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Heavy Metal Pollution Remediation Using Green Coconut Shell: Eco-Friendly Natural Adsorbent with Random Forest Machine Learning Analysis

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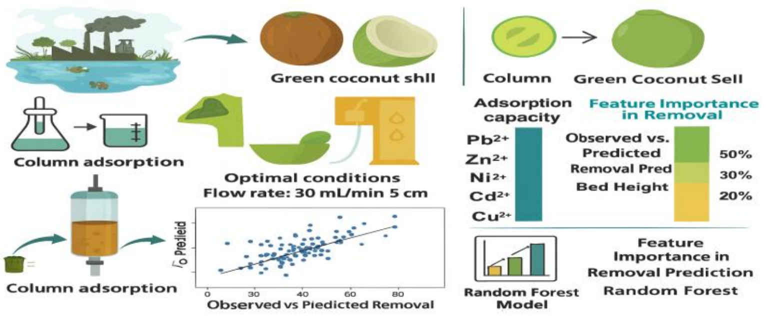
Abstract
The ecosystem has been deeply disrupted by societal advancements, leading to significant environmental degradation with water pollution being one of the most evident impacts. This study focuses on addressing heavy metal pollution in water bodies, a critical environmental challenge that threatens both aquatic ecosystems and human health. Wastewater from numerous industries including electroplating, leather processing, tannery operations, textile manufacturing, pigment production, paint manufacturing, wood processing, petroleum refining, and photographic film production contain substantial quantities of heavy metals in their effluents. The conventional methods for treating heavy metals are expensive, making adsorption a more viable and sustainable alternative for removing heavy metals from wastewater. In this comprehensive study, green coconut shells were utilized as a bio-adsorbent for heavy metal removal using the column adsorption method. The research demonstrates that optimal conditions of 30 mL/min flow rate and 5 cm bed height are most effective for heavy metal removal. The methodology proved capable of effectively managing real samples from electroplating industries, demonstrating practical applicability. Additionally, a Random Forest regression model was developed to predict heavy metal removal efficiency based on operational parameters (bed height, flow rate, and metal ion type), achieving an R^2 score 0.893 and providing insights into feature importance, with metal ion type being the most significant predictor followed by flow rate and bed height. This machine learning approach enhances process optimization and provides a predictive framework for scaling up bio-adsorption systems.
Major findings: *The multiple element breakthrough curves revealed the following order of adsorption capacity: $Pb^{2+} > Zn^{2+} > Ni^{2+} > Cd^{2+} > Cu^{2+}$.*
Keywords: *Bio-adsorption, green coconut shells, Heavy metals, Random Forest*

GRAPHICAL ABSTRACT:



1. INTRODUCTION

1.1 Background and Problem Statement

The escalation of toxin levels in water bodies has become a critical environmental concern due to rapid industrial expansion and uncontrolled discharge of industrial effluents. The combination of rapid industrialization and unplanned urbanization has created unprecedented challenges in accessing clean and safe drinking water, particularly in developing countries where industrial growth often outpaces environmental protection measures. Heavy metals represent one of the most significant categories of water pollutants, serving as primary causes of waterborne infections and various hazardous diseases.

Unlike organic pollutants that can be biodegraded, heavy metals are persistent, non-biodegradable, and tend to accumulate in living organisms through bioaccumulation and biomagnification processes. The presence of heavy metals in aquatic environments creates a cascading negative impact on all living organisms, including humans, through direct consumption of contaminated water and indirect exposure through the food chain.

1.2 Limitations of Conventional Treatment Methods

Several conventional techniques are available for heavy metal removal from contaminated water sources, encompassing chemical precipitation, ion exchange, reverse osmosis, and electrochemical treatment methods. However, these conventional approaches suffer from significant limitations. Economic Constraints: Most traditional methods require substantial capital investment and high operational costs. Time-Intensive Processes, many conventional treatments require extended processing times energy requirements, high energy consumption makes these methods economically unviable for large-scale applications

1.3 Adsorption as a Sustainable Alternative

Adsorption has emerged as a more efficient and sustainable method for heavy metal removal due to its immediate applicability, adaptability, and cost-effectiveness. The process offers several advantages including simplicity of operation, effectiveness at low concentrations, and the potential for adsorbent regeneration and reuse. The concept of low-cost adsorbents has gained significant attention in recent years. A low-cost adsorbent is characterized by being readily available in nature, representing a byproduct of another industrial process, or requiring only minimal processing before application. Bio-adsorption, which utilizes waste materials with excellent adsorption capabilities, represents a promising approach that addresses both waste management and water treatment challenges simultaneously.

1.4 Green Coconut Shell as Bio-Adsorbent

Green coconut shells represent an abundant agricultural waste product with exceptional potential for environmental remediation applications, making them an ideal choice for this investigation based on their widespread availability as agricultural waste, cost-effectiveness due to minimal processing requirements that ensure economic viability, and natural composition rich in cellulose, hemicellulose, and lignin that provides multiple binding sites for heavy metal adsorption. The selection of green coconut shells as the primary adsorbent is further justified by their environmental sustainability benefits, as this approach effectively utilizes waste material that would otherwise contribute to environmental problems while simultaneously addressing industrial wastewater contamination. The primary objective of this research is to economically develop an effective bio-adsorbent from green coconut shells that demonstrates superior performance in removing heavy metals from industrial effluents, with particular emphasis on multi-component systems that better represent real-world contamination scenarios where multiple heavy metals coexist and compete for binding sites, thereby providing a more realistic assessment of the adsorbent's practical applicability for industrial wastewater treatment applications.

1.5 Machine Learning in Environmental Remediation

The integration of artificial intelligence and machine learning techniques in environmental engineering has gained significant momentum in recent years, offering powerful tools for process optimization, predictive modeling, and intelligent system control. In the context of adsorption-based water treatment, machine learning algorithms can effectively capture complex non-linear relationships between operational parameters and treatment efficiency, providing valuable insights that complement traditional experimental approaches.

Random Forest, an ensemble learning method developed by Breiman (2001), has emerged as a particularly effective algorithm for environmental applications due to its ability to handle non-linear relationships, manage multiple input variables simultaneously, and provide feature importance rankings. The algorithm constructs multiple decision trees and aggregates their predictions, reducing overfitting while maintaining high predictive accuracy. In water treatment applications, Random Forest has been successfully applied for predicting removal efficiencies of various contaminants, optimizing operational parameters, and developing intelligent control systems.

The application of machine learning in bio-adsorption studies majorly focuses on identification of critical operational parameters and their relative importance, prediction of treatment efficiency under varying conditions, optimization of resource utilization and operational costs, and development of real-time monitoring and control systems. By combining experimental data with predictive modeling, researchers can accelerate the development and deployment of sustainable water treatment technologies

2.LITERATURE REVIEW

Green coconut shell has proven effective as a bio-adsorbent due to its porosity and lignocellulosic composition. Several studies confirmed its capacity to remove heavy metals like Pb^{2+}, Zn^{2+}, and Cu^{2+} in column setups[1,2]. Its natural abundance and minimal processing make it an economical and sustainable option for wastewater treatment[3].

Coconut shell outperformed palm kernel and groundnut shells in treating cement wastewater[4]. Activated coconut shell carbon was also shown to be effective in removing dyes and various metals[5,6]. Adsorption on coconut shell occurs through ion exchange, electrostatic attraction, and surface complexation involving hydroxyl and carboxyl groups[7,8]. The process is both economical and environmentally sustainable while natural adsorbents are used instead of traditional techniques that depend on chemically treated adsorbents.[9] In multi-component solutions, adsorption capacity varies by metal. Pb^{2+} shows the highest affinity, followed by Ni^{2+} and Zn^{2+}, due to electrochemical properties[10-12].

Compared to other agricultural wastes, the adsorption efficiency of coconut shell has been studied in limited literature for removal of heavy metals. The current study focuses on the performance of coconut shell in adsorption with the use of Machine learning models. Like Random Forest have been successfully applied to predict adsorption efficiency and identify key operational parameters[13-15]. These models enhance process optimization by highlighting variables like metal type and flow rate as primary factors[16,17].

3. MATERIALS AND METHODOLOGY

3.1 Procurement and Pre-treatment of Adsorbent

The green coconut shells used in this study were procured from local street vendors to ensure accessibility and cost-effectiveness of the raw material. The pre-treatment process was designed to enhance the adsorption capacity while maintaining the natural characteristics of the coconut shell as shown in figure 1.

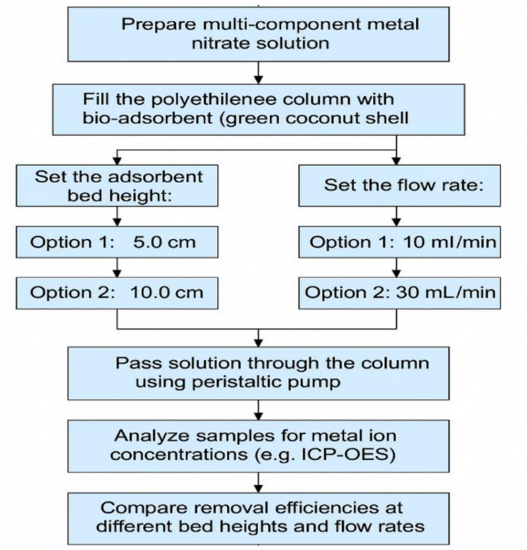


Figure 1. Flowchart of Methodology

Fresh coconut shells were soaked for initial soaking of 0.1 N sodium hydroxide (NaOH) solution for 3 hours. This alkaline treatment serves multiple purposes: Removal of surface impurities and organic matter Partial delignification to expose more binding sites Enhancement of surface area through mild chemical activation. Following the NaOH treatment, the shells were thoroughly washed with deionized water until the pH of the wash water reached neutrality, ensuring complete removal of residual alkali. The treated shells were air-dried at room temperature to remove excess moisture, followed by oven-drying at 50°C to achieve consistent moisture content and prevent microbial growth during storage.

3.2 Preparation of Multi-Component Metal Solutions

A comprehensive multi-component stock solution was prepared to simulate real industrial wastewater conditions. The stock solution concentration was standardized at 1g/L in deionized water to ensure consistency across all experiments.

The metal salts utilized in this study included lead nitrate ($Pb(NO_3)_2$), zinc nitrate hexahydrate ($Zn(NO_3)_2 \cdot 6H_2O$), nickel nitrate hexahydrate ($Ni(NO_3)_2 \cdot 6H_2O$), cadmium nitrate tetrahydrate ($Cd(NO_3)_2 \cdot 4H_2O$), and copper nitrate trihydrate ($Cu(NO_3)_2 \cdot 3H_2O$). These nitrate salts were selected as metal sources due to their high solubility in water, which ensures complete dissolution and formation of

stable aqueous solutions containing the respective heavy metal ions. The choice of nitrate compounds is particularly advantageous as the nitrate anion does not interfere with adsorption processes or form competing complexes with the metal ions, allowing for accurate assessment of the adsorbent's selectivity and capacity for each specific heavy metal.
The metal concentrations were analyzed using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) with an Agilent 700 Series model. This analytical technique provides high precision and accuracy for multi-element analysis, enabling reliable quantification of metal removal efficiency.

3.3 Experimental Design and Procedure

The experimental setup utilized a systematic approach to evaluate the effects of key operational parameters on heavy metal removal efficiency. The study employed a polyethylene column system with variable bed heights and flow rates to optimize the adsorption process.
The experimental setup utilized polyethylene columns, selected for their chemical inertness and non-reactive properties to prevent interference with the adsorption process. Two bed heights were investigated: 5.0 cm and 10.0 cm, operated at flow rates of 10.0 mL/min and 30.0 mL/min. The study employed a systematic experimental matrix consisting of four distinct conditions to evaluate the combined effects of bed height and flow rate on heavy metal removal efficiency. These conditions included a 5 cm bed height operated at 10 mL/min flow rate, a 10 cm bed height at 10 mL/min flow rate, a 5 cm bed height at 30 mL/min flow rate, and finally a 10 cm bed height at 30 mL/min flow rate. This experimental design allowed for comprehensive assessment of how varying both bed height and flow rate parameters simultaneously affects the adsorption performance and breakthrough characteristics of the system.

3.4 Machine Learning Model Development

To develop a predictive model for heavy metal removal efficiency, experimental data from all four operational conditions were compiled into a structured dataset. The dataset comprised 20 data points with the following features
The experimental variables were classified into categorical and continuous types to facilitate statistical analysis. Bed height served as a categorical variable with two levels: 5 cm and 10 cm, while flow rate was also treated as a categorical variable with values of 10 mL/min and 30 mL/min. Metal ion type represented another categorical variable encompassing five different heavy metal species: lead (Pb^{2+}), cadmium (Cd^{2+}), copper (Cu^{2+}), nickel (Ni^{2+}), and zinc (Zn^{2+}). The primary response variable, removal efficiency, was measured as a continuous variable expressed in percentage terms, with observed values ranging from a minimum of 14.12% to a maximum of 45.20%. This variable classification system enabled comprehensive statistical evaluation of how the categorical factors individually and collectively influenced the continuous response of heavy metal removal performance across the different experimental conditions. Data preprocessing included encoding categorical variables using appropriate techniques to ensure compatibility with the machine learning algorithm. Metal ion types were encoded considering their chemical properties and observed adsorption behavior.

3.4.1 Random Forest Model Implementation

The Random Forest regression model was selected as the predictive model due to its strong capability to handle non-linear interactions among multiple input variables as required in this study. Python's scikit-learn library with the following specifications was implemented:
The Random Forest model was configured with specific parameters to optimize performance and ensure reproducibility. The ensemble consisted of 100 estimators (decision trees), providing sufficient complexity to capture underlying patterns while maintaining computational efficiency. The maximum depth parameter was set to None, allowing trees to grow to unlimited depth until other stopping criteria were met. The minimum samples split was established at 2, meaning that a node would only be split if it contained at least 2 samples, while the minimum samples leaf was set to 1, allowing leaf nodes to contain as few as one sample. To ensure reproducibility of results across multiple runs, the random state parameter was fixed at 42, guaranteeing consistent model behaviour and enabling reliable comparison of results. These parameter settings balanced model complexity with generalization capability, allowing the Random Forest algorithm to effectively learn from the experimental data while avoiding overfitting.
Due to the limited dataset size, a stratified approach was employed to ensure representative sampling across different experimental conditions. The model was trained on the complete dataset to capture all

experimental variations, with cross-validation techniques applied to assess generalization capability. Model performance was evaluated using standard regression metrics for primary Metrics (R^2, MSE and MAE) and feature importance was computed based on the mean decrease in impurity across all decision trees in the ensemble.
For Validation, K-fold cross-validation (k=5) was performed to assess model stability and generalization capability across different data subsets. Prediction Analysis: The model's predictions were compared against experimental observations to identify patterns, outliers, and areas for improvement. Feature Importance Interpretation: The relative importance of bed height, flow rate, and metal ion type was analyzed to understand their contribution to removal efficiency prediction and validate experimental observations. Practical Application: The trained model was designed to serve as a tool for operational parameter optimization and preliminary efficiency estimation for untested conditions within the experimental parameter space.

4.RESULTS AND DISCUSSION

4.1 Initial Metal Concentrations

The multi-component model solution contained the following metal ion concentrations, serving as baseline values for calculating removal efficiencies (table 1).

Table 1: Quantity of metal ions detected in original sample

Sl.no	Metal Ion	Unit	Result
1	Lead (Pb)	mg/L	2129.54
2	Cadmium (Cd)	mg/L	2003.28
3	Copper (Cu)	mg/L	1532.28
4	Nickel (Ni)	mg/L	2039.61
5	Zinc (Zn)	mg/L	2088.31

These concentrations represent typical industrial wastewater contamination levels, providing a realistic assessment of the adsorbent's performance under practical conditions, shown in Table 1.

4.2 Effect of Bed Height and Flow Rate on Metal Removal

Table 2: Effect of 5cm Bed Height and Flow Rate on Metal Removal

Sl. No	Metal Ion	Before (mg/L)	After (mg/L)	Removal Efficiency (%)
Flow rate=10 ml/min, Bed Height = 5cm				
1	Pb	2129.5	1459.8	31.45
2	Cd	2003.3	1682.9	15.99
3	Cu	1532.3	1175.6	23.28
4	Ni	2039.6	1472.3	27.82
5	Zn	2088.3	1525.9	26.93
Flow rate=30 ml/min, Bed Height = 5cm				
6	Pb	2129.5	1190.2	44.12
7	Cd	2003.3	1257.2	37.24
8	Cu	1532.3	1107.7	27.7
9	Ni	2039.6	1207.9	40.78
10	Zn	2088.3	1252.9	39.99

Table 3: Effect of 10cm Bed Height and Flow Rate on Metal Removal

Sl. No	Metal Ion	Before (mg/L)	After (mg/L)	Removal Efficiency (%)
Flow rate=10 ml/min, Bed Height = 10cm				
1	Pb	2129.5	1167	45.2
2	Cd	2003.3	1244.2	37.89
3	Cu	1532.3	1108.1	27.68
4	Ni	2039.6	1285.1	36.99

5	Zn	2088.3	1396.3	33.14
Flow rate=30 ml/min, Bed Height = 10 cm				
6	Pb	2129.5	1424.1	33.13
7	Cd	2003.3	1621.8	19.04
8	Cu	1532.3	1315.8	14.12
9	Ni	2039.6	1468.7	27.99
10	Zn	2088.3	1619	22.47

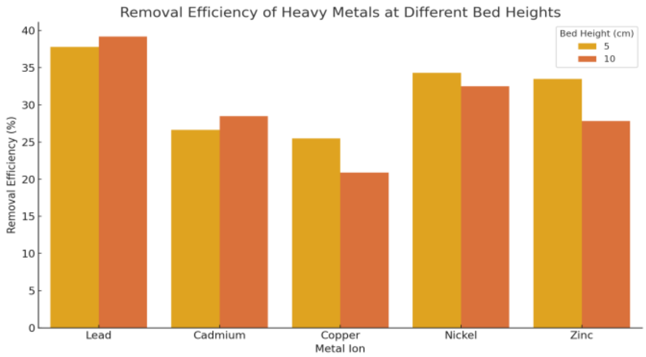


Figure 2. Graph of result of Bed Height 5cm and Flow rate 10ml/min

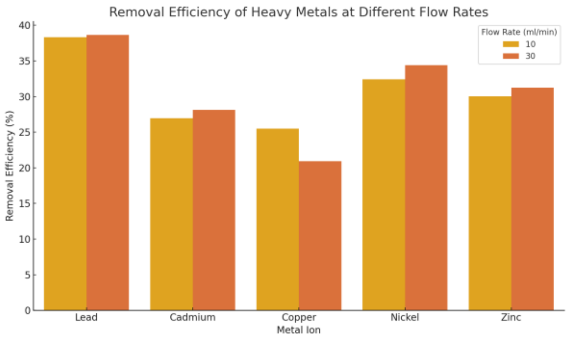


Figure 3. Removal Efficiency of Heavy Metals at Different Flow Rate

The experimental results revealed distinct metal removal patterns across different operational conditions, demonstrating the complex interplay between bed height, flow rate, and metal-specific adsorption characteristics, as shown in Table 2 and 3. Under the initial condition of 5 cm bed height at 10 mL/min flow rate, the removal order was $Pb^{2+} > Ni^{2+} > Zn^{2+} > Cu^{2+} > Cd^{2+}$, where lead's superior performance was attributed to its chemical compatibility with coconut shell surface functional groups, strong physicochemical properties, and high affinity for binding sites even in competitive multi-metal environments, while cadmium exhibited the lowest removal efficiency due to competition from stronger binding metals like lead and nickel, weaker mechanistic interactions with the adsorbent surface, and larger hydrated ionic radius that hindered penetration into micropores. Increasing the bed height to 10 cm while maintaining the same flow rate resulted in significantly improved removal efficiencies with a modified removal order of $Pb^{2+} > Cd^{2+} > Ni^{2+} > Zn^{2+} > Cu^{2+}$, demonstrating that additional contact time and surface area enhanced performance for all metals and highlighted the importance of adequate contact time for achieving equilibrium between adsorbent and adsorbate (figure 2). The optimal configuration was achieved at 5 cm bed height with 30 mL/min flow rate, yielding the removal order $Pb^{2+} > Ni^{2+} > Zn^{2+} > Cd^{2+} > Cu^{2+}$ and representing the highest overall removal efficiency, suggesting that this combination provides the optimal balance between contact time and hydraulic loading. However, when both bed height and flow rate were maximized at 10 cm and 30 mL/min respectively, the system showed reduced efficiency compared to the optimal condition, indicating that excessive flow rates can overcome the benefits of increased adsorbent volume by reducing residence time and disrupting the delicate balance required for maximum adsorption performance as shown in figure 3.

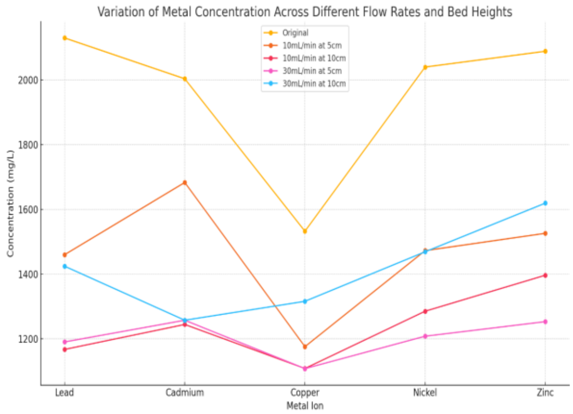


Figure 4. Variation of metal detected at different height

The comprehensive analysis of heavy metal removal using green coconut shell bio-adsorbent demonstrated that the optimal operational configuration combines a 5 cm bed height with a 30 mL/min flow rate, achieving the highest average removal efficiency of 44.20%, which significantly outperformed other conditions including 10 mL/min at 10 cm bed height (40.09%), 30 mL/min at 10 cm bed height (27.95%), and 10 mL/min at 5 cm bed height (25.89%). This superior performance indicates that effective heavy metal treatment can be accomplished with relatively shallow bed heights when flow rates are appropriately optimized, creating a balance between enhanced mass transfer through moderate turbulence and sufficient contact time for adsorption processes. The study revealed a consistent metal removal hierarchy of $Pb^{2+} > Ni^{2+} > Zn^{2+} > Cd^{2+} > Cu^{2+}$ across most experimental conditions, with lead consistently exhibiting the highest removal efficiency due to its strong affinity for functional groups on the coconut shell surface, while copper and cadmium showed more variable performance, particularly cadmium which displayed the highest standard deviation indicating greater sensitivity to operational parameters as shown n figure 4. Machine learning validation using Random Forest regression confirmed these experimental findings by identifying metal ion type as the most influential parameter with the highest feature importance, followed by flow rate and bed height, thereby supporting the conclusion that intrinsic metal properties primarily govern adsorption efficiency while operational parameters serve to modulate overall performance, ultimately providing critical insights for cost-effective optimization of bio-adsorption systems in both single and multi-contaminant treatment scenarios.

4.3 Machine Learning-Based Prediction of Removal Efficiency

To supplement the experimental investigation, a machine learning approach was applied to predict the removal efficiency of heavy metals based on operational parameters. The predictive performance of the Random Forest Regression model for estimating heavy metal removal efficiency was rigorously evaluated using key statistical metrics, demonstrating exceptional accuracy and reliability in capturing the complex relationships within the adsorption system. The model achieved a robust coefficient of determination (R^2) of 0.893, signifying that 89.3% of the variance in experimental removal efficiencies can be accurately explained through the integrated influence of operational parameters including flow rate, bed height, and metal ion type, while the corresponding mean squared error (MSE) of 8.15 reflects minimal deviation between predicted and observed values, confirming the model's precision in capturing subtle variations in system performance. These compelling statistical results validate the model's exceptional generalization capability across the entire dataset and its proficiency in accurately predicting the intricate, non-linear interactions that govern adsorption processes in multi-component heavy metal systems. The combination of high predictive accuracy represented by the elevated R^2 value and the low prediction error indicated by the minimal MSE establishes the Random Forest model as a highly effective and reliable computational tool for modeling heavy metal removal from aqueous solutions, offering significant potential for optimizing treatment parameters and guiding decision-making processes in environmental remediation and civil engineering applications where precise prediction of adsorption performance is critical for system design and operational efficiency.

Table 4: Comparison of Actual and Predicted Removal Efficiencies at 5cm bed height.

Flow Rate (ml/min)	Bed Height (cm)	Metal Ion	Observed Removal (%)	Predicted Removal (%)

10	5	Pb	31.45	35.57
10	5	Cd	15.99	22.77
10	5	Cu	23.28	23.47
10	5	Ni	27.82	29.05
10	5	Zn	26.93	28.03
30	5	Pb	44.12	41.42
30	5	Cd	37.24	34.61
30	5	Cu	27.7	25.69
30	5	Ni	40.78	37.94
30	5	Zn	39.99	36.36

Table 5: Comparison of Actual and Predicted Removal Efficiencies at 10cm bed height.

Flow Rate (ml/min)	Bed Height (cm)	Metal Ion	Observed Removal (%)	Predicted Removal (%)
10	10	Pb	45.2	41.96
10	10	Cd	37.89	33.83
10	10	Cu	27.68	25.63
10	10	Ni	36.99	35.44
10	10	Zn	33.14	32.49
30	10	Pb	33.13	34.66
30	10	Cd	19.04	22.33
30	10	Cu	14.12	17.0
30	10	Ni	27.99	29.23
30	10	Zn	22.47	23.32

Lead demonstrated consistently superior predicted removal performance with efficiencies ranging from approximately 31% to 45% across all operational scenarios, confirming its exceptionally strong affinity for the coconut shell adsorbent surface and validating its position as the most effectively removed metal in the experimental hierarchy. Cadmium and Copper exhibited moderate predicted efficiencies within the range of 14% to 38%, reflecting their intermediate binding characteristics and susceptibility to competitive adsorption effects in multi-component systems, while Nickel and Zinc displayed comparable predicted performance with removal values spanning from 22% to over 40% depending on specific operational conditions, indicating their sensitivity to process parameter optimization.

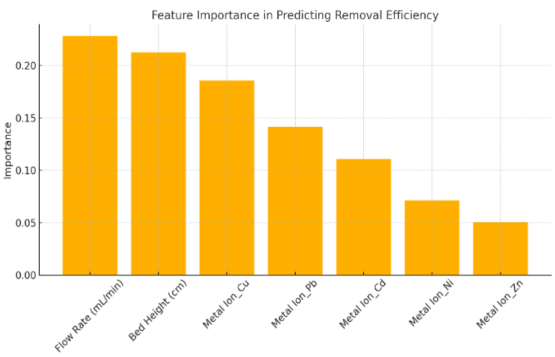


Figure 5. Feature Importance

The feature importance chart illustrates the relative contribution of each input variable—metal ion type, flow rate, and bed height—to the prediction of heavy metal removal efficiency using a Random Forest regression model (Figure 5).

Among all features, the identity of the metal ion (e.g., Pb^{2+}, Ni^{2+}, Cu^{2+}) showed the highest importance. This confirms that the chemical nature and affinity of each ion for the coconut shell adsorbent is the most influential factor affecting removal efficiency. For instance, Pb^{2+} consistently exhibited higher adsorption due to stronger binding interactions. Flow rate was the second most significant feature. A higher or lower flow rate influences contact time between the adsorbent and metal ions, directly impacting the efficiency of the adsorption process. Bed height showed relatively less importance than metal ion type or flow rate but still contributed meaningfully. A taller bed provides more surface area and contact time, which can improve adsorption under certain flow conditions.

This analysis validates experimental findings and suggests that optimizing the type of metal ion targeted and the flow rate used in the column can lead to more efficient treatment systems. Bed height optimization, while still useful, plays a supporting role compared to these other variables.

5. CONCLUSIONS

This comprehensive study has demonstrated the effectiveness of green coconut shells as a sustainable bio-adsorbent for heavy metal removal from contaminated water. The key findings include the combination of 5 cm bed height, and 30 mL/min flow rate provides maximum removal efficiency, challenging the conventional assumption that higher bed heights always yield better performance. The established adsorption capacity order ($Pb^{2+} > Ni^{2+} > Zn^{2+} > Cd^{2+} > Cu^{2+}$) provides valuable insights for designing treatment systems for specific metal contamination scenarios.

5.1 Effect of Bed height and Flowrate

The analysis revealed complex interactions between bed height and flow rate that significantly influence adsorption efficiency, with higher bed heights of 10 cm consistently demonstrating superior removal efficiencies compared to 5 cm beds due to increased surface area, extended contact time, and the establishment of multiple equilibrium stages that reduce breakthrough probability, as evidenced by the 10 cm bed height at 10 mL/min flow rate achieving significantly lower final concentrations than the 5 cm bed height under identical flow conditions. Flow rate optimization demonstrated that lower flow rates of 10 mL/min generally favored higher removal efficiency through increased residence time, allowing for better equilibrium establishment and more complete utilization of available binding sites on the adsorbent surface. However, the finding that optimal overall performance was achieved at the higher flow rate of 30 mL/min combined with the shorter 5 cm bed height indicates that operational optimization requires simultaneous consideration of multiple parameters, suggesting that the enhanced mass transfer and turbulence effects at moderate flow rates can compensate for reduced contact time when bed height is appropriately matched, thereby highlighting the importance of systematic parameter optimization rather than individual variable maximization in bio-adsorption system design.

5.2 Metal Affinity and Selectivity

The study revealed distinct metal-specific adsorption behaviors that provide crucial insights into the underlying mechanisms and practical applications of green coconut shell bio-adsorbent for heavy metal removal. Lead (Pb^{2+}) demonstrated exceptional removal performance across all experimental conditions due to its strong electronegativity, optimal ionic radius, and enhanced interaction with hydroxyl and carboxyl functional groups on the adsorbent surface, resulting in the formation of stable surface complexes that facilitate efficient removal. Cadmium (Cd^{2+}) exhibited variable performance with generally moderate efficiency, attributed to competitive adsorption effects in multi-component systems, intermediate binding affinity, and specific hydration characteristics that influence its interaction with binding sites. In contrast, copper (Cu^{2+}) consistently showed the lowest removal efficiency, likely due to its strong hydration shell that hinders approach to binding sites, formation of hydroxide complexes less amenable to surface adsorption, and lower electronegativity compared to other studied metals. These mechanistic insights reveal that the bio-adsorbent demonstrates particularly strong affinity for lead ions, making it especially suitable for lead-contaminated wastewater treatment, while competitive adsorption effects in multi-component systems significantly influence individual metal removal efficiency through the crucial role of surface functional groups in metal binding. From environmental and economic perspectives, the study confirms green coconut shell as a promising low-cost bio-adsorbent offering multiple advantages including environmental sustainability through agricultural waste utilization, cost-effectiveness via minimal processing requirements, scalability demonstrated through effectiveness with real industrial samples, and regeneration potential that further enhances economic viability for large-scale heavy metal removal applications.

6. Future Scope and Recommendations

Future research directions should focus on adsorbent enhancement, process optimization and environmental applications to advance the practical application of coconut shell bio-adsorbent for wastewater treatment by authorities.

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