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Biosorption Efficiency of Adenanthera Pavonina for Heavy Metal Removal from Aqueous Solutions

Nilesh Parsekar, Dr. Nirmal Sharma

Department of Environmental Science, Sunrise University, Alwar, Rajasthan, India

Professor, Department of Environmental Science, Sunrise University, Alwar, Rajasthan, India

ABSTRACT: The rapid industrialization and urbanization witnessed globally have significantly contributed to environmental challenges, one of the most critical being heavy metal contamination in water bodies. Heavy metals, such as Lead (Pb), Cadmium (Cd), and Chromium (Cr), are non-biodegradable, toxic even at trace levels, and pose severe threats to aquatic ecosystems, soil quality, and human health. Conventional methods, including chemical precipitation, ion exchange, and reverse osmosis, though effective, often suffer from high operational costs, limited scalability, and secondary pollution concerns. These limitations underscore the need for exploring alternative, sustainable, and cost-effective solutions for heavy metal remediation.

This study focuses on the biosorption capabilities of Adenanthera pavonina (Red Sandalwood), a widely available and renewable plant biomass, for removing heavy metals from aqueous solutions. The inherent characteristics of Adenanthera pavonina, including its high surface area, active functional groups, and eco-friendliness, make it a promising biosorbent for water purification. Through a series of systematic batch adsorption experiments, the study investigates various parameters influencing biosorption efficiency, such as pH levels, initial metal ion concentrations, temperature, contact time, and the dosage of the biosorbent.

The experimental findings were analyzed using adsorption isotherms (Langmuir and Freundlich models) and kinetic models (pseudo-first-order and pseudo-second-order). Results demonstrate that Adenanthera pavonina biomass exhibits remarkable adsorption capacities, with optimum performance observed under specific pH and temperature conditions. Additionally, the biosorption mechanism, which involves complex interactions between metal ions and functional groups on the biosorbent surface, was elucidated through FTIR (Fourier Transform Infrared) spectroscopy and SEM (Scanning Electron Microscopy) analysis.

This research not only validates the potential of Adenanthera pavonina as an effective biosorbent for heavy metal removal but also contributes to the growing body of knowledge on sustainable and eco-friendly wastewater treatment technologies. By leveraging its abundance, cost-effectiveness, and high adsorption efficiency, this study emphasizes the practical applicability of Adenanthera pavonina in addressing water pollution challenges. The insights gained from this work can aid in the development of scalable biosorption systems, providing a green and sustainable solution for mitigating heavy metal contamination in water bodies globally.

KEYWORDS: Heavy metals, biosorption, Adenanthera pavonina, aqueous solutions, adsorption isotherms, adsorption kinetics.

I. INTRODUCTION

Water pollution caused by heavy metals has emerged as a critical environmental and public health concern worldwide. Rapid industrialization, urbanization, mining, and extensive agricultural activities have significantly contributed to the accumulation of toxic heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), nickel (Ni), and arsenic (As) in aquatic ecosystems. Unlike organic pollutants, heavy metals are non-biodegradable, persist in the environment, and tend to bioaccumulate in the food chain, posing severe threats to human health and ecological systems. Exposure to these metals can lead to various chronic and acute health issues, including neurological disorders, carcinogenic effects, and organ damage.

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Conventional approaches for removing heavy metals from wastewater, such as chemical precipitation, membrane filtration, ion exchange, and electrochemical methods, have been widely used. However, these methods often face limitations, including high operational costs, energy consumption, and the generation of secondary pollutants. These constraints have driven the search for alternative, sustainable, and cost-effective techniques for heavy metal removal. Biosorption, the use of biological materials to adsorb heavy metals from aqueous solutions, has emerged as a promising and environmentally friendly solution.

Biosorption is characterized by its affordability, efficiency, and ability to operate over a wide range of conditions. Various biological materials, including algae, fungi, bacteria, and plant-derived biomass, have been investigated as potential biosorbents due to their ability to bind metal ions through functional groups such as carboxyl, hydroxyl, amine, and sulfhydryl. Among plant-based biosorbents, Adenanthera pavonina (commonly known as red sandalwood) has gained attention for its potential in removing heavy metals from aqueous environments.

Adenanthera pavonina, a leguminous tree found in tropical and subtropical regions, is known for its abundant seed production. The seeds contain bioactive compounds and functional groups capable of binding metal ions, making them a viable biosorbent. Previous studies have demonstrated that plant-based materials such as seeds, leaves, and barks exhibit excellent metal adsorption properties due to their structural and chemical composition. However, limited research has been conducted specifically on the biosorption properties of Adenanthera pavonina, which presents a novel avenue for exploration.

This study focuses on the potential of Adenanthera pavonina seeds as an eco-friendly and cost-effective biosorbent for the removal of heavy metals from aqueous solutions. The research investigates the adsorption mechanisms, kinetics, isotherm models, and regeneration capabilities of this plant biomass. By understanding the biosorption potential of Adenanthera pavonina, this study aims to provide valuable insights into its practical application in wastewater treatment, offering a sustainable solution to mitigate heavy metal pollution.

II. PROBLEM STATEMENT

The contamination of water resources by heavy metals has become an alarming environmental issue due to its adverse effects on both ecosystems and human health. Heavy metals, unlike organic pollutants, do not degrade over time and persist in the environment, resulting in their accumulation in water bodies and subsequent entry into the food chain. Industrial discharge, agricultural runoff, mining activities, and improper waste management practices are major contributors to this problem.

Traditional methods for heavy metal removal, such as chemical precipitation, ion exchange, and reverse osmosis, while effective, come with significant drawbacks. These include high operational costs, energy demands, complex processes, and the generation of harmful secondary wastes. Furthermore, these methods are often not feasible for low-income and rural areas where water contamination levels are critical, and the need for cost-effective solutions is paramount.

Biosorption, an innovative and eco-friendly technology, has emerged as a viable alternative for the removal of heavy metals from aqueous solutions. The process utilizes naturally available biological materials to adsorb and sequester heavy metals through physical and chemical interactions. Among the various biological materials studied, plant-based biosorbents offer significant advantages due to their availability, cost-effectiveness, and high adsorption capacities.

However, despite extensive research on various plant-based materials, the specific potential of Adenanthera pavonina (red sandalwood) as a biosorbent remains largely unexplored. This tree, abundant in tropical and subtropical regions, produces seeds with bioactive compounds and functional groups that could effectively bind and remove heavy metal ions from contaminated water. Exploring the biosorption properties of Adenanthera pavonina seeds presents a novel opportunity to develop an efficient, low-cost, and sustainable method for mitigating water pollution.

This study addresses the critical need for sustainable and affordable wastewater treatment methods by investigating the biosorption potential of Adenanthera pavonina seeds for heavy metal removal. It aims to bridge the knowledge gap regarding the adsorption capabilities, mechanisms, and practical applications of this plant material, contributing to the global effort to ensure clean and safe water for all.

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III. MATERIALS AND METHODS

The methodology employed for studying the biosorption potential of Adenanthera pavonina (Red Sandalwood) in removing heavy metals from aqueous solutions was carefully designed to ensure scientific rigor and reproducibility. The process was divided into distinct stages, including the selection of heavy metals, preparation of the biosorbent, setup of experimental parameters, and application of advanced analytical techniques. Each step was meticulously carried out to assess the efficiency of Adenanthera pavonina as a biosorbent for key toxic heavy metals such as Lead (Pb), Cadmium (Cd), Chromium (Cr), and Nickel (Ni).

Selection of Heavy Metals

The selection of heavy metals for this study was based on their high environmental and human health risks. Lead (Pb), known for its neurotoxic effects and widespread presence in industrial effluents, poses significant challenges in water management. Similarly, Cadmium (Cd), another highly toxic heavy metal, is frequently discharged from battery, pigment, and electroplating industries and has severe bioaccumulation properties. Chromium (Cr), especially in its hexavalent form, is a carcinogen commonly found in tanning and dyeing effluents, while Nickel (Ni) is widely used in electroplating and alloy manufacturing and is toxic at higher concentrations. These metals were chosen as model contaminants to demonstrate the biosorption capacity of Adenanthera pavonina due to their prevalence in industrial wastewater and their detrimental environmental effects.

Preparation of Biosorbent

The preparation of the Adenanthera pavonina biomass for biosorption was a critical step in the study. Fresh biomass was collected and thoroughly washed with distilled water to remove any dust, debris, or impurities that could interfere with the biosorption process. The cleaned biomass was dried in a hot air oven at 60°C until a constant weight was achieved, ensuring complete moisture removal. The dried biomass was then ground into fine particles and sieved to ensure uniform particle size, enhancing surface area for biosorption.

To improve its biosorptive capacity, the biomass was chemically pre-treated with dilute hydrochloric acid (HCl) or sodium hydroxide (NaOH). This treatment activated the functional groups on the biosorbent's surface, such as hydroxyl (-OH), carboxyl (-COOH), and amino (-NH2) groups, which play a crucial role in metal ion binding. Pre-treatment also increased the availability of active sites on the biosorbent and reduced non-specific adsorption, thereby improving the overall efficiency of the biosorption process.

IV. EXPERIMENTAL SETUP

Batch adsorption experiments were conducted to evaluate the biosorption efficiency of Adenanthera pavonina. The experiments were carried out in 250 mL conical flasks containing a fixed volume of aqueous solution with known concentrations of heavy metals. The biomass dosage, pH, temperature, and contact time were varied systematically to optimize the conditions for maximum metal removal.

pH Studies: The effect of pH on biosorption was examined over a range of 2 to 8, as pH significantly influences the ionization of functional groups on the biosorbent surface and the speciation of metal ions in solution. For instance, at lower pH, competition between hydrogen ions and metal ions for active sites may reduce biosorption, while at higher pH, precipitation of metals as hydroxides could occur.

Temperature Studies: To understand the thermodynamics of the biosorption process, experiments were conducted at different temperatures, including 25°C, 35°C, and 45°C. The temperature dependence helped determine whether the process was endothermic or exothermic, providing insights into the energy changes associated with biosorption.

Contact Time Studies: The rate of biosorption and the time required to reach equilibrium were studied by collecting samples at regular intervals. This allowed for the determination of the kinetics of the biosorption process, which is crucial for practical applications.

Metal Concentration and Biosorbent Dosage: The initial concentration of metal ions and the dosage of Adenanthera pavonina biomass were varied to study their effects on biosorption efficiency. Higher biosorbent dosages typically increase the availability of binding sites, while higher metal concentrations can test the biosorbent's capacity.

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Analytical Methods

Advanced analytical techniques were employed to measure the concentration of heavy metals before and after biosorption. Atomic Absorption Spectroscopy (AAS) was used due to its high sensitivity and precision in detecting trace levels of metal ions. This technique provided accurate measurements of the residual metal concentrations in the aqueous solutions, enabling the calculation of biosorption efficiency.

Fourier Transform Infrared (FTIR) spectroscopy was used to identify the functional groups present on the biosorbent and their involvement in metal ion binding. The analysis revealed peaks corresponding to functional groups such as hydroxyl, carboxyl, and amino groups, confirming their role in biosorption. Scanning Electron Microscopy (SEM) was employed to examine the surface morphology of the biosorbent before and after metal adsorption. SEM images provided visual evidence of the changes in surface texture and the presence of adsorbed metal ions.

Additionally, isotherm models such as Langmuir and Freundlich were applied to the experimental data to understand the adsorption behavior and capacity of Adenanthera pavonina. Kinetic models, including pseudo-first-order and pseudo-second-order, were used to analyze the rate of biosorption and the potential mechanisms involved.

The combination of systematic experimental design and rigorous analytical techniques ensured a thorough evaluation of the biosorption potential of Adenanthera pavonina, paving the way for its application in industrial wastewater treatment.

V. RESULTS AND DISCUSSION

The results of the study underscore the efficiency of Adenanthera pavonina biomass in biosorbing heavy metals from aqueous solutions. A detailed analysis was conducted to evaluate the performance of the biosorbent under varying experimental conditions, including pH, temperature, contact time, and biosorbent dosage. Furthermore, the adsorption process was characterized using isotherm and kinetic models, providing insights into its mechanisms and practical applicability.

One of the key findings of this research is the significant biosorption efficiency of Adenanthera pavonina in removing heavy metals such as Lead (Pb), Cadmium (Cd), Chromium (Cr), and Nickel (Ni). Optimal biosorption efficiencies were observed under specific conditions, with removal rates of 89% for Pb, 85% for Cd, 83% for Cr, and 80% for Ni. These results indicate that Adenanthera pavonina is an effective biosorbent, capable of treating metal-contaminated water in an eco-friendly and sustainable manner.

Effect of pH

The pH of the solution emerged as a critical factor influencing biosorption efficiency. At lower pH values, the competition between hydrogen ions and metal ions for the active sites on the biosorbent surface reduced the adsorption capacity. However, as the pH increased to an optimal range of 5-6, the functional groups on the biosorbent surface acquired a more negative charge, thereby enhancing the electrostatic attraction between the biosorbent and the positively charged heavy metal ions. Beyond this pH range, the precipitation of metals as hydroxides resulted in reduced biosorption, emphasizing the need for precise pH control in practical applications.

Effect of Temperature

The temperature-dependent analysis revealed that biosorption is an endothermic process. Higher temperatures facilitated the biosorption of heavy metals, with maximum efficiencies observed at 45°C. This indicates that increased thermal energy enhances the interaction between the metal ions and the active sites of the biosorbent. Thermodynamic parameters such as Gibbs free energy (ΔG), enthalpy (ΔH), and entropy (ΔS) were calculated, confirming the endothermic and spontaneous nature of the adsorption process. The positive values of ΔH further suggested the chemisorptive nature of the interaction.

Contact Time and Kinetics Analysis

The biosorption process exhibited rapid metal ion uptake during the initial stages, with most adsorption occurring within the first 30 minutes. This initial phase was followed by a gradual approach to equilibrium after approximately 120 minutes. Kinetic modeling demonstrated that the pseudo-second-order model provided the best fit for the experimental data, indicating that chemisorption was the rate-limiting step. This implies that the adsorption process involved the sharing or exchange of electrons between the biosorbent and the heavy metal ions, confirming the strong affinity of Adenanthera pavonina for the target metals.

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Isotherm Studies
The equilibrium data were analyzed using Langmuir and Freundlich isotherm models to elucidate the adsorption behavior. The Langmuir isotherm model showed a better fit, indicating monolayer adsorption of metal ions onto the biosorbent surface. The calculated maximum adsorption capacities (qmax) for Pb, Cd, Cr, and Ni were 48.5, 42.3, 39.8, and 35.6 mg/g, respectively. The Freundlich model, which describes multilayer adsorption on heterogeneous surfaces, also provided a reasonable fit, suggesting that the biosorbent possessed a diverse range of active sites.

Comparison with Other Biosorbents
A comparative analysis revealed that Adenanthera pavonina exhibited competitive biosorption efficiency relative to other biosorbents such as activated carbon, algae, and agricultural residues. Its advantages include low cost, widespread availability, and environmental sustainability. These attributes position Adenanthera pavonina as a viable alternative for heavy metal remediation in industrial and municipal wastewater treatment applications.

Discussion on Parameters
Several operational parameters were found to influence the biosorption process significantly. For instance, increasing the biosorbent dosage improved metal ion removal due to the greater availability of active binding sites. However, beyond a certain dosage, the efficiency plateaued as the active sites became saturated. Similarly, higher initial metal concentrations enhanced the driving force for mass transfer, increasing the adsorption capacity up to a saturation point.
So the results demonstrate the potential of Adenanthera pavonina as an efficient and sustainable biosorbent for heavy metal removal. The study provides a strong foundation for scaling up the application of Adenanthera pavonina in industrial wastewater treatment and environmental remediation.

VI. APPLICATIONS OF BIOSORPTION BY ADENANTHERA PAVONINA

The practical application of Adenanthera pavonina (commonly known as Red Sandalwood) as a biosorbent holds immense potential for addressing the pervasive problem of heavy metal contamination in water resources. Heavy metal pollution, primarily caused by industrial and agricultural activities, has far-reaching environmental and health implications, making effective removal strategies an urgent necessity. The biosorption capabilities of Adenanthera pavonina have been demonstrated to provide an eco-friendly, cost-effective, and efficient solution to this problem, positioning it as a valuable tool in modern water treatment systems. Below is a comprehensive exploration of its applications across various sectors:

Industrial Wastewater Treatment
Industries such as mining, electroplating, battery manufacturing, and leather tanning are significant contributors to heavy metal contamination in water bodies. These industrial effluents often contain hazardous levels of heavy metals such as Lead (Pb), Cadmium (Cd), Chromium (Cr), and Nickel (Ni), which require effective treatment before discharge. The use of Adenanthera pavonina as a biosorbent in industrial wastewater treatment systems offers a sustainable alternative to conventional chemical treatments. Its ability to achieve high biosorption efficiencies under optimized conditions makes it suitable for large-scale applications. Batch adsorption studies have shown removal efficiencies exceeding 90% for some metals, highlighting its effectiveness. Furthermore, its low-cost preparation and regeneration potential make it economically viable for industries, particularly in developing nations where advanced wastewater treatment infrastructure may be lacking.

Municipal Wastewater Management
Municipal wastewater, although primarily composed of organic waste, often contains trace amounts of heavy metals due to urban runoff, household discharges, and other sources. These metals can accumulate in aquatic ecosystems and pose risks to both human and environmental health. Adenanthera pavonina biomass can be integrated into municipal wastewater treatment plants as part of secondary or tertiary treatment processes. Its biosorption properties ensure the removal of residual heavy metals that escape primary treatment methods, ensuring compliance with environmental discharge standards. By incorporating this biosorbent into existing treatment systems, municipalities can enhance the overall quality of treated water and reduce the ecological impact of their wastewater discharge.

Environmental Remediation
The biosorption potential of Adenanthera pavonina extends beyond controlled industrial or municipal settings to environmental cleanup efforts. Natural water bodies, such as rivers, lakes, and groundwater systems, often suffer from heavy metal pollution due to industrial spills, agricultural runoff, and improper waste disposal. Adenanthera pavonina can be deployed in situ to absorb heavy metals from such contaminated water sources. Field applications, such as the

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installation of biosorption units in polluted rivers or the use of biosorbent filters in rural communities, have shown promising results in mitigating the impact of heavy metal contamination. Its biodegradable nature and minimal ecological footprint further enhance its suitability for environmental remediation projects.

Agricultural Applications

While the primary focus of Adenanthera pavonina biosorption research is on water treatment, the potential reuse of biomass after metal recovery offers additional applications in agriculture. Once the heavy metals are desorbed and recovered, the remaining organic material can serve as a soil conditioner, enriching soil fertility and promoting sustainable waste management. This dual-purpose approach not only addresses water pollution but also contributes to the circular economy by repurposing biosorbent waste into valuable agricultural inputs.

Integration with Advanced Technologies

The use of Adenanthera pavonina can be further enhanced through integration with advanced water treatment technologies. Hybrid systems combining biosorption with techniques such as membrane filtration, ion exchange, or nanotechnology can achieve higher efficiencies and broader applicability. For instance, immobilizing Adenanthera pavonina biomass onto polymeric or ceramic substrates can improve its mechanical stability and enable its use in continuous flow systems. Similarly, incorporating biosorbent materials into advanced adsorption columns or reactors can optimize their performance and scalability for industrial applications.

Field Case Studies

Experimental studies simulating real-world conditions have demonstrated the efficacy of Adenanthera pavonina biosorption systems. Pilot-scale experiments conducted in industrial settings, such as electroplating plants, have shown significant reductions in heavy metal concentrations, with removal rates often exceeding 85%. These studies provide a blueprint for scaling up biosorption technologies and integrating them into existing treatment frameworks. The versatility of Adenanthera pavonina allows it to adapt to diverse environmental and operational conditions, further solidifying its role as a practical solution for heavy metal remediation.

Economic and Social Benefits

In addition to its environmental advantages, the use of Adenanthera pavonina as a biosorbent presents significant economic and social benefits. Its low cost of preparation, combined with its high efficiency, makes it an attractive option for low-income communities and developing nations. By adopting this natural biosorbent, industries and municipalities can reduce their reliance on expensive and potentially hazardous chemical treatments. Furthermore, the promotion of eco-friendly water treatment practices aligns with global sustainability goals, fostering a culture of environmental stewardship and responsibility.

VII. CHALLENGES AND LIMITATIONS IN APPLICATION

Despite its numerous advantages, the application of Adenanthera pavonina biosorption systems is not without challenges. Scaling up from laboratory to industrial levels requires addressing issues such as biosorbent regeneration, stability under diverse conditions, and the disposal of used biomass. However, ongoing research and innovation continue to address these limitations, paving the way for broader adoption of this technology.

Challenges and Limitations of Biosorption by Adenanthera pavonina

While Adenanthera pavonina has shown significant promise as a biosorbent for the removal of heavy metals from aqueous solutions, its practical application on a larger scale is accompanied by several challenges and limitations. These challenges must be addressed to maximize its potential as an eco-friendly and sustainable water treatment solution.

One major challenge lies in scaling up the biosorption process from laboratory experiments to industrial or municipal wastewater treatment systems. Laboratory studies often yield promising results under controlled conditions, but replicating such efficiency in large-scale systems is complex. Factors such as maintaining consistent biosorption performance, handling varying wastewater compositions, and operating continuous treatment systems pose technical and operational difficulties. Additionally, scaling up requires significant engineering expertise, infrastructure development, and financial investment, which may hinder its feasibility.

Another critical limitation is the regeneration and reuse of Adenanthera pavonina biomass. For biosorption to be economically viable and environmentally sustainable, the biosorbent must be reusable over multiple cycles. However,

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the regeneration process often leads to reduced efficiency due to incomplete desorption, structural degradation, or fouling of the biomass. Developing effective regeneration techniques, such as chemical, thermal, or biological methods, remains an area requiring further research and innovation.

The disposal of used biomass is another pressing concern. Biomass laden with heavy metals can pose significant environmental risks if not disposed of properly. Improper disposal may lead to secondary pollution, undermining the environmental benefits of biosorption. Safe disposal or recycling methods, such as incineration or recovery of heavy metals from the spent biomass, need to be standardized to mitigate these risks effectively.

The biosorption efficiency of Adenanthera pavonina can also be highly variable, depending on factors such as the type and concentration of heavy metals, pH, temperature, contact time, and the presence of competing ions in the solution. This variability may limit its application in real-world scenarios, where wastewater compositions can vary widely. For instance, wastewater generated by different industries or geographic locations may require customized treatment protocols to achieve optimal biosorption results.

Furthermore, the durability and stability of Adenanthera pavonina biomass under varying environmental conditions is a concern. Prolonged exposure to wastewater, high temperatures, or extreme pH levels can compromise the structural integrity of the biosorbent. Enhancing its mechanical and chemical stability, perhaps through immobilization or surface modifications, could improve performance. However, these processes can also increase the complexity and cost of biosorption.

The adoption of biosorption as a mainstream water treatment solution also faces competition from well-established conventional methods, such as chemical precipitation, ion exchange, and membrane filtration. These technologies are widely used in industrial and municipal settings and often offer faster and more reliable results. While biosorption has distinct advantages, such as being cost-effective and environmentally friendly, convincing industries to switch to biosorption requires robust evidence of its economic and environmental benefits and solutions to existing technical challenges.

Economic viability is another significant limitation. While the use of Adenanthera pavonina biomass is cost-effective compared to synthetic adsorbents, the costs associated with biomass collection, preparation, and pre-treatment, along with the challenges of regeneration and disposal, can make large-scale applications financially challenging. Competing with cheaper and readily available synthetic adsorbents further complicates its widespread adoption.

A lack of standardization in biosorption studies and applications also poses a challenge. Research methodologies, experimental conditions, and analytical techniques vary widely across studies, making it difficult to establish universal protocols. This lack of consistency can hinder the reproducibility and scalability of biosorption processes, limiting their practical application in real-world settings.

Research gaps in understanding the long-term stability of biosorption systems, the impact of complex wastewater matrices, and the integration of biosorption with other treatment technologies also remain significant challenges. More comprehensive studies are needed to evaluate the lifecycle environmental and economic impacts of biosorption systems.

Lastly, environmental and regulatory challenges can influence the adoption of biosorption technologies. In some regions, stringent regulations on biomass disposal or the lack of clear guidelines for biosorption processes create uncertainty for industries considering this technology. Collaboration between researchers, policymakers, and industries is essential to establish supportive policies and standardized protocols for biosorption technologies.

VIII. CONCLUSION

The study of the biosorption potential of Adenanthera pavonina (Red Sandalwood) for the removal of heavy metals from aqueous solutions demonstrates its significant promise as an eco-friendly and cost-effective solution for addressing water pollution. The findings highlight the biosorption efficiency of this natural biomass in removing toxic metals such as lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni) under various experimental conditions. The adaptability of Adenanthera pavonina to diverse environmental parameters like pH, temperature, and contact time underscores its potential for real-world applications.

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The application of isotherm and kinetic models such as Langmuir, Freundlich, and pseudo-second-order kinetics provides a robust scientific basis for understanding the adsorption process. These models confirm the ability of Adenanthera pavonina to achieve high adsorption capacities under optimal conditions, thus making it a viable biosorbent. Furthermore, the comparison of its performance with other biosorbents reveals its competitive efficiency, reinforcing its suitability for industrial and municipal wastewater treatment.

Despite its many advantages, the challenges associated with scaling up, biomass regeneration, variability in biosorption efficiency, and the safe disposal of metal-laden biomass must be addressed to ensure its successful adoption. The integration of biosorption with conventional water treatment technologies and the development of innovative biomass modification and regeneration techniques will be critical in overcoming these challenges.

Additionally, the economic viability of Adenanthera pavonina as a biosorbent must be established through detailed cost-benefit analyses and lifecycle assessments. These evaluations will demonstrate its feasibility as an alternative to synthetic adsorbents and conventional treatment methods.

Looking ahead, biosorption by Adenanthera pavonina offers immense potential for mitigating heavy metal pollution in water systems, particularly in regions where traditional methods are either unaffordable or environmentally unsustainable. Collaborative efforts between researchers, industries, and policymakers are essential to further explore the potential of Adenanthera pavonina and to promote its adoption in addressing global water pollution challenges. With continued innovation and support, biosorption can emerge as a cornerstone of sustainable environmental management practices.

This conclusion reaffirms the pivotal role that Adenanthera pavonina can play in creating greener, safer, and more sustainable solutions for heavy metal contamination, paving the way for a cleaner and healthier environment.

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