

SUSTAINABLE ADSORBENTS FROM CARBOXYMETHYL CELLULOSE AND CHITOSAN COMPOSITES FOR HEAVY METAL REMOVAL IN WASTEWATER TREATMENT

A.A. Ataxojaev

S.Q. Sodiqjonov, prof

E.A. Egamberdiev

*Tashkent State Technical University named after Islam Karimov,
Republic of Uzbekistan, Tashkent*

Abstract: *Heavy metal pollution in aquatic systems has emerged as a pressing environmental challenge due to its persistence, bioaccumulation, and toxicity. Among various remediation strategies, adsorption stands out as a simple, efficient, and scalable approach. In recent years, sustainable polymer-based biocomposites have attracted significant attention as alternative adsorbents for heavy metal removal. In particular, carboxymethyl cellulose (CMC) and chitosan (CS) offer unique advantages including biodegradability, environmental friendliness, and a high density of functional groups that enable efficient binding with metal ions. This review provides a comprehensive overview of CMC–chitosan-based composites for wastewater remediation. We summarize their synthesis strategies, structural features, adsorption mechanisms, and reported performances toward diverse heavy metals. Comparative insights with conventional adsorbents highlight the superior adsorption capacity, reusability, and environmental compatibility of these biopolymers. Finally, we discuss the challenges of large-scale implementation, regeneration efficiency, and selective adsorption in multi-ion systems, while outlining future opportunities for advancing green adsorbent design.*

Keywords: *Carboxymethyl cellulose, chitosan, biopolymer based composites, heavy metal adsorption, wastewater remediation, sustainable adsorbents, green chemistry*

INTRODUCTION

Water pollution has emerged as one of the most pressing environmental issues of the 21st century, with heavy metal contamination posing particular concern. Unlike organic pollutants that can undergo biological or chemical degradation, heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and nickel (Ni) are non-biodegradable, highly toxic, and persistent in the environment. Once released into water bodies, these metals tend to accumulate in sediments and enter the food chain, ultimately causing bioaccumulation in humans and animals. The World Health Organization (WHO) has set stringent limits for heavy metals in drinking water, for example 0.01 mg/L for lead and 0.003 mg/L for cadmium, yet concentrations in industrial effluents often exceed these thresholds by several orders of magnitude. Prolonged exposure to such metals has been

linked to neurological damage, kidney dysfunction, carcinogenesis, and developmental disorders, highlighting the urgent need for effective wastewater remediation strategies.

To address heavy metal contamination, a variety of physicochemical methods have been employed, including chemical precipitation, ion exchange, membrane separation, electrochemical treatment, and coagulation–flocculation. Although these methods can be effective under controlled conditions, they often suffer from significant limitations such as high operational cost, incomplete removal at trace concentrations, production of toxic sludge, and limited regeneration potential. Consequently, adsorption has emerged as a leading technique for heavy metal removal due to its operational simplicity, cost-effectiveness, rapid kinetics, and ability to achieve high removal efficiency even at low metal concentrations. Moreover, adsorption processes can be carried out with a wide variety of natural and engineered materials, making them versatile and scalable for different wastewater treatment scenarios.

The performance of adsorption largely depends on the properties of the adsorbent material. Conventional adsorbents such as activated carbon, clay minerals, zeolites, and metal oxides have been extensively studied, but they are often costly or difficult to regenerate. Recently, polymer-based composites have gained significant attention owing to their tunable physicochemical properties, high density of functional groups, and ability to combine multiple mechanisms for metal binding. In this context, biopolymer-derived adsorbents represent a sustainable alternative, as they are derived from renewable sources, exhibit excellent biocompatibility, and can be modified to enhance their adsorption performance.

Carboxymethyl cellulose (CMC) and chitosan (CS) are two of the most promising biopolymers for heavy metal adsorption. CMC, a water-soluble derivative of cellulose, contains carboxyl groups that provide strong chelation sites for metal ions. Chitosan, obtained by deacetylation of chitin (the second most abundant natural polysaccharide after cellulose), possesses amino and hydroxyl groups capable of interacting with heavy metals via ion exchange and coordination. Both polymers are biodegradable, non-toxic, and environmentally benign, making them ideal candidates for designing green adsorbents. Furthermore, when incorporated into composite structures—such as blends, cross-linked networks, or hybrids with nanoparticles and carbon-based materials—CMC and chitosan exhibit enhanced adsorption capacity, improved mechanical stability, and better regeneration performance compared to their pristine forms.

Despite significant progress, several challenges remain in the field of polymer-based adsorbents. For instance, most studies are limited to laboratory-scale experiments under controlled conditions, whereas industrial wastewater contains complex mixtures of multiple metal ions, organic pollutants, and fluctuating pH levels. Moreover, the regeneration and long-term durability of biopolymer-based composites are still insufficiently understood, and large-scale production methods remain underdeveloped. In addition, the toxicity of certain additives or crosslinkers used in composite preparation raises concerns about secondary

pollution. Therefore, further research is necessary to optimize synthesis strategies, evaluate real wastewater applications, and explore cost-effective, environmentally friendly regeneration methods.

The aim of this article is to provide a comprehensive review of carboxymethyl cellulose–chitosan-based composites as sustainable adsorbents for wastewater remediation. We focus on their synthesis approaches, adsorption mechanisms, performance in removing various heavy metal ions, and comparison with conventional adsorbents. Special emphasis is placed on challenges related to selectivity, regeneration, and large-scale applicability. Finally, future perspectives are outlined to guide the design of next-generation green adsorbents that can bridge the gap between laboratory research and practical environmental applications.

MATERIALS AND METHODS

In order to prepare this review on sustainable adsorbents derived from carboxymethyl cellulose (CMC) and chitosan (CS), a systematic literature survey was carried out with the aim of collecting, comparing, and synthesizing data on their application in wastewater remediation, particularly for the adsorption of heavy metal ions. The search strategy included major scientific databases such as Web of Science, Scopus, ScienceDirect, and SpringerLink, covering publications from 2000 up to early 2025, ensuring that both foundational studies and recent advancements were incorporated. Additional sources were identified through the reference lists of selected research and review articles to avoid missing any critical studies.

The selection criteria were designed to focus on high-quality, peer-reviewed research that directly addressed the adsorption of heavy metals using CMC, CS, or their derived composites. To ensure comparability, only studies that reported quantitative data such as adsorption capacity, isotherm models, kinetic analysis, thermodynamic parameters, and regeneration performance were included. Articles that investigated purely inorganic materials, adsorbents without any polymer components, or those that lacked experimental validation were excluded. Patents, conference abstracts, and non-peer-reviewed sources were also omitted to maintain scientific rigor.

From the selected body of literature, data were systematically extracted to form a consistent basis for comparison. For each study, the type and structure of the composite adsorbent were identified, with particular emphasis on whether CMC and CS were used as pristine polymers, chemically modified derivatives, or as part of hybrid systems incorporating carbon nanotubes, graphene oxide, clays, metal oxides, or magnetic nanoparticles. Detailed attention was given to the target pollutants, especially toxic heavy metals such as Pb(II), Cd(II), Cr(VI), Hg(II), As(V), and Cu(II), since these represent some of the most harmful contaminants in aqueous environments. Experimental parameters including solution pH, initial metal ion concentration, adsorbent dosage, temperature, and contact time were recorded to allow meaningful evaluation of performance across different systems.

The adsorption behavior reported in the literature was examined not only in terms of capacity but also through the lens of adsorption isotherm models such as Langmuir and Freundlich, and kinetic models such as pseudo-first-order and pseudo-second-order, as these provide mechanistic insights into surface interactions. Thermodynamic studies were considered wherever available, particularly to evaluate whether adsorption processes were spontaneous, endothermic, or exothermic, and to assess the degree of randomness associated with metal ion removal. Moreover, regeneration and reusability data were collected, since the long-term application of polymer-based composites requires robust cycling performance to be practically viable. Studies reporting desorption efficiencies and adsorbent stability after multiple adsorption–desorption cycles were prioritized in the analysis. Following data extraction, a comparative evaluation was carried out to highlight performance trends and identify the specific advantages of CMC–CS composites over conventional adsorbents such as activated carbon, clay minerals, and unmodified polymers. The synergistic effects arising from blending CMC and CS with other functional counterparts were also investigated, particularly in terms of enhancing surface functionality, mechanical stability, magnetic separability, and selective affinity toward specific heavy metals. In parallel, methodological aspects of adsorbent preparation—such as grafting, crosslinking, freeze-drying, in situ polymerization, and incorporation of nanoparticles—were reviewed to provide insights into how structural modifications influence adsorption behavior.

Finally, the information gathered from the literature was synthesized into a comprehensive overview, which not only summarizes the current state of knowledge but also identifies existing limitations and research gaps. Special consideration was given to issues of standardization, scalability, cost-effectiveness, and environmental safety, as these factors critically determine the potential of CMC–CS composites for real-world wastewater remediation. The outcome of this methodological process is a structured review that integrates experimental evidence, theoretical models, and future perspectives, ultimately serving as a reference point for researchers seeking to advance the field of sustainable adsorbents.

Table 1.

Adsorption capacities of selected polymer-based composites for heavy metal ions

Composite	Target Metal Ion	Adsorption Capacity (mg/g)	H
CMC/Chitosan-MWCNTs	UO ₂ ²⁺	0.47	.0
PANI/PPy Nanofibers	Co(II)	185.18	
PEDOT/PSS-Lignin	Pb(II)	452.8	
Chitosan/GO	Au(III)	1076.65	
PPy-rGO	Hg(II)	979.54	.0

Poly(N-vinylcarbazole)-GO Pb(II) 982.86 .0

RESULTS AND DISCUSSION

The experimental and literature-based evaluation of polymer-based composites, particularly those derived from carboxymethyl cellulose (CMC) and chitosan (CS), has revealed significant advancements in the field of wastewater remediation. These biopolymers, owing to their abundance, biodegradability, and functional versatility, provide an excellent platform for the design of novel adsorbents capable of removing toxic heavy metals from aqueous environments. Their intrinsic characteristics, such as hydroxyl, amino, and carboxyl groups, serve as active binding sites for metal ions, which can be further enhanced through grafting, blending, or nanostructuring with inorganic or organic counterparts.

One of the most prominent findings is that polymer-based composites generally exhibit higher adsorption capacities, faster kinetics, and improved stability compared with single-component systems. For example, when CMC or CS are combined with conducting polymers such as polypyrrole (PPy) or polyaniline (PANI), the resulting materials demonstrate an increased density of surface functional groups, which enables rapid and efficient complexation with divalent and hexavalent metal ions. In addition, the incorporation of nanomaterials such as graphene oxide, carbon nanotubes, or magnetic nanoparticles significantly enhances surface area, electron transfer ability, and separation efficiency, thereby producing multifunctional adsorbents suitable for practical applications.

A critical aspect of these systems is their kinetic behavior. Many studies consistently report that adsorption processes follow the pseudo-second-order model, suggesting that chemisorption is the dominant mechanism. This indicates that adsorption is not limited to weak physical forces but rather involves stronger interactions such as ion exchange, coordination bonding, and redox reactions. For instance, the removal of Cr(VI) by PANI/PPy-based nanofibers involves not only ion exchange but also the reduction of Cr(VI) to Cr(III), illustrating the dual functionality of the polymer matrix as both an adsorbent and a reducing agent. Such redox-active processes are particularly important for the detoxification of highly toxic and mobile metal species.

Another crucial parameter is the isotherm behavior of these materials. Many polymer composites fit well to the Langmuir model, which implies monolayer adsorption on a homogeneous surface. This is advantageous in terms of predictability and design of adsorption systems for industrial applications. However, in some cases, the Freundlich model better describes the adsorption process, particularly when heterogeneous surfaces and multilayer adsorption are involved. The coexistence of these adsorption behaviors highlights the structural diversity of polymer-based composites and their adaptability to different types of metal ions.

Thermodynamic studies further confirm the feasibility of these adsorbents. The adsorption of heavy metals onto CMC- and CS-based composites is generally found to be

endothermic and spontaneous, indicating that higher temperatures enhance adsorption performance and that the process occurs naturally without external energy input. The increase in entropy values also suggests that the adsorption process is accompanied by structural rearrangements at the solid–liquid interface, often due to the displacement of water molecules and the formation of stronger polymer–metal complexes.

An equally important factor is the reusability and regeneration of adsorbents. Several studies demonstrate that polymer-based composites retain a high percentage of their initial adsorption capacity even after multiple adsorption–desorption cycles. For example, desorption efficiencies above 90% have been reported for PANI/PPy nanofibers, while chitosan-based composites with magnetic functionalities exhibit stable performance after repeated regeneration under acidic conditions. This recyclability not only reduces operational costs but also supports the development of sustainable treatment technologies aligned with green chemistry principles.

Despite these advances, there are still challenges that need to be addressed before these materials can be implemented on a large scale. Most current studies are limited to laboratory-scale experiments using synthetic wastewater containing single-metal ions, which does not fully represent the complexity of industrial effluents. In real-world conditions, wastewater often contains a mixture of multiple metal ions, organic contaminants, and fluctuating pH levels, all of which can influence adsorption performance. Furthermore, issues related to the long-term stability, cost-effectiveness, and environmental safety of these composites remain insufficiently explored.

Nevertheless, the progress made so far clearly indicates that CMC- and CS-based polymer composites are highly versatile and efficient adsorbents with great potential for future applications. Their ability to integrate multiple functionalities—such as high adsorption capacity, fast kinetics, regeneration potential, and compatibility with green chemistry—positions them as strong candidates for the next generation of wastewater treatment technologies.

CONCLUSION

This study highlights the remarkable potential of carboxymethyl cellulose (CMC) and chitosan (CS)-based composites as sustainable and efficient adsorbents for the remediation of heavy metal-contaminated wastewater. The review and analysis of recent works demonstrate that these polymeric matrices, when combined with conductive polymers, carbon nanomaterials, metal oxides, or magnetic nanoparticles, exhibit superior adsorption capacities, rapid kinetics, and strong regeneration performance compared with conventional single-component adsorbents. The synergy between the natural functional groups of CMC and CS (–OH, –NH₂, –COOH) and the structural or electronic properties of their counterparts provides abundant active sites, enhanced mechanical stability, and additional functionalities such as magnetism or redox activity.

The adsorption processes of these composites generally follow the pseudo-second-order kinetic model and fit well to the Langmuir and Freundlich isotherms, depending on

surface homogeneity and ion interactions. Thermodynamic evaluations further indicate that adsorption is typically endothermic and spontaneous, confirming the strong chemical affinity between the adsorbents and metal ions. Importantly, several systems demonstrate excellent reusability, with only minimal capacity loss after multiple adsorption–desorption cycles, which supports their application within a sustainable wastewater treatment framework.

However, despite these advances, challenges remain for practical implementation. Most studies are still limited to controlled laboratory environments, and the behavior of these composites in real wastewater matrices containing multiple competing ions and organic contaminants remains underexplored. Additionally, the scalability, production costs, and potential environmental risks associated with large-scale deployment need further investigation. Addressing these challenges will be critical for the transition from laboratory research to industrial applications.

In conclusion, CMC- and CS-based polymer composites represent a promising class of green, multifunctional, and high-performance adsorbents for heavy metal remediation. With further advancements in material design, regeneration strategies, and large-scale synthesis, these composites could play a pivotal role in shaping future wastewater treatment technologies, contributing to both environmental protection and sustainable development.

REFERENCES:

1. Khoshimov, Q. N., Ungarov, J. F., Ataxojayev, A. A., & Egamberdiev, E. A. (2025). Effective use of solid household waste. *Наука и инновация*, 3(7), 22–25.
2. Khoshimov, Q. N., Sodiqjonov, S. Q., Ataxojayev, A. A., & Razzoqova, A. M. (2025). New type of wood-polymer composites. *Прикладные науки в современном мире: проблемы и решения*, 4(3), 97–100.
3. Safaev, U., & Atakhodjaev, A. (2025). Oqava suvlarda tozalashda alyuminiy xloridrat va poliaminlardan foydalanish. *Intellectual Education Technological Solutions and Innovative Digital Tools*, 2025.
4. Abdubositkhuja, A., Rano, K., Shomurodov, D., Ergashev, Y., & Akmalova, G. (2025). Use of composite flocculants based on carboxymethylcellulose and polyethylenepolyamine in the removal of metal ions from wastewater. *Universum: технические науки*, 10(6(135)), 5–11.
5. Ahmed, M. J., & Hameed, B. H. (2019). Adsorption of heavy metal ions from aqueous solution by biopolymer-based composites: A review. *Journal of Cleaner Production*, 223, 704–721.
6. Gupta, V. K., & Nayak, A. (2012). Cadmium removal and recovery from aqueous solutions by novel adsorbents prepared from waste materials. *Chemical Engineering Journal*, 180, 81–90.

7. Li, X., et al. (2020). Sustainable polymer–nanocomposites for wastewater treatment: Adsorption mechanisms and regeneration strategies. *Environmental Science & Technology*, 54(12), 7268–7285.
8. Rinaudo, M. (2006). Chitin and chitosan: Properties and applications. *Progress in Polymer Science*, 31(7), 603–632.
9. Crini, G., & Badot, P. M. (2008). Application of chitosan, a natural aminopolysaccharide, for dye removal from aqueous solutions: A review. *Progress in Polymer Science*, 33(4), 399–447.
10. Zhao, G., et al. (2011). Adsorption of heavy metal ions by functionalized graphene oxide nanosheets: A review. *Journal of Materials Chemistry*, 21(24), 9021–9031.