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Recent Approaches to Antibacterial Textile Production Using Inorganic, Organic, and Sustainable Bioactive Substances: A Review

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ABSTRACT:
Antibiotics have ushered in a new era in the treatment of bacterial infections. However, over time, microorganisms have developed resistance mechanisms that increasingly limit available treatment options. Consequently, identifying novel antibacterial bioactive substances and advancing research in this field have become urgent priorities. Beyond medical treatment, preventive approaches such as antibacterial textiles can contribute to the reduction of bacterial contamination.
Textile materials, due to their moisture content and nutrients, provide a suitable growing medium for bacteria. Bacteria that grow in contaminated textiles pose a threat to public health and reduce textile performance. Textile materials produced from various raw materials, such as cotton, polyester, and wool, can be gained antibacterial properties via appropriate bioactive substances and under appropriate conditions. Bioactive substances used in antibacterial textile applications are primarily divided into two categories: organic and inorganic. These substances can be produced synthetically or derived from natural sources, such as chitosan and casein, or from sustainable sources, such as coffee and tea waste.
This study analyzes antibacterial textile research published between 2015 and 2025, retrieved from the Web of Science and ScienceDirect databases. The studies were categorized as either organic or inorganic according to the type of bioactive substances used in antibacterial textile production, and these categories were further subdivided based on production methods. The article presents an overview of the production processes of these bioactive substances, their application methods on textile materials, and the outcomes of antibacterial performance evaluations.
Keywords: *Antibacterial; antibacterial textile; bioactive compounds; functional textiles*

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INTRODUCTION

Antibacterial textiles can contribute prevent nosocomial infections and reduce the spread of antibacterial resistance. The World Health Organization (WHO) emphasized that more research should be conducted on antimicrobial textiles because textiles used in hospitals provide a suitable environment for the growth of hospital-acquired microorganisms (WHO, 2023). Antibacterial textiles can significantly benefit high-traffic areas such as hospitals, schools, public transportation, and gyms. In healthcare settings, antibacterial textiles can provide benefits in surgical gowns, bed linens, and curtains. Additionally, these materials can be an important strategy for reducing contamination and the spread of antibiotic-resistant microorganisms because they come into contact with people.

Following the COVID-19 pandemic, increased attention to hygiene and health in consumer habits has increased the demand for antibacterial textiles. People have begun to prioritize the health and safety features of the textile products they use in their daily lives, as well as their aesthetic and comfort features (Research and Markets, 2025). Grand View Research (2024) estimates that the antimicrobial textile market, which was USD 11.93 billion in 2023, will rise to USD 19.04 billion in 2030. Additionally, products with antibacterial properties, such as bed sheets, pillowcases, and towels, have gained market share in the home textile sector.

Antibacterial textiles are created by integrating bioactive substances into different composition of textiles, such as cotton, polyester, and silk, in various forms, including fibers, yarns, and fabrics. The chemical structure of the bioactive agent and the textile material, as well as the functional groups present in the polymer chain, are crucial in these processes. Sometimes pretreating the textile material with plasma treatment, chemical modification, or mordanting creates active groups to which the bioactive agent can bind. Additionally, bioactive substances can be incorporated into the fiber structure during spinning processes, such as electrospinning or melt spinning, to create antibacterial fibers or surfaces. Washing resistance is another important consideration. Single-use products are not expected to be wash-resistant, but reusable products, such as sheets, pillowcases, and duvet covers, are. Washing resistance generally relates to the nature of the bioactive agent's binding to the textile material and the bond's resistance to washing conditions (Korkmaz, 2019).

Antibacterial textile materials are evaluated using various qualitative and quantitative standards. Qualitative methods typically examine the formation of inhibition zones on textiles placed on microorganism strains inoculated onto solid media. Quantitative methods focus on the percentage of bactericidal or bacteriostatic activity of a sample in contact with a bacterial solution over a specific period. These methods involve incubating the contaminated sample and the control under equal conditions for an equal period, inoculating the samples onto solid media, counting the resulting colonies, and comparing the percentage to that of the control. Standards such as the agar diffusion method and AATCC 147 stand out in qualitative methods. However, the literature shows that the AATCC 100, JIS 2801, JIS 1902, ASTM E2149, and ISO 20743 standards are frequently used in quantitative methods (Balakumaran et al., 2016; Guzińska et al., 2018; Maślana et al., 2022)

Bioactive substances used in the production of antibacterial textiles can be classified as organic or inorganic. Organic substances can be obtained from natural sources, such as neem oil, carotenoid and quinoa (Diksha et al., 2021; Suneeta et al., 2021; Taherirad et al., 2024) or synthetic substances such as quaternary ammonium salts (QAS), polypentamethylene guanidine sulfate (PPGS), and naphthalimide derivatives (Li et al., 2023; Staneva et al., 2019; L. Wang et al., 2024). The use of organic substances has been observed to impart antibacterial properties to various textile raw materials. Metals and metal oxides, particularly silver, zinc, and titanium, constitute another important class of bioactive substances in antibacterial textile applications. Inorganic bioactive substances predominantly contain metals and metal oxides and can be classified as substances obtained through biosynthesis with the help of a plant extract or microorganism (Rilda et al., 2023; Y. Zhou and Tang, 2018), or as commercially available substances (Dong et al., 2017). Bioactive substances from biowastes, such as coffee waste, olive tree leaves, and quince tree leaves, can also be evaluated for antibacterial textile production (Yılmaz and Bahtiyari, 2020; Zargarian et al., 2024). Antibacterial textiles can be produced through the extraction or direct application of these waste products, which currently have no commercial value but contain antibacterial properties.

This review focuses on the production of antibacterial bioactive substances and their application to textiles. Bioactive substances can be classified as organic, inorganic, or sustainable substances derived from waste. The study used Sciencedirect and Web of Science search engines to find recent studies on antibacterial textiles published between 2015 and 2025. The study aimed to inform future research by providing an overview of the production of antibacterial bioactive substances, their application to textile materials, binding mechanisms, and antibacterial activities.

Literature Summary on Antibacterial Textiles Obtained with Different Classes of Bioactive Substances

Antibacterial Textiles Prepared with Organic Bioactive Substances

Naturally Sourced Bioactive Substances and Textile Applications

Zhang et al. (2020) studied tannic acid (Figure 1) and the tannic acid-iron complex in order to impart antibacterial and flame-retardant properties to silk fabric. Their study revealed that untreated silk exhibited weak (22%) antibacterial activity against *Staphylococcus aureus* and *Escherichia coli,* whereas silk treated with ferrous sulfate exhibited moderate (50%) activity. Fabrics treated with tannic acid or the tannic acid-iron complex exhibited excellent activity (99.99% and 93%, respectively). Fabric treated with the complex maintained significantly higher activity even after 20 washing cycles (W. Zhang et al., 2020). Diksha et al. (2021) prepared an extract of *Glebionis coronaria (L.) Cass. ex Spach* and used spectroscopic methods to show the presence of carotenoid and flavonoid structures in the extract (Figure 2). Extraction was carried out in methanol and dichloromethane solutions. Cotton fabrics that were pretreated and premordanted with different mordants were immersed in prepared dye baths and impregnated for 10–15 minutes. Although antibacterial evaluation of the dyed fabrics was not conducted, the prepared extracts were examined at 10 mg/mL concentrations against *S. aureus* and *Aeromonas sp*. strains using the disk diffusion method. Both extracts exhibited activity against *S. aureus*, while the methanol extract was ineffective against *Aeromonas sp.* (Diksha et al., 2021).

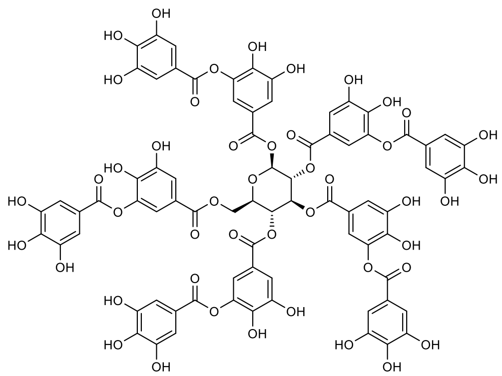

Figure 1. Chemical structure of tannic acid

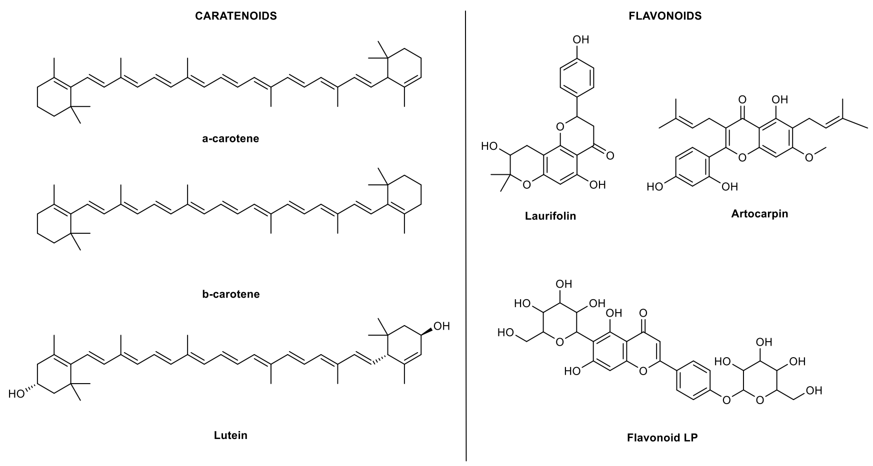

Figure 2. Chemical structures of some flavonoids and carotenoids (Diksha et al., 2021)

Taherirad et al. (2024) examined the performance of natural dyes obtained from the flowers, leaves, and stems of the quinoa plant, as well as the antibacterial properties of wool yarns dyed with these dyes. UV-VIS absorption analyses of the extracts revealed peaks associated with aromatic amino acids, carotenoids, chlorophyll, and betacyanins (Figure 3). Yarns dyed with leaf extracts after pre-mordanting with copper and iron exhibited antibacterial activity against the *S. aureus* bacterial strain. These yarns also exhibited excellent light and washing fastness, ranging from 3/4 to 4/5. However, no antibacterial activity was observed against *E. coli* in the samples (Taherirad et al., 2024).

Wu et al. (2025) oxidized a chitosan polymer obtained from natural sources. They then attempted to bond the resulting carboxyl groups to the hydroxyl groups of cellulose (Figure 4). First, the chitosan was oxidized in an HNO_3/H_3PO_4-$NaNO_2$ system. Then, it was treated with a 1:1:1 ratio of oxidized chitosan, cotton, and sodium phosphite at a 1:40 bath ratio at 80°C for one hour.

The fabrics were dried at 105 °C and fixed at 150 °C for five minutes. The antibacterial activities of the oxidized chitosan and the treated fabrics were investigated against *S. aureus* and *E. coli*. A quantitative evaluation of the fabrics, which formed an inhibition zone of 15-16.7 mm using the agar diffusion method, showed 99.99% activity against *S. aureus* and 98% activity against *E. coli*, even after 30 washes. The fabric also exhibited strong antiviral activity against bacteriophage MS2 (Y. Wu et al., 2025).

Ibrahim et al. (2016) produced antibacterial cotton fabrics by treating them with sericin (Figure 5), chitosan, and a mixture of the two. They performed the pad-dry-cure method in a padding machine using citric acid and NaH_2PO_2 as a catalyst at a 1/15 dye ratio for two hours. The dyed fabrics were dried at 80°C and fixed at 150°C for two minutes. In antibacterial analyses against *S. aureus*, the fabric treated with 10 mg/mL of chitosan exhibited 87% antibacterial activity. Meanwhile, the fabrics treated with sericin and sericin-chitosan exhibited 68% and 78% activity, respectively. After 10 washings, the activity levels were 63%, 42%, and 56%, respectively (Ibrahim et al., 2016).

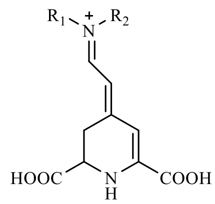

Figure 3. Chemical structure of betalain

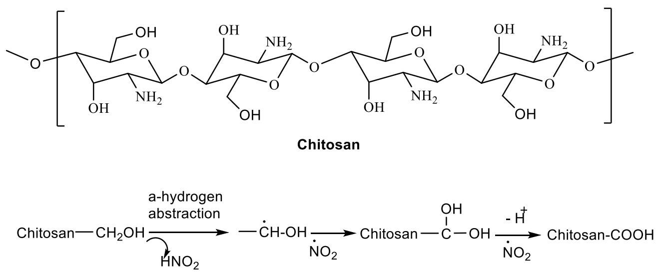

Figure 4. Chemical structure of chitosan and chitosan oxidation

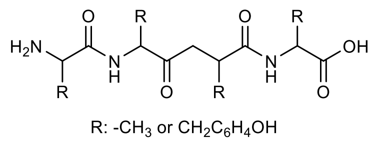

Figure 5. Chemical structure of the sericin (Aad et al., 2024)

Another study examined the interaction between chitosan and cotton. The study used commercially available chitosan, as well as chitosan synthesized by diacetylation of shrimp and crab waste. The cotton fabrics were modified with the chitosan derivative from shrimp shells, which exhibited the highest antibacterial activity. The chitosan-coated cotton samples were obtained by immersing the fabric in a solution of 2% acetic acid and chitosan for 24 hours. A 2.5% (v/v) triethyl orthoformate (TEOF) solution was also used as a crosslinker to bond the chitosan to the cellulose fibers (Figure 6). The results showed that the crosslinked fabrics produced 15 and 13 mm inhibition zones against the *S. aureus* and *E. coli* bacterial strains and exhibited stronger activity than the other sample, which produced 7 and 5 mm inhibition zones after 30 washes (Bukhari et al., 2023).

Moxibustion therapy is a traditional treatment method in Chinese medicine. Chen et al. (2024) investigated the antibacterial properties of moxa plant ashes and their extract by applying them to 100% cotton fabrics (Figure 7). They extracted the ashes in 50% ethanol at pH 4 with acetic acid at 80°C for 70 minutes. The fabrics were pre-mordanted with 3% soy protein and then dyed at 85°C for one and a half hours. In another application, moxa ash was placed on a grid and cotton fabric was placed under the grid. The ash was applied by pouring 80-90°C water onto the ashes several times. After both applications, the fabrics exhibited over 99% antibacterial activity against bacteria such as *S. aureus, Bacillus cereus,* and *E. coli* (J. Chen et al., 2024).

Another study examined the antibacterial properties of fabrics printed with Gardenia yellow dye (Figure 8). Fabrics pretreated with 10 g/L of tannic acid were colored with an inkjet printer using Gardenia yellow dye prepared at concentrations of 30–70 mmol/L. These fabrics exhibited over 95% antibacterial activity against *S. aureus* and *E. coli* bacterial strains. Tannic acid pretreatment was also found to increase washing, rubbing, and light fastness (M. Wang et al., 2023).

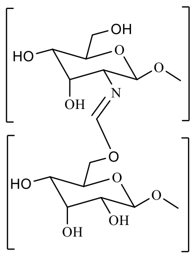

Figure 6. Chitosan bonded cellulose fiber

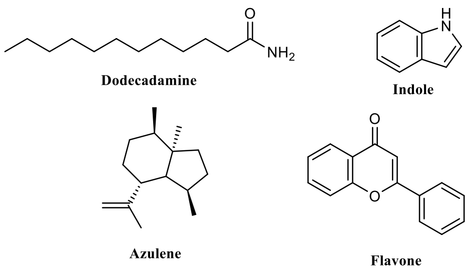

Figure 7. Some components found in moxa ash

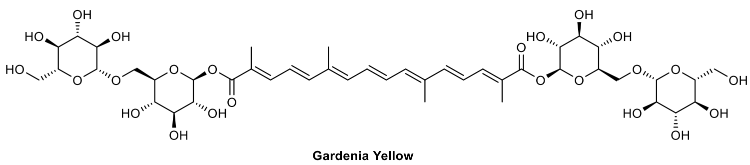

Figure 8. Chemical structure of Gardenia yellow dye

Zhang et al. (2023) prepared a coating material using lysozyme and tannic acid (Figure 9). Cotton, viscose, polyester, and wool fabrics were coated through two immersions in the coating bath, two spin cycles, and drying at 40°C. The cotton fabrics underwent an additional sol-gel process with 3-mercaptopropyltriethoxysilane (MPTES) and dimethyloctadecyl[3-(trimethoxysilyl)propyl]ammoniumchloride (DTSAC). Fabrics produced using this method exhibited over 99% antibacterial properties against S. *aureus* and *E. coli*. These fabrics were reported to withstand 50 washes and 10 rub cycles, and they also exhibited UV protection and antioxidant activity (N. Zhang, Wang, et al., 2023).

In another study of antibacterial textiles made from natural materials, researchers made zein and rosin baths using 70% ethanol (Figure 10). They added cotton fabrics to the baths and stirred them for two hours before rinsing them with distilled water. The antibacterial activity of the fabrics was observed to be 92.2% and 87.2% against *E. coli* and *S. aureus*, respectively (Z. Zhang et al., 2023).

Kumar et al. (2023) created microcapsules containing several active ingredients, including frankincense oil as the bioactive substance and chitosan as the shell (Figure 11). They applied the microcapsules to cotton fabrics using a padding mangle with the pad-dry method, incorporating 100 g/L of microcapsules and 30 g/L of binder. The fabrics were then dried at 80 °C for 5 minutes. The resulting fabrics exhibited 94.5% and 88.69% activity against *S. aureus* and *E. coli*, respectively. The fabrics also exhibited antioxidant, flame-retardant, mosquito-repellent, and fragrance-emitting properties (Kumar et al., 2023).

Attia et al. (2022) obtained multifunctional fabrics using the milk protein casein (Figure 12). After preparing the casein solution, they dispersed halloysite nanotubes into it using ultrasonication to form nanocomposite coating materials. The cotton fabrics were soaked in the coating solution for 10 minutes, squeezed in a two-roller padder, and dried and cured at 130°C. The fabrics formed a zone of 9 to 17.6 mm against *Bacillus sp.* and *E. coli.* The fabrics also exhibited flame-retardant properties and over 90% antiviral activity against adenovirus and herpesvirus (Attia et al., 2022).

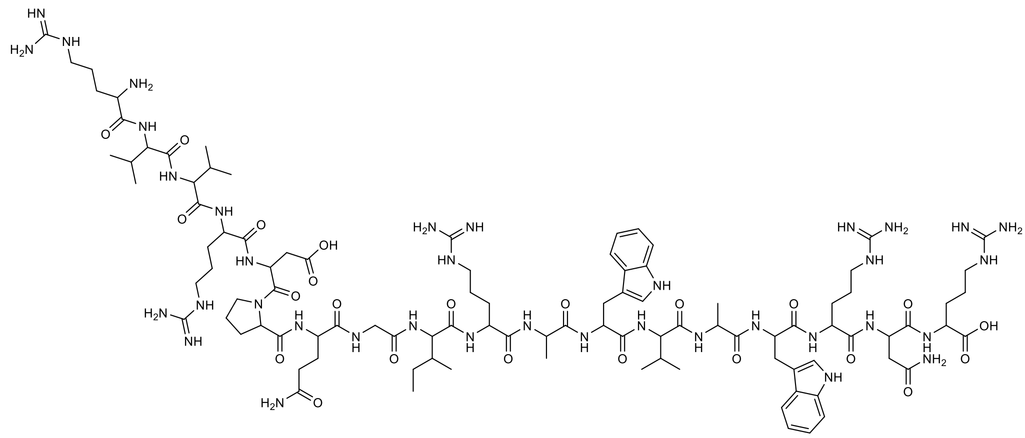

Figure 9. Chemical structure of lysozyme

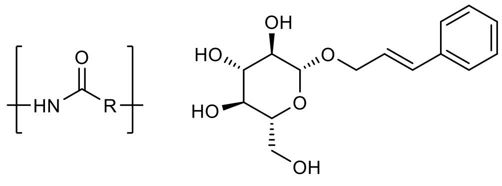

Figure 10. Chemical structures of zein and rosin

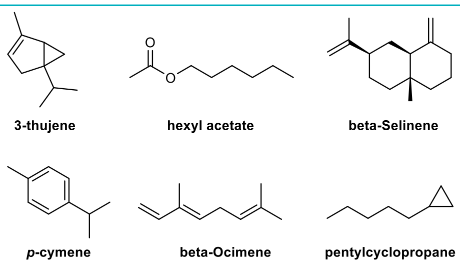

Figure 11. Some substances found in frankincense oil

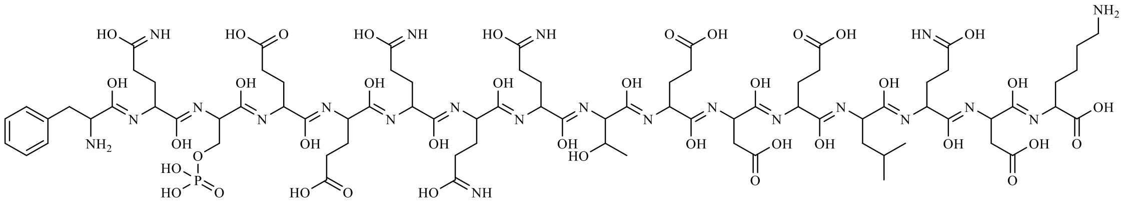

Figure 12. General structure of casein

Neem oil is effective for treating dermatological conditions such as psoriasis and eczema. Figure 13 shows some of the structures contained in neem oil. Suneeta et al. (2020) examined the process of treating cotton fabrics with neem oil extract using alum and copper sulfate as mordants. They investigated the antibacterial activity of the fabrics against *S. aureus* and *Salmonella typhi* bacteria using the AATCC 100 method. The fabrics exhibited similar levels of antibacterial activity against both bacterial species exceeding 99% with both mordants. However, it was observed that the antibacterial activity decreased to 55% and 38%, respectively, after 10 washes (Suneeta et al., 2021).

Synthetic Organic Bioactive Substances and Textile Applications

Zhou and Kan (2015) coated cotton fabrics using a combination of nitrogen plasma treatment and 5,5-dimethylhydantoin (DMH), applying the substances in different sequences. One sample was prepared without plasma treatment. Finally, they used chlorination with sodium hypochlorite to form N-halamine (Figure 14). The results showed that plasma treatment as a pretreatment resulted in better DMH binding to the fabric surface. These fabrics were reported to exhibit strong antibacterial activity against *S. aureus* and maintain this activity after rechlorination and washing (C. E. Zhou and Kan, 2015).

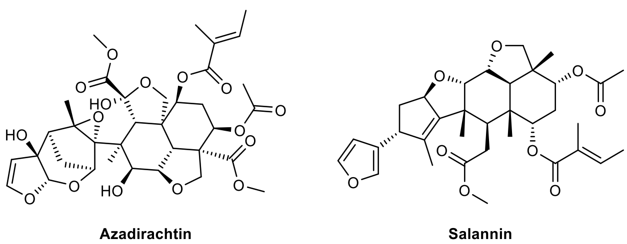

Figure 13. Some components found in neem oil

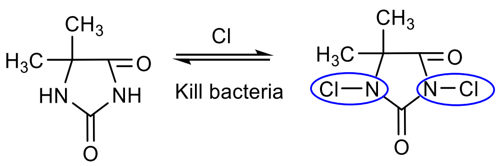

Figure 14. Reversible redox reaction of DMH with halamine structures (N-halamine structures highlighted by blue cycles)

Wang et al. (2024) prepared biobased, antibacterial polyamide 6 (PA6) fibers using an ethylene-methyl acrylate-glycidyl methacrylate (EMA) terpolymer as a binder and polypropylene glycol succinate (PPGS) as an antibacterial agent (Figure 15). The fibers prepared with a 1% binder exhibited 99.99% antibacterial activity against the *S. aureus* and *E. coli* bacterial strains (L. Wang et al., 2024).

Akkaya and Özseker (2019) pretreat polyacrylonitrile (PAN) fabric with a nitrilase enzyme (Figure 16), followed by coating it with tetracycline. Characterization revealed the formation of -COOH groups in the polymer backbone due to the enzymatic treatment. Sample fabrics were analyzed against *S. aureus* bacterial strains using a similar agar diffusion technique. The results showed that although the fabric did not create an inhibition zone, no bacterial growth occurred in the area in contact with the fabric. The antibacterial activity of the fabric was maintained for eight weeks (Akkaya and Ozseker, 2019).

He et al. (2017) synthesized a zwitterionic sulfobetaine (CSPB) compound that contains a triazine group. They applied this compound to cotton fabrics (Figure 17). They applied a 30 x 40 cm^2 cotton fabric sample to a 20 g/L CSPB solution using a 10 g/L $NaCO_3$ padding method and cured it at 90 °C for three minutes. The authors reported that the betaine group in the compound's structure provided antibacterial activity and that the reactive triazine group provided binding. The resulting fabrics exhibited 95% and 98% activity against *S. aureus* and *E. coli* bacterial strains, respectively. The authors observed that the activity persisted for 30 washings (He et al., 2017).

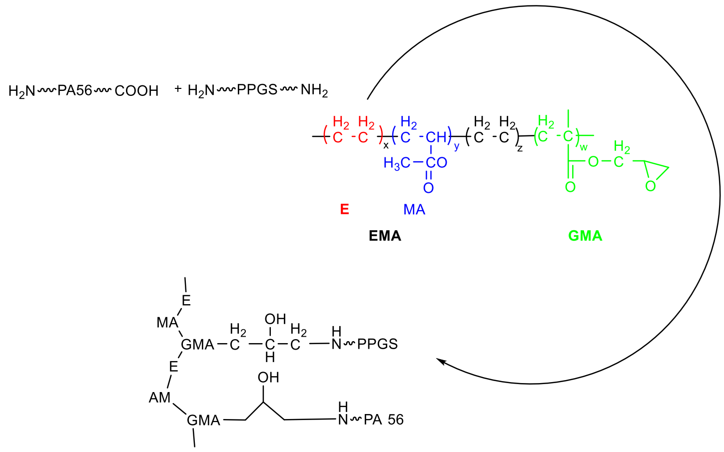

Figure 15. Modification of PA56 fibers

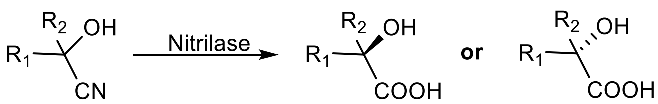

Figure 16. Nitrilation of PAN fibers

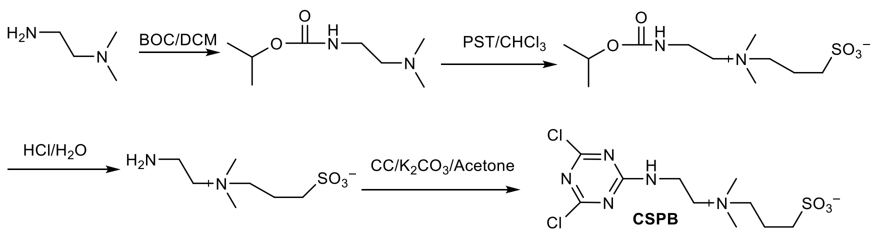

Figure 17. Syntehsizing of CSPB compound

Staneva et al. (2019) treated cotton fabric with chloracetyl chloride (CAC) in an *N,N*-dimethylformamide solution. After rinsing the fabrics with distilled water and drying them, they were dyed with a 1,8-naphthalimide derivative (NI). The researchers synthesized the NI according to a method found in the literature. The fabrics were dyed at a 1/40 bath ratio, at pH 8, and at 40 °C for 80 minutes (Figure 18). Finally, the fabrics were washed with ethanol and distilled water, followed by a nonionic detergent wash. The prepared samples exhibited 75%, 62%, and 47% antibacterial activity, respectively, against the bacterial strains *B. cereus, Acinetobacter johnsonii,* and *Pseudomanas aeruginosa* (Staneva et al., 2019).

Hongrattanavichit and Aht-Ong (2021) modified nanocellulose derived from sugarcane pulp using organosilane derivatives. The nanocellulose and organosilane derivatives were pre-hydrolyzed at a 1:3 ratio in an ethanol-water mixture at 60 °C. Then, the mixture was adjusted to pH 4 with acetic acid, and the solution was treated at 60 °C for two hours to prepare the silane-modified nanocellulose. The modified nanocelluloses were prepared at different concentrations, and cotton fabrics were immersed in these solutions for varying lengths of time. The fabrics were then fixed at 120 °C for two hours (Figure 19). Finally, unadhered components were removed by washing with acetone. All treated fabrics exhibited 99.99% activity against *S. aureus* and *E. coli bacterial* strains. Fabrics treated with APMS at a concentration of 0.50%-0.75% exhibited 99.99% activity against both bacterial species after ten washes (Hongrattanavichit and Aht-Ong, 2021).

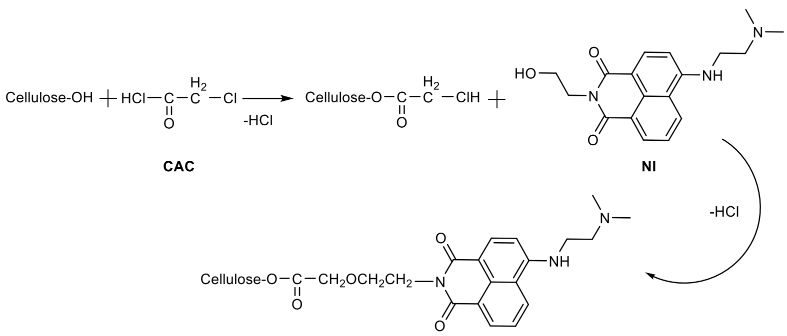

Figure 18. Synthesis of a 1,8-naphthalimide derivative and modification of cellulose

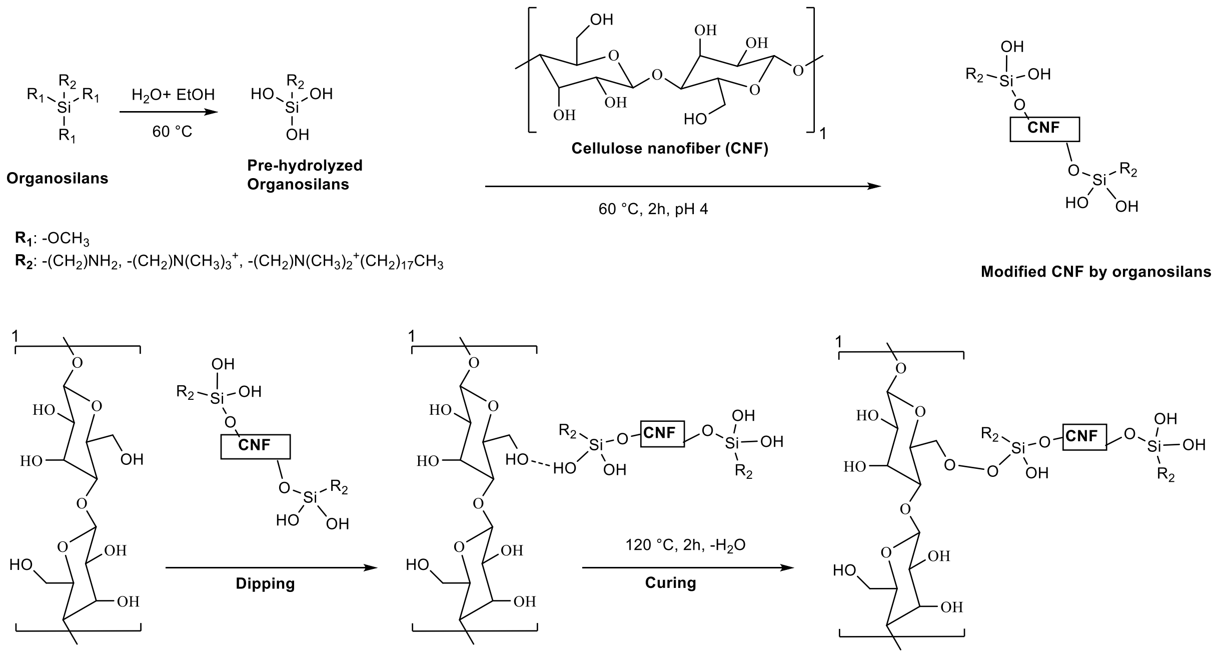

Figure 19. Synthesizing of CNF-organosilan derivatives and treatment of cellulose by CNF-organosilanes

Zheng et al. (2022) grafted QAS onto cellulose nanocrystals (CNCs), as shown in Figure 20. They added these materials to a PAN solution to form the shell of the yarn, which was produced using the co-spinning method with a cotton core. However, only CNC-PAN and QAS-PAN shell yarns were produced. Fabrics obtained from yarns with CNC-PAN shells did not exhibit antibacterial activity. In contrast, yarns with QAS-PAN shells exhibited 93% and 99% activity against *S. aureus* and *E. coli*, respectively. Fabrics obtained from CNC-QAS-PAN shell yarns exhibited 99.99% bacteriostatic activity against both bacterial species within 120 minutes. The activity of fabrics stored in the dark for 60 days persisted, remaining above 99% after 10 washings (Zheng et al., 2022).

Deng et al. (2023) developed high-antibacterial-activity cellulose-based nonwoven fabrics by combining MXene quantum dots with antibacterial agents. In the study, Ti_3AlC_2 was treated with lithium fluoride and HCl at 35 °C for 24 hours. Then, the layers were separated using washing, centrifugation, and sonication in ethanol and dispersed in deionized water. These processes resulted in the formation of Ti_3AlC_2 (MXene) nanosheets. These nanosheets were then mixed with ethylenediamine and deionized water in an ultrasonic bath for 40 minutes. The mixture was then subjected to hydrothermal treatment at 180 °C. MXene quantum dots (MQDs) were prepared by filtration. On the other hand, the NCA compound was synthesized by neutralizing neomycin sulfate with $NaHCO_3$, reacting it with 3,4-dihydroxybenzaldehyde, and reducing it with $NaBH_4$ (Figure 21). To produce functional fabrics, cellulose nonwovens were sequentially immersed in an MQDs suspension, a Ni^+ solution, and finally an NCA solution in a nitrogen atmosphere. This last step was carried out with slow mixing for nine hours. The resulting fabrics exhibited 99.99% antibacterial activity against *S. aureus* and *E. coli*, as well as sensor properties, producing different fluorescent shades at different bacterial concentrations (Deng et al., 2023).

Li et al. (2023) oxidized cotton fibers using the NaBr/TEMPO/NaClO system, forming carboxylate groups on the cellulose chains. Functional cotton fibers were obtained after treating the oxidized fibers with trimethylstearylammonium chloride (STAC) in distilled water at 60 °C for three hours. The fibers were then rinsed with deionized water and dried in a vacuum (Figure 22). Spunlace nonwoven fabrics were obtained by blending these fibers with 0–75% untreated cotton fibers at various ratios. Fabrics containing 10% functional fibers exhibited 90% activity against *S. aureus*, 99% activity against *E. coli*, and 85% activity against *Candida albicans*, respectively. They exhibited 99.99% activity against all microorganisms at a concentration of 50% (Li et al., 2023).

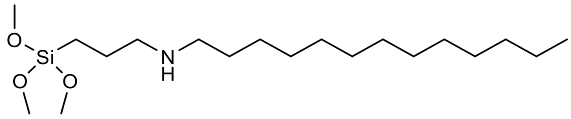

Figure 20. Chemical structure of QAS

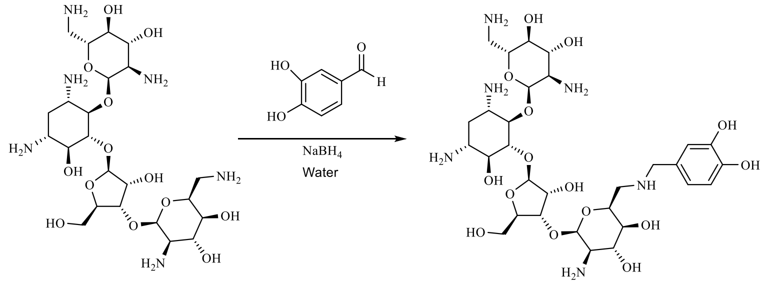

Figure 21. Catechol-functionalized neomycin (NCA)

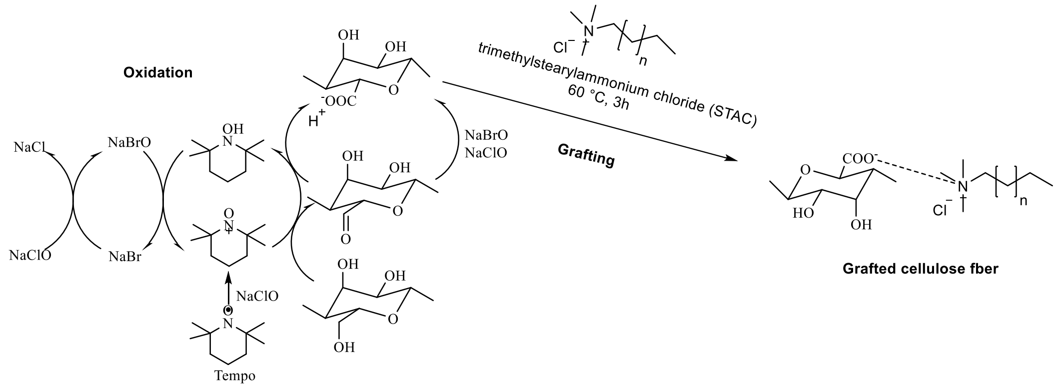

Figure 22. Oxidation of cellulose fiber and STAC-grafted cellulose fiber

In accordance with the literature, Demirdogen et al. (2020) synthesized 2-fluoropyridine derivatives and their Ni, Cu, and Co complexes (Figure 23). They prepared functional cellulose acetate gels by mixing the synthesized complexes with cellulose acetate at a 1:60 mass ratio in acetone for one hour at room temperature. Microfibrils were obtained by electrospinning. The obtained complex compounds exhibited the following activity against *S. aureus* and *E. coli*: 39 and 78 µg/mL for the Co complex, 78 and 150 µg/mL for the Ni complex, and 10 and 310 µg/mL for the Cu complex, respectively. Disk diffusion assays produced similar results against both bacterial strains, ranging from 14.8 to 19.3 mm. Textile fibers functionalized with the three complexes exhibited antibacterial activity ranging from 75 to 80% against both bacterial strains. The quantitative analysis results were similar for each complex (Demirdogen et al., 2020).

Xu et al. (2021) conducted a study on imparting antibacterial properties to PAN fibers. In this study, they formed hydroxyl groups on the PAN polymer chain by first treating it with COO-Na in a NaOH medium, and then with 0.1 M HCl (P-COOH). Then, chitosan was attached to the membrane in the presence of 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide (EDC) and N-hydroxysuccinimide (P-COOH-CS). Then, dyeing was carried out in a basic medium containing salt at 70 °C for six hours (P-COOH-CS-Dye). Finally, poly(hexamethylene biguanide) hydrochloride (PHMB) was immobilized on the dyed membranes for three hours (Figure 24). The antibacterial activities of the obtained membranes were investigated qualitatively and quantitatively. The authors reported that the P-COOH, P-COOH-CS, P-COOH-PHMB, and P-COOH-CS-PHMB membranes exhibited approximately 15%, 60%, 70%, and 90% activity, respectively, when compared with previous studies. Samples stained with Reactive Green 19 (RG19) and Reactive Red 141 (RR141) exhibited antibacterial activity against *E. coli* close to 100% and were wash-resistant (Xu et al., 2021).

Chen et al. (2023) formed dialdehyde groups on the cellulose polymer chain as a result of oxidation of cotton fabric with $NaIO_4$. Oxidized cotton fabrics were then added to Salmon protamine (PM) solutions prepared in deionized water and stirred at 25 °C for up to 3 hours to form a Schiff base, followed by ultrasonication with deionized water (Figure 25). The modified fabrics were found to exhibit 99% antibacterial activity against *S. aureus* and *E. coli*, withstanding 50 washing cycles and 500 mechanical treatments (M. Chen et al., 2023).

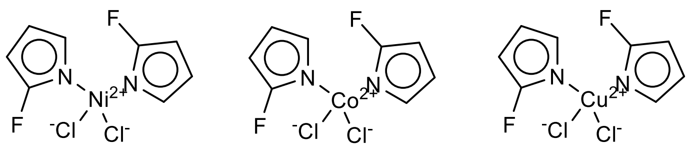

Figure 23. 2-fluoropyridine metal complexes

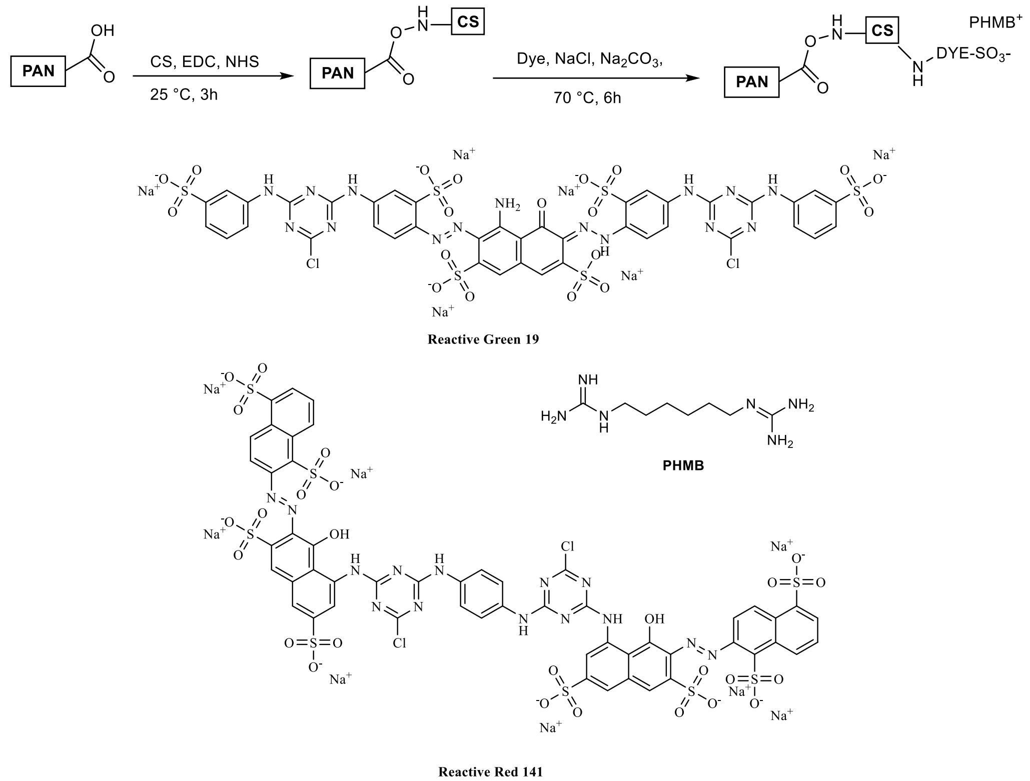

Figure 24. Preparing of P-COOH-CS-Dye-PHMB, chemical structure of RG19, RR141 and PHMB

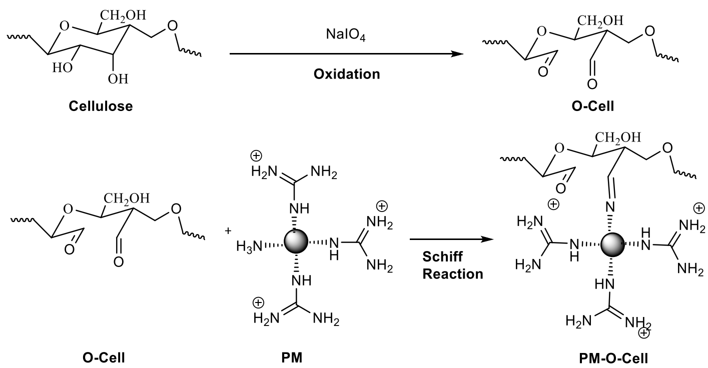

Figure 25. Cellulose oxidation and PM treatment on oxidized cellulose

Researchers investigated the antibacterial properties of fabrics made from polyester, poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), and polylactic acid (PLA) fibers, which were coated with polylactide oligomers (PLAO) (Figure 26). The study used fifty patient rooms from four different sections where the PLAO-coated textiles were placed. After seven days, six bacterial species (*S. aureus, Enterococcus faecalis, Haemophilus influenzae, E. coli,* and *P. aeruginosa*) were isolated and measured. As a result of the clinical study, 94% of the samples had fewer than 20 colony-forming units (CFU)/100 cm², and 50% had 0 CFU/100 cm², which meets hygiene standards. In the in vitro study, uncoated fabrics exhibited 99.9% and 88% activity against *S. aureus* and *E. coli*, respectively. However, after five washes, activity decreased to 95% and 72%, respectively. Coated fabrics maintained 99.9% activity after five washes (Ma et al., 2024).

Naz et al. (2025) first subjected cotton fabric to a cationization treatment using 20 g/L mercaptopropyltris(methyloxy)silane at a 1:50 bath ratio, at 50 °C for 6 h. The fabrics were then cured at 100 °C for 1 min. The cationized cotton fabrics were subsequently coated with a 4% CQD solution (Figure 27). The CQD-coated fabrics exhibited over 88%

antibacterial activity against *S. aureus* (Naz et al., 2025).

First, Wu et al. (2024) dissolved alphalipoic acid (ALA) in ethanol (EtOH) and prepared solutions of ALA, 1-(3-dimethylaminopropyl)-3-ethyl carbodiimide hydrochloride (EDC), and N-hydroxysuccinimide (NHS) in a 2:2:1 molar ratio, respectively. They added PEI to this solution and stirred it for 24 hours. Then, they removed the EtOH in an evaporator and dried it by freeze-drying to obtain ALA-grafted PEI (mPEI) (Figure 28). Then, mPEI was grafted onto vinylated cotton fabric after 24 hours at 4 °C in a 50 g/L methacrylic anhydride solution via a thiol-ene click reaction. Finally, AgNPs were bonded to the cotton fabric via an in situ reaction with $AgNO_3$. The fabrics exhibited over 99% antibacterial activity against both *S. aureus* and *E. coli* after 30 minutes. This effect was observed to persist even after 20 washing cycles (L. Wu et al., 2024).

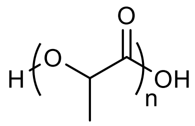

Figure 26. Chemical structure of PLAO

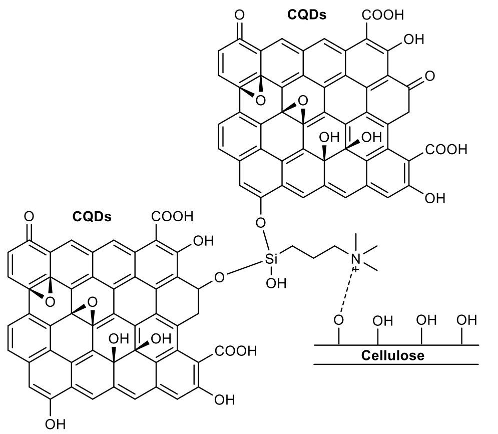

Figure 27. CQDs-treated cationized cellulose

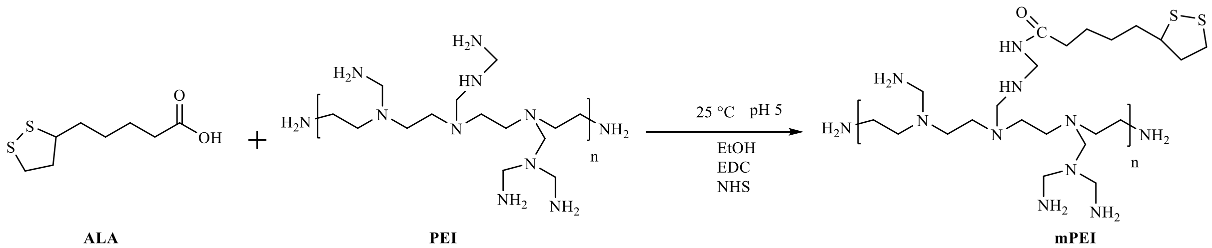

Figure 28. Synthesizing of mPEI

Antibacterial Textiles Prepared with Inorganic Bioactive Substances

Biosynthesized Inorganic Bioactive Substances and Textile Applications

The flowers of the Lonicera japonica Thunb. tree, commonly known as honeysuckle and found in East Asia, are rich in chlorogenic acid, which is known for its bioactive properties (Figure 29). Chlorogenic acid acts as a reducing agent in the biosynthesis of silver nanoparticles (AgNPs). Zhou and Tang (2018) used honeysuckle extraction to synthesize and stabilize AgNPs. The researchers prepared AgNPs by shaking

$AgNO_3$ in honeysuckle extract at pH 9, 50 °C, and for 60 minutes. The silk fabrics were then treated in an AgNP solution at pH 4, 80 °C for 1 hour. After treatment, the fabrics exhibited antibacterial activity against *S. aureus* and *E. coli*. They maintained over 70% activity against both bacteria even after 30 washings (Y. Zhou and Tang, 2018).

Rilda et al. (2023) synthesized zinc oxide nanorods (ZnO-NRs) from the mushroom *Agaricus bisporus* using the sol-gel hydrothermal method. First, ZnO seeds were mixed with zinc nitrate in a basic medium. Then, hexamethylenetetramine (HMT), polyethylene glycol (PEG) 6000, and mushroom powder were added and stirred for six hours. The gel was then autoclaved at 160 °C for 12 hours. The resulting gel was dried at 200 °C for four hours and then calcined at 700 °C for four hours to produce ZnO-NRs. Cotton fabrics were treated with 0.5 M adipic acid and 0.3 M NaH_2PO_2 as crosslinkers for 12 hours. The ZnO-NRs were transferred to the fabrics using the dip-spin coating method. To provide hydrophobicity, the fabric was treated with a 20% dodecyltriethoxysilane (DTES) solution (Figure 30) and then cured at 170 °C after rinsing. Finally, the fabrics were cured in an autoclave at 120 °C for three hours. The fabrics produced inhibition zones of 20 mm and 30 mm against the *S. aureus* and *P. aeruginosa* bacterial strains, respectively (Rilda et al., 2023).

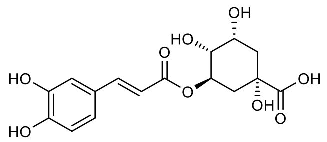

Figure 29. Chemical structure of chlorogenic acid

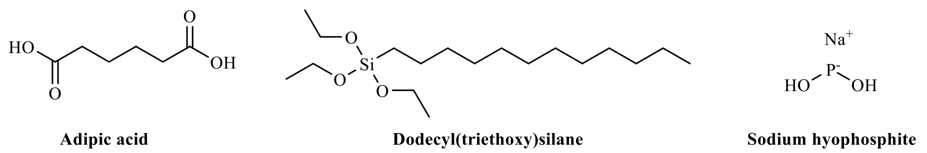

Figure 30. chemical structure of adipic acid, DTS, and sodium hypophosphite

In another study of ZnONPs, the fungus *Aspergillus terreus* was employed. The fungus was incubated in a Czapek Dox medium at a pH of 6.0, at a temperature of 28 °C, and at a speed of 150 rpm for three days. After incubation, the biomass was separated using Whatman paper. ($Zn(CH_3CO_2)_2$) was then added to the filtrate at various ratios, after which the mixture was incubated at 28 °C for 24 hours. The solid material formed during incubation was filtered and dried at 150 °C for 48 hours. Cotton fabrics measuring 30 cm^2 x 15 cm^2 were immersed in the prepared ZnONP solution for five minutes, wrung out, dried, and cured at 150 °C for two minutes. Microdilution results showed that the minimum inhibitory concentration (MIC) values against the Gram-positive bacteria *S. aureus* and *Bacillus subtilis* were 250 µg/mL, while the MIC value against the Gram-negative bacteria *E. coli* and *P.* aeruginosa was 500 µg/mL. Fabrics coated with a 20 ppm ZnONPs solution exhibited 82% and 75% antibacterial activity against Gram-positive (*S. aureus* and *B. subtilis*) and Gram-negative (*P. aeruginosa* and *E. coli*) bacterial strains, respectively. The fabrics also exhibited anti-UV properties (Fouda et al., 2018).

Ibrahim et al. (2016) isolated the bacterial strain *Streptomyces sp*. from marine sediment and used it to synthesize AuNPs. First, cotton and viscose fabrics were treated with O_2 plasma. Then, the fabrics were coated with AuNPs and a combination of these nanoparticles, ZnO and TiO_2, at a 1/15 bath ratio at pH 9 in an ultrasonic bath at 60 °C for 30 min. The fabrics were coated with 2% of the nanoparticles at a bath ratio of 1:15 at pH 9 in an ultrasonic bath at 60 °C for 30 minutes, after which they were rinsed with distilled water. The fabrics exhibited significant antibacterial activity against *S. aureus* and *E. coli* strains, maintaining their activity even after 15 washings. Fabrics treated with AuNPs/ZnONPs, AuNPs/TiO2NPs, and AuNPs exhibited the strongest activity, respectively (Ibrahim et al., 2016).

Thanka Rajan et al. (2024) synthesized cerium dioxide (CeO_2) nanoparticles using a chemical precipitation method. Additionally, they synthesized nanocarbons using orange juice and ethanol and hybrid nanoparticles by ultrasonicating the mixture overnight. Fabrics were mixed in dispersions prepared from the resulting nanohybrid and other nanoparticles for two hours. Then, the fabrics were ultrasonicated in the same bath for 30 minutes at 60 °C. Experiments with *S. aureus* and *E. coli* bacterial strains revealed that fabrics treated only with nanocarbon did not create inhibition zones. In contrast, the nanohybrid-coated fabric formed zones of inhibition measuring 45 mm and 25.25 mm, respectively. Fabrics treated only with CeO_2 NPs formed zones of inhibition measuring 40 mm and 23 mm (Thanka Rajan et al., 2024).

Attia et al. (2023) synthesized CNCs from waste cotton clothing and phosphorylated them (F-CNCs). They coated viscose fabrics with F-CNCs, a graphene layer obtained by carbonizing tangerine peel, and polyaniline (Figure 31) and polypyrrole nanofibers. The treated viscose fabric produced 14.5 mm and 18.4 mm of inhibition against the *S. aureus* and *E. coli* bacterial strains, respectively. The fabric also exhibited flame-retardant, UV-resistant, and electrically conductive properties (Attia et al., 2023).

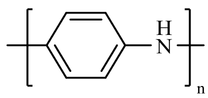

Figure 31. Chemical structure of polyaniline

Commercially Supplied Inorganic Bioactive Substances and Textile Applications

Spielman-Sun et al. (2018) examined the antibacterial properties of polyester fabrics treated with various forms of silver, as well as the release of silver after contact with artificial sweat and wastewater leachate. Specifically, they examined the antibacterial activity of fabrics treated with AgNp, AgCl, and AgO fibers following exposure to artificial sweat and wastewater leachate. Contact with solutions containing Cl ions (such as NaCl and artificial sweat) resulted in increased silver release compared to deionized water. However, sodium sulfide and acetic acid solutions reduced the release. Furthermore, AgCl-coated fabrics were found to be more chemically resistant than fabrics containing AgO. In summary, the authors reported that fabrics containing 10 µg of silver retained high antibacterial activity (Spielman-Sun et al., 2018).

Zhang et al. (2023) used lysozyme to stabilize molybdenum disulfide nanosheets during ultrasonic peeling. In a reducing environment, the lysozyme transformed into an amyloid-like phase, accumulated on the wool fabric, and then coated the AgNPs in situ. The resulting fabrics produced reactive oxygen species in the presence of light and exhibited antibacterial activity by releasing silver ions. The fabrics exhibited nearly 100% activity against *S. aureus* and *E. coli* and maintained over 99% of their activity after 50 washing cycles (N. Zhang, Shi, et al., 2023).

Dong et al. (2017) developed polyvinylidene fluoride (PVDF) nonwovens with one surface coated with PAN and the other surface coated with ZnO. First, PVDF was mixed in a dimethylformamide (DMF)/acetone mixture containing 1,3-diaminopropane (DAP), and then nanofiber layers were produced on aluminum foil by electrospinning. The layers were then coated with silane in an ethanol solution containing 10% (3-aminopropyl)trimethoxysilane (APTES) at 70 °C for ten hours. Then, ZnO cores were formed in an ethanol solution containing zinc acetate dihydrate and NaOH. The ZnO cores were then grown in solutions containing zinc nitrate hexahydrate and hexamethylenetetramine (HMTA) at 90 °C to obtain

ZnO-coated PVDF. Due to the use of aluminum foil, only one surface was coated with ZnO. Finally, a 7% PAN solution was applied to both the ZnO-coated and uncoated surfaces by electrospinning to prepare bifacially modified nanofiber sheets. Agar diffusion evaluation show that the ZnO-coated surfaces exhibited 8.8-13 mm inhibition zone against *E. coli* (Dong et al., 2017).

MXenes are two-dimensional, thin-layered materials composed of transition metal carbides, nitrides, or carbonitrides. They are used in sensors, water treatment, and textiles. These structures can adversely affect bacteria by generating reactive oxygen species when exposed to light. Yu et al. (2024) studied antibacterial cellulose nonwoven fabrics. In their study, the researchers bonded nanocellulose (CNs) to MXene and coated the outer layer with zeolitic imidazolate framework-8 (Figure 32). The MXene exhibited antibacterial activity by generating ROS under light and enhanced the binding of ZIF-8 on the outer layer. This smart material is photocatalytically triggered and was observed to rapidly destroy pathogenic bacteria (*S. aureus* and *E. coli*) within five minutes. The authors also found that Zn^{2+} ions released from the outer layer inhibited bacterial growth for two days (Yu et al., 2024).

The formation of ZnO nanoparticles was achieved through a systematic procedure involving the addition of 50 milliliters of a 1% hexamethyltriethylene tetramine (HMTETA) solution (see Figure 33) to 150 milliliters of zinc nitrate solutions, which had been prepared at concentrations ranging from 6.66 to 20 grams per liter. These solutions were then subjected to a stirring process for a duration of 30 minutes. Cotton fabrics were added into the resulting solution at a 1/50 bath ratio and agitated for a duration of 20 minutes. The fabrics were rinsed with distilled water, followed by drying and a cured at 140°C for three minutes. The coated fabrics demonstrated approximately 90% antibacterial activity against *S. aureus* and *E. coli* even after 20 wash cycles (Shaheen et al., 2016).

In a recent study, Jiang et al. (2025) fabricated PA6 fibers comprising Cu_2O-GO nanocomposites, which exhibited both immediate and sustained effects. The first step in the synthesis was to disperse graphene oxide (GO) in deionized water, followed by the addition of EDTA-2Na (Figure 34) and stirring for a period of three hours. Subsequently, $CuSO_4 \cdot 5H_2O$ was incorporated for a duration of one hour to facilitate the chelation process. Thereafter, NaOH and ascorbic acid were added and thoroughly mixed for an additional ten minutes. The synthesis of Cu_2O-GO nanocomposites was completed by subjecting the mixture to vacuum drying at a temperature of 60°C for a duration of 12 hours. The production of composite fibers entailed the incorporation of dispersions prepared from the nanocomposites into the caprolactane polymerization reactor at a 1/9 ratio. Subsequent polycondensation and purification of the resulting resins through melt spinning were then employed. Fibers containing 0.6% Cu_2O-GO demonstrated near-total activity against *B. subtilis* and *E. coli* within 10 minutes and retained 99.99% of their activity even after 50 washes (Jiang et al., 2025).

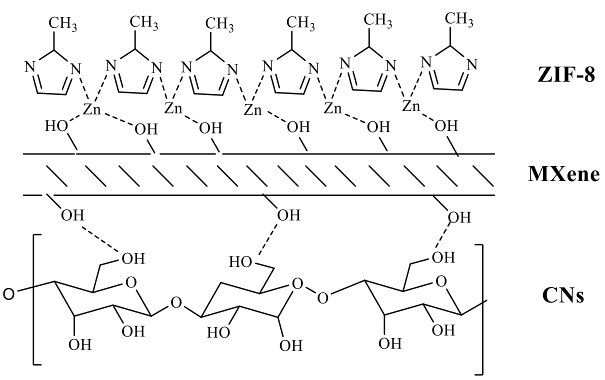

Figure 32. ZIF-8-MXene modified CNs

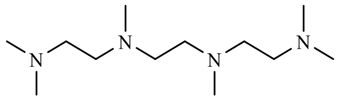

Figure 33. Chemical structure of HMTETA

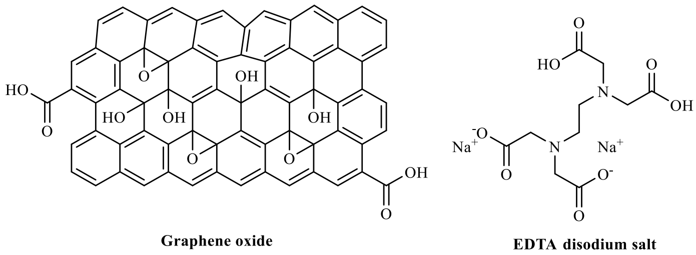

Figure 34. Chemical structure of graphene oxide and EDTA disodium salt

In a related study, Najmi et al. (2023) reported that a $CuSO_4$ solution was stirred at 60 °C in the presence of NaOH in a basic medium until the color turned black. The resulting nanoparticles were separated by centrifugation. Then, they were washed and dried. The drying process was done at a temperature of 400°C for two hours to strengthen the crystal structure. The fabrics were cut into 2x2 cm^2 pieces, and 100 µL of a nanoparticle solution with a concentration of 70 µg/mL was applied to fabrics made of different raw materials. Then, the fabrics were dried at 60°C for three hours. The coated fabrics showed 50% and 70% antibacterial activity against *Staphylococcus epidermidis* for nylon and neoprene, respectively (Najmi et al., 2024).

Fang et al. (2023) created a special coating for polyester fabrics using a spray method. They used a material called polyacrylate polymer and copper oxide spheres of different sizes. We made copper oxide nanospheres of different sizes by using different amounts of copper acetate and trisodium phosphate. Depending on their size, nanospheres in purple, blue-green, yellow, and orange colors were obtained. First, a 20% polyacrylate solution was sprayed onto polyester fabrics. Then, it was heated to 160°C for three minutes. Finally, 1% Cu_2O nanospheres were coated on the surface using the same method and cured under the same conditions. Fabrics coated with 202-nm green nanospheres showed almost 100% antibacterial activity against *S. aureus* and *E. coli* bacteria (Y. Fang et al., 2023).

In a later study, cotton fabrics measuring 5x10 cm^2 were put into a liquid that had 1 milligram of ZnO particles and 2% OWF cellulase in it. After 30 minutes of treatment at 55°C, the samples were rinsed with distilled water and dried. The fabrics were 70% effective against *S. aureus* and 98% effective against *E. coli*. After just one wash cycle, the activity levels were recorded as 50% and 68%, respectively (Petkova et al., 2016).

Vieira et al. (2023) used gold-hydroxyapatite nanoparticles (AuNPs-HAp) to make cotton, polyester, and cotton/polyester fabrics more antibacterial. The fabrics were initially treated with bleach and a special plasma treatment. The bleaching process was done only on 100% cotton fabric, using a plasma treatment that used an atmospheric pressure DBD apparatus. The cotton/polyester and polyester fabrics were exposed to plasma treatment under the same conditions. Then, the fabrics were coated with a mixture of gold nanoparticles and a special liquid called Hap at a pH of 9. After that, the fabrics were then tested against *S. aureus, E. coli, P. aeruginosa,* and *S. epidermidis*. The findings showed that the 100% cotton fabric exhibited the highest antibacterial activity. The other two fabrics were less effective against *S. epidermidis* but demonstrated comparable performance to cotton in inhibiting the growth of *P. aeruginosa* (Vieira et al., 2023).

Sharifikolouei et al. (2021) coated the surface of a polybutylene terephthalate nonwoven fabric with Zr, Cu, and Ag. The fabric was able to stop 95% of bacteria from forming biofilm on the fabric. Additionally, the ion release of the fabrics over a period of 24 to 120 hours was assessed through ICP-MS, and the authors concluded that the fabrics effectively conducted indirect assessments of cell compatibility (Sharifikolouei et al., 2021).

Sunthar et al. (2021) conducted a study on aluminum nitride-coated cellulose acetate composite materials. Initially, powdered cellulose acetate was dissolved in acetone, triacetin was incorporated as a plasticizer, and aluminum nitride (AIN) was added as an antibacterial agent. The mixture was thoroughly stirred until achieving homogeneity. The material was dried at 60°C overnight to completely remove the solvent, and the composites were ready for analysis. An AIN content that exceeds 10% has been demonstrated to result in a decrease in mechanical strength and an increase in thermal resistance. A specimen that had been treated with 20% AIN showed strong antibacterial effectiveness against *S. epidermidis* and *E. coli* bacterial strains. This led to a significant reduction in biofilm and bacterial counts after 24 hours (Sunthar et al., 2021).

In a separate study, aluminum oxide in the form of a dispersion was prepared in pure water by means of an ultrasonic bath. Modified glyoxylic resin was also incorporated into the bath, functioning as a catalyst and wrinkle-reducing agent. In the coating process, 100% linen fabrics were immersed in a prepared bath. The fabrics were first dried at room temperature, then at 110°C, and finally cured at 150°C for 2-3 minutes. Fabrics coated at a concentration of $5x10^4$ ppm demonstrated over 99% antibacterial activity against *S. aureus* and *E. coli* bacterial strains. Subsequent to five wash cycles, the activity levels were found to be 99% and 93%, respectively (Yılmaz and Bahtiyari, 2021).

Bioactive Substances Derived from Biowaste and Sustainable Textile Applications

Resource depletion increases the importance of the terms reuse, recycling, and reduction (3R). The processing or recycling of waste materials aims to meet the need for raw materials and semi-finished products in many sectors, thereby reducing the environmental burden. This section summarizes antibacterial textile studies based on the processing or recycling of waste (X. Zhang et al., 2025).

Tea and coffee consumption are among the important biowastes, and these are being tested in biocomposite production, soil conditioning, and antibacterial applications (Murthy and Naidu, 2012; Yun et al., 2020; Cervera-Mata et al., 2019; Yılmaz and Bahtiyari, 2020). Figure 35 shows some substances in tea and coffee extracts. Xia et al. (2022) extracted coffee and black tea waste in a slightly alkaline medium with sodium bicarbonate in a 50% ethanol solution. This process produced dyes that they expected to have antibacterial properties. They dyed silk and wool fabrics with the resulting dyes at a pH of 4.8 and a temperature of 90°C for 90 minutes. Researchers reported that the resulting fabrics showed over 90% antibacterial activity against *E. coli, S. aureus,* and *C. albicans*, as well as antioxidant and ultraviolet protection (Xia et al., 2023).

Sülar et al. created textile surfaces with different layer counts and content ratios using waste tea and coffee pulp, polyethylene terephthalate fibers, waste cotton fibers, and a cotton woven fabric as a backing. The results did not indicate structures with strong antibacterial activity. Subjective evaluation of color changes after dripping milk on the surface followed by incubation indicated that the surface containing 1.5 g of waste tea—composed of a cotton/polyester bottom layer, a polyester/tea waste middle layer, and a polyester/cotton outer layer—exhibited antibacterial properties (Sülar et al., 2025).

Zargarian et al. (2024) obtained a coffee-integrated PAN nanosurface by electrospraying the suspension obtained from the coffee waste after washing, sieving, and grinding the used coffee grounds, and by simultaneously applying PAN electrospinning to the same collector. They then aimed to obtain antibacterial surfaces by conducting dopamine polymerization on the surface (Figure 36). Coffee biowaste contains structures such as lignin and melanoidins, which exhibit antibacterial properties. The authors observed that this nanomaterial exhibited strong bactericidal activity against the bacterial strain *S. aureus* under near-infrared light (Zargarian et al., 2024).

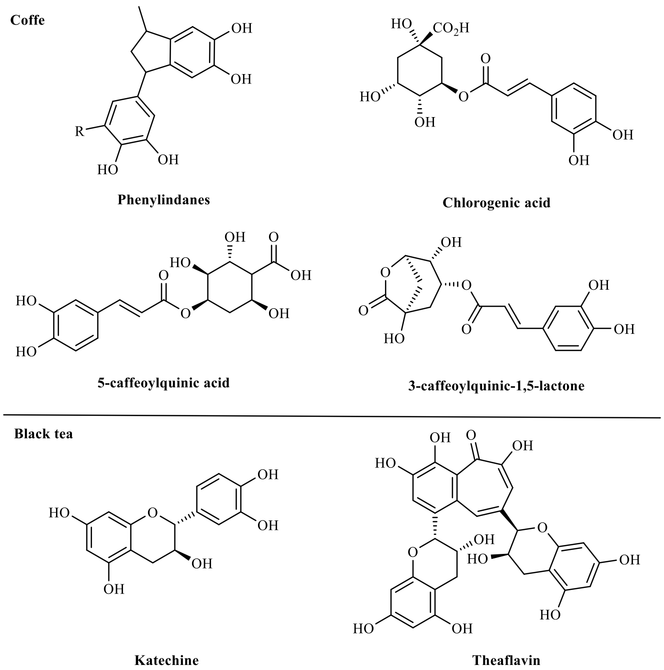

Figure 35. Some substances in tea and coffee extracts (Xia et al., 2023)

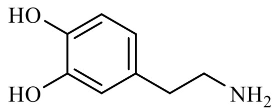

Figure 36. Chemical structure of Dopamine

Sludge generated during the treatment processes of textile factories poses an environmental burden due to its toxic components such as formaldehyde and lead. The biocidal properties of the oil obtained by pyrolysis of this structure are a significant research topic. Scheibe et al. (2022) pyrolyzed textile sludge at 500°C for 70 minutes and analyzed the elemental composition of the resulting byproducts using GC-MS. The researchers examined the antibacterial effects of pyrolysis oil on *E. coli, S. aureus, P. aeruginosa, and Klebsiella pneumoniae*. Structures such as pyridine, aniline, alcohols, aromatic hydrocarbons, ketones, and organosilicones were detected in the oil phase fraction, and this fraction exhibited antibacterial activity in the range of 9–17 mg/mL. The authors suggested that the oil phase fraction could be purified and transformed into a sustainable source of antibacterial agents, and that antibacterial textile research would be beneficial in this direction (Scheibe et al., 2022).

Plant based dyes are generally considered eco-friendly dyes due to their non-toxicity. These dyes may also contain bioactive compounds, such as phenolic compounds, which can impart antibacterial properties to fabrics. Zhang et al. (2021) published a study on the potential use of the seed coats of the *Eriobotrya japonica L. (loquat)* tree as antibacterial textile dyes. These substances are typically disposed of as waste. However, these fruits contain biologically active compounds, including flavonoids. This study examined the dyeing of wool fibers extracted from loquat seeds using traditional mordants and biomordants derived from Chinese Tallow, Folium Artemisiae Argyi, and Cinnamomum Camphora plants. The dyes were characterized by a variety of analytical methods, including UV–vis, FT-IR, SEM, TGA, EDS, and DSC analyses. Dyeings with biomordants exhibited higher color strength and stronger antioxidant, UV protection and antibacterial activity (against *S. aureus, E. coli)* than dyeings with iron, aluminum and copper mordants (Figure 37) (Y. Zhang et al., 2021).

In another study on the extraction of dyes from plant waste, Hassan (2021) utilized dyes derived from feijoa fruit peel (B1) and mango pit (B2), in addition to commercial tannic acid (B3), to dye wool. Figure 38 shows some components of mango seed kernel and feijoa peel extracts. The results of the study indicate that B1 exhibited the optimal antistatic properties, B3 dyes demonstrated the strongest UV protection and antioxidant activity, and wool fabrics dyed with mango pit dye displayed the most potent anti-insecticide and antibacterial properties. Antibacterial analysis, employing the AATCC 147 method, revealed that the fabrics did not form zones; however, B3 fabric exhibited no bacterial growth under the fabric (Against *S. aureus, P. aeruginosa, K. pneumoniae*). This outcome indicates that the fabrics demonstrate non-leaching antibacterial activity (Hassan, 2021).

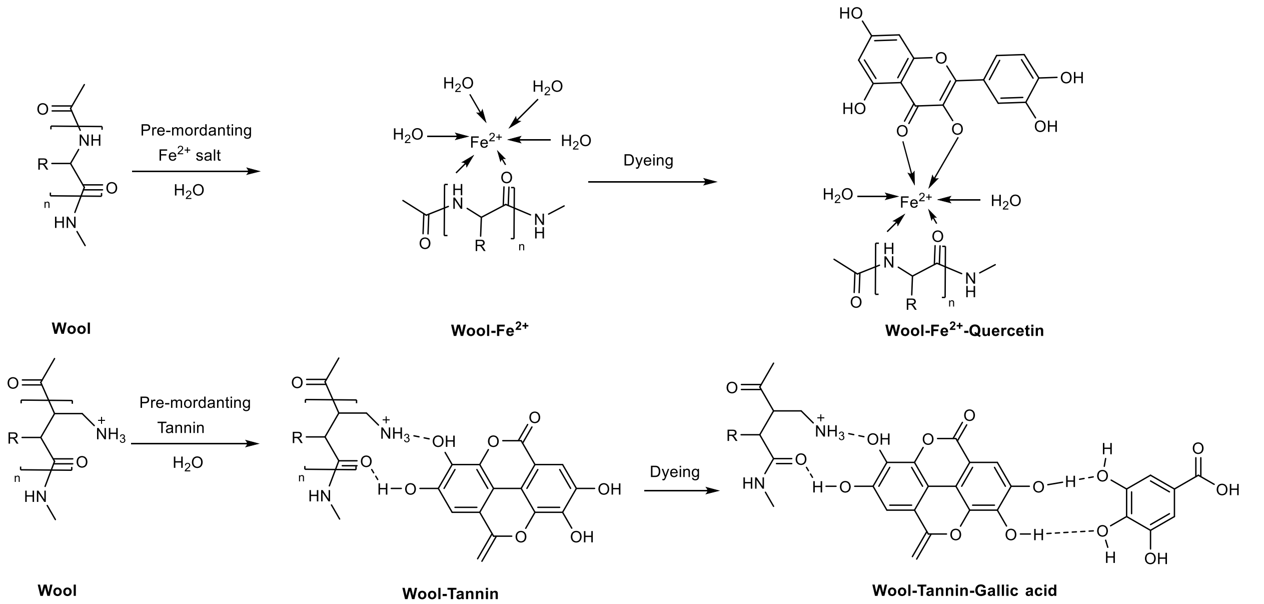

Figure 37. Binding of quercetin and gallic acid to wool pre-mordanted with metallic (Fe) and biomordant (tannic acid)

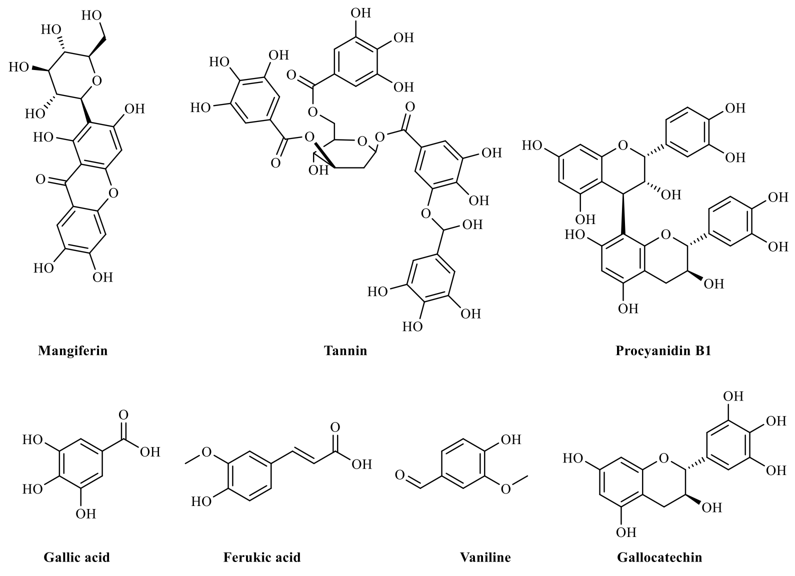

Figure 38. Some substances of of feijoa peel and mango seed

Olives are one of the most important agricultural products in Turkey and some other parts of the world. During the olive harvest, the leaves are separated and thrown away. Olive leaves contain active compounds such as phenolic compounds, p-coumaric acid, vanillin, luteolin, and vanillic acid. Yılmaz and Bahtiyari (2020) used the ground solid form of olive tree leaves and the dyes obtained by their extraction to dye cotton. The antibacterial activities of fabrics dyed with mordant-free extracts at 80°C and with ground leaves without extraction were determined to be 99.99% and 90%, respectively, against *S. aureus*. The same values were measured for *E. coli* at 95% and 70%, respectively. These fabrics were also found to have very good light and washing fastness values (4-5) (Yılmaz and Bahtiyari, 2020).

Another byproduct of silk production is sericin protein, which is separated during the process. Sericin, a protein found in silk, helps the silk cocoon stay intact. During the process of making silk fiber, this material is removed. Gökçe et al. (2020) soaped silk industry wastewater at a pH level of 9-10. Then, they removed the soap at a pH level of 3.5. Finally, they recycled sericin in powder form through filtration, precipitation, and lyophilization. Ag-Sericin nanocomposites (Ag-SNP) were made using a reductive system ($NaOH/NaBH_4$) with sericin from $AgNO_3$. Fabrics treated with 20 g/L of AG-SNP in a slightly acidic environment were observed to be 100% effective against *S. aureus* and *E. coli* bacterial strains, even after 20 washe cycles (Gokce et al., 2020).

Umesh et al. (2023) isolated pigments from the fungus *Talaromyces albobiverticillius* using liquid and solid commercial media and pineapple peel waste as media for use as textile dyes. The resulting dyes were applied to cotton fabrics with and without the mordants $CuSO_4$ and $FeSO_4$. Although the antibacterial activity of the fabrics was not investigated in this study, the antibacterial activity of the dye against *S. aureus, B. subtilis, P. aeruginosa,* and *E. coli* was investigated. The dye was inactive against *E. coli* at a concentration of 500 µg/mL, while it formed inhibitory zones of 1.3–1.9 cm in diameter against other bacterial strains. (Umesh et al., 2023).

Cerempei et al. (2016) studied how to dye wool fibers with dyes made from the water extraction of waste quince leaves (*Cydonia oblonga*). The fabric was dyed at 100°C for two hours. Fabrics were treated with zinc chloride and silver nitrate in a separate bath after mordanting at 70°C, resulting in shades ranging from beige to reddish brown. They found that fabrics treated with silver nitrate were able to kill bacteria like S*. aureus, E. coli,* and *P. aeruginosa.* These fabrics also had very good color, washing, and rubbing fastness values (Cerempei et al., 2016).

Fang et al. (2022) used sweet potato leaves to dye silk, cotton, wool, and polyester fabrics. The authors tried to create a more affordable and environmentally friendly dyeing method by applying the dyes directly, without using mordants. All fabrics were dyed in 60% ethanol at a 1:10 bath ratio at 90°C and pH 7 for 90 minutes under the same conditions. The fabrics exhibited more than 98% antibacterial activity against S*. aureus* and *E. coli*. They maintained activity after 10 washing cycles, with 97% of their strength remaining, and 83% after 30 washing cycles. This study demonstrated that a single active ingredient can dye textile fibers with different functional groups without a mordant (J. Fang et al., 2022).

CONCLUSION

This review comprehensively examines antibacterial bioactive agents derived from organic, inorganic, and biological wastes and their textile applications. The reviewed studies focus on the preparation of bioactive agents, their application to textile materials, and the antibacterial activity of these materials. Furthermore, a schematic presentation of the bioactive agents, the auxiliary chemicals used, and the binding mechanisms to textile materials is provided.

Metal and metal oxide nanoparticles are attracting attention due to their easy binding properties to textile materials and their strong antibacterial effects. However, concerns exist regarding this class, such as potential toxic effects on human cells and potential environmental health hazards from wastewater. On the other hand, extracts isolated from plants offer an environmentally friendly and sustainable alternative for antibacterial textile production thanks to their organic bioactive components. Antibacterial bioactive agents derived from environmental wastes and their textile applications also hold promise in terms of sustainability. However, limitations in this class relate to the regular supply of waste and the continuity of production. Antibacterial textiles can play a crucial role in reducing the spread of antibacterial resistance genes and the incidence of hospital-acquired infections, thereby contributing to the protection of public health. The literature summarized in this review is intended to guide future research in this field.

Conflict of Interest

The author declare no conflict of interest.

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