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Recent advancements in bio-based polymers for pollutant removal from water

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ABSTRACT

The issue of water contamination has prompted significant research into sustainable remediation techniques. Bio-based polymers, both synthetic and natural, have emerged as eco-friendly options for pollutant extraction due to their biodegradability, renewability, and customizable properties. This review explores recent advancements in utilizing bio-based polymeric materials for water purification, highlighting their effectiveness in removing heavy metals, organic contaminants, and emerging pollutants. It also considers various performance evaluation criteria, including adsorption capacity and the impact of factors like pH, temperature, and pollutant concentration, alongside comparisons to traditional materials. Additionally, the potential for revitalizing and reusing bio-based polymeric adsorbents to enhance their practical application is examined. Finally, the challenges related to the implementation of bio-based polymers—such as scalability, stability, and cost-effectiveness—are addressed, along with future opportunities for improving their efficiency and integration into sustainable water treatment systems.

Keywords: Bio-based polymers, bio-based synthetic polymers, bio-based natural polymers, water purification, environmental sustainability, water treatment challenges

Introduction

The rise in living standards and industrial activity has increased water pollution due to hazardous substances released from processes like electroplating, dyeing, and urban runoff. These pollutants accumulate in the ecosystem and pose risks to health by entering the food chain. Effective removal of contaminants from wastewater is essential for safe drinking water. While methods range from basic sedimentation to advanced techniques, each approach needs to be tailored for cost-effectiveness and quality. Physical treatments remove solids, chemical treatments eliminate pollutants, biological treatments break down organic matter, and advanced methods provide additional purification. Sludge treatment focuses on managing and disposing of solid byproducts from wastewater treatment. Recognizing the various treatment methods is crucial for effectively removing contaminants, allowing the safe release or reuse of treated water. Conventional technologies include coagulation, advanced oxidation, ion exchange, adsorption, reverse osmosis (RO), and membrane processes like nanofiltration and ultrafiltration. Adsorption is popular for transferring contaminants from liquid to solid surfaces because it is cost-effective, versatile, simple, and requires less energy than other method. Various materials, such as activated carbon, clay, cellulose, metal-organic frameworks (MOFs), and ion exchange membranes, are used to remove pollutants from wastewater. While these methods can be effective, they may also introduce additional pollution. Non-degradable polymers are popular in water treatment for their stability but pose environmental risks due to unreacted monomers that can cause pollution. Additionally, they can break down into toxic substances, and disposing of used membranes and adsorbents can lead to further environmental harm. Although materials like activated carbon, cellulose, and clay are affordable and have large surface areas, they are often ineffective at removing specific contaminants due to low binding affinity and limited reuse capabilities. Their surfaces lack the required chemical properties for selective pollutant extraction.

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Biopolymers are gaining recognition as sustainable alternatives to petroleum-based polymers due to their natural abundance and beneficial properties, such as renewability, eco-friendliness, and biodegradability. Their molecular structures feature reactive functional groups, enhancing their effectiveness in wastewater treatment. Research into biopolymers and their composites for wastewater treatment is expanding, focusing on materials like cellulose, chitosan, and polylactic acid. Biopolymers provide advantages over traditional materials, as they can selectively remove trace impurities, including heavy metals. They can be sourced from renewable materials through three main methods: extracting cellulose and other natural substances, polymerizing bio-monomers from renewable biomass, and direct production from microorganisms, such as polyhydroxyalkanoates (PHAs) [1-3].

This review article examines biopolymers, highlighting their synthesis, types, and sources. It evaluates biopolymer-based adsorbents for water purification, comparing their performance to conventional adsorbents. The article also discusses the technical and economic challenges of using biopolymers and explores emerging trends in their research and integration with advanced water purification technologies for removing organic pollutants.

Bio-based polymers

Bio-based polymers, sourced from renewable resources, are gaining popularity due to environmental concerns and the decreasing availability of fossil fuels. These polymers, which can be natural or synthetic and biodegradable or non-biodegradable, are produced from biomass and microbial processes, providing alternatives to petrochemical-based synthetic polymers [4-7].

Bio-based synthetic polymer

PLA, PHA, and bio-PE are bio-based polymers with the potential to replace traditional polymers. PLA, derived from lactic acid, is thermoplastic with good properties but limited engineering applications, though suitable for membrane fabrication and some wastewater treatment. PHAs, bacterial fermentation-based polyesters, have good mechanical and thermal properties but suffer from slow crystallization, needing improvements. Bio-PE, produced from bioethanol, is chemically identical to traditional PE and can replace it in all applications, addressing PE's degradation issues [4, 8-13].

Bio-based natural polymers

Cellulose, chitin/chitosan, and starch are important bio-based polymers with various applications. Cellulose, found in plant cell walls, requires modification for use in films, fibres, and water treatment membranes. Chitin and chitosan, derived from crustacean shells, are low-cost, strong, and biocompatible, making them suitable for heavy metal adsorption. Starch, composed of amylose and amylopectin, is abundant and non-toxic, used in eco-friendly catalyst systems and thermoplastic products, with its properties influenced by plasticizers and crosslinking [12, 14-22]

treatment processes and the metrics used to evaluate their efficiency in pollutant removal

Performance evaluation

Biopolymers such as starch, chitin, and chitosan are classified as inexpensive adsorbents. Chitosan is a promising and cost-effective biopolymer that serves as an adsorbent for heavy metal ions. Its high adsorption capacity is attributed to its unique chemical properties and functional groups. However, chitosan tends to aggregate and poses challenges for recovery, which limits its application. To address these issues, researchers are enhancing chitosan by combining it with magnetic nanoparticles. This combination not only improves its adsorption capabilities but also simplifies the recovery process. Modified chitosan nanocomposites have been shown to adsorb heavy metals from aqueous solutions effectively. The adsorption behavior is described by isotherm models, such as Langmuir and Freundlich, which provide insights into the adsorbent's surface characteristics, its interactions with the adsorbate, and the overall adsorption mechanism [23]. The study is investigated the adsorption of Cr(VI) using chitosan-cinnamaldehyde (CTS-Cin) and iron oxide-chitosan-cinnamaldehyde (Fe_3O_4@CTS-Cin) nanocomposites, utilizing Langmuir and Freundlich adsorption models.
Batch experiments assessed the effects of pH, contact time, adsorbent mass, Cr(VI) concentration, and temperature. Potassium dichromate ($K_2Cr_2O_7$) was used, with Cr(VI) concentrations measured spectrophotometrically at 542 nm using 1,5-diphenylcarbohydrazide. Langmuir isotherm parameters indicated a strong fit (R^2 = 0.9919 for CTS-Cin and 0.9935 for Fe_3O_4@CTS-Cin), with maximum adsorption capacities (q_m) of 61.349 mg/g for CTS-Cin and 58.139 mg/g for Fe_3O_4@CTS-Cin. The RL values ($0 < R_L < 1$) suggested that both adsorbents are effective for removing Cr(VI) from aqueous solutions (Eq. 1 & 2) [23].

$$C_e / q_e = 1/(q_m K_L) + C_e / q_m \quad (1)$$
$$R_l = 1/(1+ K_L C_0) \quad (2)$$

Analysis of the log q_e vs. log C_e plot revealed Freundlich isotherm parameters (1/n and k_F). The 1/n values (0.395-0.465) indicate heterogeneous surfaces and favorable Cr(VI) adsorption. However, a higher correlation coefficient (R^2 = 0.971) for the linear regression of the Langmuir model for CTS-Cin compared to Fe_3O_4@CTS-Cin (R^2 = 0.94) suggests the Langmuir model provides a better fit for describing Cr(VI) adsorption onto these adsorbents than the Freundlich mode (Eq3)(Fig. 1) [23].

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$$log\ q_t = log\ K_f + 1/n(\ logC_e) \quad (3)$$

The effects of varying pH, temperature, contact time, pollutant concentration, adsorption capacity, and removal rate using CTS-Cin and Fe_3O_4@CTS-Cin adsorbents are as follows:

i) The effect of pH levels ranging from 1 to 8 on the removal of Cr(VI) was studied. The maximum removal efficiency was observed at pH 3.0 for CTS-Cin and at pH 2.0 for Fe_3O_4@CTS-Cin. At lower pH values (below 2 for Fe_3O_4@CTS-Cin and below 3 for CTS-Cin), competition between H_2CrO_4 and protons for adsorption sites likely reduced the uptake of chromium. Conversely, at higher pH levels (8), the competition between $Cr_2O_4^-$ and OH^- ions diminished the adsorption capacity. Therefore, optimal pH values of 3.0 for CTS-Cin and 2.0 for Fe_3O_4@CTS-Cin were selected for further studies. Additionally, CTS-Cin demonstrated a higher capacity for Cr(VI) removal due to the increased availability of cinnamaldehyde moieties available for chelation (Fig. 2) [23].

ii) The study investigated the effect of contact time (ranging from 0 to 300 minutes) on the adsorption of Cr(VI) ions. The adsorption capacity increased with longer contact times, reaching equilibrium at approximately 35 minutes for CTS-Cin, which achieved a removal rate of 93%, and at 80 minutes for Fe_3O_4@CTS-Cin, which achieved a removal rate of 95%. The rapid initial uptake, where 90% of Cr(VI) was removed within the first 10 minutes, was due to the availability of charged sites and the quick chelation of Cr(VI). As time progressed, competition for the remaining sites slowed down the rate of adsorption. Additionally, Fe_3O_4@CTS-Cin showed higher efficiency and capacity compared to CTS-Cin, likely due to its greater porosity and smaller particle size (Fig. 3) [23].

iii) Increasing the initial concentration of Cr(VI) from 5.0 to 300.0 mg/L led to a rise in the adsorption capacity of both CTS-Cin (from 3.32 to 59.74 mg/g) and Fe_3O_4@CTS-Cin (from 1.63 to 56.92 mg/g). However, the percentage removal of Cr(VI) decreased for both adsorbents—falling from 100% to 59.74% for CTS-Cin and from 97.71% to 56.92% for Fe_3O_4@CTS-Cin. This increase in adsorption capacity is attributed to the greater occupation of available binding sites and enhanced interaction between the chromium ions and the adsorbent particles at higher concentrations. The initial concentration serves as a driving force that helps overcome the mass transfer resistance between the aqueous solution and the adsorbents (Fig. 4) [23].

iv) The percentage removal of Cr(VI) by CTS-Cin and Fe_3O_4@CTS-Cin increased with dosages up to 0.25 g, after which it plateaued. Conversely, adsorption capacity decreased with higher dosages.

For CTS-Cin, increasing the dosage from 0.025 g to 0.4 g raised removal from 64% to 92.2%, while capacity dropped from 64.04 mg/g to 5.76 mg/g. For Fe_3O_4@CTS-Cin, removal increased from 34.2% to 100% as dosage rose, with capacity declining from 34.19 mg/g to 6.25 mg/g. The higher capacity at lower dosages is due to easier access to active sites. As dosage increases, although available sites rise, the ratio of Cr(VI) to active sites declines, reducing capacity. Fe_3O_4@CTS-Cin reached 100% removal at 0.3 g, likely due to its larger surface area and smaller particle size observed by transmission electron microscopy (TEM) (Fig. 5) [23].

The adsorption effectiveness of CTS-Cin and Fe_3O_4@CTS-Cin for Cr(VI) removal was assessed against chitosan and other chitosan-derived adsorbents (Table 1). Most chitosan-based adsorbents operate in acidic solutions, where protonated amino groups attract Cr(VI). CTS-Cin and Fe_3O_4@CTS-Cin exhibited higher adsorption capacities than many other bioadsorbents, underscoring the benefits of their modifications. While they may not be the absolute best, their performance rivals or exceeds that of other modified magnetic chitosan adsorbents. These results indicate that CTS-Cin and Fe_3O_4@CTS-Cin are promising for Cr(VI) removal from wastewater [23]. Cellulose is a promising material for removing pollutants like heavy metals and dyes from water due to its porosity, surface area, and hydroxyl groups. The effectiveness of heavy metal adsorption depends on the behavior of metal ions and mechanisms like chemical complexation and ion exchange. Surface modification of nano-cellulosic materials enhances their ionization and complexation capabilities.

Modified cellulose combined with chitosan, polymers, or nanoparticles as well as nanocellulose and microcellulose, offers key advantages over traditional cellulose: i) enhanced adsorptio: greater capacity and selectivity for pollutants. ii) higher surface area: more active sites increase efficiency. iii) faster kinetics: smaller particles improve access to pollutants and speed up adsorption. iv) regeneration and reuse. These materials can be regenerated and reused, making them cost-effective and environmentally friendly [24, 25].

The carboxylation process, which can be achieved using carbamylating agents such as maleic anhydride, succinic anhydride, phthalic anhydride, methacrylic acid, itaconic acid, and polyacrylic acid, can improve the adsorption performance of functionalized nanocellulose towards metal ions and toxic dyes.

The lone pair of electrons present in the carboxyl group contributes to chelation with positively charged metal ions, and the overall negative surface charge on nanocellulose materials facilitates the adsorption of cationic dyes by electrostatic interaction, such as methylene blue, malachite green, and basic fuchsin. Sodium carboxymethyl cellulose (CMC) is a copolymer containing two monomer units: β-D-glucose and β-D-glucopyranose 2-O-(carboxymethyl)-monosodium, which can be formed from cellulose fibers using sodium chloroacetate. Maleic anhydride also undergoes acylation similarly through the -OH group of cellulose/nanocellulose.

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On the other hand, amine functionalization of cellulose/nanocellulose helps in the chelation of anionic pollutants from water, thereby increasing the adsorption process. Adsorption with amino-modified cellulose is generally greater at low pH (<7) compared to a high pH environment (>7). Since amine groups are easily protonated under acidic conditions, anionic pollutants are adsorbed through electrostatic interaction and the ion exchange process. Therefore, amine-functionalized cellulose/nanocellulose is significantly effective for the removal of anionic dyes such as congo red and basic yellow (Fig. 6) [24].

A study introduced a method for creating chemically modified cellulose and a Schiff base from aeschynomene sesban L. This material, synthesized with 5-methyl salicylaldehyde and benzaldehyde, achieved a cadmium ion adsorption capacity of 9.5 mg/g at pH 4.1, using 0.01 to 0.02 g/L of biomass and cadmium concentrations of 150 to 152 mg/L. Separately, Bekiado et al. developed an adsorbent from waste lyocell fabric through carboxymethylation and cross-linking, significantly enhancing Cd (II) removal with a 17-fold increase in uptake, especially in neutral to alkaline conditions. Table 2 summarizes the adsorption capacities of various modified celluloses for different pollutants [26].

For industrial wastewater treatment, bio-adsorbents should be reusable, easily regenerated, efficient, sustainable, and cost-effective. Li et al. found that microcrystalline cellulose composites filled with copper (Cu) and mercury (Hg) maintained significant adsorption capacity after ten regeneration cycles with 1 M nitric acid (HNO_3), achieving 70.5% retention for Cu^{2+} and 79.4% for Hg^{2+}. These cellulose-based composites are biodegradable and environmentally friendly, making them a practical choice for rapid recovery in wastewater treatment [26].

Polyhydroxamic acid (PHA) is a biopolymer that effectively forms stable chelates with heavy metal ions due to its strong structure. It is synthesized by reacting hydroxylamine with poly(acrylic ester) or polyacrylic polymers like acrylonitrile. The hydroxyl and carbonyl groups in PHA are key to heavy metal removal [27].

Rahman et al. developed a cellulose kenaf-based poly(hydroxamic acid) ligand designed to remove rare earth metals (La^{3+}, Ce^{3+}, Pr^{3+}, Gd^{3+}, Nd^{3+}, Eu^{3+}, and Sm^{3+}) from water. The adsorption process followed the Langmuir isotherm model, indicating a monolayer formation on a homogeneous surface, and conformed to pseudo-second-order kinetics.

The maximum adsorption capacities ranged from 1.27 to 1.87 mmol/g. Notably, the adsorbent maintained significant efficiency even after six cycles of adsorption and desorption. In the batch adsorption experiments, 0.150 g of the adsorbent was added to 10 mL of a 0.1 M single metal ion solution at a pH of 3 to 6. A calculation (Eq. 3) was employed to determine the amount adsorbed[28]. Additionally, experiments were conducted with trace concentrations (10 mg/L) of metal ions, utilizing 0.150 g of adsorbent in 5 mL of solution at pH 6, with metal ion concentrations analyzed by ICP-MS (Eq. 4) [28].

$$q_e = (C_o - Ce)V/L \quad (4)$$

A batch method was used to assess the ligand's adsorption behavior towards rare earth metals, specifically La^{3+}, Ce^{3+}, Pr^{3+}, Gd^{3+}, Nd^{3+}, Eu^{3+}, and Sm^{3+} on different pH values. Maximum adsorption occurred as pH increased from 3 to 6, with the highest affinity noted for La^{3+} ions. The peak adsorptions at pH 6 were 260 mg/g for La^{3+}, and 245 mg/g for Ce^{3+}. The binding properties of these ions were pH-dependent, demonstrating the ligand's effective complexation performance (Fig. 7) [28].

Factors influencing performance (e.g., pH, temperature, concentration of pollutants)

Water scarcity is a major 21st-century issue. Hydrogels, 3D cross-linked polymer networks that absorb large amounts of water without dissolving, are a promising solution. Their hydrophilic functional groups enable water absorption, while cross-links maintain structure. Bio-based natural hydrogels are viable for contaminant detection and removal in water treatment. Hybrid and composite hydrogels combine natural/synthetic or organic/inorganic components for enhanced performance. Cellulose-based hydrogels (CBHs) are superabsorbent materials for removing organic pollutants, heavy metals, and dyes. CBHs attract metal cations through electrostatic interactions with carboxyl groups, but metal complex stability can deteriorate with changes in temperature, pH, or substance concentrations, leading to microprecipitation . Researchers have investigated modifications to cellulose for the purpose of heavy metal adsorption. One team developed Cell-CM and Cell-EDTA from pineapple leaf cellulose, while Zannagui et al. cross-linked hydroxyethylcellulose (HEC) with EDTA dianhydride (EDTAD) to create an innovative HEC-based adsorbent. The initial concentration of pollutants (ICP) plays a significant role in adsorption, as higher ICP levels generally result in increased adsorption capacity until a plateau is reached. The pH at the point of zero charge (pHPZC) also greatly influences adsorption, as it alters the chelating ability by affecting swelling and ion interactions.

When the pH is below pHPZC, the adsorbent surface carries a positive charge, which promotes anion adsorption. Conversely, when the pH exceeds pHPZC, the surface becomes negatively charged, favoring cation adsorption. Amr El-Hag Ali found that the adsorption capacity of carboxymethyl cellulose (CMC) hydrogels for heavy metals increased with rising pH levels, while metal ion uptake decreased at very low pH due to competition from H^+ ions (Fig 8) [29-45].

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Comparative analysis of bio-based polymers versus conventional materials

In recent decades, the demand for alternative energy sources and materials to replace non-renewable fossil fuels has grown significantly. The volatility of oil prices highlights the need for these alternatives. Bio-based polymers, derived from renewable feedstocks, are a key area for sustainable development. While modifying functional groups and crosslink densities can affect biodegradability, using natural materials often results in products with similar or improved properties compared to petroleum-based options. Thus, bio-based materials address current polymer demands while helping to reduce environmental concerns [47].

While biopolymers and biodegradable polymers offer positive environmental impacts, their mechanical properties are generally inferior to those of petroleum-based plastics. To improve these properties for structural applications, plasticizers and reinforcing agents like mineral fillers and fibers are added. For example, poly(butylene adipate-co-terephthalate) (PBAT) has been blended with polylactic acid (PLA) to enhance flexibility and elongation, although this combination still suffers from poor thermal and mechanical properties.

Compatibilizers such as poly(butylene succinate) (PBS) and polyhydroxybutyrate-valerate (PHBV) can also be added to PLA/PBAT blends, slightly impacting thermal properties and increasing melt flow. Biodegradable PHBV oligomers and graft copolymers have been synthesized to improve moisture resistance.Conversely, conventional petroleum-based polymers resist degradation. Additives, including pro-oxidants based on metal compounds, can be used to facilitate biodegradation by initiating free radical chain reactions that produce low molecular weight oxidation products that are more favorable for microorganisms[47, 48]

Regeneration of bio-based polymeric adsorbents

Adsorption, while effective for water purification, doesn't break down contaminants, making adsorbent regeneration crucial for recovery, cost-effectiveness, and waste reduction. Desorption is a common regeneration technique, but regenerated adsorbents typically have reduced capacity compared to new ones. The optimal regeneration approach depends on environmental factors, regeneration time, cost, and the specific adsorbent. Zhou et al. developed a PAO-CI bio-based polymer for Pb(II) removal and demonstrated its reusability after six cycles, it maintained over 94% of its Pb(II) sorption capacity, showing excellent regeneration and reusability (Fig. 9)[49, 50].

Rice husk is a promising, inexpensive bio-based adsorbent. Selecting the correct solvent for desorption is critical. Conifer tree rosin-based polyamine resins also show promise due to high adsorption capacity, easy regeneration, and stability. Huang et al. introduced ethylenediamine rosin-based resin (EDAR) removed heavy metals, but its dynamic adsorption capacity decreased to 67.5% of the initial value after five regeneration cycles using HCl and $NaHCO_3$. Chen et al. used sodium alginate/lignin (SA/Lig) composite hydrogel beads for methylene blue (MB) removal; these beads exhibited good regeneration, with the adsorption capacity decreased only slightly (from 14.55 mg/g to 13.80 mg/g) after five cycles while maintaining over 90% removal efficiency using HCl [51, 52].

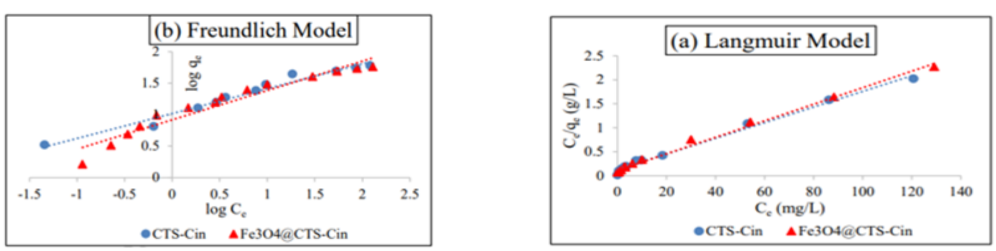

Fig. 1. Different adsorption isotherm models for Cr(VI) adsorption onto CTS-Cin and Fe_3O_4@CTS-Cin [23]

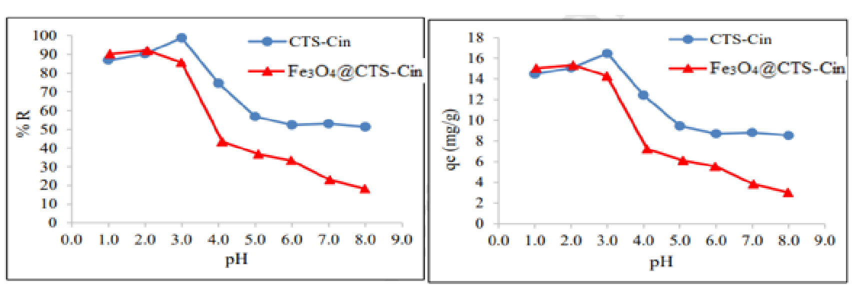

Fig. 2. Effect of pH on the % removal and adsorption capacity of Cr(VI) onto CTS-Cin and Fe_3O_4@CTS Cin[23]

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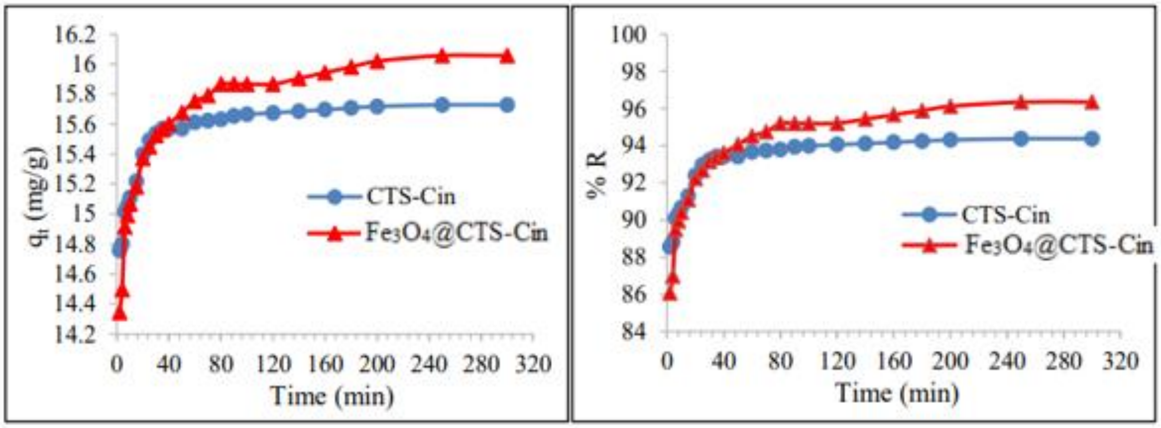

Fig. 3. Effect of contact time on Cr(VI) adsorption capacity onto CTS-Cin and Fe3O4@CTS-Cin [23]

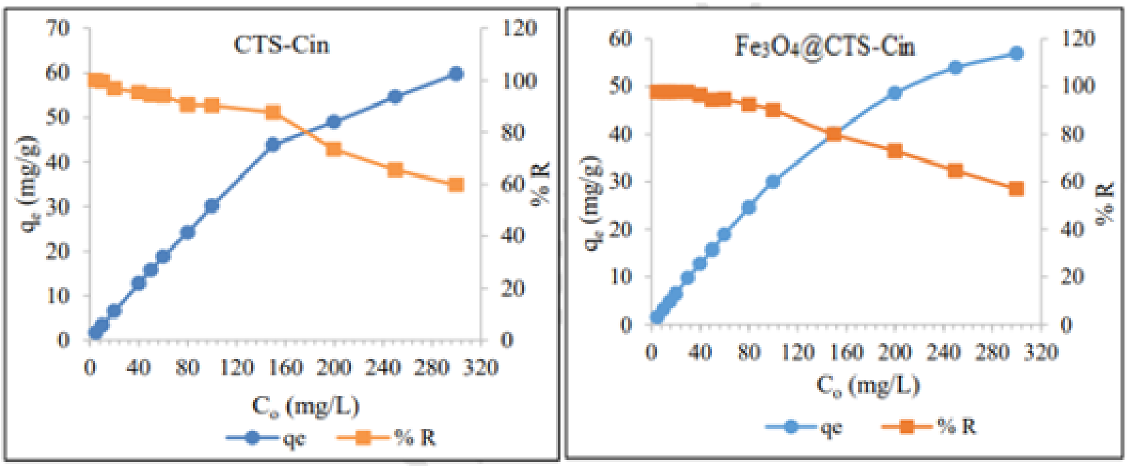

Fig. 4. Effect of initial concentration of Cr(VI) onto CTS-Cin and Fe_3O_4@CTS-Cin) and effect of adsorbent dosage [23]

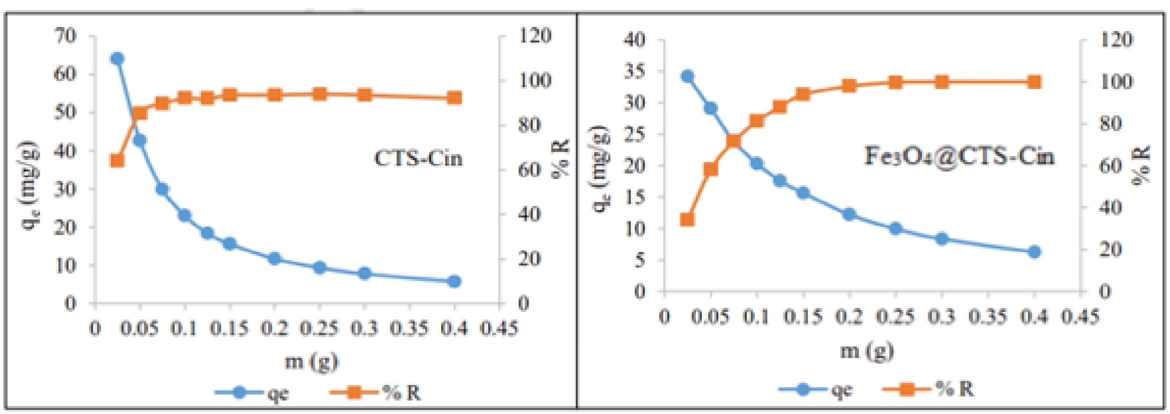

Fig. 5. Effect of adsorbents dosage on Cr(VI) uptake onto CTS-Cin and Fe_3O_4@CTS-Cin [23]

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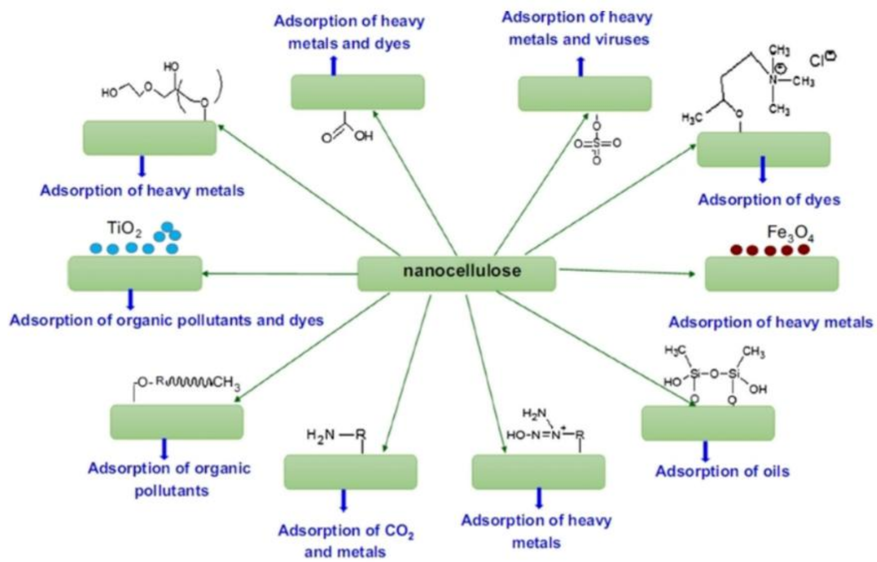

Fig. 6. Functionalization of nanocellulose for selective adsorption of pollutants from water [24]

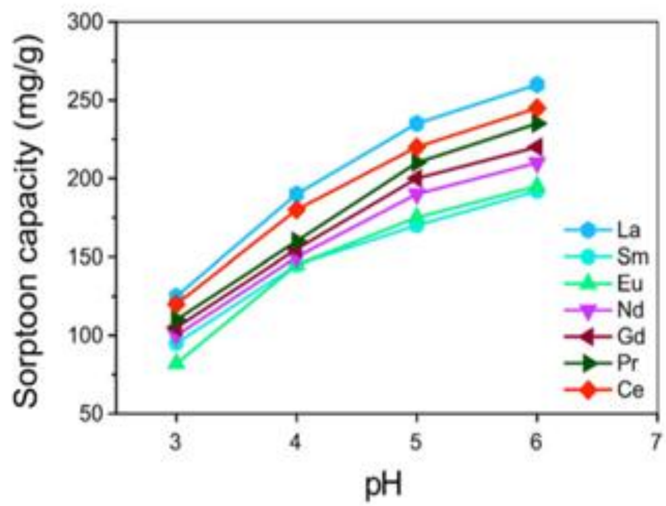

Fig. 7. Adsorption capacity of the poly(hydroxamic acid) ligand versus different pH [28]

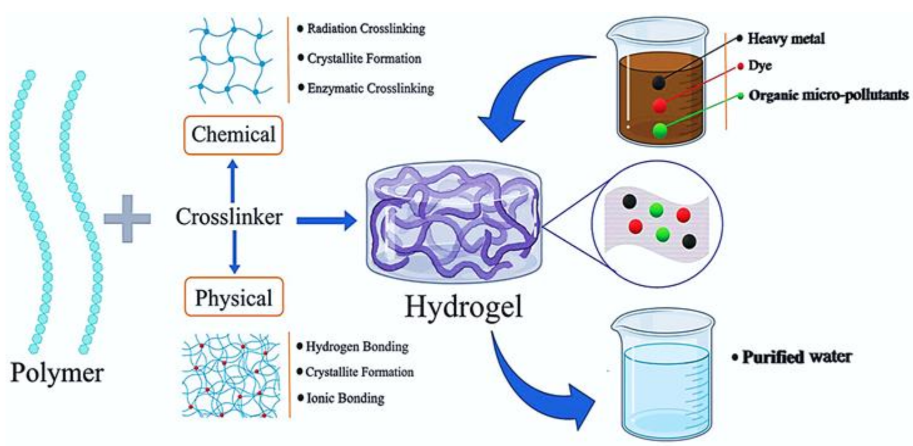

Fig. 8. Bio-based hydrogels in water treatment [46]

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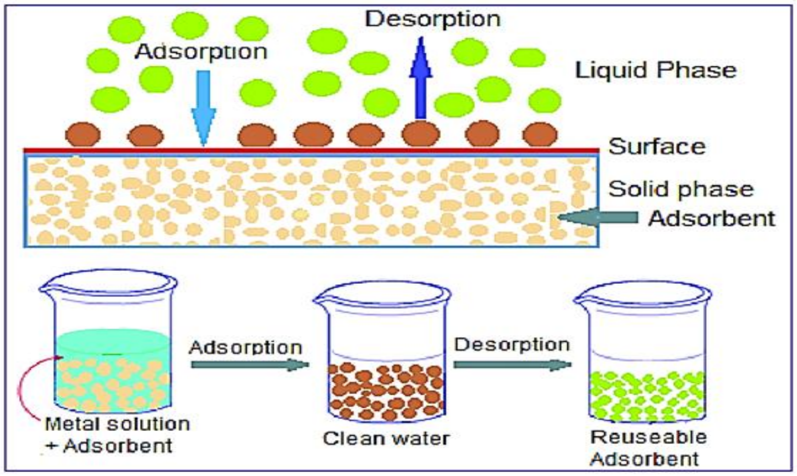

Fig. 9. The mechanism of metal-ions adsorption-desorption process in water treatment [53]

Table 1. Comparison of Cr(VI) adsorption by CTS-Cin and Fe_3O_4@CTS-Cin with other chitosan derived adsorbents

Adsorbents	pH	q_m (mg/g)
CTS chitosan	5.0	78
n-butylacrylate grafted chitosan adsorbent	3.5	17.15
(EDTA-2Na-GO-CTS) graphene oxide/chitosan composite with disodium ethylene-diaminetetraacetate	2.0	86.17

Table 2. Cellulose-modified materials for pollutant removal

Cellulose adsorbents	Adsorption capacity	Pollutants
Cellulose modified with acrylic acid	55.9 mg/g, 17.2 mg/g, 30.3 mg/g	Pb^{2+} Cu^{2+}, Cd^{2+}
Cellulose modified with hydrogels	128.24 mg/g	Cu^{2+}
Cellulose modified with succinic anhydride and triethylenetetramine	0.82 mmol/g	Cr^{6+}

Challenges and limitations

Biopolymers have many advantages but face challenges such as low porosity and sensitivity to harsh environmental conditions, like high temperatures and extreme pH levels. To address these issues, methods for developing porous biopolymer composites include nanoparticle composites, gel formation (hydrogels and aerogels), and alkaline pretreatment. However, biopolymeric adsorbents often struggle with performance variations due to factors like pollutant concentration and solution temperature, as well as issues with selectivity and separation from solutions.

Their mechanical instability can hinder effectiveness in water purification, particularly under high filtration pressures that risk membrane breakage. To improve these drawbacks, researchers are modifying biopolymers to enhance mechanical stability, antifouling properties, and water permeability. This includes blending with other polymers for better separation performance, as well as introducing functional groups like sulfur, amine, hydroxyl, and carboxylic groups to improve adsorption affinity for pollutants. Overall, these modified biopolymers offer a sustainable solution for targeted pollutant removal and effective wastewater treatment without harmful chemicals or by-products [54-65].

Identifying effective technologies for wastewater treatment and reuse is essential for sustainability in the industry. However, selecting the best treatment method is often complicated by factors such as pollutant types, the chosen process, and significant treatment costs. In biopolymer production, the costly synthesis and purification processes, combined with low yields, hinder cost-effective manufacturing.

Biopolymeric membranes face challenges like poor solubility and mechanical strength, which increase production costs and necessitate enhancements through blending, crosslinking, and nanofillers. Limited research on the reuse and recycling of these membranes further complicates their evaluation for water treatment. To unlock the potential of biopolymers in adsorption and membrane technologies, researchers need to improve their solubility and mechanical strength. Industrial production is also faced with challenges like health and safety concerns, complex operations, high energy needs, and expensive equipment. High-quality biopolymers are vital for medical and food applications, while lower-grade variants are suitable for wastewater treatment. However, variations in their physicochemical properties pose barriers to translating lab techniques into practical applications [66-70].

Conclusion

Recent research on bio-based polymers for water treatment has aimed at enhancing adsorption efficiency, selectivity, and reusability.

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Innovations in polymer modification, such as nanomaterial functionalization, responsive moieties, and crosslinking techniques, have improved pollutant removal performance. Additionally, the development of hybrid bio-based polymer composites with advanced structural properties is gaining momentum. There is also increasing interest in using computational modeling and machine learning to optimize polymer design and predict adsorption behavior more accurately.

Integrating bio-based polymers with advanced water treatment technologies—such as membrane filtration, electrochemical methods, and photocatalysis—can enhance efficiency and broaden applications.

This synergy improves pollutant removal rates while ensuring sustainability. Additionally, combining bio-based polymeric adsorbents with bioremediation techniques that utilize microorganisms or enzymes presents a promising approach to enhance water treatment processes. Future research will focus on scaling up these integrated systems while maintaining cost-effectiveness and operational stability.

This review underscores the notable advancements in the development and application of bio-based polymers for water purification. Both synthetic and natural bio-based polymers effectively adsorb a variety of pollutants, including heavy metals, organic contaminants, and emerging pollutants. Key performance metrics adsorption efficiency, regeneration capability, and environmental impact illustrate their effectiveness relative to conventional materials.

Although these polymers have many advantages, factors such as pH, temperature, and pollutant concentration affect their adsorption behavior. Comparative studies reveal that bio-based polymers can rival or even exceed traditional materials, especially when functionalized or used in conjunction with other treatment methods.

Bio-based polymers are set to play a vital role in the shift toward more sustainable water treatment solutions. Their biodegradability, renewability, and lower environmental impact make them appealing alternatives to synthetic materials. However, it is crucial to tackle challenges like scalability, long-term stability, and cost-effectiveness to unlock their full potential.

Future progress in material science, process engineering, and interdisciplinary collaborations will be essential for addressing these issues. By combining bio-based polymers with innovative water treatment technologies, researchers can create efficient, economically viable, and environmentally sustainable solutions for global water purification.

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