CELLULOSE-BASED BIOCOMPOSITE SORBENTS FOR THE TREATMENT OF HEAVY-METAL-CONTAMINATED WASTEWATER

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Abstract: *In this study, a cellulose-based biocomposite sorbent was developed using carboxymethylcellulose (CMC) and polyethylenepolyamine (PEP) to remove heavy metal ions from industrial wastewater. The material combines adsorption, ion exchange, and flocculation mechanisms in a single biodegradable system. The composite exhibited very high removal efficiencies for Pb(II), Cd(II), Cu(II), and Ni(II), reaching up to 98% at low dosage levels (~50 mg/L). In addition, the amount of sludge produced during treatment was reduced by approximately 35%, which significantly lowers disposal and operational costs. The results indicate that cellulose-based biocomposites are a promising sustainable alternative to conventional chemical flocculants and inorganic coagulants.*

INTRODUCTION

Industrial wastewater, especially from mining, metallurgical, and oil-related industries, often contains high concentrations of heavy metal ions and colloidal contaminants. These pollutants are toxic, non-biodegradable, and capable of accumulating in ecosystems, posing serious risks to human health and the environment. Conventional treatment technologies such as chemical precipitation, membrane filtration, ion exchange, and inorganic coagulation are widely used, but they suffer from high costs, secondary pollution, sludge generation, and low selectivity for dissolved metal ions.

In recent years, increasing attention has been given to polymer-based materials, particularly cellulose derivatives and amine-containing polymers, due to their environmental compatibility, availability, and strong affinity for metal ions. Cellulose is a renewable biopolymer rich in hydroxyl groups, while amine-based polymers provide positively charged sites capable of binding negatively charged or neutral metal complexes. By combining these two components, it is possible to create multifunctional materials that act simultaneously as sorbents and flocculants.

Therefore, the objective of this study is to develop and evaluate a cellulose-based biocomposite sorbent for the efficient removal of heavy metals from wastewater and to analyze its adsorption and flocculation behavior.

2. Materials and Methods

Carboxymethylcellulose (CMC) and polyethylenepolyamine (PEP) were used as the main components of the biocomposite. These polymers were mixed in different ratios in aqueous medium to obtain a stable composite material. Due to electrostatic interactions and hydrogen bonding between carboxyl and amine groups, a three-dimensional porous network was formed. The resulting material was insoluble in water but could swell significantly, providing a large active surface area for metal binding.

Synthetic wastewater solutions containing Pb(II), Cd(II), Cu(II), and Ni(II) ions were prepared at different concentrations. Batch adsorption experiments were conducted to study the effects of pH, contact time, temperature, and initial metal concentration. The metal ion concentrations before and after treatment were measured using standard analytical methods, and the removal efficiency was calculated.

3. Results and Discussion

3.1 Removal efficiency-The cellulose-based CMC–PEP biocomposite demonstrated very high efficiency in removing heavy metals from aqueous solutions. Under optimal conditions, the removal efficiency ranged from 93% to 98%, depending on the type of metal ion. Lead(II) showed the highest affinity to the composite, followed by cadmium(II) and copper(II).

The high performance of the biocomposite can be explained by the presence of multiple functional groups. Carboxyl groups from CMC provide negatively charged sites that attract metal cations, while amine groups from PEP form strong coordination bonds with metal ions. This dual interaction significantly enhances the binding strength compared to conventional single-function flocculants.

3.2 Adsorption mechanism- The adsorption behavior of heavy metal ions on the CMC–PEP composite followed the Langmuir isotherm model, indicating monolayer adsorption on a homogeneous surface. This suggests that metal ions form strong, localized bonds with active sites on the polymer matrix. Kinetic studies showed that the process follows a pseudo-second-order model, confirming that chemical interactions such as chelation and ion exchange dominate the adsorption process.

Scanning electron microscopy (SEM) analysis revealed that after adsorption, the surface of the composite becomes covered with metal-containing clusters, and significant morphological changes occur. Energy-dispersive spectroscopy (EDS) confirmed the presence of heavy metals on the polymer surface, further validating the adsorption mechanism.

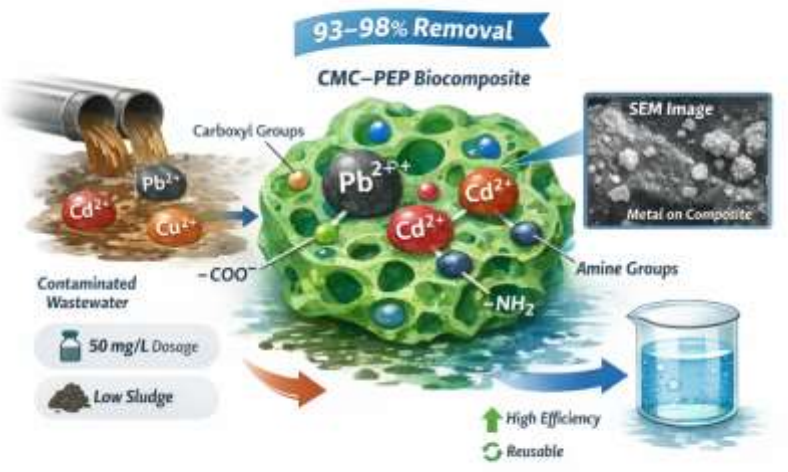

Figure. Graphical representation of the adsorption–flocculation mechanism of heavy metal ions on the CMC–PEP biocomposite.

3.3 Comparison with conventional flocculants-Compared to traditional inorganic coagulants and synthetic flocculants, the cellulose-based biocomposite requires much lower dosage to achieve the same or higher removal efficiency. While conventional reagents often require 300–500 mg/L, the CMC–PEP composite is effective at approximately 50 mg/L. In addition, sludge formation is reduced by about 35%, which simplifies handling and disposal.

The biodegradable and non-toxic nature of the biocomposite makes it particularly attractive for sustainable wastewater treatment, as it does not introduce harmful residues into the treated water.

The composite sorbent retained more than 85% of its original efficiency after five adsorption–desorption cycles, indicating good stability and reusability. This feature significantly reduces operational costs and material consumption, making the system suitable for long-term industrial applications.

4. Conclusion

This study demonstrates that cellulose-based biocomposite sorbents, particularly those formed from carboxymethylcellulose and polyethylenepolyamine, are highly effective for removing heavy metal ions from industrial wastewater. The combination of adsorption, ion exchange, and flocculation in a single biodegradable material results in superior performance compared to conventional treatment chemicals. With removal efficiencies up to 98%, reduced sludge generation, and excellent reusability, the proposed biocomposite represents a promising and environmentally friendly solution for modern wastewater treatment systems.

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