alternatives and stronger regulatory standards. The biodegradability and toxicity of selected antimicrobial agents are presented in Table 3 for a better grasp of commonly used antimicrobial agents' impact after use.

Table 3 underscores the necessity of considering both toxicity and biodegradability when choosing antimicrobial agents for any application. Current literature emphasizes the pressing demand for sustainable substitutes and better regulation to mitigate the environmental persistence and toxicity of toxic antimicrobial agents, particularly the synthetic ones.[130] For example, Kumari et al.[133] discussed the environmental risks of triclosan. At the same time, Li et al.[136] and Mohapatra et al.[135] emphasized the lethal effect of QACs on the environment and animals/humans and the need for advanced treatment technologies for QAC removal from wastewater. Stamou et al.[143] and de Lima et al.[141] explored the life cycle assessment and ecotoxicological effects of nAg, emphasizing the creation of greener nanomaterials.

Collectively, explored/overviewed studies call for a balance between antimicrobial efficacy and environmental safety in future research.

5. EFFICACY OF ANTIMICROBIAL TEXTILES AGAINST PATHOGENS AND ADOPTED TEST STANDARDS FOR ANTIMICROBIAL EFFICACY

5.1. Efficacy of Antimicrobial Textiles against Pathogens. Many antimicrobial textiles show high efficacy against common pathogens like *S. aureus, E. coli, and C. albicans*, often achieving >99% reduction in microbial load.[6,9,10,14,22,44,45,71,73,74,128] However, the level of effectiveness again could vary due to the nature and concentration of the antimicrobial agent, substrate textile, and pathogen involved. For instance, treatments containing Ag are usually effective in a broad target range, and some natural compounds may be active toward specific bacterial genera/species.[6,9,10,14,22,44,45,71,73,74,128]

One of the parameters often discussed to determine the effectiveness of a particular antimicrobial treatment is its duration and how long it would take for the substance to lose efficacy within a specific number of wash cycles. However, the effectiveness of the antimicrobial agents incorporated into these textiles can be further affected by parameters possibly found in the surrounding environment, such as pH, temperature, and humidity. However, one might also discuss the possibility of pathogen's resistance to some kinds of antimicrobial agents as a perspective and worrisome issue that requires further investigation and development of new strategies and methods.[6,9,10,14,22,44,45,71,73,74,128]

With the growing use of antimicrobial textiles in the healthcare sector, sportswear, and communal utilities, understanding their performance against various pathogens is of particularly critical importance for researchers and manufacturers in this industry.

5.2. Adopted Test Standards for Antimicrobial Textile Efficacy. The efficacy of antimicrobial textiles is evaluated using various standardized test methods designed to measure their ability to inhibit or kill microorganisms. Here are some commonly adopted test standards:[71]

5.2.1. ASTM E2149. This standard test method measures the antimicrobial activity of treated materials using the dynamic liquid contact method.[71] It is widely used to assess the efficacy of antimicrobial coatings and treatments.

5.2.2. ISO 20743. This International Standard specifies a method for determining the antimicrobial activity of textile products.[71] It involves inoculating the textile with a standardized suspension of bacteria and assessing the reduction in bacterial count over time.

5.2.3. JIS L 1902. This Japanese Industrial Standard describes methods for testing the antibacterial activity and efficacy of textile products.[71] It includes both the agar diffusion method and the shake flask method.

5.2.4. AATCC 100. This American Association of Textile Chemists and Colorists (AATCC) method is used to evaluate the antimicrobial effectiveness of textile materials treated with antimicrobial agents.[71] It involves incubating the treated textile with a bacterial suspension and measuring the reduction in bacterial count.

5.2.5. EN 1499. This European Standard specifies a method for determining the bactericidal activity of chemical disinfectants used on hard surfaces, which can also be adapted for testing antimicrobial textiles.[71]

5.2.6. GB/T 20944.2/3. This Chinese National Standard describes the method for testing the antibacterial activity of textile products.[71] It includes the agar diffusion method and the shake flask method.

5.2.7. ISO 18184. This standard specifies a method for determining the antiviral activity of textile products against enveloped viruses.[71] It is particularly relevant for assessing the efficacy of textiles in preventing viral transmission.

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5.2.8. EN ISO 20645 (European Standard). Textile fabrics - Determination of antibacterial activity - Agar diffusion plate test.[71,145] EN ISO20645 is a European standard that describes a method for testing the antibacterial activity of treatments applied to textiles.

5.2.9. AATCC 30 (American Association of Textile Chemists and Colorists). activity, assessment on textile materials.[71,146,147] AATCC Test Method 30 is a standard developed by the American Association of Textile Chemists and Colorists to evaluate the antifungal properties of textile materials.

5.2.10. AATCC 147 (American Association of Textile Chemists and Colorists). Antibacterial activity assessment of textile materials: parallel streak method.[71,148] The American Association of Textile Chemists and Colorists established this standard test method to measure the antibacterial activity of textile materials.

5.2.11. DIN EN 14119 (German Institute for Standardization). Testing of textiles - Evaluation of the action of microfungi.[71,147] It is a European standard adopted by the German Institute for Standardization (Deutsches Institut für Normung) to assess the action of microfungi on textiles.

5.2.12. SN 195920 (Swiss Standard). Textile fabrics - Determination of the antibacterial activity: Agar diffusion plate test.[71,149] It is a Swiss standard test method for determining the antimicrobial activity of textiles.

These test standards establish a framework for assessing the antimicrobial efficacy of textiles under regulated circumstances, guaranteeing that the results are reproducible and similar across laboratories and products. The choice of the test procedure may depend on the particular purpose and the specific kind of microorganism being targeted.[71]

6. CASE STUDIES AND/OR ONGOING INNOVATIONS WITH RESPECT TO POTENTIAL INTEGRATION OF ANTIMICROBIAL PROPERTIES WITH/IN SMART TEXTILES

The incorporation of antimicrobial characteristics into smart textiles represents a thrilling field of development, combining cutting-edge materials science and innovative material systems such as wearable technology. Current developments and case studies with respect to research on smart antimicrobial textiles are herewith discussed in this section.

6.1. Case Studies and Innovations. *6.1.1. Quaternized N-Halamine-Coated Smart Cotton Textiles for Healthcare.*[150] *6.1.1.1. Application.* Antimicrobial hospital gowns, bed linens, and hygiene protection (wound dressings).

6.1.1.2. Innovation. The study presents/presented QACs/Hals/cotton-Cl, which functions through in situ free radical copolymerization to synergize QACs with N-halamine in antibacterial cotton fabric preparation. Through this advancement, the antibacterial active centers became more efficient, so *S. aureus* and *E. coli* bacteria could both be completely wiped/killed out within 10 min.[150] The fabric material also promoted wound repair and demonstrated outstanding water resistance with contact angles exceeding 130°, and it demonstrated a long-term lifespan during friction exposure, UV light, and storage conditions. This system was developed for lasting antimicrobial operation and enabled mass-scale manufacturing of reusable antibacterial fabrics that work well in medical care along with hygiene.

6.1.1.3. Outcome. The combination of antimicrobial properties and smart recharging along with self-cleansing presents a potential for reduced hospital-acquired infections (HAIs), improved patient monitoring and safety of personals and patients.

6.1.2. nAg-Tunable Color, Durable Antimicrobial, Self-Healing, and Superhydrophobic Smart Textile Fabrics.[151] *6.1.2.1. Application.* Protective health PPE, sportswear, and military uniforms.

6.1.2.2. Innovation. To address the issue of AgNPs' color fastness on cotton textiles and to incorporate multipurpose colored cotton fabrics, the study presents a technically straightforward solution-dipping technique for depositing composite films onto cotton textiles. Fluorinated-decyl polyhedral oligomeric silsesquioxane (F-POSS), branched poly(ethylenimine) (PEI), and AgNPs of customized colors were sequentially deposited in three steps using the solution-dipping method. This resulted in cotton with adjustable colors and long-lasting antibacterial and self-healing superhydrophobic qualities. In addition to maintaining the AgNPs' antibacterial abilities, the self-healing superhydrophobicity of the cotton fabrics dyed with AgNPs significantly improved the AgNPs' color fastness against mechanical damage and laundering.

6.1.2.3. Outcome. In this work, a portfolio of wearable, colored textiles with long-lasting antibacterial and self-healing superhydrophobic properties was shown. These multipurpose cotton textiles with self-healing superhydrophobic qualities, long-lasting antibacterial potentials, and vibrant colors can be used as protective apparel that inhibits bacteria that cause odors and have antimicrobial qualities. Additionally, its smart features improve functionality for health workers, soldiers, and athletes.[151]

6.1.3. Chitosan-Based Temperature and pH Responsiveness Proactive Antibacterial and UV Protection Smart Textiles.[152] *6.1.3.1. Application.* Eco-friendly activewear and/or medical textiles.

6.1.3.2. Innovation. CTS, a biodegradable polymer derived from chitin, in synergy with nAg, was used here to impart a holistic antimicrobial property. The research presents an innovative approach to developing smart viscose fabric, which integrates temperature-sensitive and pH-sensitive functionality along with antibacterial and UV-protective properties. The study used PNCS (poly(*N*-isopropylacrylamide)/chitosan) hydrogel as a carrier for biosynthesis of nAg to create a smart viscose fabric with pH and temperature-responsive attributes. $AgNO_3$ and bioderived-sumac leaf extract were used to create Ag NPs in an environmentally friendly manner without the use of hazardous chemicals. Direct immobilization and in situ synthesis on PNCS-modified fibers were the two functionalization techniques adopted. Higher nAg concentrations were obtained using the in situ technique, which also provided UV protection and antibacterial performance (>90% reduction against *E. coli* and *S. aureus*). As a reservoir, the PNCS hydrogel also ensured regulated nAg release while preserving moisture control.

6.1.3.3. Outcome. The smart multifunctional fabric establishes an environmentally friendly functionalization method that unites nanotechnology with hydrogel principles combined with advanced material engineering to create next-generation, state-of-the-art smart protective woven fabrics.[152]

6.1.4. TiO_2-SiO_2 and nAg Multifunctional (Superhydrophilic Yet Hydrophobic, Self-Cleaning, UV-Resistance,

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Antimicrobial) Smart Textile Fabrics. 6.1.4.1. Application. Eco-friendly, high-performance health PPE, sportswear, and protective gear.

6.1.4.2. Innovation. Researchers introduced a novel technique to create multilayered smart nanotextiles, which exhibit improved functional properties as the main aspect of this study. The researchers produced SiO_2 and TiO_2, along with nAg, utilizing a process that omitted toxic organic compounds to functionalize wool fabrics. Low pH solutions provided electrostatic binding conditions between wool and NPs that led to durable functionalization. nAg provided antibacterial effectiveness to the solution, and SiO_2 NPs enhanced surface hydrophilic properties while TiO_2 NPs enabled self-cleaning functions. Strengthening the performance came from integrating all three NP systems simultaneously because SiO_2 and Ag created antibacterial and superhydrophilic attributes, yet TiO_2 supported hydrophobicity with self-cleaning properties activated by sunlight.

6.1.4.3. Outcome. It was shown how the fabrication of smart antimicrobial textiles is achievable: functionalize wool fabrics with SiO_2, Ag, and TiO_2 NPs to create superhydrophilic, antibacterial, and partially self-cleaning materials in a straightforward, novel, and eco-friendly manner.[153]

6.1.5. Phase-Change Material (PCM) Smart Textiles with Thermal Energy Storage and Antimicrobial Properties.[154] *6.1.5.1. Application.* Multifunction antimicrobial textiles with energy storage ability

6.1.5.2. Innovation. The innovation of this study is the development of multifunctional microencapsulated phase change materials (MEPCMs) with thermal energy storage, photothermal conversion, UV blocking, and superhydrophobicity applicable for smart textiles. A one-step interfacial polymerization synthesized the n-eicosane core and CuO-doped polyurea shell with hierarchical, dendritic structure microcapsules. The microcapsules showed superior thermal stability while storing 162.3 J/g heat, performing efficient photothermal operations, and blocking 30% of UV rays. The textile applications benefit from these microcapsules because of their superhydrophobic characteristic, which delivers both enhanced thermoregulation and extended durability through their measured contact angle exceeding 148°.

6.1.5.3. Outcome. Infrared thermal conversion, hydrophobic properties, UV protection, thermal energy storage, and thermal insulation were cleverly combined to create MEPCM.

6.1.6. Smart Wearable Antimicrobial Textile Sensors for Breath Monitoring.[155] *6.1.6.1. Application.* Multifunctional smart textile-based PPE

6.1.6.2. Innovation. The main novelty from this research is that it presents smart, wearable cotton fabric with enhanced rapid-photothermal antibacterial destructive potential while monitoring microrespiratory patterns. The electrostatic self-assembly process produces the fabric by integrating chitosan quaternary ammonium salt (HACC) with MXene nanosheets. The high-density integration of the fabric materials endowed it with outstanding softness, efficient breathability, and continuous electrical conductivity. The MXene/HACC fabric was used to monitor/detect breathing depth and periodicity through its ability to take up and release water content. The fabric demonstrated dual functionality under light irradiation because it swiftly transformed light energy into heat to destroy microorganisms. Remarkably, even after ten washings, the fabric's high antibacterial efficiency (~100%) remained, making it highly resilient and appropriate for innovative wearable applications, especially in bacterial prevention and health monitoring.

6.1.6.3. Outcome. The researchers developed a protective fabric for monitoring breath activity and exhibiting instant photothermal antibacterial properties. The MXene material demonstrated inherent photothermal properties to deactivate bacteria quickly, reaching 100% antibacterial effectiveness for *E. coli* and *S. aureus* while using an irradiation power of 400 mW/cm^2 in <5 min.[155]

6.1.7. pH- and Temperature-Responsive Smart Antimicrobial Textile with Synergistic Moisture Management.[156] *6.1.7.1. Application.* Smart textiles for innovative applications

6.1.7.2. Innovation. These researchers developed an innovative antimicrobial textile system that used stimuli-responsive moisture management properties as its main innovation. nAg received two treatments before or after cotton fabric application through PNCS microgel incorporation methods for producing AgCl nanocrystals through in situ synthesis or colloidal silver integration. A dual functionality emerged in the cotton fabric because its temperature and pH dependency delivered nAg in a controlled manner, causing antimicrobial effects against *E. coli* and *S. aureus*. The smart textiles achieved a promising solution through silver addition, which slightly affected moisture management but provided effective yet controlled antimicrobial action.

6.1.7.3. Outcome. No matter the type of nAg adopted, the PNCS-modified cotton sample's ability to control moisture was impacted by the nAg embedding. On the fiber surface, in situ synthesis decreased the amount of modified PNCS microgel, but it did not affect the ability to swell. A greater concentration of applied modified PNCS microgel particles on the fiber surface was observed upon direct integration of colloidal nAg, which inhibited the swelling process of the fibers to some extent.[156]

Despite the great strides made thus far, challenges with regard to durability, biocompatibility, cost-effectiveness, and integration of multiple functions within a single textile material persist.[157] First, antimicrobial properties need to maintain their effectiveness when textiles undergo multiple washing cycles and normal wear. Second, manufacturers need to create materials that can safely remain on human skin while being environmentally sustainably produced. Third, the production costs need to be reduced to enable accessible antimicrobial smart textile availability for broad implementation. Finally, the integration of antimicrobial capabilities with multiple smart technology features needs to be achieved without degrading the overall functionality of the smart antimicrobial textile.

The incorporation of antimicrobial characteristics in intelligent clothing is a newly developing area with immense scope for breakthroughs in healthcare, sporting apparel, defense applications, and everyday wear.[157] Technologies such as N-Halamine coatings, nAg, and/or nAg-filled fibers are transforming multifunctional textiles that not only have resistant properties against pathogens but also offer sophisticated sensing and monitoring features. Ongoing development and research processes aim to circumvent existing bottlenecks and increase the portfolio of applications for these next-generation materials.

7. APPLICATIONS

7.1. Healthcare. Antimicrobial textiles have revolutionized healthcare settings by enhancing infection control measures,

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improving patient safety, and reducing the transmission of pathogens.[9,22,45,79] These textiles inhibit microbial growth on surfaces, garments, and medical devices, creating a safer environment for healthcare workers and patients. Below, we explore the diverse applications of antimicrobial textiles in healthcare, supported by relevant literature. These textiles are integral to medical uniforms and scrubs to reduce the spread of infections among healthcare personnel, space scientists, and even military personnel.[9,22,45]

Fabrics treated with antimicrobial agents, such as nAg or chlorhexidine, help inhibit bacterial colonization on uniforms and scrubs, reducing cross-contamination.[79] Antimicrobial finishes enhance the durability of medical textiles by preventing microbial degradation and maintaining hygiene through multiple wash cycles.[79] Antimicrobial textiles in hospital bedding and linens play a critical role in preventing healthcare-associated infections (HAIs): The application of antimicrobial treatments on textiles used for patient gowns, bed sheets, and pillowcases help control bacterial and fungal growth, reducing the risk of infections transmitted through contact.[158] These fabrics provide an additional barrier against pathogens, enhancing infection control protocols in healthcare facilities.[6,9,10,14,22,44,45,71,73,74,128]

Antimicrobial textiles are essential in surgical attire and drapes to maintain sterility and reduce the risk of surgical site infections (SSI). The antimicrobial coatings on surgical drapes and gowns help maintain sterility during procedures, minimizing microbial contamination and improving patient outcomes.[9,10,22,44,45,71,73,74,128] Antimicrobial barriers in surgical textiles prevent the ingress of pathogens into the surgical field, supporting aseptic practices in operating rooms.[159] Antimicrobial textiles in diagnostic tools, such as ultrasound probe covers and examination table covers, reduce microbial contamination and improve patient safety during procedures.[160]

High-touch surfaces in healthcare facilities, including textiles, provide an ideal environment for pathogenic bacteria to grow, which makes it necessary to incorporate effective antibacterial agents into textiles. Hospital-acquired infections are prioritized by public health systems due to the significant burden they pose to society. A highly lasting antibacterial gel-like solution called Ag Shell finish, which contains AgCl microparticles coupled to chitosan, was introduced by Mirmohammadsadeghi and his associates.[36] Their investigation focused on the coating's endurance under repeated washings, health hazards, and influence on the environment. The TEM pictures demonstrated a core-shell structure, with chitosan around collections of Ag microparticles in a protective shell. The homogeneous deposition of Ag Shell on the fabric surfaces was shown using FESEM. The antibacterial qualities of the fabrics coated with Ag microparticles were quantitatively examined using AATCC Test Method 100. The two types of bacteria used in this investigation were *E. coli* and *S. aureus*. The cross-linking agent-coated samples exhibited a 100% reduction in *S. aureus* and *E. coli* after 75 wash cycles, according to the antibacterial data. After 50 washing cycles, 99.88% and 99.81% decreases for *S. aureus* and *E. coli* were shown in the coated samples without a cross-linking agent. The antibacterial characteristics of the MG1655 model *E. coli* strain (ATCC 29213) and a multidrug-resistant clinical isolate were compared with those of nonpathogenic and pathogenic strains of the same species. The outcomes demonstrated the Ag ShellTM solution's antibacterial efficacy (up to 99.99% decrease) when applied to CF. The AATCC-147 assay was utilized to examine the leaching characteristics of the coated samples and the impact of the cross-linking agent on *S. aureus* and *E. coli*. Even after 75 wash cycles, the antibacterial effectiveness of all coated samples was remarkably high. By promoting a strong bond between the cotton substrate and Ag microparticles, the cross-linking agent reduced the number of particles that were released from the fabrics. To evaluate the color variations brought about by the coating procedure, color measurements were made. Table 4 shows the fixation values that were obtained after 25, 50, and 75 washing cycles, which were 44%, 32%, and 28%, respectively.[36]

Table 4. AATCC100 Effects of Crosslinking and Washing Cycles on Antibacterial Properties[a]

		E. coli		*S. aureus*	
Samples	Washing cycles	Percent reduction	Log 10 reduction	Percent reduction	Log 10 reduction
Control	0	0	0	0	0
A34	0	100	>6	100	>6
	25	100	>6	100	>6
	50	99.88	2.927	99.81	2.723
AgMP034	0	100	>6	100	>6
	25	100	>6	100	>6
	50	100	>6	100	>6
	75	100	>6	100	>6
SS26	0	100	>6	100	>6
	25	100	>6	100	>6
	50	100	>6	100	>6
	75	100	>6	100	>6

[a]Reproduced with permission from Mirmohammadsadeghi et al.[36] Copyright 2024, the Authors.

Advances in sustainable antimicrobial agents and eco-friendly textile finishes aim to minimize environmental impact while enhancing antimicrobial efficacy.[43,44,79,82,122] Increasing consumer awareness and demand for antimicrobial textiles drive innovations in product development and regulatory compliance.[22]

Ongoing research focuses on developing advanced antimicrobial textiles using nanotechnology and sustainable antimicrobial agents to improve efficacy and safety in healthcare settings.[6,9,10,71] Instances of the application of these advanced textile materials used in sports, healthcare, household, etc., are presented in section 7.5. Ensuring antimicrobial textiles meet regulatory standards for medical use, including efficacy, safety, and durability, to support infection control practices is very important.[14,71,73]

7.2. Apparel and Personal Protective Equipment (PPE). Antimicrobial textiles play a crucial role in apparel and PPE by enhancing hygiene, safety, and comfort for wearers. These textiles inhibit microbial growth, reduce odors, and contribute to overall protection against pathogens in various settings. Below, we explore the diverse applications of antimicrobial textiles in apparel and PPE, supported by relevant literature citations.

These coatings on surgical gowns provide an additional layer of protection against microbial contamination during surgical procedures, reducing the risk of surgical site infections (SSI).[6,9,10,14,22,71,73,161] Antimicrobial fabrics in face masks and respirators help inhibit bacterial and viral growth on the mask surface, enhancing protection and hygiene.[26] An

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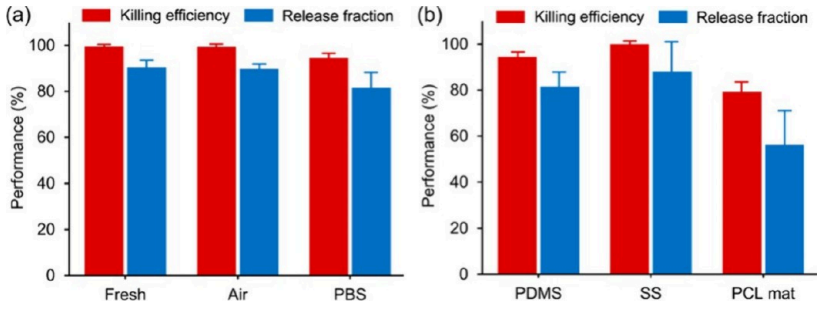

Figure 26. (a) Comparison of bacteria-killing and bacteria-releasing properties of Au-TA/Fe-PNIP surfaces against *E. coli* before and after storage in air or PBS for 10 days. (b) Summary of killing efficiencies and release fractions of different substrates coated with TA/Fe-PNIP hybrid films. Data are mean ± SD (n = 3). Reproduced with permission from Wang et al.[162] Copyright 2019, ACS Publications.

outstanding example of this is the creation of a totally bio-based photodynamic eco-textile by Lv et al.[26] using chemical cross-linking and dyeing techniques to load pigments made of silkworm excrement and QCTS onto spunlace cotton. Even in simulated office light conditions, the photodynamic eco-textile demonstrated all-season photodynamic effectiveness against microbes, inactivating 99.99% of MRSA within 15 min using daylight conditions (simulated) and reaching 95% inhibition within 30 min. After daily use under conditions of light, washing, and abrasion, the photodynamic textile's antibacterial activity persisted at over 90%, indicating consistent stability for use. The production of singlet oxygen by silkworm feces pigments under illumination and the electrostatic action of QCTS on bacteria have been identified as the photodynamic eco-textile's antibacterial mechanism. Additionally, it demonstrated the benefits of sustainability, biocompatibility, and touch comfort. The finishing agent cost for this technique was approximately 0.93 dollars per kilogram of photodynamic eco-textile. As a result, this research offers a useful method for dealing with bacterial illnesses that are resistant to drugs, which could lead to the large-scale production of completely bio-based photodynamic antibacterial fabrics.[26]

In a different investigation, a lignin-ZnO/water-based polyurethane system, comprising five distinct fractions of lignin to ZnO, was applied to PLA spunlace nonwoven fabrics using a film applicator, and the fabrics were then temperature-cured.[29] The cloth coated in WPU-1:5 formulation yielded a UV protection factor of 215.47 and a water WCA of 90.27°. Evident antibacterial action against *S. aureus* and *E. coli* bacteria was demonstrated by a nonwoven fabric coated with the WPU-1:5 formulation, with 89% and 100% of the former showing such activity, respectively. PLA nonwoven fabric showed better antibacterial activity as well as UV-shielding activity after lignin/ZnO was added to the WPU coating paste. Nevertheless, good outcomes were achieved despite the composite coatings' reduction of the materials' hydrophobicity and air and vapor permeability. The outcomes show that PLA nonwoven fabrics have improved mechanical and functional qualities after being coated with lignin/ZnO/WPU composites, which makes them a suitable material for use in protective medical textiles.[29]

Wang et al.[162] developed a practical and dependable method for immobilizing poly(*N*-isopropylacrylamide) (PNIPAAm) after depositing a tannic acid/Fe^{3+} ion (TA/Fe) complex layer on a variety of substrates, allowing them to switch between bacteria-killing and bacteria-releasing roles regularly. The improved photothermal properties of the TA/Fe complex enabled the modified surfaces to irradiate over 99% of adhering bacteria, including the multidrug-resistant strain MRSA, in less than 5 min of NIR irradiation, as illustrated in Figures 26a and b. Furthermore, the immobilized PNIPAAm's thermally triggered fouling-repellent characteristic allowed it simple to remove dead bacteria and debris from the surface by lowering the temperature. Under appropriate storage settings, the changed surfaces were stable for several days, and even after numerous "kill-release" cycles, the antibacterial activity was sustained. Thus, our discovery may offer a highly effective, broadly applicable, and antibiotic-free strategy to combat surface-attached bacteria for a range of applications.[162] The authors also discovered that the modified PDMS and SS surfaces showed a high NIR-activated bactericidal capacity, killing over 95% of attached bacteria. Furthermore, as seen in Figure 26b, they revealed that lowering the temperature resulted in the liberation of majority of the dead bacteria from the surfaces. They also discovered that the killing effectiveness and release fraction of the modified PCL mat were lower than those of modified flat substrates, possibly due to their porous nature. The authors also revealed that a 5 min NIR irradiation caused no morphological changes in bacteria linked to the Au surface, but it did cause severe shrinkage and membrane destruction in bacteria attached to the Au-TA/Fe and Au-TA/Fe-PNIP surfaces. Taken together, these findings indicated that the TA/Fe complex could effectively convert absorbed light energy to heat, thereby killing the attached bacteria via the hyperthermal effect; such a physical killing mechanism was said to provide a high-efficiency, broad-spectrum, and biocide-free solution to the problems associated with surface-attached bacteria over traditional biocide-based approaches.[162]

In addition, the scientists assessed the antibacterial surfaces' broad applicability and storage stability, both of which are critical for real-world use. A first batch of Au-TA/Fe-PNIP surfaces was made, which were either air-exposed or immersed in PBS for 10 days. These surfaces' antibacterial activity, photothermal property, and thermal responsiveness of wettability were evaluated and compared to those of a newly formed surface. Storage in PBS only marginally reduced bacterial release ability, showing significant stability over time, whereas air storage did not affect surface features or antibacterial action, as depicted in Figure 26a. Furthermore, because of the TA/Fe complex's universal adhesive capacity, the modification technique for the model Au surface is believed to apply to some real materials with differing chemistry or topography. The substrates for modification were polycaprolactone electrospun nanofiber mat (PCL mat), stainless steel (SS), and polydimethylsiloxane (PDMS). Modified PDMS and SS surfaces were shown to have highly

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effective NIR-activated bactericidal action against more than 95% of adhered microorganisms. As seen in Figure 26b, reducing the temperature caused the bulk of the dead bacteria to be released from the surfaces. It was revealed that the modified PCL mat had a lower killing effectiveness and release fraction than the changed flat substrates. This finding could be because of the permeable structure.[162]

The use of rhamnolipid as a biosurfactant to create CuO NPs via a hydrothermal process was demonstrated by Haripriya and colleagues in their research effort.[41] Gram-(+ve) (*S. aureus*) and gram-(−ve) (*E. coli*) bacteria were tested for the antibacterial activity of the synthesized sample using the spread plate method. The NPs' MIC and minimum biochemical concentration (MBC) against *S. aureus* and *E. coli* were 0.8 and 1.2 mg/mL, respectively. Even at low concentrations of RL-CuO NP, as shown in Figure 27a−d, the

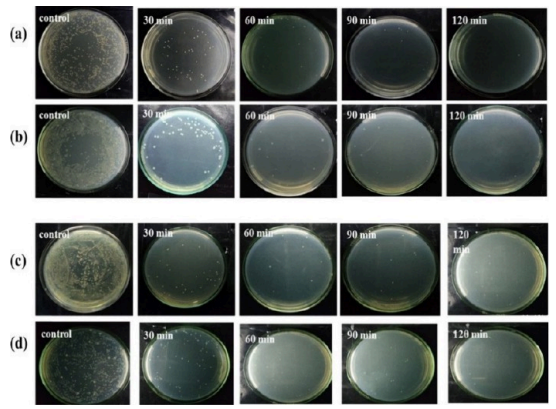

Figure 27. Antimicrobial activity of the RL-CuO screen-printed polypropylene fabric (a) *S. aureus* and (b) *E. coli* and antimicrobial activity of RL-CuO screen-printed CF on (c) *S. aureus* and (d) *E. coli*. Reproduced with permission from Haripriya et al.[41] Copyright 2024, IOPSCIENCE.

combined effects of rhamnolipid-induced cell membrane permeabilization and CuO-induced ROS generation might have produced improved antibacterial action. The antibacterial activity of the RL-CuO NPs was assessed against *S. aureus* and *E. coli* after they were successfully coated on cotton and polypropylene fabrics via screen printing. The outcomes showed that both types of bacteria, *S. aureus*, and *E. coli*, had bacterial reductions of more than 94% after 2 h of contact.[41]

In their research, Vojnits,[3] investigated a novel strategy to lessen the negative effects of illnesses brought on by antibiotic-resistant ESKAPE viruses on human health and the economy. They specifically looked into how antimicrobial textiles for PPE might stop the spread of infections. The research employed a methodical technique in conjunction with a quantitative approach to evaluate antimicrobial fabrics that prioritize user health and cost-effectiveness while simultaneously effectively targeting bacteria. The study has important ramifications for the development of the textile sector as well as for the real-world application of improved defense against microbial diseases, as presented in Table 5. With the information from this study, the textile industry will be able to create antimicrobial fabrics that not only fight diseases but also prioritize durability and safety, meeting the needs of extensive applications and settings. This will be a major step in bettering public health, slowing the spread of infectious diseases, and raising people's general well-being.[3]

Table 5. Summary of the Bacteriostatic Reduction (BR) Rate for Each Tested Bacteria Species[a]

Fabric coating agent name	BR (%), *E. coli*	BR (%), *K. pneum*	BR (%), *MRSA*
Silver nitrate	99.87	100	84.05
Silver nitrate sterilized	97.67	100	24.35
Zinc chloride	99.87	100	99.71
Zinc chloride sterilized	99.85	100	97.83
HM4005	99.34	100	0
HM4005 sterilized	65.78	0	36.03
HM4072	72.18	98.35	25.52
HM4072 sterilized	0	21.48	0
Tea tree oil	100	100	99.13
Tea tree oil sterilized	100	97.67	23.88

[a]Reproduced with permission from Vojnits et al.[3] Copyright 2024, MDPI (under an open access Creative Common CC BY license).

According to Tang et al.,[163] there is still a noticeable lack of functional textiles with antibacterial and antioxidant qualities, even with great interest in the medical and pharmaceutical fields. As shown in Figure 28, a novel composite fabric made of covalently linked nanostructured bacterial cellulose (BC) and cerium oxide NPs (BC@CeO_2 NPs) was presented in their work. Using an in situ chemical deposition method aided by microwaves, CeO_2 NPs were synthesized on the BC and produced mixed valence Ce^{3+}/Ce^{4+} CeO_2 NPs. Using this method guarantees that the composite fabric will hold up against repeated washings. The composite does not change CeO_2 NPs' ability to scavenge ROS or their quick and effective elimination of >99% of model microorganisms, including *E. coli*, *P. aeruginosa*, and *S. aureus*. Filter layers of BC@CeO_2 NPs cross-linked with propylene or cotton fibers are used to manufacture antimicrobial face masks, which shows the viability of using the fabric in commercial applications. In comparison to respirator masks, these masks demonstrated superior breathability, increased filtration efficiency, and total suppression of bacterial growth in all three bacterial strains. This work offers important new information on the creation of functional BC@CeO_2 NPs biotextiles, whose design can be used to produce medical dressings and cosmetics with mixed antimicrobial, antioxidant, and anti-inflammatory properties.[163]

Over the past decade, researchers have focused on developing advanced antimicrobial textiles using nanotechnology and sustainable antimicrobial agents to improve efficacy and durability,[10,14,41,62,70,73,88,161] and ensuring antimicrobial textiles meet regulatory standards for safety and effectiveness in various applications, including medical and consumer use.[9,10,30,44]

7.3. Household Textiles. The use of textiles and related products with antimicrobial properties has gained acceptance in homes, besides helping to reduce microbial growth, they help extend the useful life of textiles. From bedding to upholstery, these textiles offer benefits in maintaining cleanliness and reducing odors.[164]

Antimicrobial textiles in bedding and linens play a critical role in promoting sleep hygiene and preventing the growth of bacteria and fungi. The use of antimicrobial treatments assists in lessening allergens and decreases the microbial population on pillows and mattress covers, which in turn makes the bedroom a cleaner place to sleep.[165] Fabric or coatings containing antimicrobial properties include Ag ions or QACs, which keep the freshness of fabrics and inhibit the growth of

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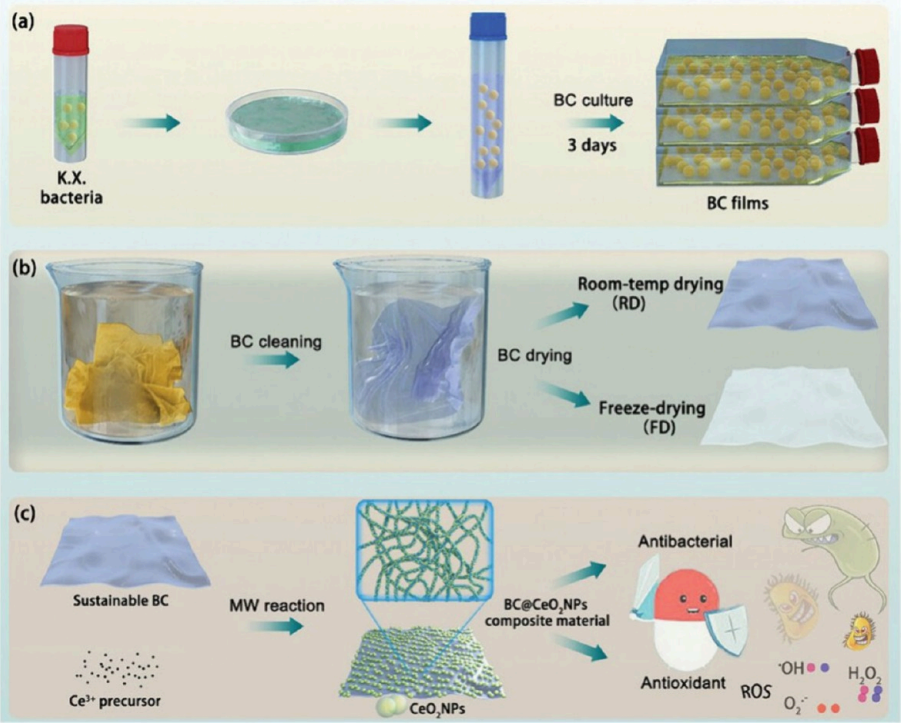

Figure 28. Schematic illustration of the formation of the BC@CeO_2NPs membranes with combined antibacterial and antioxidant activities. (a) The synthesis begins with the harvesting of K. Xylinum culture for 3 days to obtain the BC membrane. (b) After cleaning, the membranes are dried via two different methods, namely solvent evaporation at room-temperature (RD) or freeze-drying by sublimation of the frozen solvent (FD). (c) The microwave-assisted in situ chemical synthesis of crystalline CeO_2NPs covalently linked to the BC structure takes place via incorporation of the Ce^{3+} precursor in the wet (undried) BC membrane and further pH increase. These result in stable BC@CeO_2NPs membranes that are dried as in B. Reproduced with permission from Tang et al.[163] Copyright 2024, Wiley.

bacteria that cause bad odors.[166] Antimicrobial processed covers, fabrics and other home products prevent the growth of bacteria and fungi, especially in instances of high humidity, thereby keeping apparel fresh and long-lasting.[167]

One of the benefits of antimicrobial textiles is that upholstery and drapery enhance indoor air quality and reduce the spread of microbes on household surfaces. The antimicrobial treatments, therefore, allow the prevention of microbial occurrences on upholstery fabrics to enhance a clean indoor environment, particularly in houses that have drafting animals and young children.[168] Using antimicrobial finishes on curtains and blinds helps prevent mold formation and decreases the amounts of allergens so air is improved and less maintenance is needed.[169] Antimicrobial textiles in kitchen and dining areas contribute to food safety and hygiene by preventing cross-contamination: Sanitization procedures on table cloths include cases of antimicrobials that are useful in preventing the growth of bacteria during feeding and preparation of foods.[170]

Fabrics with antimicrobial properties in kitchen towels and aprons reduce the spread of bacteria and foodborne pathogens, enhancing food handling safety.[170] Also, antimicrobial textiles in children's products promote health and safety by reducing microbial exposure and maintaining cleanliness. Antimicrobial covers for crib mattresses inhibit mold and mildew growth, creating a safer sleep environment for infants.[170] Treatment of these materials with antimicrobial agents can help prevent microbial contamination and reduce the risk of infections in humans, especially children playing on the flooring.[170] Additionally, antimicrobial textiles in laundry and cleaning products contribute to maintaining cleanliness and preventing microbial recontamination: Antimicrobial finishes on cleaning textiles inhibit bacterial growth, prolonging their effectiveness and reducing the spread of pathogens during cleaning.[170]

Roy et al.'s study concentrated on utilizing the potential of an isolated bacterium known as *Burkholderia sp. EIKU21* for the synthesis of biogenic ZnO NPs (NPs) and pigment production while solubilizing bulk-ZnO (bZnO).[124] This allowed for the dyeing and coating of textiles with improved antimicrobial properties. After being optimized using CIElab and Kubelka-Munk (K/S) measurement, the pigment in the cell-free supernatant was effectively utilized to dye CFs under various conditions. The results showed excellent color retention at 100 °C for 60 min (K/S-0.5244), even after washing with water and detergent. Moreover, the application of stable biogenic ZnO NPs to the dyed cloth was validated by SEM and EDAX studies and bolstered by FTIR spectral analysis. Distinct levels of antibacterial activity against *Bacillus subtilis*, *S. aureus*, *E. coli*, and *Enterobacter aerogenes*, as well as *P. aeruginosa*, were demonstrated by the dyed fabric, highlighting their potential application in fabric with improved longevity and hygiene. The results of our study demonstrate the advantages of using pigments generated from Burkholderia sp. EIKU21 is coupled with biogenic ZnO NPs for sustainable textile dyeing as well as antibacterial coating on the fabric to promote environmentally friendly and practical solutions for the textile sector.[124] The authors suggested that the production of antibacterial fabric coated in biogenic ZnO-NPs and dyed with natural pigments serves as an inspiration for the environmentally friendly creation of antibacterial wipes and fabric materials.

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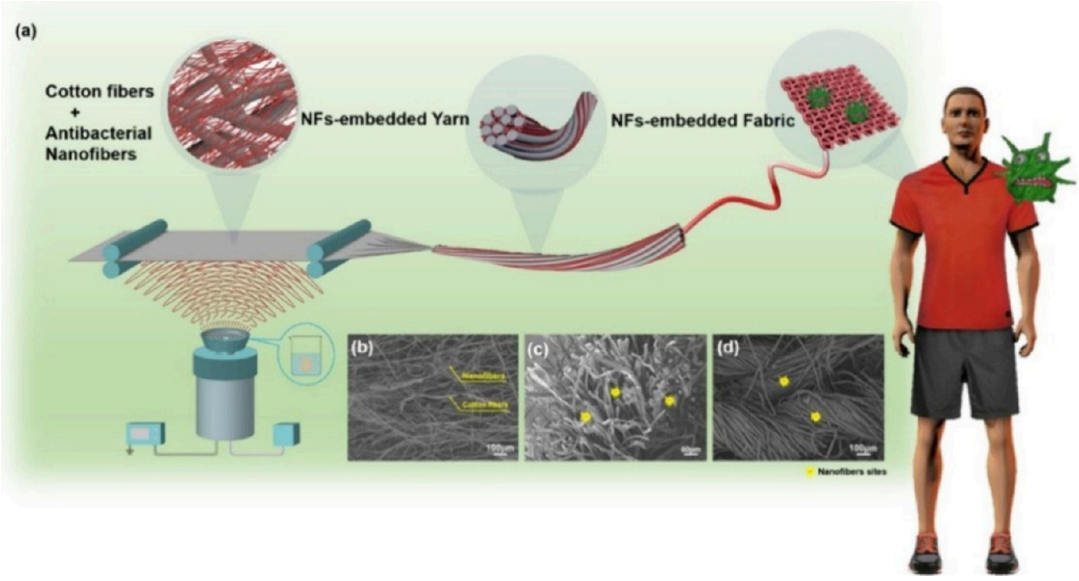

Figure 29. Fabrication of antibacterial NFs-embedded textiles. (a) Schematic illustration of the fabrication of antibacterial NFs-embedded textiles and their application in sportswear. (b) SEM image of fiber-mesh. (c) SEM image of the NFs-embedded yarn and (d) NFs-embedded fabric. Reproduced with permission from Qui et al.[171] Copyright 2020, Elsevier Science Ltd.

7.4. Sports and Outdoor Gear. Antimicrobial application in sport and outdoor wear is adopted for increasing the comfort of the dorsum, efficiency, and hygiene for the sporting and backpacking enthusiast.[127,171] These textiles hinder the growth of bacteria, control the smell, and increase endurance; therefore, they are commonly used where conditions are harsh and unforgiving. Antimicrobial textiles play a crucial role in sportswear by protecting against microbial contamination and enhancing athlete comfort:[127,171] Fabrics treated with antimicrobial compounds, like polymeric coatings, triclosan, nanographene, and nAg, assist in controlling moisture by wicking perspiration away from the skin and inhibiting the growth of bacteria and fungi that can produce odors.[127,172] Sportswear with antimicrobial treatments keeps clothes fresher between washes by preventing the growth of microorganisms that cause odors. For example, athletes participating in contact sports (such as football and wrestling) can lessen the spread of skin diseases like MRSA (Methicillin-resistant *S. aureus*) by wearing antimicrobial-treated jerseys and equipment.[22,70]

Antimicrobial materials are crucial for outdoor clothing to endure severe weather conditions and preserve hygiene during prolonged outdoor activities. Tent and sleeping bag fabrics treated with antimicrobial agents prevent the growth of mold and mildew, making camping cleaner and healthier.[72]

Antimicrobial textiles are increasingly used in sports and performance wear to regulate moisture, prevent odors, and improve comfort. Antimicrobial-treated fabrics, such as nAg, triclosan, or ZnO, prevent microbial development and minimize odor buildup during strenuous activities.[171] Compression gear with antimicrobial coatings helps regulate moisture and inhibit bacterial growth, promoting muscle function and recuperation.[70] Antimicrobial treatments in socks and shoe linings prevent fungal infections (e.g., athlete's foot) and minimize odor-causing microorganisms, particularly in moisture-prone situations[9,171] These components are necessary for protective gear and outdoor gear to withstand environmental challenges and preserve hygiene. Antimicrobial treatments on outerwear fabrics help ensure durability and maintain clean outdoor environments by inhibiting the formation of mold and mildew.[70] Furthermore, antimicrobial treatments in gloves and hats defend against microbial contamination and lower the risk of infections, particularly in severe or high-contact conditions.[70] Additionally, antimicrobial materials enhance user comfort and hygiene in daily clothing and accessories. Intimate garments with antimicrobial coatings improve comfort and hygiene by preventing bacteria development and preserving freshness.[173] Additional defense against microbial contamination is provided by antimicrobial treatments in gloves, hats, and scarves, especially during the cold and flu seasons.[165]

Current research looks at enhancing the antimicrobial properties of the coatings through nanotechnology-based treatment to enhance the coatings' durability and effectiveness in sports and outdoor wear.[171] Other works examine the ecological effects of antimicrobial agents from the textiles as well as develop solutions that are environmentally friendly yet effective.[171]

In the study by Qui et al.,[171] antibacterial electrospun nanofibers were deposited into cotton fiber mesh, which was subsequently spun into functional textiles as depicted in Figure 29.

This resulted in nanofiber-embedded textiles (NFs-embedded textiles) with long-lasting antibacterial activity. The NFs-embedded textiles demonstrated potent antibacterial activities in their prepared state. For both *S. aureus* and *E. coli*, the inhibition rate was 99.99%. Furthermore, the cytotoxicity test conducted on the produced textiles demonstrated that the textiles containing NFs exhibited a minimal cytotoxic reaction when exposed to seeded cells in vitro. Based on these characteristics, sportswear made of antibacterial textiles was created, which showed exceptional antibacterial durability, remaining over 95% effective against *E. coli* and *S. aureus* even after 35 washing cycles. It was hypothesized that the NFs-embedded textiles would offer a revolutionary process for durable, functional textiles.[171]

Researchers elsewhere have examined how the creation of novel functionalized fabrics, like those with antibacterial qualities, has been aided by the increased concern over health

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and cleanliness and the advancement of technology concerning sport-based antimicrobial textiles.[174] In addition to assessing the impact of the knitting structure and wash/dry conditions (natural air-drying or drying in a dryer), they also sought to evaluate the antibacterial activity and durability of textiles functionalized with Ag through two distinct methods: fiber extrusion (functional fiber) and exhaustion (surface functionality). Using the absorption method, the antibacterial activity was assessed in accordance with JIS L 1902:2008 guidelines. A good antibacterial activity was obtained for 100% of the inhibition of germ growth for both functionalization techniques, as shown in Figure 30a. Concerning washing

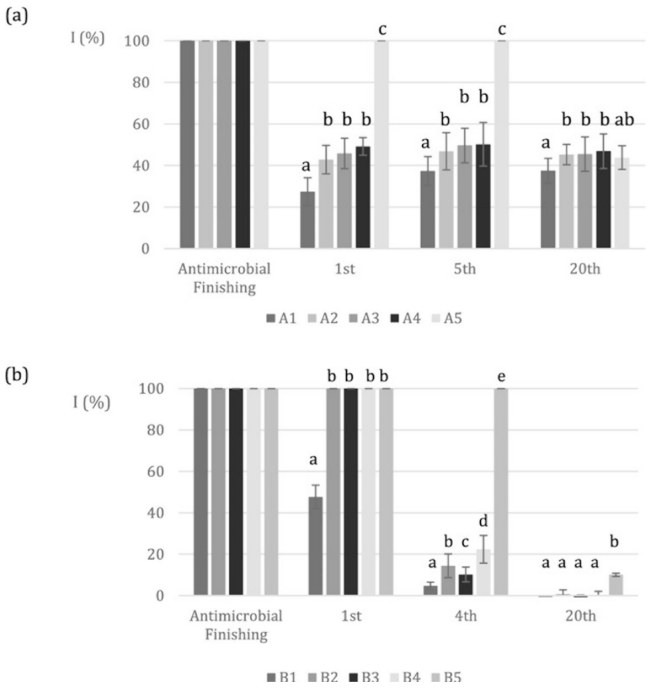

Figure 30. Percentage of *Staphylococcus aureus* growth inhibition (I%) of the samples at the end of the finishing and after the washing and tumbler drying cycles of the five knitting structures with antimicrobial functionalization by the extrusion method (a) and by fiber exhaust method (b). Error bars represent standard deviations (SD). Different lowercase letters indicate significant differences between knitting structures ($p < 0.05$). Reproduced with permission from Pintu et al.[174] Copyright 2024, Springer Nature.

cycle durability, both techniques demonstrated poor levels of durability (growth inhibition below 50% after 20 wash cycles for samples functionalized by fiber extrusion and below 10% after 20 wash cycles for samples functionalized by exhaustion) as per Figure 30b. Furthermore, it was confirmed that the laundry/drying circumstances and knitting structure affected the antibacterial activity's persistence. Repurposed textiles using fiber extrusion were retained and showed 100% growth inhibition following five cycles of washing and drying on a flat surface, as per Figure 30. For extrusion functionalization, knitting constructions with greater mass per unit area and samples that were cleaned and allowed to dry naturally, longer functionalization durability was generally achieved.[174]

7.5. Industrial and Environmental Applications. Antimicrobial textiles play an important role in a variety of industrial and environmental applications, providing solutions to limit microbial contamination, improve hygiene, and boost durability in demanding settings.[1,2,25] The various applications of antimicrobial fabrics, as well as their significance in industrial and environmental protection, are briefly discussed here. These fabrics are commonly used in healthcare institutions to limit pathogen transmission and prevent HAIs. The principal applications are textiles used for hospital beds, sheets, and patient gowns to assist in maintaining sanitary conditions and limit the possibility of cross-contamination.[158]

Antimicrobial-treated textiles offer additional protection during surgery, reducing the possibility of SSI and improving patient safety.[175] Medical textiles with antimicrobial coatings, such as bandages, wound dressings, and catheters, reduce microbial colonization and infections, improving patient outcomes. Sportswear and sporting equipment with antimicrobial materials reduce odor-causing bacteria, inhibit microbial growth, and maintain freshness during intense exercise.[79] By preventing fungal growth in wet settings, antimicrobial treatments used in socks and shoe linings help prevent fungal illnesses like athlete's foot.[70,79] Moreover, antimicrobial finishes in curtains, upholstery, and carpets inhibit mold, mildew, and bacterial growth, improving indoor air quality and hygiene in residential settings.[22,73,166,176] Additionally, antimicrobial textiles have diverse industrial applications to enhance safety, hygiene, and durability. These textiles are used in food processing facilities, and packaging materials help maintain food safety by preventing microbial contamination and spoilage.[22,73,176] The fabrics are crucial in cleanroom environments where maintaining sterility and minimizing microbial contamination are critical for sensitive manufacturing processes.[73,168]

In their work, Radha et al.[37] concentrated on creating antimicrobial fibers for the textile industries that serve the medical and healthcare fields. To attach cotton textile cellulose fibers and improve their adherence to glycogens on bacterial surfaces, carbon dots (CDs) were engineered with boronic acid groups. Various approaches were used to manufacture and describe CDs based on curcumin and boric acid, demonstrating zeta potential values and nanoscale dimensions. *S. epidermidis* and *E. coli* bacteria were unable to proliferate when exposed to the CDs; the antibacterial activity of UV-activated CDs was enhanced. After that, the CDs' antibacterial activity was examined, and the results showed that they had a high adhesion to the fibers of cellulose paper, no CD diffusion, and a strong inhibition of bacterial growth. Human cell lines used in cytotoxicity experiments revealed no toxicity to cells at doses as low as 100 μg/mL. Still, at concentrations higher than 1000 μg/mL, there was a rise in toxicity. Nevertheless, human cell lines tested the CD-modified cellulose paper fibers, and they revealed no toxicity, indicating that their antibacterial qualities are safe for human consumption. These results indicated promising potential for using these discoveries in industrial and therapeutic settings.[37]

Antimicrobial textiles contribute to environmental protection by reducing microbial contamination in sensitive ecosystems and improving sustainability:[27] Antimicrobial membranes and textiles in water filtration systems help eliminate microbial pathogens, improving water quality and safety.[27] An excellent instance is found in the report by Ye et al.[27] In a different work, membrane substrates based on hydrolyzed polyacrylonitrile (HPAN) were used to create polydopamine/tobramycin composites by a one-step codeposition process that was started by ammonium persulfate.[27] Possessing a remarkable ability to oxidize, ammonia persulfate can easily initiate the codeposition of tobramycin and

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dopamine through Schiff base and Michael addition reactions. This creates a dense, defect-free polydopamine/tobramycin composite layer with a uniformly narrowed pore size that functions as a tight ultrafiltration membrane. In specific, a tight composite ultrafiltration membrane with a MWCO of 3692 Da (also known as the M4 membrane) was created following a 2.0-h codeposition, and it demonstrated >98.0% retention against four reactive dyes (molecular weights: <1000 Da) and <0.8% rejection of NaCl (10.0 g/L). Given the goal of recovering sustainable resources from high-salinity textile wastewater, the stark difference between reactive dyes and NaCl highlights the tight composite ultrafiltration membrane (M4) (as shown in Figure 31) as potentially applicable for dye

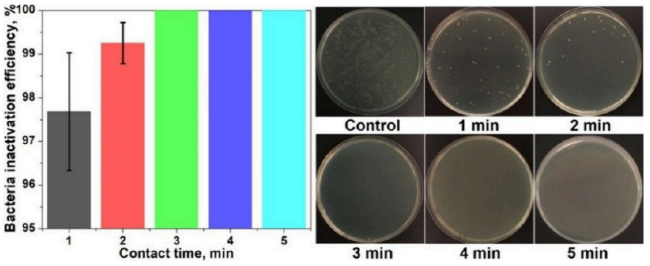

Figure 31. Antibacterial performance of the polydopamine/tobramycin composite membrane (M4) under different contact times. Reproduced with permission from Ye et al.[27] Copyright 2024, Elsevier Science Ltd.

and NaCl separation. Tobramycin's intercalation into the polydopamine-based composite layer also creates a tight ultrafiltration membrane (M4) with exceptional antibacterial qualities. Since the integrated tobramycin, a broad-spectrum antibiotic, effectively targets the ribosome of *E. coli* bacteria to hinder its translation for protein synthesis, a complete inactivation efficiency (i.e., 100%) against *E. coli* bacteria was achieved in a very short-time contact (i.e., 3 min) with the M4 composite membrane. As a result, the tight composite ultrafiltration membrane made by quickly codepositing tobramycin and dopamine demonstrated consistently stable dye/salt fractionation performance as well as unmatched antimicrobial activity, providing a platform technology for the sustainable recovery of resources (salts or dyes) from the high-salinity textile wastewater.[27]

Some of the uses of antimicrobial textiles include crop protection and soil protection against microbial infections, hence increasing agricultural production.[177] Antimicrobial textiles are also used in waste management applications, including landfill liners and waste containment barriers, which inhibit microbial decomposition and control the release of toxic substances.

The general control of microbial resistance to antimicrobial agents and the ability to maintain the effectiveness of antimicrobial finishes on textiles is crucial. Evaluating the consequences of antimicrobial agents leaching from textiles and identifying eco-friendly options. It is crucial to meet and gain compliance per the set regulations, Codes, and certifications, as many applications of antimicrobial textiles are for making articles that are in direct and prolonged contact with people's skin, including underclothes. The recent trend is the development of advanced antimicrobial textile materials with synergistic property performance, as presented in Table 6.[178] Table 6 overviews the application niches, formulations, fabrication approaches, antimicrobial agents, mechanisms, and corresponding references for antimicrobial textiles. Each row highlights a specific application area and relevant details of formulation, fabrication, antimicrobial agent, efficacy, application niche, and mechanism of action.

7.6. Emerging Applications. Because of the development in material science and nanotechnology, innovative applications of antimicrobial textiles are finding a place in industries such as aerospace, military, wearable electronics, innovative fabrics, and smart packaging.[179−181] Antimicrobial textiles will be one of the significant interests in interplanetary missions because maintaining hygiene in confined habitats is critical in aerospace. In the military, antimicrobial textiles are applied in combat uniforms to minimize the chance of infection caused by their prolonged usage under extreme conditions.[179]

Another frontier is that of wearable electronics, wherein antimicrobial fabrics integrated with sensors offer hygiene and allow continuous health monitoring.[179−181] Smart fabrics with integrated stimuli-responsive antimicrobials, such as temperature-responsive polymers, are proposing new solutions for wearable technology.[179] Also, in smart packaging, smart antimicrobial textiles provide an environmental way of enhancing the shelf life of perishable goods with lesser environmental impact using biodegradable active agents like chitosan and ZnO NPs.[180] While these textiles are bound to revolutionize safety and hygiene in critical and emerging areas of concern, continuous research efforts are still needed for sustainable and durable antimicrobial agents.

8. CHALLENGES

Designing and integrating antimicrobial textiles raise major technical, regulatory, environmental, and economic issues.[21,199] These challenges can have consequences for controlling the effectiveness, safety, and profitability of antimicrobial textiles. In this section, we have explored the key challenges facing the development and application of antimicrobial textiles as per the literature covered in this review paper in brief.

8.1. Efficacy and Durability. Microorganisms can develop resistance to antimicrobial agents over time, reducing the effectiveness of antimicrobial textiles.[21] Ongoing research is required to create novel antibacterial agents and tactics that can circumvent resistance mechanisms. After numerous launderings, textiles used in consumer and healthcare environments must retain their antibacterial potency. It is a technical difficulty to make sure that antibacterial agents endure typical washing procedures without losing their efficacy.[200]

8.2. Safety and Toxicity. Unique concerns have been expressed regarding the release of nAg and some biocides into the environment; some of these compounds are toxic to humans if they leach from the textiles.[123] Their use, duration of action, frequency, and combinations must be adequately regulated to achieve optimal antimicrobial activity while minimizing safety concerns that could compromise the agencies' approval and consumers' acceptance. The redundancy of antimicrobial textiles can cause these agents to be discharged into wastewater and aquatic ecosystems, affecting microbial communities and marine life. Environmentally friendly antimicrobial materials and coatings for which environmental impact is reduced are needed.[123]

8.3. Regulatory Compliance. Antimicrobial textiles are subject to stringent regulations governing their safety, efficacy, and labeling in different regions.[4,22,199] Such operating in these regulatory environments demands extensive testing and

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Table 6. Development and Application of Antimicrobial Textiles

Application niche	Formulation	Fabrication approach	Antimicrobial agent	Mechanism	Efficiency/efficacy	Ref.
Healthcare apparel and PPE	DADMAC@nylon/cotton	SM + padding + plasma induced in situ polymerization	DADMAC	Charge interaction, chemical, membrane disruption, enzyme inhibition, etc.	99.9% effective against *K. pneumoniae* and *S. aureus*	32
	TiO_2@CF	SM + dip-coating + UV activation	TiO_2	PK (photodynamic), ROS, disruption of the bacterial cell membrane, etc.	99.99% effective against *S. aureus* and *E. coli*	25
	Artemisia afra and *Eucalyptus globulus*@cotton and polyester fabric	SM + dip-coating	*Artemisia afra* and *Eucalyptus globulus* plant extract	PK (photodynamic), ROS, disruption of the bacterial cell membrane, etc.	Effective antimicrobial activity	33
	2-Methyl 2-oxazoline@textile fabric	Plasma treatment	2-methyl 2-oxazoline	PK (photodynamic), ROS, disruption of the bacterial cell membrane, etc.	Effective against *P. aeruginosa* and *S. aureus*	51
	Bacterial cellulose (BC)@ CeO_2	SM + microwave-assisted in situ chemical deposition	CeO_2	PK, ROS, disruption of bacterial cell membrane, photocatalytic, etc.	>99% effective against *E. coli*, *P. aeruginosa*, and *S. aureus*	163
	Essential oils-CTS@CF	SM + dip-coating (soaking)	Essential oils-CTS	PK and disruption of bacterial cell membrane	99.99% *S. aureus* and *E. coli*	34
	QCTS@NW cotton	NW technology + padding	QCTS	PK (photodynamic)	99.99% MRSA kill	26
	Nylon: Spandex plain-weave fabric/ $ZnCl_2$-nAg-tea tree oil	SM + spray coating	Refer to Table 3	PK and disruption of bacterial cell membrane	Refer to Table 3	3
	Tannic acid Au-Fe^{3+}@PNIPAAm-NH_2	Grafting-to + coordination complex	Fe^{3+}@PNIPAAm-NH_2	PK (photodynamic)	>90%	162
	CTS-biomordant/pomegranate rind-onion peel extract@CF	SM + dyeing	Pomegranate rind and onion peel extract	PK and disruption of bacterial cell membrane	93.8−99.9% against *S. aureus* and *K. pneumoniae*	182
	Onion peel extract (polyphenols)@ cotton, nettle, hemp, linen, and/or bamboo fabrics	SM + in situ dyeing onion peel extract inclusion	Onion peel extract	PK and disruption of bacterial cell membrane	-	183
	RL-CuO@PP and RL-CuO@CF	Screen printing	Rhamnolipid@CuO NPs	ROS generation, PK, and biofilm inhibition	94% against S. aureus, *E. coli* and SARS-CoV-2	41
	Lignin/zinc@PLA NW fabric	SM + coating (4-sided film applicator)	Quaternary ammonium@lignin/zinc	Chemical (Zn^{2+} release), ROS, membrane disruption, photocatalytic activity, etc.	89 and 100% against S. aureus and *E. coli*	29
	Neem dye@jute fabric	SM + in situ dyeing neem inclusion	Neem dye	PK, chemical, membrane disruption, etc.	Effective against *E. coli* and *S. aureus*	97
	Justicia schimperiana plant leaves extract@CF	SM + in situ dyeing Justicia schimperiana inclusion	*Justicia schimperiana* plant leaves extract	Antioxidant activity, quorum sensing inhibition, membrane disruption, etc.	Effective against *S. aureus* and *E. coli*	87
	Thymol-poly(N,N-dimethylethyl methacrylate) (TP)@CF	SM + dip-coating	TP	Chemical, PK, and disruption of bacterial cell membrane	98% effective against *E. coli*, *S. aureus*, and MRSA (drug-resistant bacteria)	35
	Propolis@gelatin/erythritol/collagen/glycerol-cotton nonwoven	Sol-gel process	Propolis-erythritol	Chemical, PK and disruption of bacterial cell membrane, inhibition of bacterial cell division, etc.	Effective against bacterial infection in wounds	98
	Microbial pigment@lyocell knitted fabric	SM + in situ dyeing	Microbial pigment	Chemical, PK and disruption of bacterial cell membrane, inhibition of bacterial cell division, etc.	99.9% effective against *S. aureus*	184
	CaF_2@CF	Screen printing	CaF_2	Chemical (fluoride ion release), PK and disruption of bacterial cell membrane, inhibition of bacterial cell division, etc.	≥93% effective against *E. coli* and *S. aureus*	42
	nAg-PVA@cotton	SM + pad-dry-cure (padding)	nAg	PK and disruption of bacterial cell membrane	100% inhibition against *E. coli*, *S. aureus*, and *E. aerogenes*	185
	nAg-PVA@PET	SM + pad-dry-cure (padding)	nAg	PK and disruption of bacterial cell membrane	100% inhibition against *E. coli*, *S. aureus*, and *E. aerogenes*	185

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Table 6. continued

Application niche	Formulation	Fabrication approach	Antimicrobial agent	Mechanism	Efficiency/efficacy	Ref.
	nAg-CTS@CF	SM + dip-coating	nAg-CTS	ROS) generation, PK, membrane disruption, photodynamic effect, etc.	99.88% and 99.81% effective against *S. aureus* and *E. coli*	36
	TiO_2-nAg@CF	SM + in situ dyeing-TiO_2-nAg inclusion	TiO_2-nAg	ROS, PK, membrane disruption, photodynamic effect, etc.	Effective against *S. aureus* and *E. coli*	186
Sports and outdoor gear	Triclosan-PAN@cotton	SM + ES	Triclosan	Fatty acid synthesis inhibition, membrane disruption, protein, and RNA synthesis inhibition, etc.	95% effective against *E. coli* and *S. aureus*	171
	nAg@knitted polyamide fabric	SM + fiber coating + knitting	nAg	PK and disruption of bacterial cell membrane	100% inhibition against *S. aureus*	174
	Nutmeg seeds extract-essential oil@ textile underarm pads	SM + impregnation/ soaking	Nutmeg seeds extract-essential oil	PK and disruption of bacterial cell membrane	Effective against sweat odor and eliminating bacteria	30
	Birch leaves extract-essential oil@ textile underarm pads	SM + impregnation/ soaking	Birch leaves extract-essential oil	PK and disruption of bacterial cell membrane	Effective against sweat odor and eliminating bacteria	30
	Tea tree extract-essential oil@textile underarm pads	SM + impregnation/ soaking	Birch leaves extract-essential oil	PK and disruption of bacterial cell membrane	Effective against sweat odor and eliminating bacteria	30
	Marigold flower extract-essential oil@ textile underarm pads	SM + impregnation/ soaking	Birch leaves extract-essential oil	PK and disruption of bacterial cell membrane	Effective against sweat odor and eliminating bacteria	30
	Rosemary leaves extract-essential oil@ textile underarm pads	SM + impregnation/ soaking	Birch leaves extract-essential oil	PK and disruption of bacterial cell membrane	Effective against sweat odor and eliminating bacteria	30
	Pine needle oil extract-essential oil@ textile underarm pads	SM + impregnation/ soaking	Birch leaves extract-essential oil	PK and disruption of bacterial cell membrane	Effective against sweat odor and eliminating bacteria	30
	Chamomile flower extract-essential oil@textile underarm pads	SM + impregnation/ soaking	Birch leaves extract-essential oil	PK and disruption of bacterial cell membrane	Effective against sweat odor and eliminating bacteria	30
Household textiles	ZnO@cotton	SM + in situ dyeing-ZnO inclusion	ZnO-NPs	ROS, PK, membrane disruption, photodynamic effect, etc.	Effective against *E. coli*, *S. aureus*, and *E. aerogenes*	124
	Vanillin@CF	SM + in situ dyeing-vanillin inclusion	Vanillin	ROS, PK, membrane disruption, photodynamic effect, etc.	50% effective against *S. aureus* and *E. coli*	187
	Diammonium phosphate octadecyl citrate (DAPOC)@CF	SM + padding (pad-dry-cure)	DAPOC	ROS, PK, membrane disruption, photodynamic effect, etc.	Effective against *S. aureus* and *E. coli*	113
	Gallotannin@CF	Screen printing	Gallotannin	PK and disruption of bacterial cell membrane, biofilm inhibition, etc.	Effective against *S. aureus* and *K. pneumonia*	43
	CTS@CF	Screen printing	CTS	PK and disruption of bacterial cell membrane, biofilm inhibition, etc.	Effective against *S. aureus* and *E. coli*	44
	Melamine-formaldehyde@ triclosan-CF	Screen printing	Melamine-formaldehyde@triclosan (shell@core) microcapsules	Fatty acid synthesis inhibition, membrane disruption, protein, and RNA synthesis inhibition, etc.	Effective against *S. aureus* and *E. coli*	188
	nAg@CF	In situ generation and coating	nAg	PK and disruption of the bacterial cell membrane, etc.	95% and 92% effective against *S. aureus* and *E. coli.*	189
	nAg@polytetrafluoroethylene (PTFE)	SM + ES	nAg	ROS, DNA/RNA damage, photocatalytic activity, etc.	97.0% and 97.1% effective against *S. aureus* and *E. coli*	190
Industrial applications	Carbon dots (CDs)@cellulose fibers	SM + dip-coating	CDs	ROS generation, PK, membrane disruption, photodynamic effect, etc.	90−98% effective against *E. coli* and S. aureus	37
	Daphne mucronate extract (dye)@ wool fabric	SM + in situ dyeing-antimicrobial dye inclusion	Daphne mucronate extract (dye)	Phytochemical, membrane disruption, antioxidant activity, protein denaturation, etc.	Effective against *S. aureus*	191
	Mikania micrantha leaves extract@CF	SM + padding	Mikania micrantha leaves extract	Phytochemical, membrane disruption, antioxidant activity, protein denaturation, etc.	Effective against *S. aureus*	192

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Table 6. continued

Application niche	Formulation	Fabrication approach	Antimicrobial agent	Mechanism	Efficiency/efficacy	Ref.
Environmental textiles	Tobramycin-tobramycin@HPAN	SI/SM + in situ polymerization of dopamine-tobramycin	Tobramycin	Bactericidal action, membrane damage, and protein synthesis inhibition	100% effective against *E. coli*	27
	m-aramid-vanillin@cotton	SM + drop coating	Vanillin	Membrane disruption, biofilm inhibition, and antioxidant activity	Effective against *S. aureus* and *K. pneumoniae*	193
	nAg@cotton and nAg@flax fabrics	SM + in situ nAg generation/coating	nAg	PK and disruption of bacterial cell membrane	99.37% effective against *E. coli*	1
	SiO_2/nAg CF	Plasma treatment + SPC	SiO_2/nAg	Phytochemical, membrane disruption, antioxidant activity, protein denaturation, etc.	100% against *E. coli* and *S. aureus*	31
Emerging technologies:						
Antimicrobial/flame retardant textiles	Phytic acid (PhA)-polyhexamethylene guanidine phosphate (PHMG-p)@cotton/PET woven fabric	SM + drop coating (padding)	PhA and MG-p	Chemical, PK, membrane disruption, etc.	100% against *E. coli* and *S. aureus*	194
Smart antimicrobial textile	pH-responsive iodine-loaded-Zn-based zeolite-imidazolate frameworks (ZIFs)-7@cotton	SM + layer-by-layer (LBL) technique	Iodine-loaded ZIF	Chemical, PK, membrane disruption, etc.	Effective against *E. coli* and *S. aureus*	195
Antimicrobial fibers	Phormium tenax fibers (PTF) and hemp hurds (HH)	SM + dip-coating	Aryl diazonium-CTS	Chemical, PK, membrane disruption, etc.	100% effective against *S. aureus*	38
Antimicrobial E-textiles	nAg@cellulose yarn/PEDOT:PSS	SM + dip-coating + embroiling	nAg	Chemical, PK, membrane disruption, electron transport chain disruption, etc.	100% and 99.85% against *E. coli* and *S. aureus*	39
Multifunctional textile	Silicon@cotton NW fabric	NW technology + padding	Silicon	Superhydrophobic nature	-	196
Photocatalytic self-cleaning, self-sterilization, and FR materials	nAg/TiO_2/organofunctional trialkoxysilane@CF	SM + padding	nAg/TiO_2	ROS, DNA/RNA damage, photocatalytic activity, etc.	93% and 98% effective against *E. coli* and S. aureus	178
UV shielding, antioxidant activities, antimicrobial properties, and Hg^{2+} sensor	nAg@viscose fibers	SM + in situ dyeing	nAg	ROS, DNA/RNA damage, photocatalytic activity, etc.	Very good activity against yeast, poor activities against fungi, and effective against both Gram-(+ve) and Gram-(−ve) bacteria	197
Perspective engineering applications, such as hospital floors and hotel room decorations	TiO_2@kilim fabric	SM + dip-coating	TiO_2	ROS, DNA/RNA damage, photocatalytic activity, etc.	93% and 98% effective against *E. coli* and *S. aureus*	40
Wound dressing	Curcumin-PVA	SM + ES	Curcumin	Chemical (curcumin release), DNA/RNA damage, membrane damage, etc.	100% effective against *S. aureus* and *E. coli*	59
Wound dressing	Starch-PVA	SM + centrifugal spinning	nAg	ROS, DNA/RNA damage, photocatalytic activity, etc.	Effective against *S. aureus* and *E. coli*	56
Wound dressing	Gentamicin sulfate@poly-L-lactide (PLLA)	SM + MSP + braiding	Gentamicin sulfate	Self-promoted uptake, binding to ribosomes, membrane damage, ROS, etc.	Effective against *Pseudomonas putida* (*P. putida*)	52
Wound dressing	ZnO@PLA nonwoven fabric	MSP-spun bonding	ZnO	ROS, PK, membrane disruption, photodynamic effect, etc.	Effective against *S. aureus* and *E. coli*	53
Surgical suture	Ciprofloxacin@poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate) fiber yarn	SM + ES	Ciprofloxacin	Chemical, DNA fragmentation, SOS response activation, biofilm disruption, etc.	Effective against *S. aureus* and *E. coli*	198

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compliance processes that increase costs and time to develop. Policing the actual use of antimicrobials for textiles and ensuring that scientific findings support such claims and do not breach regulatory standards is not easy. Manufacturers are responsible for establishing that products have antimicrobial properties but must do so without confusing the buyers and the other healthcare stakeholders.[4,22]

8.4. Cost and Scalability. Integrating antimicrobial treatments into textiles can increase manufacturing costs due to the expense of antimicrobial agents and specialized production processes.[5,24,26,157] Achieving cost-effective solutions that do not compromise efficacy or safety is essential for widespread adoption. Scaling up the production of antimicrobial textiles to meet demand across various sectors, including healthcare, consumer goods, and industrial applications, requires efficient manufacturing processes and supply chain management.[5,26]

8.5. Consumer Perception and Acceptance. For acceptance and adoption, it is essential to inform customers and end users about the advantages and restrictions of antimicrobial textiles.[24] Some people may not know the correct information about antimicrobial resistance or how their purchase impacts the environment. For consumers to accept antimicrobial textiles in the market, their properties must be similar to those of normal textiles in terms of comfort, breathability, and appearance.[24]

8.6. Technological Advancements. Therefore, ongoing research and innovation of these textiles need to be encouraged in future studies. New antimicrobial agents, sustainable treatments, and smart textiles that change properties in response to microbial threats can inspire future development.[4,24,26] Solving these problems requires multidisciplinary efforts from the research community, manufacturers, government agencies, and customers to develop efficient, safe, and eco-friendly antimicrobial textiles for various consumer and industrial applications in healthcare, consumer, and other sectors. However, achieving this is highly challenging.

9. CURRENT TRENDS AND FUTURE PROSPECTS

9.1. Current Trend. The use of biodegradable or natural-based sustainable antibacterial agents is becoming increasingly popular. Examples include plant extracts, chitosan, and bio-based polymers.[2,5,24,26,29] These substances minimize their adverse effects on the environment while providing potent antibacterial qualities.

Additionally, nanotechnology is increasingly being used to develop antimicrobial textiles with enhanced properties. NPs such as Ag, copper, and ZnO are incorporated into textiles to impart durable antimicrobial effects without compromising fabric properties like breathability and comfort.[2,22] Moreover, more focus has been noted on smart textiles to have the ability to function on their own as influenced by different situations or means it can change their status to accommodate certain environmental conditions or the needs of a user. Smart textiles for healthcare and sports, as well as day-to-day wear, encompass antimicrobial functionalities to offer real-time protection against pathogens.[22] Moreover, luxury fabrics are slowly being engineered to include other features in addition to their antimicrobial capabilities. For instance, antimicrobial, moisture management, UV protection, and odor control create additional values and suit diverse consumer and industrial requirements.[123] Additionally, there is still an appreciable demand for antimicrobial textiles in the healthcare sector, where infection control is paramount. Thus, the areas to be focused on in the development of effective barrier prevention are, for instance, antimicrobial surgical gowns, wound dressings, and hospital bedding to prevent healthcare-associated infections.[176]

9.2. Future Directions. More advanced study deviations are planned to elaborate new classes of antimicrobials with a relatively wide spectrum of activity and minimal capability to induce microbial resistance. This also includes the search for new materials or modifications of existing ones in efforts to target particular pathogens or biofilms.[2,22] Again, there will be more focus on how to make antimicrobial textiles, including coated or treated textiles, biocompatible and safe for use, mainly in the medical and healthcare industry.[29] Research into biodegradable antimicrobial agents and coatings that degrade harmlessly in the environment will gain traction about the vital aspects of Circularity, Sustainable Development Goals (SDGs), and Environmental and Consumer Safety considerations in antimicrobial textiles.[2,22,201]

9.2.1. Circularity in Antimicrobial Textiles. Circularity in antimicrobial textiles will undoubtedly be focused on sustainable fiber selection, safe antimicrobial agents, product longevity, and end-of-life considerations (easy recycling and/or biodegradation).[201]

9.2.1.1. Sustainable Fiber Selection. Selecting environment-friendly fabrics, including organic cotton, hemp, or recycled polyester, to lower the impact on ecology, would be the major drive for the world of antimicrobial textiles.[201] Recycling or biodegradable materials should be used on these products.

9.2.1.2. Safe Antimicrobial Agents. Introducing techniques of giving this clothing an antimicrobial characteristic while at the same time not being toxic to the surroundings and not having a tendency to pollute the environment at the end of the useful life span of the textile would be a viable approach for safe antimicrobial agents usage.[202] New antimicrobial agents derived from chitosan or plant origin have shown to be more effective than synthetic chemicals like Ag or triclosan, the latter of which can become a persistent threat to ecosystems.

9.2.1.3. Product Longevity. Antimicrobial textiles are designed so that they will not allow bacterial growth which makes such textiles last longer, and patients do not have to change them frequently.[202] This is an input to circularity since it increases the product's lifespan.

9.2.1.4. End-of-Life Considerations. The antimicrobial textiles should be made in such a way they are recyclable or can be easily degraded[202] ensuring that it can be safely biodegradable or reused for other purposes reduces landfill waste and pollution affecting the environment.

9.2.2. Alignment with SDGs. Another aspect that is expected to be taken seriously is the design and fabrication of antimicrobial textiles that are in alignment with SDGs, notably:[203]

9.2.2.1. SDG 3 (Good Health and Well-Being). Antimicrobial textiles decrease the possibility of spreading infection-causing bacteria, fungi, or viruses through the fabrics.[203] This is particularly important in healthcare settings where hospital linen, wear, and face masks are used.

9.2.2.2. SDG 6 (Clean Water and Sanitation). Since antimicrobial textiles decrease the rate of washing and therefore extend the life of fabrics, water saving is ensured.[203] Reduced frequency of washing also minimizes the utilization of

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water and detergent products, hence fitting the goal of effective water use.

9.2.2.3. SDG 9 (Industry, Innovation, and Infrastructure). Technological advancements of green chemistry and environmentally sound approaches to the antimicrobial treatments approach responsible industrial processing and environmentally economic productions.[203] Such innovations also set pressure on industries to become environmentally friendly.

9.2.2.4. SDG 12 (Responsible Consumption and Production). It draws consumers' attention to accountable consumption by developing products with a long-life span, which reduces frequent reproduction.[178] Practice that relates to this goal includes less use of toxic chemicals in production and more use of sustainable materials.

9.2.2.5. SDG 13 (Climate Action). Less washing frequency also helps in reducing carbon emission, lesser water and energy utilization, and organic and natural fabric also helps in tackling the issue of climate change.[203]

9.2.3. Environmental Aspects of Antimicrobial Textiles. One of the critical considerations is the environmental consequences, already mentioned, and another is the choice of antimicrobial agents.[44,72,79,122,201,202] These factors are briefly discussed below.

9.2.3.1. Antimicrobial Agent Selection. nAg, Cu, and/or triclosan, known as traditional antimicrobial chemical agents, may pose some environmental risks. Some of these substances sink in many water bodies where they bioaccumulate and harm aquatic life and water quality. Such environmental threats are minimized by using eco-friendly antimicrobial treatments.

9.2.3.2. Microplastic Pollution. Antimicrobial textiles produced from fibrous materials such as polyester or nylon fabric release microplastics whenever a material is washed, which is a problem for the environment. These plastics are not biodegradable, and therefore, they end up in water bodies, affecting marine life and, to a significant extent, other animals.

9.2.3.3. Energy and Resource Efficiency. In this way, antimicrobial surface treatments can also have a positive environmental effect since, on the one hand, they increase the life cycle of textiles, and on the other hand, there is no need to manufacture new products from new raw materials. Nevertheless, applying antimicrobial agents in the manufacturing process should be done with some precaution to avoid adding to energy consumption and chemical pollutants.

9.2.3.4. Degradation and Disposal. The antimicrobial agents to be incorporated into textiles must not be toxic at the termination of the life cycle of the textile material.[72,94,122,127,128] Products in textiles that include banned hazardous chemicals are dangerous because, upon decomposition or disposal, the hazardous contents are likely to mix up with the soil and water, presenting a significant threat to animal and plant life.

9.2.4. Consumer Safety in Antimicrobial Textiles. Consumer safety is a top priority, especially since antimicrobial textiles are in direct contact with the skin. Some vital considerations are included, as discussed below.

9.2.4.1. Nontoxic Antimicrobial Agents. The antimicrobial treatments that are predetermined to be applied on the textiles should not be hurtful to human skin; they should be nontoxic.[72,94,122,127,128] Still, substances such as agents like nAg are guaranteed to be safe, but their side effects might include skin rash or penetration by the NPs through the skin into the bloodstream. The safer alternatives for use are biocompatible antimicrobial agents such as chitosan or natural plant extracts and, recently, graphene quantum dots or carbon dots.[204,205]

9.2.4.2. Allergenicity and Sensitization. There are some chemicals (formaldehyde, specific dyes (especially azo dyes), flame retardants, and some softeners) used in textile finishing which, if not washed off properly, trigger skin sensitization or irritation among personnel who have prolonged exposure to these chemicals.[206] Manufacturers must ensure that the products they design pass severe dermatological tests, proving that they are safe to be used frequently.

9.2.4.3. Regulatory Compliance. Antimicrobial textile fabrics must meet global safety standards and quality accreditation like **OEKO-TEX Standard 100**, which looks at the merits of the fabrics based on their ability to hold no dangerous chemicals.[207] It is, therefore, necessary to observe REACH regulation to reduce risks and thus protect the consumers.[208]

9.2.4.4. Risk of Antimicrobial Resistance. A worrisome trend exists in the use of antimicrobial agents and the subsequent development of antimicrobial resistance (AMR).[19] This is an added disadvantage that, if not controlled, could be worsened by the use of antimicrobial textiles. It is recommended that this risk be reduced or minimized by employing natural antimicrobials instead of synthetic antimicrobial treatments.

Antimicrobial textiles must be designed and manufactured as circularly as possible, incorporating the SDGs, environmental sustainability, and consumer safety. Through the choice of materials used in antimicrobial textiles, sustainable antimicrobial agents, and the end-of-life effects, antimicrobial textiles can significantly contribute to infection reduction while being sustainable.

As the concept of antimicrobial textiles develops, there will be a growing demand to address its difficulty in defining and developing regulations and standards that will protect the consumer and the environment. To aid the advancement of market access and to increase consumers' trust, international laws must be harmonized.[5] Also, the further development of antimicrobial textiles might be toward individualization, where requirements are derived from genetic information or conditions. Another potential wearable technology research area is the self-regulating antimicrobial function of clothing that changes in response to stimuli such as the physical environment or even the skin.[4] These textiles may begin to incorporate features that enable the tracking and regulating of microbial activity. This could encompass smart textiles that incorporate microbial sensors, as well as intelligent coatings that release antimicrobial substances in particular conditions.[162]

The growth and commercialization of antimicrobial textiles are growing increasingly with improvements in material science, nanotechnology, and ecology. Future trends point toward more effective, sustainable, and multifunctional solutions that cater to diverse industry needs while addressing regulatory and environmental challenges, as well as the fabrication and application of smart textiles to e-textiles.[29]

10. CONCLUSION AND RESEARCH GAPS

10.1. Conclusion. Antimicrobial textiles are among the most revolutionary products of diversified sectors of healthcare and consumer products due to the increasing demands to offer better hygiene, reduction of infections, and meet sustainable development. This review explains state-of-the-art antimicro-

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bial textiles that cover mechanisms, fabricating methods, efficacies against an extensive array of pathogens, and their applications. Antimicrobial textiles have come a long way, revealing advances that include nanotechnology, sustainable antimicrobial agents, and smart textiles. Among various types of NPs, the use of Ag, Cu, and ZnO NPs turned out to be quite effective in combating bacterial, fungal, and viral agents, being effective as a permanent finish with excellent compatibility with the fabric properties and comfort. Moreover, increasing reliance on natural products for antimicrobial treatments in textile manufacturing reflects a new era of enhanced environmental sensitivity. The use of natural products as antimicrobial agents has been grossly underrepresented as per the literature covered herewith. The application domains of antimicrobial textiles are expansive, encompassing healthcare, sports and outdoor gear, household textiles, apparel, and personal protective equipment (PPE). Reports on the processing and/or application of antimicrobial textiles to be utilized in space and/or other planets as high-performance technical textiles are rare/limited and require more exploration, seen the drive to colonize other planets like Mars and Moon recently spearheaded by SpaceX and NASA. In healthcare settings, antimicrobial textiles are pivotal in reducing HAIs by maintaining sterile environments and safeguarding patients and healthcare workers. Similarly, antimicrobial textiles offer enhanced freshness, odor control, and prolonged product lifespan in consumer products.

As the focus shifts to the future, the following leading issues and trends characterize the future prospects of antimicrobial textiles. Concerns that need to be addressed, or "opportunities" to use the current business language, include Controlling microbial resistance, compliance with legislation, environmental effects, and cost aspects. Future prospects for developing new and improved antimicrobial materials comprise specific fibrous materials and textiles, as well as merging with digital intelligence systems for functionality and user interaction.

Therefore, it can be concluded that technologies associated with antimicrobial textiles still have vast potential for transforming global health, conservation, and textile technology. Sustaining innovation, interdisciplinary cooperation, and commitment to high scientific standards shall remain critical for exploiting the beneficial possibilities of antimicrobial textiles in protecting the population's health and improving quality of life.

10.2. Research Gap(s) as per Overviewed Literature.

The section discussed highlights topics that need more investigation and development and describes the research gaps in the field of antimicrobial fabrics. A breakdown of the key points regarding these research gaps is presented here in brief as a guide for researchers working in this niche.

10.2.1. Limited Durability and Wash Fastness. Current antimicrobial coatings frequently have poor endurance and lose their efficacy after prolonged usage or washing. Because of this, they must be reapplied frequently, which raises questions about the expense and potential effects on the environment.

10.2.2. Environmental Sustainability. Concerns exist regarding the environmental persistence and possible ecological repercussions of the extensive usage of several antimicrobial drugs. Creating environmentally friendly antimicrobial agents or increasing the recyclability of textile fabrics treated with them is essential.

10.2.3. Antimicrobial Resistance (AMR). The development of antimicrobial resistance in microorganisms due to the overuse of specific antimicrobial agents is an increasing issue. To reduce this danger, cutting-edge antimicrobial agents with various modes of action require investigation.

10.2.4. Integration with Smart Textiles. There is still much to learn about the potential of smart textiles with self-cleaning and self-monitoring capabilities for antimicrobial applications. The creation of such fabrics may provide sophisticated and long-lasting antibacterial protection.

10.2.5. Standardization and Regulations. Global standardization and strengthening of regulatory frameworks are required to guarantee the security and effectiveness of antimicrobial textiles. This will give both consumers and manufacturers clear instructions.

10.2.6. Focus on Broader Spectrum Activity. Many existing antimicrobial textiles target specific types of microbes. Research on broad-spectrum antimicrobial agents that can fight a greater variety of infections is essential.

10.2.7. Balancing Functionality with Aesthetics and Comfort. Incorporating antimicrobial functionalities into textile materials should not compromise their aesthetics, comfort, or breathability. Developing methods for achieving both functionality and user comfort is an ongoing challenge.

10.2.8. Cost-Effectiveness. Some antimicrobial textiles can be expensive to produce, limiting their accessibility.[157] For broader use, research on affordable ways to add antibacterial qualities to fabrics is essential.

In summary, antimicrobial textiles have enormous potential to advance safety, public health, and cleanliness. By filling the research gaps mentioned above, researchers and developers can produce next-generation antimicrobial fabrics that are not only efficient but also long-lasting, environmentally friendly, and easy to use.

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Notes

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