

Antimicrobial Polymer-Based Nanocomposites for Pollutants Removal

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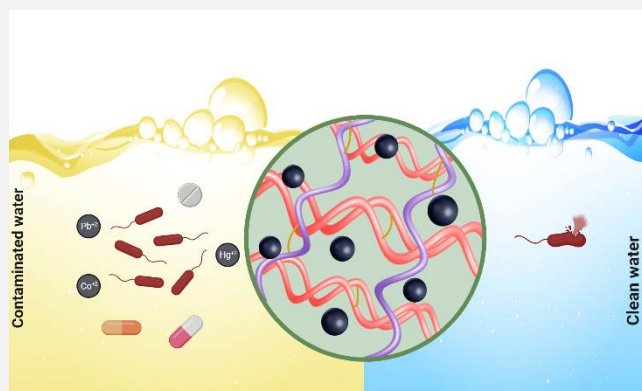


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ABSTRACT

Antimicrobial polymer-based nanocomposite adsorbents have emerged as promising materials for water purification due to their unique properties, including high surface area, low cost, abundance, and ease of interaction with contaminants. These materials can be prepared using a variety of methods, including solvent casting, in situ polymerization, and electrospinning. The application of polymer-based antimicrobial nanocomposite adsorbents in water purification has been widely reported in the literature, with promising results for the removal of a wide range of pollutants, including heavy metals, organic dyes, and bacteria. This review manuscript aims to provide a comprehensive overview of polymer-based antimicrobial nanocomposite adsorbents for water purification. The review will begin with a discussion of the different types of polymer-based antimicrobial nanocomposites and the methods used to prepare them. The next section will review the application of these materials in water purification, with specific examples of their use to remove various pollutants. Finally, the review will conclude with a discussion of the challenges and opportunities for the future development of polymer-based antimicrobial nanocomposite adsorbents for water purification. This review will be of interest to researchers and practitioners in the field of water purification, as well as those working on the development of new materials for environmental remediation.



Keywords: Antimicrobial polymer, nanocomposites, pollutants, removal, water treatment

1. Introduction

Polymer-based antimicrobial nanocomposite adsorbents have emerged as promising materials for water purification due to their unique properties, including high surface area, low cost, abundance, and ease of interaction with contaminants. These materials can be prepared using a variety of methods, including solvent casting, in situ polymerization, and electrospinning. The application of polymer-based antimicrobial nanocomposite adsorbents in water purification has been widely reported in the literature, with promising results for the removal of a wide range of pollutants, including heavy metals, organic dyes, and bacteria.

Although there are some review articles about antimicrobial polymers [1-3], recent progress in this topic has been rarely reviewed [4]. More importantly, the role of nanomaterials in combination with polymer matrixes has not been considered together. In addition, reviewing the polymer-based nanocomposites with both antimicrobial and water pollutant absorption properties is still lacking. This review manuscript aims to cover these issues and provide a short overview of polymer-based antimicrobial nanocomposite adsorbents for water purification. The review will begin with a discussion of the different types of polymer-based antimicrobial nanocomposites and the methods used to prepare them. The next section will review the application of these materials in water purification, with specific examples of their use to remove various pollutants. Finally, the review will conclude with a discussion of the challenges and opportunities for the future development of polymer-based antimicrobial nanocomposite adsorbents for water purification. This review manuscript will cover the following topics:



- Types of polymer-based antimicrobial nanocomposites
- Methods for the preparation of polymer-based antimicrobial nanocomposite adsorbents
- Application of polymer-based antimicrobial nanocomposites as adsorbents in water purification
- Challenges and opportunities for the future development of polymer-based antimicrobial nanocomposite adsorbents for water purification

2. Antimicrobial polymer-based nanocomposites

There are two potential approaches for the preparation of antimicrobial nanocomposites, which are described as follows (**Figure 1**):

2.1. Antimicrobial polymers

This innovative approach involves replacing the existing matrix in polymer-based composites with an antimicrobial polymer. Antimicrobial polymers are chemically stable and have low cellular toxicity. They can prevent the growth of bacteria, fungi, and viruses by disrupting microbial membranes, making them effective against drug-resistant microbes. Natural polymers like chitosan are examples of cationic antimicrobial polymers with intrinsic antimicrobial activity, requiring no additional modification. Besides natural cationic polymers, antimicrobial polymers for use as matrices in composites can be prepared by functionalizing monomers or desired polymers with antimicrobial agents such as quaternary ammonium salts, phosphonium salts, or forming triazole three-membered rings (using click chemistry) [1-3, 5, 6].

2.2. Antimicrobial nanoparticles

Some metallic (such as Ag, Au, etc.) and non-metallic materials (such as CuO, ZnO, TiO₂, MgO, Fe₂O₃, MgO, CaO, and so on) exhibit antimicrobial activity. This activity significantly is enhanced when they are synthesized on a nano-scale, known as antimicrobial nanoparticles. Nanostructured materials provide higher surface area (high surface-to-volume ratio) and more active sites. In addition, because of the very small size of nanoparticles, they can cause irreversible damage to microbial cell membranes through penetrating the cell walls. Therefore, they are ideal candidates to be used as antimicrobial agents [7-12].

Antimicrobial nanoparticles are used in combination with a polymer matrix to prepare antimicrobial nanocomposites. Some nanoparticles, like silica and hydroxyapatite, inherently lack acceptable antimicrobial activity and need to be modified using antimicrobial agents. The nanoparticle-polymer composites can hinder microbial vitality, adhesion, and biofilm formation with diverse mechanisms, making them promising for developing new-generation antimicrobial matrixes [7, 8, 10].

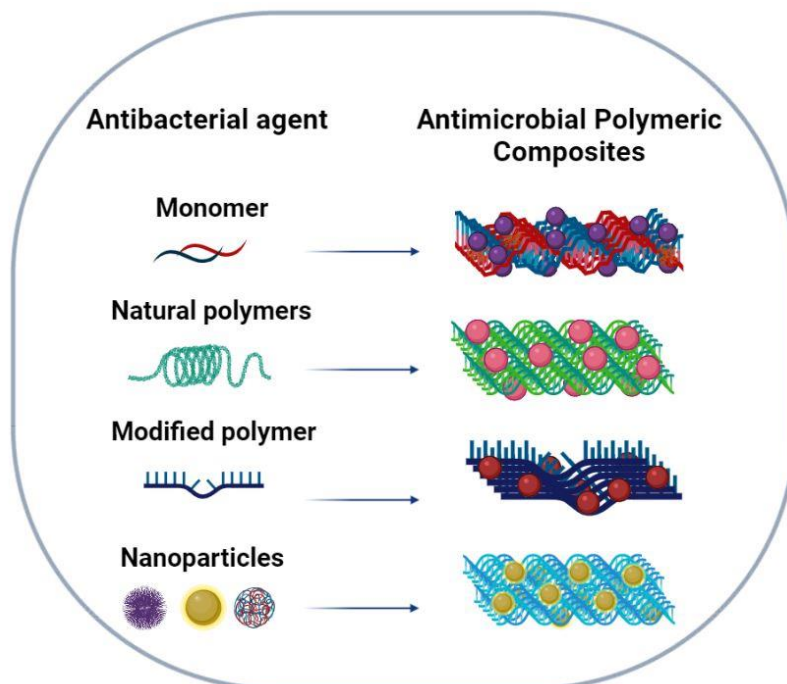


Figure 1: Types of polymer-based antimicrobial nanocomposites.

3. Preparation methods of antimicrobial polymer-based nanocomposite adsorbents

The fabrication of selective and efficient adsorptive antimicrobial nanocomposite adsorbents in different conditions is essential. Generally, three major methods for producing polymer-based antimicrobial nanocomposite adsorbents have been proposed using antimicrobial polymers and nanoparticles, including solvent casting, in situ polymerization, and electrospinning.

3.1. Solvent casting

Solvent casting is one of the oldest methods for creating polymer films (**Figure 2A**). It is commonly used for producing flexible polymer components, mainly in the medical equipment industry. This method involves dispersing or dissolving antimicrobial/non-antimicrobial polymers and nanoparticles in suitable solvents in separate containers, then mixing the solutions for a specified period and finally evaporating the solvent to produce composite films. The advantages of this method include low cost, no need for special equipment, and the production of films with uniform thickness. Additionally, the use of non-toxic organic solvents to create a homogeneous solution with minimal solid content and low viscosity, eliminating the need for additional solvents, is a benefit of this method [13-15].

3.2. In situ polymerization

In situ polymerization is a popular process for preparing polymer-based nanocomposite adsorbents (**Figure 2B**). In this method, antimicrobial/non-antimicrobial monomers are mixed with desired antimicrobial/non-antimicrobial nanoparticles in a suitable solvent, and an appropriate polymerization initiator is then added. The key to this method is how nanoparticles are distributed in the polymer matrix. By controlling the bond between nanoparticles and the polymer matrix, a desirable and uniform distribution can be achieved. Advantages of in situ polymerization include good dispersion of nanoparticles in the polymer matrix and the possibility of covalent bonding between the polymer and nanoparticles. However, precise control of initiator, monomer, and nanoparticle amounts, as well as temperature control, are drawbacks of this method [16-18].

3.3. Electrospinning

Electrospinning is a novel and efficient method for producing composite antimicrobial nanofiber adsorbents (**Figure 2C**). This method is one of the most commonly used approaches for producing nanofibers in various forms, such as core-shell nanofibers, hollow nanofibers, and porous nanofibers. Electrospinning is considered one of the best methods for producing nanofibers due to its advantages over other methods. Using electrospinning, fibers with diameters ranging from 3 nanometers to 10 micrometers can be produced. As **Figure 2C** represents, after mixing polymer solution and nanoparticle dispersion, the mixture is entered into a syringe. A high direct electrical field (DE) is then applied between the syringe needle and the opposite substrate. The electrical charges in the polymer mixture interact with the applied electric field to form the well-known Taylor cone [19, 20]. If the DE is strong enough with an appropriate gradient at the cone tip, a jet of fluid is drawn out from the needle tip. During the jet flow through a long enough path, various forces such as surface tension, gravitational and Coulombic forces, electrical force induced by external DE, etc., are imposed onto the traveling jet particles, leading to bending and spinning of the flow. In addition, the DE stretches the jet and makes it extremely thinner, and micro/nanofibers are formed after solution evaporation and are collected on the surface of the opposite substrate. Successful implementation of this method requires optimizing environmental conditions (pressure, temperature, humidity), solution properties (viscosity), and concentration, as well as processing parameters (electric potential, flow rate, needle diameter, collector distance) to achieve the desired fiber properties. The advantages of electrospinning include a straightforward process, low-cost setup, and precise control over fiber diameter, orientation, and composition. However, the use of toxic solvents and limited control over porous structures are disadvantages of this method [13, 21-23].

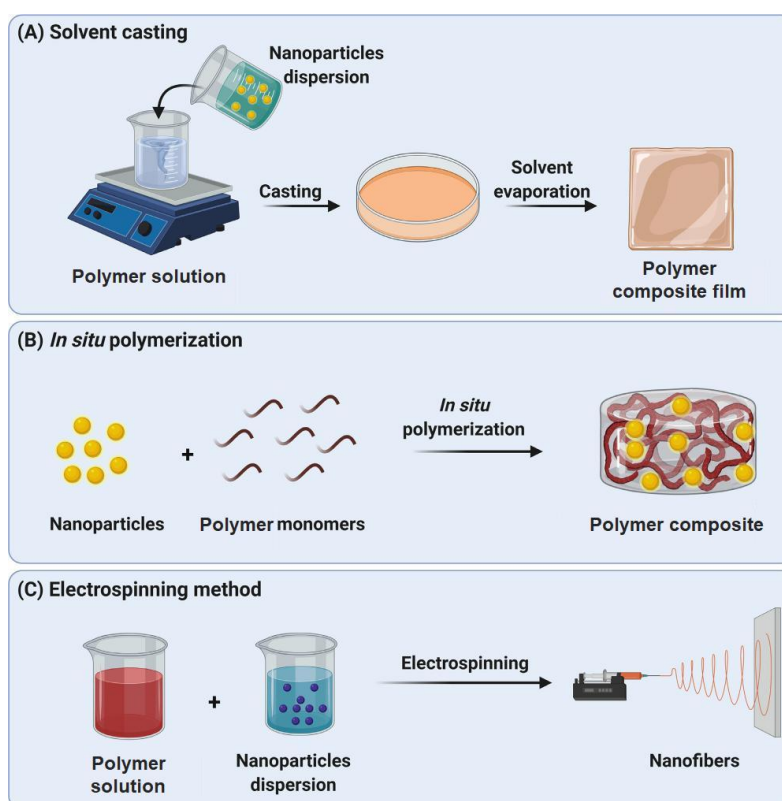


Figure 2. Different methods for fabricating polymer-based antimicrobial nanocomposite adsorbents, solvent casting (A), in situ polymerization (B), and electrospinning (C). Reprinted with permission from ref. [24].

4. Application of antimicrobial polymer-based nanocomposites as adsorbents in water purification

The presence of certain microorganisms such as bacteria and fungi in water, in addition to other contaminants, can lead to a decrease in the quality of water systems and, consequently, have adverse effects on public health. Therefore, the development of antimicrobial nanocomposite adsorbents is of great importance due to their excellent properties, including high surface area, low cost, abundance, and ease of interaction with contaminants, resulting in high adsorption efficiency. Numerous studies have reported the use of polymer-based antimicrobial nanocomposite adsorbents for the removal of various pollutants from water.

One antimicrobial nanocomposite was developed using polyvinyl alcohol nanofibers and silver nanoparticles, and it was effectively used to remove Cd^{2+} ions from water. The maximum adsorption capacity for Cd^{2+} ions by this nanocomposite and silver nanoparticles was 40.65 and 28.4 mg/g, respectively, under optimal adsorption conditions. The investigation of theoretical and experimental results revealed that the adsorption occurred chemically through electron exchange. It was also reported that this nanocomposite exhibited long-lasting antimicrobial activity against both Gram-negative strains (*Escherichia coli* (*E.coli*), *Klebsiella pneumonia*, *Salmonella*, and *Pseudomonas aeruginosa*) and Gram-positive strains (*Streptococcus* and *Staphylococcus aureus*) [25].

In another study, an antimicrobial nanocomposite was prepared using modified chitosan gum, polyvinyl alcohol, and silver nanoparticles and was effectively employed for the removal of Ca^{2+} and Mg^{2+} ions from water (**Figure 3**). The maximum adsorption capacity for Ca^{2+} and Mg^{2+} ions was 162.46 and 114.18 mg/g, respectively, under optimal adsorption conditions. Theoretical and experimental results indicated that the adsorption occurred chemically through electron sharing or exchange. The adsorption mechanism was a combination of ion exchange and simple adsorption processes. Moreover, this nanocomposite demonstrated good antimicrobial activity against both Gram-negative bacteria (*E. coli* and *Pseudomonas aeruginosa*) and Gram-positive bacteria (*Bacillus subtilis* and *Staphylococcus aureus*) [26].

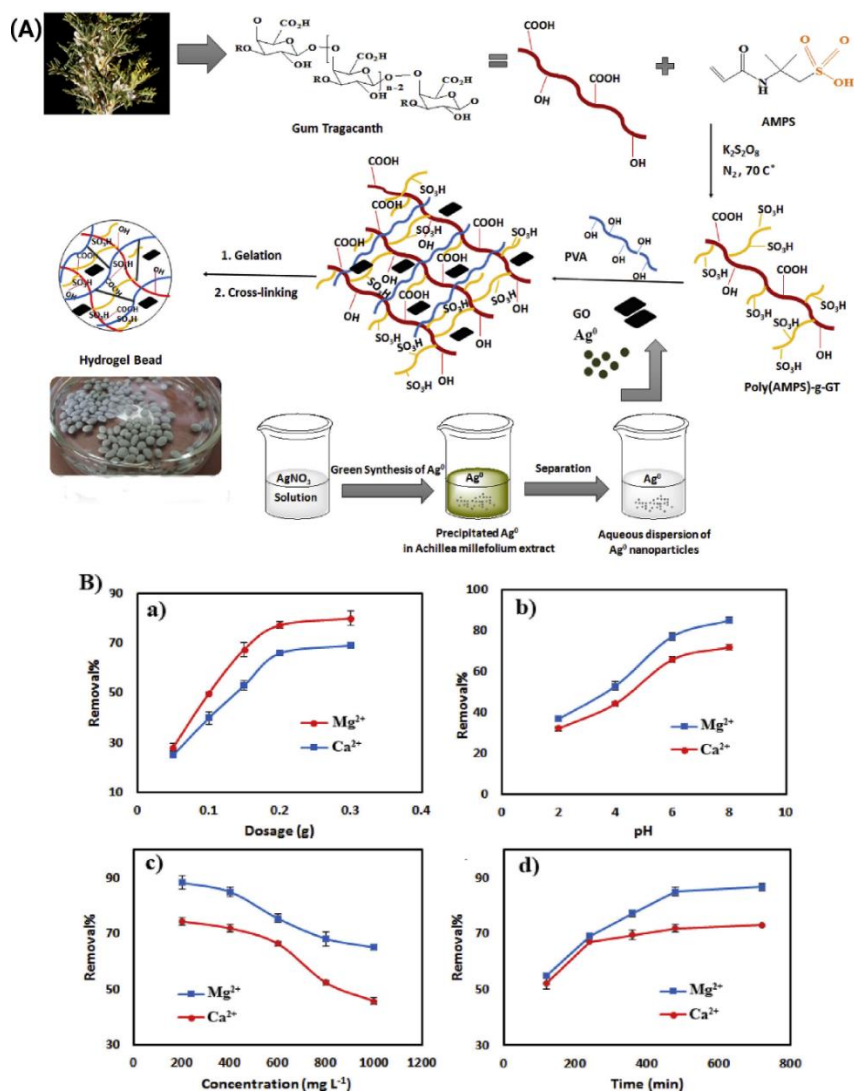


Figure 3. (A) Schematic of antimicrobial nanocomposite (B) Effect of different conditions on metal ion removal efficiency (a) Adsorbent dosage, (b) pH, (c) Initial concentration of metal ions, and (d) Contact time Removal efficiency of Ca^{2+} and Mg^{2+} ions. Reprinted with permission from ref. [26].

A biodegradable polymer-based antibacterial nanocomposite was prepared using xanthan gum and montmorillonite nanoclays via ultrasonication, followed by network polymerization with vinyl imidazole monomer. This antibacterial nanoadsorbent effectively led to the removal of toxic malachite green dye with a maximum adsorption capacity of 99.99% (1.909 mg/g) under alkaline pH conditions from a 500 ppm malachite green dye solution using 50 mg of the nanocomposite at $30\text{ }^\circ\text{C}$ for 90 minutes. Furthermore, the prepared nanocomposites exhibited excellent inhibition of bacterial growth against bacterial strains such as *E. coli* and *Staphylococcus aureus* [27]. In a similar study, a nanocomposite adsorbent with antibacterial activity was developed using xanthan gum and silicon dioxide nanoparticles through ultrasonication, followed by network polymerization with vinyl imidazole monomer (**Figure 4**). The antibacterial nanocomposite was used as an effective filter for the removal of malachite green dye and the elimination of bacterial growth from contaminated waters, including bacterial strains such as *E. coli* and *Subtilis aureus*. The maximum adsorption capacity under optimal conditions, including 10 mg of nanocomposite, 10 mL of malachite green dye (450 mg/L), pH 7, and a temperature of $30\text{ }^\circ\text{C}$, was reported to be 2.588 mg/g over 6 hours. The inhibition zone diameter against the growth of bacterial strains such as *E. coli* and *Subtilis aureus* was reported to be

25.33 and 23.5 mm, respectively [28]. These studies demonstrate the potential of biodegradable polymer-based antibacterial nanocomposites as efficient adsorbents for the removal of toxic dyes from water and the inhibition of bacterial growth, making them valuable in water treatment applications and environmental remediation.

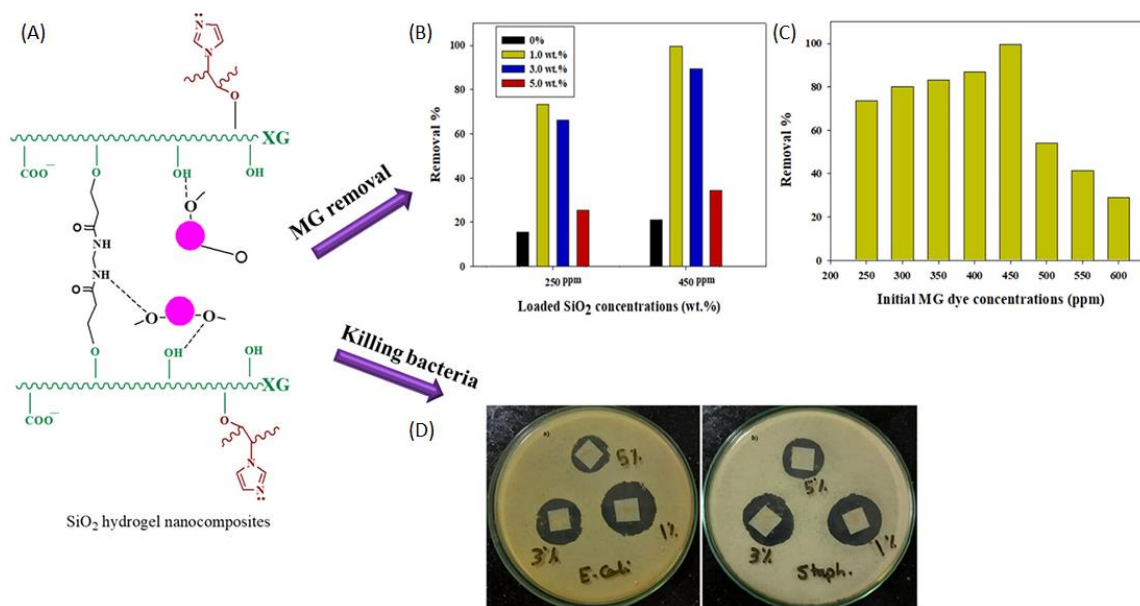


Figure 4. (A) Schematic of antimicrobial nanocomposite (B) Effect of concentration of SiO₂ nanoparticles loaded on nanocomposite and its effect on removal of green malachite contaminant, (C) Effect of green malachite dye concentration on removal percentage, and (D) Antimicrobial activity of nanocomposite against the bacterial strains of *E. coli* and *Staphylococcus aureus*. Reprinted with permission from ref. [28].

An antibacterial nanocomposite based on natural chitosan-chelated iron oxide nanoparticles (CSt-Fe₃O₄) was prepared for the efficient removal of methyl orange dye from aqueous environments. The maximum adsorption capacity for methyl orange dye was reported to be 18 mg/g after 60 minutes of contact time. Moreover, the presence of iron oxide nanoparticles in the nanocomposite improved its antibacterial properties against both Gram-negative strains (*E. coli* and *Pseudomonas aeruginosa*) and Gram-positive strains (*Bacillus cereus* and *Staphylococcus aureus*). The inhibition zone diameter against bacterial growth in the presence of the nanocomposite was reported as follows: *Pseudomonas aeruginosa* > *Bacillus cereus* > *Staphylococcus aureus* > *E. coli* [29]. In another study, an antibacterial nanocomposite based on starch and zinc oxide (CSt-ZnO) was developed for the effective removal of lead (II) ions from aqueous environments (Figure 5). The optimized parameters for maximum lead (II) removal included a contact time of 120 minutes, pH 6, a temperature of 318 K, and a lead contaminant concentration of 20 mg/L. Additionally, it was demonstrated that increasing the temperature from 298 K to 318 K increased the maximum adsorption capacity from 4.256 to 4.476 mg/g, indicating the endothermic nature of lead ion adsorption onto the CSt-ZnO nanocomposite. Furthermore, the adsorption capacity remained at approximately 68% even after four adsorption-desorption cycles, suggesting the nanocomposite's acceptable performance for reuse. The antibacterial activity of the CSt-ZnO nanocomposite was also found to be very good against strains of *Staphylococcus aureus* and *E. coli*, demonstrating its effectiveness against both negative and positive bacterial species [30].

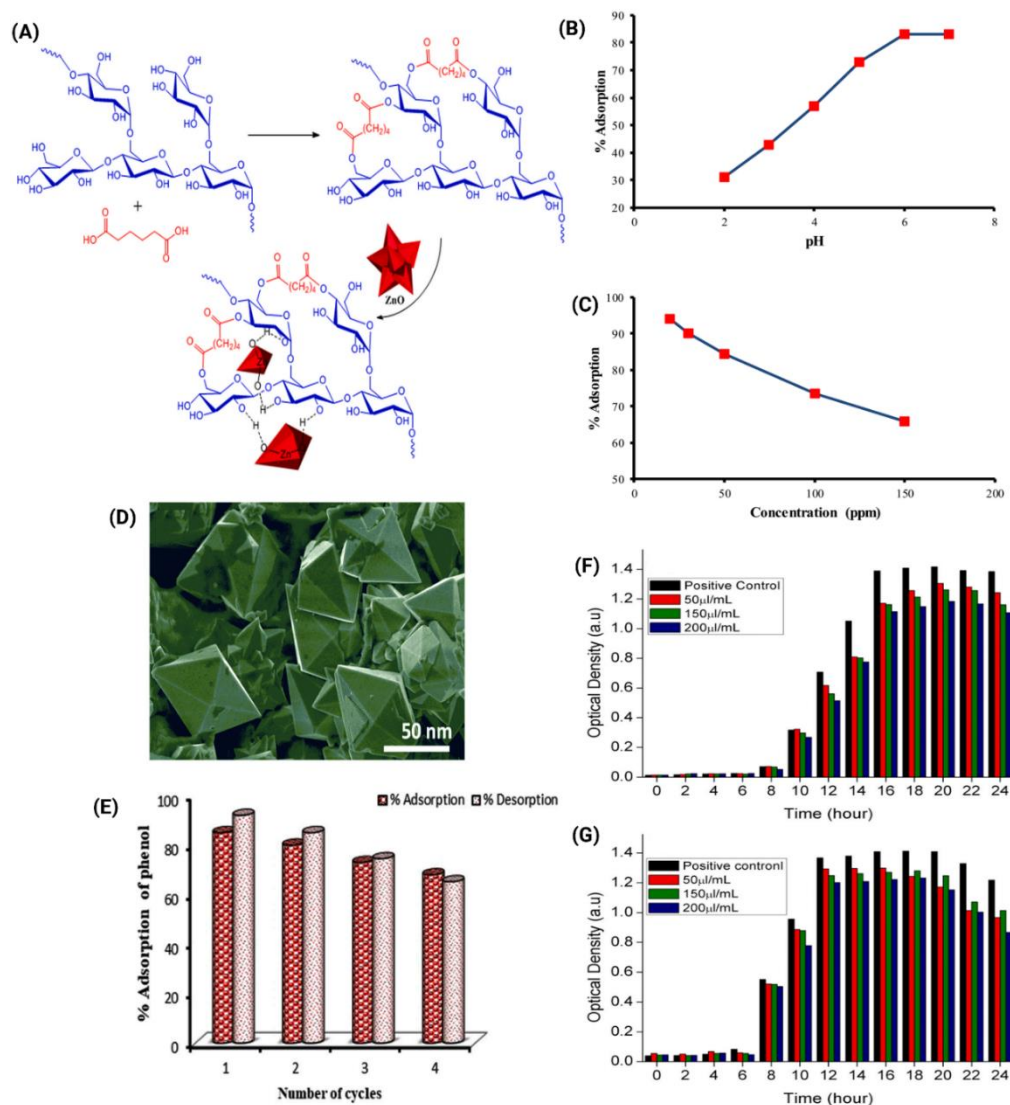


Figure 5. (A) Scheme of preparation of starch/zinc oxide nanocomposites (CSSt-ZnO), removal of lead (II) ions using CSSt-ZnO nanocomposites at (B) at different pHs (C) at different initial concentrations of Pb (II) (D) SEM image of CSSt-ZnO nanocomposites, (E) Recovery study of CSSt-ZnO using 0.1 M acid hydrochloride solution, antimicrobial activity of CSSt-ZnO nanocomposites against *Staphylococcus aureus* (F) and *E.coli* (G) using the optical density method. Reprinted from ref. [30].

A nanocomposite film with antibacterial properties was prepared using nickel oxide nanoparticles/chitosan/poly(vinyl alcohol) (NiO/CSSt/PVA) for the removal of toxic methyl orange dye. The adsorption results for methyl orange dye by nanocomposites with different weight percentages of nickel oxide nanoparticles (0.5%, 1%, 3%, and 5%), contact times (0-150 minutes), and adsorbent amounts (40, 80, and 100 milligrams) were investigated. The nanocomposite film with a 5% weight of nickel oxide nanoparticles exhibited double the percentage removal of methyl orange dye compared to the unmodified chitosan/poly(vinyl alcohol) film. Antibacterial tests demonstrated that the nickel oxide/chitosan/poly(vinyl alcohol) nanocomposite film had better antibacterial activity against Gram-negative bacteria (*Salmonella typhimurium* and *E. coli*) and Gram-positive bacteria (*Bacillus cereus* and *Staphylococcus aureus*) compared to the unmodified chitosan/poly(vinyl alcohol) film [31]. In another study, an antibacterial nanocomposite film based on multi-walled carbon nanotubes functionalized with poly(vinyl alcohol) (f-MWCNTs/PVA) was reported, using citric acid as a cross-linking agent (Figure 6). The prepared nanocomposite film was used for the removal of heavy metals and organophosphorus pesticides from

wastewater. The percentage removal of the tested pollutants increased with an increase in the weight percentage of functionalized multi-walled carbon nanotubes (with maximum adsorption observed at 10%). Moreover, the data indicated that increasing the weight percentage of functionalized multi-walled carbon nanotubes in the f-MWCNTs/PVA nanocomposite film enhanced its antibacterial activities against both bacterial and fungal species [32].

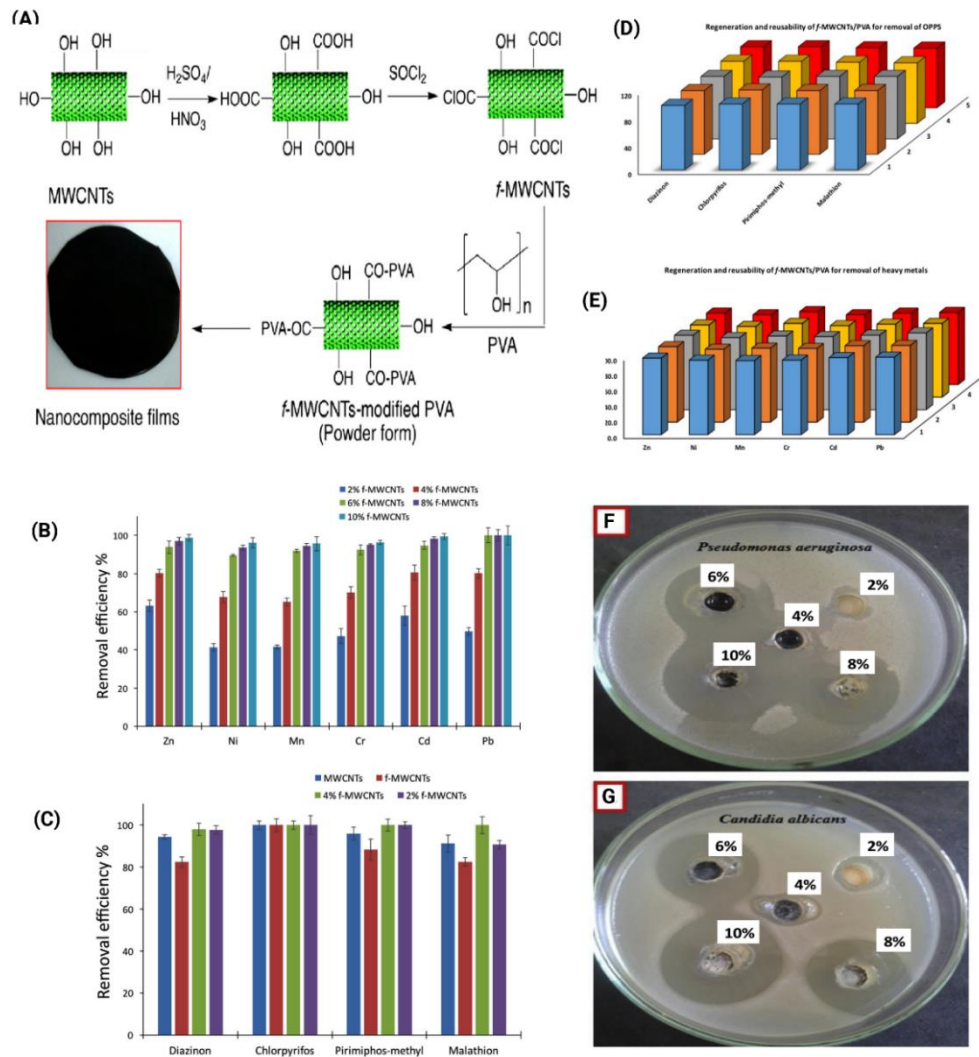


Figure 6. (A) Scheme of preparation of f-MWCNTs/PVA nanocomposite films, percentage of removal efficiency (B) of heavy metal ions and (C) toxic organic residues with MWCNT, pure f-MWCNT and various film nanocomposites Based on f-MWCNTs (4%) and f-MWCNT (2%). Recovery and reusability of f-MWCNTs/PVA to remove (D) toxic organic residues and (E) heavy metal ions, antimicrobial activity of f-MWCNTs/PVA nanocomposites against (F) *Pseudomonas aeruginosa* and (G) *Candida Albicans*. Reprinted with permission from ref. [32].

Polymer-based nanocomposite films containing poly(vinyl alcohol), melamine formaldehyde, and nickel oxide nanoparticles were prepared with dual functionality, enabling the effective removal of Congo Red dye and exhibiting antibacterial properties. The maximum adsorption capacity for Congo Red dye in the prepared polymer nanocomposite films increased by 45% to 68% with increasing contact time and by 48% to 70% with increasing dye concentration. The diameter of the no-growth zone of the prepared nanocomposite films against the growth of bacterial strains such as *E. coli*, *Klebsiella pneumoniae*, *Bacillus subtilis*, and *Staphylococcus aureus* was reported to be 25, 23, 25, and 25 millimeters, respectively [33].

In another study, an antibacterial nanocomposite based on cellulose and titanium dioxide nanoparticles was prepared using the hydrolysis-deposition method as a biosorbent for the removal of phosphate ions from aqueous environments (Figure 7). The maximum adsorption capacity of the prepared nanoadsorbent for phosphate ions was reported to be 19.57 milligrams per gram, which is six times higher than that of pure cellulose. The prepared nanocomposite exhibited antibacterial activity against *E. coli* bacteria. Furthermore, the nanocomposite demonstrated selectivity in ion adsorption, excellent anti-interference capabilities, and stability under acidic, neutral, and alkaline conditions [34].

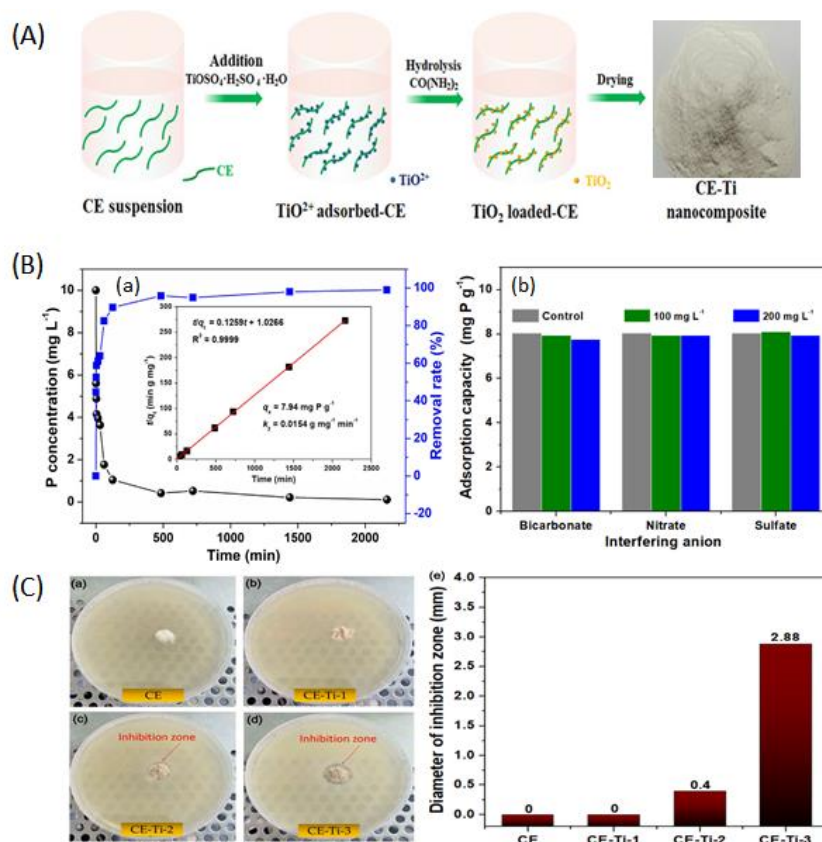


Figure 7. (A) Schematic of antimicrobial nanocomposite preparation (B) Phosphate adsorption kinetics of nanocomposite prepared as plots of phosphate concentration (black line) and removal rate (% of the blue line) versus time (t, min) (a), inset shows the pseudo-second-order kinetic plot for the adsorption effects of interfering anions on phosphate adsorption of (b), (C) The antimicrobial activity and the corresponding inhibition zone diameters of the nanocomposite against *E. coli* bacterial strains. Reprinted with permission from ref. [34].

A magnetic nanocomposite based on natural gum Guar, chitosan, and iron oxide nanoparticles was developed for efficient uranium removal, with added antibacterial properties. Under optimal conditions of pH 4 and a contact time of 60 minutes, the maximum adsorption capacity was reported to be approximately 1.28 and 0.16 millimoles of uranium per gram for non-magnetic and magnetic nanocomposites, respectively. The nanocomposite showed the ability for reuse, even after five adsorption-desorption cycles (a 5-6% reduction in adsorption performance with complete recovery). Antibacterial test results indicated that the magnetic nanocomposite exhibited good activity against Gram-negative bacteria (*Pseudomonas aeruginosa* and *E. coli*) and Gram-positive bacteria (*Bacillus subtilis* and *Staphylococcus aureus*) [35].

In another study, an antibacterial nanocomposite based on humic acid with a combination of aluminum zirconium bimetal oxide was prepared, showing pH-sensitive behavior for effective fluoride ion removal (Figure 8). The maximum adsorption capacity under optimal conditions of pH 7, an initial concentration of 100 milligrams per liter, and the room temperature was reported to be 180.26 milligrams per gram in 110 minutes. Additionally, the

nanocomposite demonstrated the potential for reuse after five adsorption-desorption cycles, indicating acceptable performance for repeated use. The antibacterial activity of the prepared nanocomposite against Gram-negative bacteria (*E. coli*) and Gram-positive bacteria (*Staphylococcus aureus*) showed high potential against both types of strains [36]. These studies showcase the development of versatile polymer-based nanocomposites with magnetic properties and antibacterial functions, making them promising materials for uranium removal and water treatment applications while addressing microbial contamination concerns.

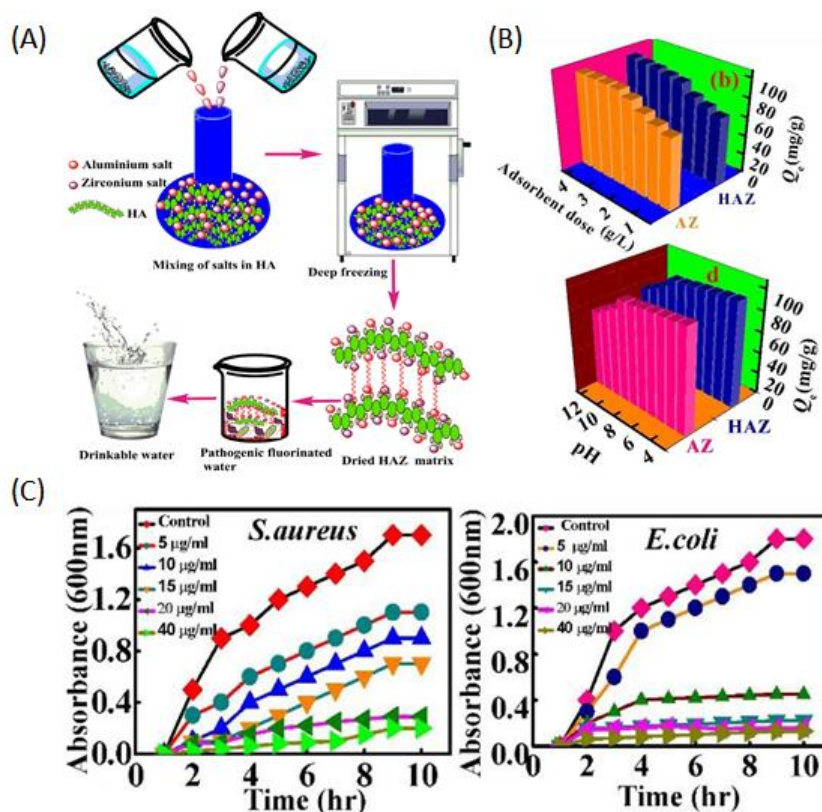


Figure 8. (A) Schematic of preparation of antimicrobial nanocomposite, (B) Effect of different conditions on fluoride removal efficiency (a) Effect of adsorbent dose, (b) pH, (C) Chart of the effect of different concentrations of nanocomposite and inhibition zone of *Staphylococcus aureus* and *E. coli*. Reprinted with permission from ref. [36].

In another study, a three-dimensional antibacterial nanocomposite based on cationic starch/nanocellulose fibers/silver nanoparticles was prepared for the effective removal of methylene blue dye (Figure 9). The maximum adsorption capacity for methylene blue dye was reported to be 1.5 grams per liter under optimal conditions, with a contact time of 30 minutes and pH 1. Experimental and theoretical data suggested that the adsorption mechanism involved electrostatic interactions and chemical reactions. Moreover, the synthesized nanocomposite exhibited efficient antibacterial properties and had the potential to inhibit the growth of Gram-positive *Staphylococcus aureus* and Gram-negative *E. coli* bacteria [37].

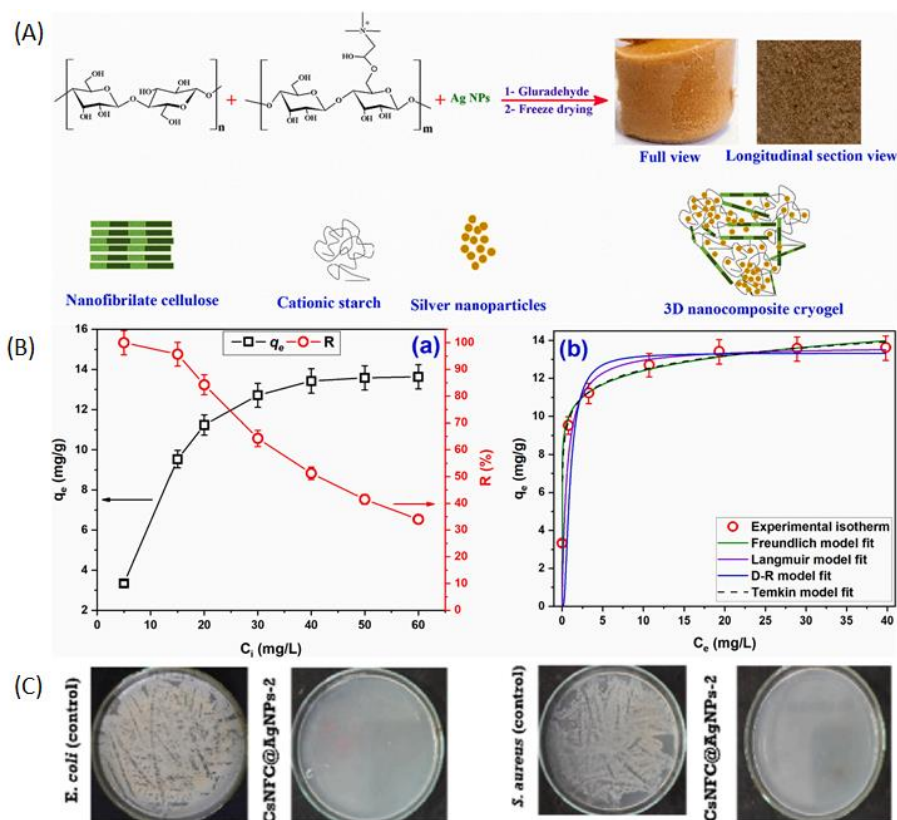


Figure 9. (A) Schematic of antimicrobial nanocomposite (B) Effect of initial concentration on adsorption capacity and adsorption percent (a), and type of used models for adsorption isotherm (b), (C) Antibacterial activity of nanocomposite prepared against *Staphylococcus aureus* and *E. coli*. Reprinted with permission from ref. [37].

In another research study, an antibacterial hydrogel nanocomposite based on sodium alginate, acrylic acid, and zinc oxide was prepared as an efficient adsorbent for the removal of lead (II) ions and inhibition of the growth of Gram-negative bacterial strains. The results indicated that an increase in temperature led to a decrease in the adsorption of lead (II) ions, and the adsorbent reached saturation after 150 minutes. Furthermore, the percentage of lead ion adsorption increased with the addition of zinc oxide nanoparticles to the composite. The best performance was reported for a nanocomposite with 1% zinc oxide nanoparticles, achieving a maximum adsorption capacity of 200 milligrams per gram. Additionally, the prepared hydrogel nanocomposite exhibited excellent antibacterial activity, inhibiting the growth of 99% of Gram-negative *E. coli* bacteria [37]. **Table 1** provides a summary of polymer-based antibacterial nanocomposites for the removal of various types of contaminants from water.

Table 1. Summary of polymer-based antibacterial nanocomposites for the removal of various types of contaminants from water.

Nanocomposites	Pollutant	Removal (%)	Microorganism	Ref.
Carbon Dots/Chitosan-Doped Nanorods	La ₂ O ₃ Rhodamine B (RhB)	94.57	<i>E.coli</i>	[38]
Titanium oxide/chitosan	Thymol violet (TV)	97.51	<i>E.coli</i>	[39]
Chitosan/CuO	Indigo carmine, congo red methyl orange	28.2	<i>Pseudomonas aeruginosa</i> (<i>P. aeruginosa</i>)	[40]
Chitosan/cobalt-silica	Methyl orange, indigo carmine and congo red	75%	<i>E.coli</i> <i>P. stutzeri</i> <i>E.faecium</i> , <i>B. s subtilis</i> <i>S. epidermidis</i>	[41]
Silver-zeolite-poly (acrylamide-co-acrylic acid) semi-interpenetrating hydrogels	Wastewater fertilizer	75%	<i>B. subtilis</i> <i>P. aeruginosa</i>	[42]
Nanocellulose/polyethyleneimine (PEI-BC)	Congo red (CR) reactive red 120(RR)	90%	<i>E.coli</i> <i>S. aureus</i>	[43]
Fe ₃ O ₄ -TSPED ^a -Tryptophan	Congo Red (CR)	183.15	<i>E.coli</i> <i>B. subtilis</i>	[44]
Chitosan/Ag-substituted hydroxyapatite	Copper ions RhB	40.11 127.61	<i>E.coli</i>	[45]
Polyurethane foam-cadmium sulfide	Reactive Orange 122 (RO122)	22.7	<i>S. aureus</i> <i>E.coli</i>	[46]
Chitosan-manganese dioxide	Pb ²⁺ ions	75%	<i>S. aureus</i> <i>E.coli</i>	[47]
Nano zerovalent iron/chitosan	Nitrate Humic acid	90% 98.1%	<i>S. aureus</i> <i>E.coli</i>	[48]
Guar gum/Al ₂ O ₃	Malachite green	90%	<i>S. aureus</i>	[49]
Carboxymethylated lignin-tetra ethoxy silane	Ni ²⁺ Cd ²⁺	70.72% 81.79%	<i>P. aeruginosa</i> <i>S. aureus</i> <i>E.coli</i> <i>B. subtilis</i>	[50]
Cellulose acetate-tin (IV) phosphate	Cd ²⁺ Mg ²⁺	highly selective for Cd ²⁺	<i>E.coli</i>	[51]
Magnetic chitosan-graphene oxide	Methyl orange	398.08	<i>E.coli</i>	[52]
zinc oxide/poly (ionic liquids) based on quaternary ammonium acrylamide methyl propane sulfonate	Methylene blue	3000 mg/L	<i>P. aeruginosa</i> <i>S. aureus</i> <i>E.coli</i> <i>B. subtilis</i>	[53]
Starch/SnO ₂	Hg ²⁺	192	<i>S. aureus</i> <i>E.coli</i>	[54]
Zirconium(IV)-loaded chitosan/Fe ₃ O ₄ /graphene oxide	Alizarin Red (AR)	231	<i>S. aureus</i> <i>E.coli</i> <i>B. subtilis</i>	[55]

5. Conclusion and perspective

Polymer-based antimicrobial nanocomposite adsorbents, with steady but slow progress, have emerged as promising materials for water purification due to their unique properties, including high surface area, low cost, abundance, and ease of interaction with contaminants. These materials can be classified according to their building-block agents including monomers, natural polymers, or modified polymers in combination with various antimicrobial nanoparticles. The polymeric antimicrobial nanocomposite materials can be prepared using a variety of methods, including solvent casting, in situ polymerization, and electrospinning. The application of polymer-based antimicrobial nanocomposite adsorbents in water purification has been widely reported in the literature, with promising results for

the removal of a wide range of pollutants, including heavy metals, organic dyes, and bacteria. Despite the significant progress that has been made, there are still some challenges that need to be addressed before polymer-based antimicrobial nanocomposite adsorbents can be widely deployed in water treatment applications. One challenge is the need to develop more scalable and cost-effective methods for the preparation of these materials. Another challenge is to develop and establish these materials to be durable, reusable, stable, and activity-controlled in a variety of water conditions. Finally, it is important to develop a better understanding of the adsorption mechanisms and antimicrobial activity of these materials to optimize their design and performance. Further clarification is needed to explain the precise mechanisms responsible for the interaction between antimicrobial polymers and diverse microbes and pollutants. Despite these challenges, the future outlook for polymer-based antimicrobial nanocomposite adsorbents in water purification is very promising. These materials offer a unique combination of properties that make them well-suited for a variety of water treatment applications. With continued research and development, polymer-based antimicrobial nanocomposite adsorbents have the potential to revolutionize the way we purify water.

Authors' contributions

All authors contributed to all sections.

Declaration of competing interest

The authors declare no competing interest.

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Data availability

Not applicable.

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