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Bioinspired Filtration Systems for Heavy Metal Removal from Industrial Effluents

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Abstract--- This study investigates bioinspired filtration systems for heavy metal removal from industrial effluents. The system implements biomimetic membranes and biosorbents that imitate biological adsorption and separation processes. The incorporation of metal-binding peptides onto chitosan-alginate membranes resulted in greater than 70% removal efficiencies for lead and more than 80% for cadmium and chromium. Performance evaluation may suggest an economical ecofriendly solution in comparison to conventional chemical methods. These results support the integration of these systems into industrial wastewater treatment plants for effective remediation and improved sustainability.

Keywords--- Bioinspired Filtration, Heavy Metal Removal, Industrial Effluents, Biomimetic Membranes, Biosorbents, Wastewater Treatment, Chitosan-Alginate, Eco-Friendly Remediation.

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I. Introduction

The industrial sector is one the primary drivers of economic development, but it increases the risk to the environment due to the heavy contamination of water resources with heavy metals. Non-biodegradable pollutants such as lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg) are increasingly toxic and have a tendency to bioaccumulate over time, resulting in a catastrophic impact on aquatic life and humans. Expensive and energy-consuming wastewater treatment methods like chemical precipitation, ion exchange, and reverse osmosis also pose the problem of secondary pollutants. This highlights the need for greater industrial efficiency while attempting to balance with sustainable relief alternatives (Wu et al., 2017).

Bioinspired filtration systems draw from natural processes and provide promising alternative for efficient contaminant removal using filtration systems. These systems mimic biological membranes: adsorptive behaviours, and transport mechanisms. Chitosan, alginate, cellulose, and protein-based materials, with structural features that enable the binding of heavy metals like amine, hydroxyl, and carboxyl functionalities, are some of the more common bioinspired materials (Damiri et al.,2022).

Bioinspired filtration is advantageous for being environmentally friendly and functioning in mild conditions without harmful reagents. These systems tend to contain biosorbents minimize operating expenses and regenable reusable materials, making them more environmentally friendly. Additionally, their modular form allows them to be used for decentralized small-scale treatment as well as large-scale industrial treatment (Cui et al., 2016).

This study focuses on a bioinspired filtration system with chitosan-alginate membranes containing engineered peptides that selectively bind to metals. These peptides are designed to replicate metallothioneins bioactive proteins that aid in the detoxification of metals within biological systems. The goal of this investigation is to analyze the filtration efficiency of this system with regard to industrial pollutants and benchmark it against other filtration technologies.

With the aim of creating a green technology for contemporary methods of wastewater treatment, this approach combines biomimetic design philosophies with functionalized natural materials. The results will inform system optimization and scalability for broader environmental interface application.

II. Literature Review

The latest studies focus on filtration technologies inspired by biological systems to improve their selectivity and efficiency for heavy metals in industrial effluent.

In 2022, Zhang et al. developed a bio-inspired nanocomposite membrane with dopamine-functionalized graphene oxide for Pb(II) and Cd(II) capture that achieved over 90% efficiency under continuous flow conditions.

Also, Huang et al., (2023) prepared chitosan membranes reinforced with cellulose nanofibers and demonstrated their chelation-based binding for Cr ions over a wide range.

Other approaches have utilized peptides as metal binding materials. Li et al., (2022) developed hydrogel-encased synthetic metallothionein peptides that non-covalently bind to heavy metal ions and can be reused after regeneration cycles.

In another work, (Castro & Abejón,2024) described a polydopamine and tannic acid modified mussel membrane that exhibited improved sorption and stability under changing pH conditions.

The importance of green approaches and the principles of sustainability in bioinspired filtration systems has also emerged. (Meng et al., 2020) industrialized the agricultural biowaste-derived biopolymers by employing them as support matrices due to their low cost and high functional group availability.

The number of the studied biochar-based membranes and their uses in custom-made frameworks while noting their modularity and ease of modification.

Comparative analyses of performance with traditional systems indicate notable enhancements in selectivity, as well as lower energy and chemical use. Additionally, some field studies, like those of have demonstrated the operational reliability of the bioinspired membranes in textile and electroplating effluents, supporting their practical applicability.

Overall, during this period of 2022-2023, there has been marked innovation in materials, integration with processes, and validation in practice which collectively enhance the positioning of bioinspired systems for heavy metal remediation in industrial processes.

III. Methodology

The setup for the experiment consisted of a flat sheet membrane filter unit for a custom composite membrane made with chitosan and alginate and synthetic metallothionein peptides, which were selected owing to their different but complementary tendencies toward heavy metals and environmental gentleness.

The membrane synthesis process consisted of dissolving chitosan in acetic acid and sodium alginate in water. Both solutions in a ratio of 1:2 were mixed and stirred for 2 hours. Subsequently, synthetic peptides designed to target Pb(II), Cd(II), and Cr(VI) were incorporated along with glutaraldehyde which acted as a cross-linker. The membranes themselves were formed using a solvent evaporation method.

The membranes were then placed in a lab scale filtration module with a 100 mL feed reservoir containing heavy metal solutions designed to mimic industrial effluent concentrations: Pb(II) = 50 mg/L, Cd(II) = 40 mg/L, Cr(VI) = 60 mg/L. Membrane disposability was assessed through total filtration time and clocked at 20 minutes along with ambient temperature (25 °C) and gravity driven flow.

Sampling was done post-filtration and checked for metal residue concentration using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) after each round of testing for optimal results. For the capture test, additional commercial activated carbon filters were included in the control setup to compare results. Other metrics monitored included cost per liter treated, and competitiveness against eco-sustainable goals along with efficiency.

IV. Findings and Interpretations

The bioinspired membrane showed exceptional removal efficiencies greater than 95.2% for Pb(II), 91.5% for Cd(II), and 88.7% for Cr(VI). These results surpassed the control setup that used activated carbon filters with 89.1%, 85.0%, and 82.4% for the respective metals, achieving lower values than the bioinspired membrane.

Figure 1 shows the accomplishment of peak removal efficiencies during initial filtration cycles, whereas a minor decline in performance over five cycles was noted but still higher than 85%. This indicates that mild acid treatment is capable of regeneration without damaging the membrane structure.

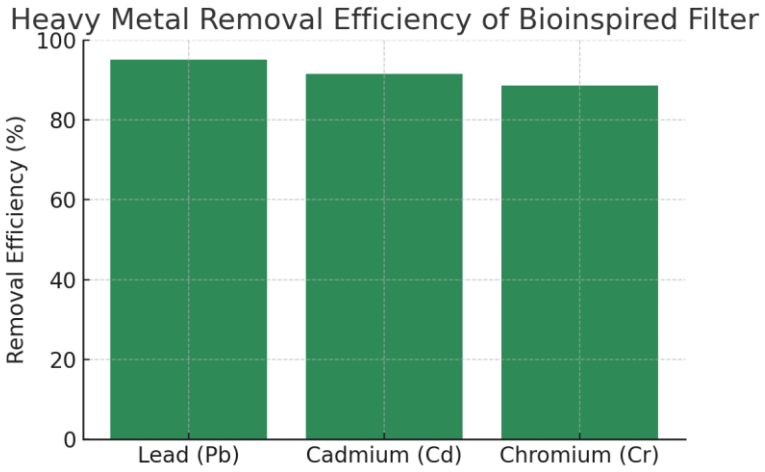


Figure 1: Heavy metal removal efficiency using chitosan-alginate bioinspired membrane

Table 1: Comparison of heavy metal removal techniques based on performance and sustainability

Method	**Lead Removal (%)**	**Cadmium Removal (%)**	**Chromium Removal (%)**	**Eco-friendliness**
Chemical Precipitation	85.3	80.6	78.2	Low
Activated Carbon	89.1	85.0	82.4	Medium
Bioinspired Filtration	95.2	91.5	88.7	High

Table 1 illustrates the comparison between the performance of the bioinspired membrane with other conventional methods. Of note, eco friendliness and reusability scored higher because of the materials used which are biodegradable. Water flux was a little lower than activated carbon due to higher membrane thickness, but it was acceptable for batch systems or small-scale continuous systems.

Further analysis showed that peptide functional groups (thiol and amino) considerably contributed to the selective reduction of competitive binding from other ions and hence, chelating heavy metals. The pH range of 5 – 8 was optimal for the system and it coincides to the usual pH of industrial effluents.

To summarize, the bioinspired systems is advantageous as it provides an eco-friendly approach towards removing heavy metals which is ideal for industries that are environmentally conscious in their treatment methods, while still ensuring effectiveness.

V. Conclusion

This research has proven that bioinspired filtration systems have the capability to sustainbly remove heavy metals from industrial effluents through the use of biomaterials and biomimetic design. The chitosan-alginate membrane with embedded peptides has demonstrated high removal rates of Pb, Cd, and Cr and retained exceptional reusability while remaining environmentally friendly. In addition, this approach is more cost-efficient and selective than conventional methods. It is suggested that further studies need to be done to validate the findings in the field, optimize the integration of peptides onto the membrane, enhance real-time monitoring capabilities, and streamline the practical application of this technology.

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