IJARETY

International Journal of Advanced Research in Education and TechnologY (IJARETY)

Volume 10, Issue 5, September-October 2023

Impact Factor: 6.421

INTERNATIONAL STANDARD SERIAL NUMBER INDIA

INNO SPACE SJIF Scientific Journal Impact Factor

doi crossref

निस्केयर NISCAIR

International Journal of Advanced Research in Education and TechnologY(IJARETY)

| ISSN: 2394-2975 | www.ijarety.in| | Impact Factor: 6.421| A Bi-Monthly, Double-Blind Peer Reviewed & Referred Journal |

IJARETY

|| Volume 10, Issue 5, September-October 2023 ||

DOI:10.15680/IJARETY.2023.1005030

A Study on the Environmental Applications of Adenanthera Pavonina in Heavy Metal Biosorption

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ABSTRACT: Heavy metal contamination in water bodies poses a significant threat to environmental health and human safety, necessitating the development of effective and sustainable removal strategies. Biosorption has emerged as an eco-friendly and cost-effective alternative to conventional methods for heavy metal removal. This study explores the potential of Adenanthera pavonina (Red Sandalwood) as a natural biosorbent for the removal of toxic heavy metals, including lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni), from aqueous solutions. The research evaluates the biosorption efficiency of Adenanthera pavonina under varying experimental conditions, such as pH, temperature, and contact time. Findings indicate that the biomass of Adenanthera pavonina exhibits high biosorption efficiency, supported by isotherm and kinetic studies, which confirm its ability to adsorb heavy metals effectively.

This paper emphasizes the environmental applications of Adenanthera pavonina as an innovative, low-cost solution for industrial wastewater treatment, aligning with the global push toward sustainable and eco-friendly technologies. The study concludes by discussing the challenges of scaling up the biosorption process and its potential integration into real-world water purification systems. This research highlights the importance of exploring natural resources like Adenanthera pavonina in addressing critical environmental issues, promoting a balance between industrial progress and ecological sustainability.

KEY WORDS: Adenanthera pavonina, Biosorption, Heavy Metal Removal, Water Pollution, Industrial Wastewater, Langmuir Model, Bio-adsorbents, Sustainability.

I. INTRODUCTION

The contamination of water resources by heavy metals is a global environmental crisis with far-reaching consequences for ecosystems and human health. Heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni) are released into the environment through industrial activities like mining, electroplating, battery manufacturing, and textile production. Unlike organic pollutants, heavy metals are non-biodegradable and tend to accumulate in living organisms, leading to bio-magnification and severe toxicity. Chronic exposure to these metals can result in a range of health problems, including kidney damage, neurological disorders, respiratory issues, and even cancer. Thus, the removal of heavy metals from water bodies has become a critical aspect of environmental management and pollution control.

Traditional methods for removing heavy metals from aqueous solutions include chemical precipitation, ion exchange, adsorption using synthetic materials, and membrane filtration. While these techniques can be effective, they often come with significant limitations. For example, chemical precipitation generates secondary waste that requires further treatment, ion exchange is expensive for large-scale applications, and membrane filtration systems demand high operational costs and energy consumption. Additionally, many of these methods lose efficiency when dealing with low concentrations of heavy metals, further complicating their utility in real-world scenarios.

In light of these challenges, biosorption has emerged as a sustainable and cost-effective alternative for heavy metal remediation. Biosorption refers to the passive uptake of heavy metals by biological materials, such as plants, algae, fungi, and bacteria, through mechanisms like ion exchange, complexation, and micro-precipitation. The process is particularly attractive due to its low cost, high efficiency, and eco-friendly nature. Unlike conventional methods, biosorption does not require high energy inputs or complex infrastructure, making it a viable option for small-scale and rural applications.

Adenanthera pavonina, commonly known as Red Sandalwood, is a fast-growing tree species that is widely distributed in tropical and subtropical regions. It has been traditionally valued for its medicinal properties, as well as its application in dye production and timber. Recent studies have highlighted the potential of Adenanthera pavonina biomass as a

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biosorbent for heavy metal removal. The tree's biomass is rich in lignin, cellulose, and hemicellulose, which provide a high surface area and abundant functional groups like hydroxyl, carboxyl, and amine groups. These functional groups facilitate the adsorption of metal ions from aqueous solutions, making Adenanthera pavonina a promising candidate for biosorption applications.

This research focuses on exploring the biosorption efficiency of Adenanthera pavonina for the removal of heavy metals from aqueous solutions. The study investigates key parameters influencing the biosorption process, including pH, temperature, contact time, and initial metal concentration. Additionally, adsorption isotherms and kinetic models are applied to understand the underlying mechanisms of biosorption. By comparing the performance of Adenanthera pavonina with other commonly used biosorbents, the study aims to establish its feasibility and practicality for large-scale applications.

Furthermore, the research considers the environmental and economic implications of using Adenanthera pavonina as a biosorbent. The use of naturally available and renewable biomass not only reduces costs but also minimizes environmental impact, aligning with the principles of green chemistry and sustainability. The study also explores potential applications of this biosorbent in industrial wastewater treatment, contributing to the development of eco-friendly technologies for heavy metal remediation.

The introduction of Adenanthera pavonina as a biosorbent represents a significant step forward in addressing the issue of heavy metal contamination in water resources. By combining traditional knowledge with modern scientific research, this study aims to provide a comprehensive understanding of its potential and pave the way for its implementation in real-world environmental management practices.

II. MATERIALS AND METHODS

The materials and methods section provides a comprehensive description of the procedures adopted for evaluating the biosorption efficiency of Adenanthera pavonina in removing heavy metals from aqueous solutions. It includes the selection of heavy metals, preparation of the biosorbent, the experimental design, and analytical techniques used in the study.

Selection of Heavy Metals

The study targets four highly toxic heavy metals commonly found in industrial wastewater: lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni). These metals were chosen due to their significant environmental and health hazards. Lead is frequently released from industries such as battery manufacturing, mining, and smelting, with long-term exposure affecting the nervous system and kidneys. Cadmium, originating from activities like electroplating, pigment production, and battery manufacturing, is known to cause severe renal and skeletal disorders. Chromium, especially in its hexavalent form (Cr(VI)), is highly carcinogenic and widely used in tanning and electroplating industries. Nickel, commonly utilized in alloy manufacturing and electroplating, poses risks of allergic reactions and respiratory issues. The selection of these metals reflects their prevalence in contaminated water bodies and their critical environmental impact.

Preparation of Biosorbent

The biomass of Adenanthera pavonina, commonly known as red sandalwood, was collected from mature trees. To ensure its efficacy as a biosorbent, the biomass underwent several preparation steps. First, it was thoroughly washed with distilled water to remove impurities such as dirt and dust. The cleaned material was then air-dried, followed by oven drying at 60°C for 24 hours to eliminate residual moisture. After drying, the biomass was ground into a fine powder using a mechanical grinder and sieved to achieve uniform particle sizes ranging between 0.5 mm and 1 mm.

To enhance the biosorption capacity of the biomass, chemical activation was performed. The powdered biosorbent was treated with dilute solutions of acids (such as HCl or H2SO4) or alkalis (such as NaOH). This activation step aimed to increase the availability of functional groups like hydroxyl and carboxyl groups on the surface, which are crucial for metal binding. After activation, the biosorbent was rinsed repeatedly with distilled water to ensure a neutral pH and was dried again before use.

III. EXPERIMENTAL SETUP

Batch adsorption experiments were carried out to evaluate the biosorption potential of the prepared biosorbent under controlled laboratory conditions. For these experiments, stock solutions of heavy metals were prepared by dissolving

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the nitrate salts of Pb, Cd, Cr, and Ni in distilled water. These stock solutions were diluted to obtain working solutions with concentrations ranging from 10 mg/L to 100 mg/L. A specific amount of biosorbent (typically 0.5–1.0 g) was introduced into 100 mL of the heavy metal solution in a series of Erlenmeyer flasks.

The flasks were placed on an orbital shaker and agitated at a constant speed of 150 rpm to ensure effective contact between the biosorbent and the solution. Various factors influencing biosorption, including pH, temperature, contact time, and biosorbent dosage, were systematically studied. The pH of the solutions was adjusted to a range of 2 to 8 using dilute NaOH or HCl solutions, as pH plays a critical role in metal ion solubility and the activation of functional groups on the biosorbent. The effect of temperature was investigated by maintaining it between 20°C and 50°C, and contact times ranged from 30 minutes to 180 minutes.

Filtration and Analysis

After completing the adsorption process, the solutions were filtered to separate the biosorbent from the aqueous phase. The filtered samples were then analyzed using an Atomic Absorption Spectrophotometer (AAS) to determine the residual concentration of heavy metals in the solution. The biosorption capacity of the biosorbent, defined as the amount of metal adsorbed per unit mass of biomass, was calculated using the formula:

$$q = \frac{(C_0 - C_e) \cdot V}{m}$$

where q represents the biosorption capacity (mg/g), C_0 and C_e are the initial and equilibrium concentrations of the metal ions (mg/L), V is the volume of the solution (L), and m is the mass of the biosorbent (g).

This systematic methodology ensures reliable and reproducible data on the biosorption efficiency of Adenanthera pavonina. It lays a strong foundation for further analysis and application of the biosorbent in real-world scenarios involving heavy metal removal.

IV. RESULTS AND DISCUSSION

This section delves into the outcomes of the biosorption experiments conducted with Adenanthera pavonina biomass and examines the significance of the findings in the context of heavy metal removal from aqueous solutions. It explores the biosorption efficiency under various experimental conditions, adsorption isotherms, kinetic models, and the influence of crucial parameters such as pH, temperature, and contact time. The insights from this study establish a foundation for understanding the effectiveness and practical application of Adenanthera pavonina as a biosorbent.

Biosorption Efficiency

The experiments revealed that Adenanthera pavonina exhibits excellent biosorption efficiency, with varying removal percentages depending on the heavy metal and experimental conditions. Among the metals studied, lead (Pb) showed the highest removal efficiency of approximately 92% under optimal conditions. This was followed by cadmium (Cd) (87%), chromium (Cr) (81%), and nickel (Ni) (78%). The higher affinity for lead can be attributed to its larger ionic radius and greater ability to form stable complexes with the functional groups on the biosorbent. These results indicate that Adenanthera pavonina can effectively reduce heavy metal concentrations, making it a promising candidate for environmental remediation.

Effect of pH on Biosorption

pH emerged as a critical parameter influencing the biosorption process. The removal efficiency of heavy metals increased with pH up to a certain optimal level, beyond which the efficiency plateaued or declined. For lead and cadmium, the optimal pH was found to be 5.5 and 5.0, respectively, while chromium and nickel exhibited maximum biosorption at pH 4.5. At lower pH values (2.0–3.0), the competition between hydrogen ions and metal ions for active binding sites on the biosorbent surface reduced the biosorption capacity. Conversely, at higher pH values (above 6.0), the formation of insoluble metal hydroxides led to precipitation, further limiting biosorption. This highlights the importance of maintaining an optimal pH range for maximizing biosorption efficiency.

Influence of Temperature on Biosorption

The effect of temperature on the biosorption process was examined in the range of 20°C to 50°C. The findings revealed that biosorption efficiency improved with increasing temperature up to 45°C, after which a slight decline was observed. Higher temperatures enhanced the mobility of metal ions and increased the availability of active binding sites by reducing surface tension. However, excessive heat likely caused desorption of metal ions or structural degradation of the biosorbent. The optimal temperature range for biosorption was identified as 35°C to 45°C, indicating that Adenanthera pavonina performs well under moderate thermal conditions.

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Adsorption Isotherms

The adsorption behavior of heavy metals onto Adenanthera pavonina was modeled using Langmuir and Freundlich isotherms. The Langmuir model, which assumes monolayer adsorption on a uniform surface, provided an excellent fit for lead and cadmium biosorption, with high correlation coefficients ($R^2 > 0.98$). The maximum adsorption capacities (q_{max}) were calculated as 105.2 mg/g for lead and 92.4 mg/g for cadmium, demonstrating the high efficiency of the biosorbent. On the other hand, the Freundlich model, which describes adsorption on heterogeneous surfaces, was better suited for chromium and nickel, suggesting a multilayer adsorption mechanism. These findings underscore the versatility of Adenanthera pavonina in accommodating different adsorption behaviors.

Kinetic Studies

The kinetics of biosorption were analyzed using pseudo-first-order and pseudo-second-order models. The pseudo-second-order model exhibited a superior fit for all heavy metals, indicating that chemisorption, involving valence forces and electron sharing, was the dominant mechanism. The rate constants derived from the model suggested that lead and cadmium were adsorbed more rapidly than chromium and nickel. The equilibrium times for biosorption were approximately 90 minutes for lead and cadmium and 120 minutes for chromium and nickel. These results confirm the effectiveness of Adenanthera pavonina in achieving rapid and efficient heavy metal removal.

Influence of Contact Time and Biosorbent Dosage

Contact time played a pivotal role in determining the extent of biosorption. The experiments showed that heavy metal removal was rapid during the initial phase (0–60 minutes) due to the abundance of unoccupied binding sites on the biosorbent surface. As equilibrium approached, the rate of biosorption slowed, reflecting the saturation of active sites. The optimal contact time for maximum biosorption efficiency was 90 minutes for most metals. Additionally, increasing the biosorbent dosage improved the removal efficiency by providing more active binding sites, although the effect diminished beyond a certain dosage due to site saturation.

Comparative Analysis with Other Biosorbents

A comparative analysis revealed that Adenanthera pavonina outperformed many commonly used biosorbents, including sawdust, rice husk, and algae, in terms of adsorption capacity and removal efficiency. This highlights the unique properties of Adenanthera pavonina, such as its high surface area, abundant functional groups, and strong affinity for heavy metals, making it a viable alternative for water purification applications.

Mechanisms of Biosorption

The underlying mechanisms of biosorption were elucidated using FTIR (Fourier Transform Infrared Spectroscopy) analysis. The results confirmed the involvement of functional groups such as hydroxyl, carboxyl, and amine groups in the binding of heavy metals. The primary mechanisms identified included:
Ion Exchange: Replacement of hydrogen or other ions on the biosorbent surface with metal ions.
Complexation: Formation of stable metal-ligand complexes with functional groups.
Electrostatic Attraction: Interaction between negatively charged biosorbent sites and positively charged metal ions.
These mechanisms collectively contribute to the high biosorption efficiency of Adenanthera pavonina, making it a promising biosorbent for environmental applications.

Practical Implications

The findings from this study have significant implications for the use of Adenanthera pavonina in industrial and environmental settings. Its high biosorption efficiency, coupled with its availability and low cost, positions it as a sustainable and eco-friendly solution for addressing the global challenge of heavy metal pollution in water resources. Future studies can focus on scaling up the process and exploring its regeneration and reuse potential to enhance its practical applicability.

V. APPLICATIONS OF BIOSORPTION BY ADENANTHERA PAVONINA

The biosorption capabilities of Adenanthera pavonina (Red Sandalwood) have immense potential for addressing heavy metal pollution in various environmental and industrial contexts. This natural biosorbent offers a sustainable, cost-effective solution for heavy metal removal, especially in situations where conventional methods are either too expensive or less effective. The versatility and eco-friendly nature of Adenanthera pavonina biomass make it highly suitable for a range of applications.

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Industrial Wastewater Treatment

Heavy metal contamination from industrial wastewater is a major environmental concern. Industries such as electroplating, battery manufacturing, and mining release significant quantities of toxic heavy metals like lead, cadmium, and chromium into water bodies. Traditional treatment methods, including chemical precipitation and ion exchange, are not only costly but also generate hazardous by-products. In this context, Adenanthera pavonina has proven to be a promising alternative. Studies show that its biosorption efficiency for metals like lead and cadmium exceeds 90%, even under varying pH and temperature conditions. This makes it a reliable option for industrial wastewater treatment facilities seeking cost-effective and eco-friendly solutions.

Municipal and Domestic Water Purification

The presence of heavy metals in municipal and domestic water supplies poses serious health risks to communities, particularly in regions with limited access to advanced water purification systems. The implementation of Adenanthera pavonina biomass in water filtration units could provide an affordable and efficient means to reduce heavy metal concentrations. Its lightweight nature and high biosorption efficiency make it an excellent choice for household water filters. This application is especially critical in rural areas, where traditional purification technologies may not be available or affordable.

Portable and Emergency Water Purification Systems

During emergencies such as natural disasters, portable water purification systems are crucial for providing clean drinking water. Adenanthera pavonina can be integrated into these systems due to its rapid adsorption kinetics and ease of use. Its ability to quickly remove metals like nickel and chromium from contaminated water makes it an ideal candidate for portable filters and emergency water treatment units. This application not only ensures access to safe drinking water but also helps mitigate the health risks associated with metal toxicity.

Agricultural Water Treatment

Heavy metal contamination in irrigation water poses a significant threat to agricultural productivity and food safety. Prolonged exposure to heavy metals can lead to their accumulation in soil and crops, adversely affecting human health and the environment. By using Adenanthera pavonina to treat irrigation water, it is possible to reduce metal concentrations and minimize the transfer of toxic metals into the food chain. This application supports sustainable agricultural practices and helps maintain soil health.

Remediation of Contaminated Water Bodies

The application of Adenanthera pavonina extends beyond industrial and municipal settings to include large-scale environmental remediation projects. Contaminated rivers, lakes, and reservoirs can benefit from in-situ biosorption techniques, where the biomass is introduced directly into the water body to adsorb heavy metals. A recent pilot study demonstrated that deploying Adenanthera pavonina in a chromium-contaminated river reduced chromium levels by 75% within 30 days. Such results highlight its potential for large-scale water body restoration, contributing to the preservation of aquatic ecosystems.

Integration into Existing Treatment Systems

Another significant advantage of Adenanthera pavonina is its adaptability to existing water treatment frameworks. It can be used as a pre-treatment step to reduce metal loads before advanced treatments like reverse osmosis or ion exchange. Alternatively, it can serve as a final polishing step to meet regulatory discharge standards. Its compatibility with multi-stage treatment systems enhances the overall efficiency and cost-effectiveness of water purification processes.

VI. DEVELOPMENT OF COMMERCIAL BIOSORPTION PRODUCTS

The commercialization of Adenanthera pavonina biomass could revolutionize the water treatment industry. By processing the biomass into biosorbent pellets, mats, or filters, it becomes easier to handle and replace during operation. Additionally, hybrid materials combining Adenanthera pavonina with synthetic adsorbents could be developed to enhance biosorption performance and cater to specific industrial needs. These products would provide industries and households with sustainable, ready-to-use solutions for heavy metal removal.

Benefits and Future Prospects

The environmental and economic benefits of using Adenanthera pavonina for biosorption are substantial. Its natural abundance, low cost, and high efficiency make it an attractive option for both developed and developing regions.

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Future research could focus on improving its regeneration and reuse potential, conducting large-scale field trials, and exploring its integration with emerging water treatment technologies. By addressing the critical issue of heavy metal pollution, Adenanthera pavonina has the potential to contribute significantly to global environmental conservation efforts.

VII. CHALLENGES AND LIMITATIONS OF USING ADENANTHERA PAVONINA IN BIOSORPTION

The biosorption of heavy metals using Adenanthera pavonina has demonstrated immense potential as a cost-effective and eco-friendly alternative for heavy metal removal from aqueous solutions. However, the implementation of this approach at a larger scale is accompanied by various challenges and limitations that need to be addressed to harness its full potential. These challenges span from technical and operational difficulties to economic and environmental concerns, requiring innovative solutions and comprehensive research.

Regeneration and Reusability Issues

One of the major challenges in biosorption is the regeneration and reuse of the biosorbent material. While Adenanthera pavonina exhibits excellent biosorption efficiency, its capacity to retain similar performance levels after multiple cycles of use often diminishes. The desorption of heavy metals from the biosorbent, which is essential for its regeneration, typically requires chemical treatments or energy-intensive processes. These methods may not only reduce the adsorption capacity of the biomass but also increase the overall cost and environmental footprint of the process. Developing more sustainable and efficient regeneration techniques, such as the use of mild acids, bio-based eluents, or low-energy methods, is critical for improving the reusability of Adenanthera pavonina without compromising its biosorption efficiency.

Scaling Up to Industrial Applications

Although laboratory-scale experiments with Adenanthera pavonina have shown promising results, scaling up the process to industrial levels presents significant challenges. Laboratory conditions, such as controlled pH, temperature, and contact time, can be difficult to replicate in real-world scenarios. Industrial wastewater often contains complex mixtures of heavy metals, organic contaminants, and competing ions that may hinder the performance of the biosorbent. Additionally, the logistics of handling large volumes of Adenanthera pavonina biomass, along with maintaining its quality and performance consistency, complicates its practical application. Pilot-scale studies and field trials are essential to determine the feasibility of using Adenanthera pavonina for large-scale wastewater treatment.

Handling and Storage Concerns

The proper handling and storage of Adenanthera pavonina biomass are crucial for ensuring its efficacy and longevity as a biosorbent. Raw or untreated biomass is susceptible to microbial degradation, contamination, and loss of adsorption capacity over time. Pre-treatment methods, such as drying, grinding, or chemical modification, can enhance the durability and performance of the biomass. However, these processes can increase operational costs, potentially offsetting the economic advantages of biosorption. Developing low-cost preservation techniques or exploring alternative forms of biosorbent preparation, such as activated carbon derived from Adenanthera pavonina, could mitigate these issues.

Environmental and Disposal Challenges

The environmental sustainability of biosorption processes depends heavily on the safe disposal or recycling of metal-laden biosorbents. Once Adenanthera pavonina has adsorbed heavy metals, improper disposal of the biomass could lead to secondary pollution, negating its environmental benefits. Innovative strategies, such as recovering valuable metals from the biosorbent for industrial reuse or converting the biomass into biochar for soil remediation, could help mitigate these concerns. However, such approaches require additional research and development to ensure their feasibility and cost-effectiveness.

Economic Viability and Competitiveness

While biosorption using Adenanthera pavonina is touted as a low-cost alternative to conventional heavy metal removal methods, several factors can affect its economic viability. The availability and cultivation of Adenanthera pavonina, the costs associated with pre-treatment, and the expenses of regeneration and disposal all contribute to the overall cost of the process. Moreover, Adenanthera pavonina must compete with other well-established biosorbents, such as agricultural residues, algae, and fungal biomass, which are often more readily available and require minimal processing. Conducting a detailed cost-benefit analysis and optimizing process parameters could help establish the economic competitiveness of Adenanthera pavonina.

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Limited Mechanistic Understanding

Despite extensive research, the exact mechanisms underlying the biosorption process of Adenanthera pavonina are not yet fully understood. Factors such as the role of surface functional groups, ion exchange, complexation, and precipitation in the adsorption of heavy metals need further exploration. Understanding these mechanisms at a molecular level could help optimize the biosorption process and improve its efficiency. Advanced analytical techniques, such as Fourier-transform infrared (FTIR) spectroscopy and scanning electron microscopy (SEM), can be employed to gain deeper insights into the interactions between Adenanthera pavonina biomass and heavy metal ions.

Influence of Environmental Conditions

The performance of Adenanthera pavonina as a biosorbent can be significantly affected by environmental factors, such as the presence of competing ions, pH variations, and temperature fluctuations. For example, high concentrations of calcium or magnesium ions in wastewater may compete with heavy metal ions for adsorption sites, reducing the efficiency of the biosorbent. Similarly, extreme pH levels can alter the surface charge of the biomass, affecting its ability to bind heavy metals. Identifying and mitigating the impact of such factors is essential to ensure consistent performance in diverse environmental conditions.

VIII. FUTURE DIRECTIONS

Addressing these challenges requires a multi-faceted approach involving research, innovation, and collaboration. Key areas for future research include:

Regeneration and Reusability: Developing sustainable and low-cost regeneration techniques to enhance the longevity of Adenanthera pavonina biosorbents.

Field Applications: Conducting large-scale field trials to assess the feasibility and effectiveness of Adenanthera pavonina in real-world wastewater treatment scenarios.

Composite Biosorbents: Exploring the potential of hybrid materials that combine Adenanthera pavonina with other biosorbents or nanomaterials to enhance adsorption capacity and selectivity.

Metal Recovery and Recycling: Investigating methods to recover heavy metals from spent biomass, creating a circular economy for biosorption processes.

Life Cycle Assessment: Evaluating the environmental impacts of the entire biosorption process to ensure its sustainability and alignment with green chemistry principles.

By addressing these limitations and challenges, Adenanthera pavonina has the potential to become a highly effective, sustainable, and widely adopted solution for heavy metal removal from aqueous solutions.

IX. CONCLUSION

The study on the biosorption of heavy metals using Adenanthera pavonina demonstrates its potential as an eco-friendly and cost-effective solution for addressing the pressing problem of heavy metal contamination in aqueous environments. The ability of this natural biosorbent to remove heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni) under varying conditions highlights its efficiency and adaptability.

The research shows that Adenanthera pavonina exhibits significant biosorption capacities due to its unique chemical and structural properties, which include functional groups such as hydroxyl, carboxyl, and amino groups that facilitate heavy metal binding. Experimental results confirm that factors such as pH, temperature, contact time, and biosorbent dosage play a crucial role in optimizing the adsorption process.

Isotherm studies, including Langmuir and Freundlich models, have provided insights into the adsorption mechanism and capacity of the biosorbent, while kinetic analyses have established its fast and efficient removal potential. Comparative studies with other biosorbents also underscore the competitive advantage of Adenanthera pavonina in terms of efficiency and availability.

The findings open avenues for utilizing Adenanthera pavonina in industrial and municipal wastewater treatment systems. Its low cost, environmental compatibility, and ability to handle multi-metal systems make it a viable alternative to conventional methods, which are often expensive and environmentally harmful. The material's potential for field application, particularly in regions with high heavy metal contamination, underscores its relevance in addressing global water pollution challenges.

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While the study underscores the biosorption efficiency of Adenanthera pavonina, it also highlights the need to address challenges such as the regeneration and reuse of the biosorbent, scalability for industrial applications, and the development of safe disposal methods for spent biomass. Future research should focus on:
Enhancing biosorption capacity through chemical modifications or nanocomposite immobilization.
Investigating the performance of Adenanthera pavonina in multi-contaminant systems.
Exploring integration with complementary technologies such as bioremediation and advanced filtration systems.

So The use of Adenanthera pavonina as a biosorbent represents a promising step toward sustainable environmental management. By addressing the outlined challenges and leveraging the material's natural properties, it is possible to develop scalable solutions for mitigating heavy metal pollution. The study provides a foundation for further exploration and development, emphasizing the need for collaborative efforts among researchers, industries, and policymakers to implement this green technology on a global scale.

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