

Sustainable Biopolymer Nanocomposite Membranes for Removal of Heavy Metals, Dyes and Microbial Contaminants from Water

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Abstract

The increasing discharge of industrial, agricultural and domestic wastewater has intensified the need for sustainable and efficient water-treatment technologies. Conventional treatment methods are widely employed, their limitations, including high energy and chemical requirements, secondary pollution, sludge generation and membrane fouling, have stimulated interest in environmentally sustainable materials. Naturally derived biopolymers such as chitosan, cellulose, alginate, starch and gelatin offer promising alternatives owing to their renewability, biodegradability, low toxicity and abundance of functional groups. This review presents recent advances in the design, fabrication and application of sustainable biopolymer nanocomposite membranes for the removal of heavy metals, synthetic dyes and microbial contaminants from water. Particular emphasis is placed on chitosan-, cellulose- and alginate-based membranes incorporating metal oxides, magnetic nanoparticles, graphene oxide, nanocellulose, biochar and other functional nanofillers. The biopolymer nanocomposite membranes offer considerable potential as sustainable, multifunctional platforms for advanced water purification.

Keywords: Biopolymers; Chitosan; Cellulose; Wastewater Treatment; Water Purification

1. Introduction

Water is one of the most important natural resources required for human health, agriculture, industrial development and ecological sustainability. Rapid industrialization, urbanization and population growth have increased the generation of wastewater containing a complex mixture of inorganic, organic and biological contaminants. Industrial activities such as electroplating, mining, metal processing, textile manufacturing, leather processing, pigment production and chemical industries can introduce heavy metals and synthetic organic compounds into aquatic environments. At the same time, untreated domestic and municipal wastewater can contain pathogenic microorganisms and other biological contaminants [1].

Heavy metals are of particular concern because many of them are persistent and cannot be biologically degraded. Lead, cadmium, chromium, mercury, copper, nickel and arsenic-containing species can accumulate in environmental systems and may produce toxic effects even at relatively low concentrations. Hexavalent chromium is especially important because of its high mobility and toxicity. The presence of such contaminants in water therefore requires efficient treatment before discharge or reuse [2].

Synthetic dyes represent another important class of water pollutants. Large quantities of dyes are consumed by textile, leather, paper, printing, plastics and related industries. A fraction of the dye used during industrial processing can be released into wastewater. Even low concentrations of dyes may impart intense colour to water and reduce light penetration, thereby affecting aquatic photosynthesis. Certain dye molecules and their degradation products may also exhibit toxic or potentially carcinogenic characteristics [3].

Microbial contamination represents a different but equally important water-quality problem. Bacteria, viruses, fungi and other microorganisms can cause waterborne diseases. Conventional filtration can remove microorganisms through size exclusion, but membrane biofouling may reduce membrane performance and service life. Consequently, modern water-treatment membranes should ideally provide not only high separation efficiency but also resistance to microbial adhesion and growth.

Several technologies are currently employed for water purification, including coagulation-flocculation, precipitation, adsorption, advanced oxidation, biological treatment, ion exchange, membrane filtration and disinfection. Each technology has specific advantages and limitations. Membrane processes are attractive because they can provide high separation efficiency, relatively compact treatment systems and continuous operation. However, conventional polymeric membranes are commonly fabricated from synthetic polymers that may have limited biodegradability. In addition, membrane fouling, mechanical degradation and chemical instability remain important challenges [4].

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Biopolymers provide an attractive alternative because they originate from renewable biological resources. Chitosan is obtained by deacetylation of chitin, while cellulose is one of the most abundant natural polymers. Alginate is derived mainly from brown algae and contains carboxylate-rich polymer chains. Starch, gelatin, lignin and other naturally derived polymers have also been explored for environmental applications.

Despite their advantages, pristine biopolymers are not always suitable for demanding membrane applications. Chitosan, for example, possesses excellent amino and hydroxyl functional groups but may exhibit limited mechanical strength and pH-dependent stability. Cellulose has excellent structural characteristics but requires suitable functionalization to improve selectivity and pollutant affinity. Alginate has strong affinity toward several metal ions but can undergo swelling and requires structural stabilization.

Nanocomposite technology provides a promising solution to these limitations. Incorporating nanomaterials into a biopolymer matrix can improve mechanical strength, surface area, hydrophilicity, thermal stability, adsorption capacity, photocatalytic activity and antimicrobial performance. Recent literature demonstrates increasing interest in chitosan-based nanocomposite membranes containing metal oxides, carbon-based nanomaterials, magnetic particles, clays and other functional fillers [5].

The objective of this review is therefore to critically discuss sustainable biopolymer nanocomposite membranes for the removal of three major classes of contaminants: heavy metals, synthetic dyes and microbial contaminants. The emphasis is placed on material design, pollutant-removal mechanisms, membrane performance, sustainability, regeneration and future research requirements.

2. Water Contaminants and Treatment Challenges

2.1 Heavy Metals

Heavy metals enter water through natural geological processes and anthropogenic activities. Industrial effluents are among the most important sources. Depending on the industrial process, wastewater can contain Pb^{2+} , Cd^{2+} , Cu^{2+} , Ni^{2+} , Zn^{2+} , Hg^{2+} and chromium species.

The treatment of metal-contaminated water is challenging because the chemical form of the metal strongly depends on pH, ionic strength, redox conditions and the presence of competing ions. Conventional precipitation may generate large quantities of sludge, while ion exchange and adsorption require regeneration or adsorbent disposal.

Biopolymers provide multiple functional groups capable of interacting with metal ions. Chitosan contains amino groups and hydroxyl groups, whereas cellulose contains abundant hydroxyl groups. Alginate contains carboxylate groups that can participate in coordination and ion-exchange processes. Functionalization can further increase the number or accessibility of active sites [6].

2.2 Synthetic Dyes

Dyes can be classified according to their chemical structure and application, including azo, anthraquinone, triphenylmethane, reactive, acidic, basic and direct dyes. Their molecular structures often contain aromatic rings and charged functional groups.

The removal of dyes from wastewater can occur through adsorption, membrane rejection, chemical oxidation or photocatalytic degradation. Adsorption is particularly attractive because it can be carried out under relatively mild conditions. However, adsorption transfers the contaminant from the water phase to a solid phase rather than necessarily destroying it.

A multifunctional membrane can address this limitation by combining adsorption with catalytic degradation. For example, incorporation of photocatalytically active metal oxides into a biopolymer membrane can enable adsorption of the dye followed by degradation under appropriate irradiation [7].

2.3 Microbial Contaminants

Microorganisms present an additional challenge because membrane surfaces can provide favourable environments for microbial attachment. Once microorganisms adhere to a

membrane, extracellular polymeric substances can facilitate biofilm formation. Biofouling reduces water flux and may increase operating pressure.

A sustainable membrane should therefore ideally possess both separation and antimicrobial properties. Chitosan is particularly interesting because its protonated amino groups can contribute to antimicrobial activity. Additional nanomaterials may provide further antibacterial mechanisms through metal-ion release, reactive oxygen species generation, direct membrane disruption or inhibition of microbial adhesion [8].

3. Biopolymers as Sustainable Membrane Materials

3.1 Chitosan

Chitosan is a linear polysaccharide derived primarily from chitin. Its chemical structure contains linked glucosamine units and residual N-acetylglucosamine units. The presence of amino and hydroxyl groups makes chitosan chemically versatile. The amino groups can interact with metal ions through coordination and can also become protonated under acidic conditions. This pH responsiveness makes chitosan attractive for selective pollutant adsorption. Chitosan can be fabricated into films, membranes, hydrogels, beads, fibres and composite structures. Nevertheless, pristine chitosan can suffer from limited mechanical strength, swelling and pH-dependent solubility. Crosslinking and nanofiller incorporation are therefore frequently used to improve its stability [9].

3.2 Cellulose

Cellulose is an abundant renewable polysaccharide consisting of β -(1 $\rightarrow$ 4)-linked glucose units. Its abundance, biodegradability and excellent mechanical properties make it highly attractive for sustainable materials. Nanocellulose, including cellulose nanofibres and cellulose nanocrystals, provides a high surface-area structure and can improve the mechanical properties of composite membranes. Surface functionalization can introduce carboxyl, amino or other groups to improve affinity toward pollutants. Cellulose can therefore function both as a structural component and as an active adsorption platform [10].

3.3 Alginate

Alginate is a naturally derived polysaccharide containing mannuronic and guluronic acid units. Its carboxylate groups provide significant affinity for various metal ions. Alginate can readily form ionically crosslinked networks in the presence of multivalent cations. This property allows the preparation of beads, films, hydrogels and membrane-like structures. The principal limitation is that alginate-based materials may exhibit excessive swelling or inadequate mechanical stability under some aqueous conditions. Combining alginate with cellulose, chitosan or inorganic nanofillers can improve structural integrity [11].

3.4 Starch and Other Biopolymers

Starch is inexpensive and widely available but generally requires modification to provide suitable water stability and mechanical properties. Gelatin contains numerous functional groups and can interact with pollutants but may exhibit poor stability under some conditions. Lignin is particularly interesting because its aromatic structure and phenolic groups provide opportunities for adsorption of organic pollutants. Combining lignin with cellulose or other biopolymers can generate bio-derived composite structures [12].

4. Design of Biopolymer Nanocomposite Membranes

The concept of a nanocomposite membrane involves incorporating a nanoscale functional phase into a polymeric matrix. The nanofiller can be dispersed within the polymer or concentrated near the membrane surface.

The membrane performance depends on several factors: Chemical compatibility between the biopolymer and nanofiller, Nanofiller dispersion, Particle size and morphology, Surface chemistry, Membrane porosity, Hydrophilicity, Mechanical stability, Nanofiller loading, Crosslinking density, Interaction between membrane and contaminant.

A low nanofiller concentration may not provide sufficient active sites, whereas excessive loading can cause particle aggregation and reduce membrane permeability. Therefore, optimization of nanofiller concentration is essential.

5. Challenges and Future Scope

Despite the considerable potential of biopolymer-based nanocomposite membranes for sustainable water purification, several challenges must be addressed before their large-scale practical implementation. The performance of biopolymer membranes is strongly influenced by their chemical composition, degree of crosslinking, hydrophilicity, swelling behaviour, mechanical strength and stability under different pH and ionic conditions. Compared with conventional synthetic polymer membranes, many pristine biopolymers exhibit relatively poor mechanical and chemical stability during prolonged exposure to water. Excessive swelling may alter membrane pore structure and reduce separation efficiency. Therefore, the development of suitable crosslinking strategies and hybrid structures is essential for improving dimensional stability without significantly reducing permeability or active-site accessibility.

Another important challenge is the uniform dispersion and long-term retention of nanofillers within the biopolymer matrix. Nanoparticle aggregation at higher concentrations can block membrane pores, reduce water flux and negatively influence mechanical properties. In addition, possible leaching of nanoparticles during continuous filtration raises concerns regarding secondary contamination and environmental safety. Future studies should therefore investigate strong interfacial bonding between biopolymers and nanofillers and systematically evaluate nanomaterial release during long-term operation and regeneration.

Future research should also focus on multifunctional membrane systems capable of removing different classes of contaminants in a single treatment process. Hybrid membranes combining adsorption, membrane separation, photocatalytic degradation and antimicrobial activity could provide more efficient treatment of complex wastewater. For example, incorporation of metal oxides or graphene-based materials into chitosan, cellulose or alginate matrices may provide active sites for heavy-metal adsorption while simultaneously promoting degradation of organic pollutants and reducing microbial growth.

The use of agricultural and industrial biomass wastes as sources of biopolymers and nanofillers represents another promising research direction. Cellulose, lignin, starch and biochar derived from renewable biomass can reduce dependence on petroleum-based materials while supporting circular-economy principles. However, the influence of biomass source, extraction method and chemical modification on membrane performance needs systematic investigation.

A major gap in current research is the limited validation of biopolymer nanocomposite membranes using real wastewater. Many studies are performed using laboratory-prepared single-contaminant solutions, which do not adequately represent the complex chemical environment of industrial wastewater. Future studies should therefore progress from single-pollutant systems to multicomponent solutions and finally to real wastewater containing heavy metals, dyes, organic matter, salts and microorganisms. Long-term continuous-flow experiments should also be conducted to establish membrane durability, fouling resistance and regeneration efficiency.

6. Conclusions

Sustainable biopolymer nanocomposite membranes represent a promising research direction for advanced water purification. Chitosan, cellulose and alginate provide renewable and biodegradable polymer matrices containing functional groups capable of interacting with inorganic and organic pollutants. However, their limitations in mechanical strength, chemical stability, swelling and selective separation can restrict direct application. Nevertheless, high laboratory-scale removal efficiency alone is insufficient to establish practical sustainability. Future research must address membrane lifetime, regeneration, fouling, nanofiller leaching, real wastewater performance, mechanical stability, scale-up and life-cycle environmental impacts. The most promising research direction is therefore the development of multifunctional, renewable, regenerable and mechanically stable biopolymer nanocomposite membranes capable of treating multiple classes of contaminants while minimizing secondary pollution.

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