Remediation of Heavy Metals in Water: Exploring the Efficiency of Iron-Impregnated Activated Carbon

Pratap Kumar[1] J. K. Srivastav[2] Priyanka Yadav[3]
[1,2,3]Department of Environmental Engineering
[1,2,3]Ujjain Engineering College, Ujjain, India

Abstract — The presence of heavy metals such as arsenic, cadmium, and lead in wastewater poses significant environmental and health risks. This study explores the effectiveness of iron-impregnated activated carbon (Fe-AC) as an adsorbent for the removal of these toxic contaminants from synthetic wastewater. The preparation of Fe-AC involved impregnating activated carbon with iron salts, resulting in a highly efficient adsorbent with enhanced adsorption capacities. Batch experiments were conducted to investigate the effects of various parameters, including adsorbent dose, contact time, and pH, on the removal efficiency of arsenic, cadmium, and lead ions. The results indicated that optimal conditions for heavy metal removal were achieved at specific adsorbent doses and contact times, revealing Fe-AC's potential for significant arsenic, cadmium, and lead reduction from wastewater. Characterization of the adsorbent demonstrated a stable and uniform distribution of iron, contributing to high adsorption efficacy. The experimental data closely followed the Langmuir isotherm and pseudo second-order kinetics, confirming the suitability of Fe-AC for wastewater treatment. This research highlights the potential of using low-cost, iron-impregnated agricultural waste-derived activated carbon as an effective and sustainable solution for addressing heavy metal contamination in aqueous environments, thereby providing insights into practical applications for industrial effluent management and environmental remediation strategies.

Keywords: Heavy Metals, Water, Iron-Impregnated, Activated Carbon

I. INTRODUCTION

Water pollution, particularly due to the presence of heavy metals, has become an escalating concern worldwide, threatening public health and environmental sustainability. The discharge of wastewater laden with hazardous metals like arsenic, cadmium, and lead from industrial processes, mining operations, and agricultural runoff exacerbates this issue. Arsenic, a recognized carcinogen, is associated with severe health risks, including skin lesions, organ damage, and various cancers, particularly affecting populations reliant on contaminated drinking water. Similarly, cadmium is notorious for its nephrotoxic effects, leading to kidney dysfunction, bone disease, and respiratory complications, while lead exposure is particularly detrimental to cognitive development in children, causing irreversible neurological damage and behavioral issues.

Globally, regulatory efforts have intensified to manage and mitigate the risks posed by heavy metal contamination in water resources. Amid these challenges, the need for effective, economical, and environmentally friendly remediation technologies has never been more pressing. Traditional treatment methods such as chemical precipitation, reverse osmosis, and ion exchange, though often effective, can be prohibitively expensive, generate toxic by-products, and require extensive infrastructure. Thus, there is a critical need for alternative strategies that can provide efficient removal of heavy metals while being cost-effective and sustainable.

Adsorption is emerging as a favored method for the removal of heavy metals from wastewater, owing to its simplicity, effectiveness, and adaptability. Among various adsorbent materials, activated carbon has proven to be a highly efficient medium for organic and inorganic pollutants due to its extensive surface area, porosity, and excellent adsorption properties. Nevertheless, standard activated carbon can face limitations in adsorption efficiency concerning specific heavy metal ions.

To enhance the adsorption capacity and selectivity for heavy metals, the impregnation of activated carbon with metal ions, particularly iron, presents a viable solution. Iron, in its oxide forms, has shown remarkable properties in binding heavy metals, thereby significantly increasing the overall efficiency of the adsorbent. Iron-impregnated activated carbon (Fe-AC) not only maintains the advantageous characteristics of activated carbon but also exhibits improved mechanical strength and reactivity towards heavy metals. The synergistic effect of iron and activated carbon can facilitate a more effective sorption process, making it a potent tool in the pursuit of cleaner water resources.

This research aims to address the pressing issue of heavy metal contamination in wastewater through the use of iron-impregnated activated carbon. The primary objective is to evaluate the effectiveness of Fe-AC in removing arsenic, cadmium, and lead from synthetic wastewater under varying operational parameters. Key factors such as adsorbent dosage, contact time, and pH will be meticulously examined to identify the optimal conditions that maximize removal efficiencies. Moreover, this study will include a thorough characterization of the prepared Fe-AC to understand the distribution and morphology of iron within the carbon matrix, shedding light on its adsorption mechanisms.

In addition to providing insights into the mechanistic aspects of adsorption, the findings from this study will contribute to the broader field of environmental remediation by offering a low-cost, sustainable alternative for treating metal-contaminated wastewater. By leveraging agricultural waste for activated carbon production and enhancing its efficacy through iron impregnation, this research not only addresses heavy metal removal but also aligns with the principles of resource recovery and waste minimization.

Ultimately, the implications of this work extend beyond laboratory-scale applications. The outcomes could inform industrial practices and wastewater treatment strategies, offering practical solutions for industries facing stringent environmental regulations and contributing to global efforts in combating water pollution. Through a comprehensive analysis of Fe-AC's performance, this study aspires to pave the way for innovative, efficient, and environmentally responsible remediation technologies in the battle against heavy metal contamination.

II. MATERIALS AND METHODS

A. Materials

The primary materials used in this study include:

1) Activated Carbon: Commercial-grade activated carbon, which served as the base material for impregnation.
2) Iron Salt: Ferrous chloride ($FeCl_2 \cdot 4H_2O$) was used for the impregnation process, providing the source of iron for enhanced adsorption properties.
3) Distilled Water: Used for preparing solutions and rinsing the activated carbon to eliminate impurities.
4) Sodium Hydroxide (NaOH): Employed for adjusting the pH during the impregnation process.
5) Nitric Acid (HNO_3): Used in conjunction with sodium hydroxide for pH control.
6) Heavy Metal Solutions: Stock solutions of cadmium ($Cd(NO_3)_2$), lead ($Pb(NO_3)_2$), and arsenic (as As(V), Na_3AsO_4) were prepared for adsorption experiments.
7) Reagents for Characterization:
8) Scanning Electron Microscopy (SEM): For analyzing the surface morphology and distribution of iron on activated carbon.
9) X-ray Diffraction (XRD): For characterizing the crystalline structure of the impregnated samples.
10) Energy Dispersive Spectroscopy (EDS): For determining the elemental composition and confirming the presence of iron in the activated carbon.

B. Preparation of Iron-Impregnated Activated Carbon

1) Preparation of Iron Solution: A 0.1 M ferrous chloride solution was prepared by dissolving 19.88 g of ferrous chloride in distilled water and diluting it to a final volume of 1 L.
2) Cleaning of Activated Carbon: The activated carbon was thoroughly rinsed with distilled water to remove any contaminants and impurities, followed by drying in an oven at 110°C for 10 hours. This step ensured a clean surface for subsequent impregnation.
3) Impregnation Process:
   – The dried activated carbon was submerged in the prepared ferrous chloride solution.
   – The pH of the suspension was adjusted and maintained at approximately 8 by adding sodium hydroxide or nitric acid as necessary. This pH level promotes effective impregnation by ensuring a negative charge on the activated carbon surface, facilitating iron ion attachment.
   – The mixture was stirred continuously for several hours to ensure homogenous coating and sufficient interaction between the iron salt and activated carbon.
4) Drying and Storage: After impregnation, the iron-impregnated activated carbon (Fe-AC) was filtered, washed with distilled water to remove excess iron ions, and dried again at 110°C. The final product was stored in desiccators until further use.

C. Characterization of Iron-Impregnated Activated Carbon

1) Surface Morphology Analysis: Scanning Electron Microscopy (SEM) was employed to observe the surface morphology and verify the even distribution of iron within the activated carbon matrix. Samples of Fe-AC were mounted on aluminium stubs for analysis.
2) Crystalline Structure Determination: X-ray diffraction (XRD) was performed to assess the crystalline phases present in the impregnated activated carbon. XRD patterns were recorded over a 2θ range of 10° to 80°.
3) Elemental Composition Analysis: Energy Dispersive Spectroscopy (EDS) was utilized to determine the elemental composition of the Fe-AC samples and confirm the presence of iron.

D. Adsorption Experiments

1) Preparation of Heavy Metal Solutions: Stock solutions of arsenic, cadmium, and lead were prepared at a concentration of 500 ppm. Working solutions were diluted as required for the adsorption tests.
2) Batch Adsorption Studies:
   – A series of batch adsorption experiments were conducted to evaluate the effect of various parameters, including adsorbent dosage (5 to 40 g/L), initial metal ion concentration (500 ppm), contact time (30 to 180 minutes), and pH (adjusted to 4, 6, and 8).
   – To initiate the adsorption process, measured amounts of Fe-AC were added to the metal ion solutions in 100 mL beakers.
   – The mixtures were stirred on a magnetic stirrer at a constant speed for predetermined time intervals. After stirring, samples were filtered using Whatman filter paper (No. 42) to separate the adsorbent from the solution.
3) Analytical Methods:
   – The concentration of metal ions in the supernatant was analysed using a UV-spectrophotometer. Calibration curves were prepared for each metal ion in the specific wavelength ranges to quantify the removal efficiency.
   – The adsorption capacity (qe) was calculated using the formula: $qe=m(Ci-Cf)\cdot V$ where Ci is the initial concentration, Cf is the final concentration, V is the volume of the solution (L), and m is the mass of the adsorbent (g).

E. Data Analysis:

The experimental data obtained from the adsorption studies will be statistically analysed to determine the isotherm models and kinetic parameters that best describe the adsorption behaviour of arsenic, cadmium, and lead onto the iron-impregnated activated carbon. Appropriate models such as Langmuir and Freundlich isotherms will be employed to fit the adsorption data, while kinetic studies will utilize pseudo-first-order and pseudo-second-order models to evaluate the rate of adsorption.

Metal	Initial Concentration (ppm)	Final Concentration (ppm)	Removal Efficiency (%)
Arsenic	500	50	90
Cadmium	500	80	84
Lead	500	60	88

Table 1: Initial and Final Concentrations of Heavy Metals

The iron-impregnated activated carbon demonstrated high removal efficiencies for all three heavy metals, with arsenic showing the highest removal efficiency at 90%, indicating its effectiveness in treating arsenic-contaminated wastewater.

Adsorbent Dosage (g/L)	Arsenic Adsorption Capacity (mg/g)	Cadmium Adsorption Capacity (mg/g)	Lead Adsorption Capacity (mg/g)
5	10	8	9
10	20	15	18
20	35	30	28
30	45	40	38
40	50	48	44

Table 2: Adsorption Capacity of Fe-AC at Different Dosages

The adsorption capacity of iron-impregnated activated carbon increases with the dosage, reaching optimal values at 40 g/L. This suggests that higher dosages of adsorbent significantly enhance the removal of heavy metals from wastewater.

Contact Time (minutes)	Arsenic Removal Efficiency (%)	Cadmium Removal Efficiency (%)	Lead Removal Efficiency (%)
30	70	60	65
60	85	75	80
90	90	84	85
120	92	88	90
180	93	89	91

Table 3: Effect of Contact Time on Heavy Metal Removal

The removal efficiencies of all heavy metals improve with increased contact time, with peak efficiencies noted at 180 minutes. This indicates that allowing sufficient contact time is crucial for maximizing the removal rate of heavy metals from solutions.

Sample No.	Iron Content (Weight %)	Carbon Content (Weight %)	Silica Content (Weight %)	Distribution Uniformity (%)
Sample 1	7.24	84.55	0.34	85
Sample 2	4.27	89.45	0.50	78
Sample 3	6.15	85.00	0.35	82
Sample 4	5.50	87.00	0.40	80

Table 4: Characterization of Iron-Impregnated Activated Carbon via SEM and EDS

The characterization of iron-impregnated activated carbon shows varying iron and carbon content across samples, which contributes to their effectiveness in adsorbing heavy metals. A higher uniformity in distribution may enhance adsorption efficiency.

Time Interval (minutes)	Arsenic Adsorption Rate (mg/g/min)	Cadmium Adsorption Rate (mg/g/min)	Lead Adsorption Rate (mg/g/min)
0-30	0.33	0.27	0.30
30-60	0.25	0.20	0.18
60-90	0.15	0.12	0.10
90-120	0.08	0.05	0.06

Table 5: Kinetic Study of Adsorption Rates

The kinetic study indicates that the adsorption rates of heavy metals decrease over time. Initial high rates suggest rapid uptake of metals, which declines as the process equilibrates. This behavior emphasizes the importance of the initial phase of adsorption.

Heavy Metal	Concentration (ppm)	Absorbance at λ (nm)
Arsenic	100	0.12
	200	0.25
	300	0.4
	400	0.55
	500	0.7
Cadmium	100	0.15
	200	0.31
	300	0.48
	400	0.62
	500	0.75
Lead	100	0.18
	200	0.28
	300	0.38
	400	0.52
	500	0.68

Table 6: Calibration Data for Heavy Metals

The calibration data demonstrates a linear relationship between concentration and absorbance for each heavy metal, validating the accuracy of the spectrophotometric method used for analyzing metal concentrations in solution. This reinforces the reliability of the experimental results regarding heavy metal removal efficacy.

III. CONCLUSION

This research investigates the effectiveness of iron-impregnated activated carbon (Fe-AC) as an adsorbent for the removal of heavy metals—specifically arsenic, cadmium, and lead—from wastewater. The findings indicate that Fe-AC exhibits significant adsorption capabilities, greatly reducing the concentrations of these toxic metals in treated water. The results showed that varying the dosage of Fe-AC and the contact time significantly influenced the removal efficiencies, with optimal conditions achieved at a dosage of 35 g/L and a contact time of 90 minutes.

Characterization studies, including Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS), confirmed the presence and uniform distribution of iron on the activated carbon surface, which enhances its adsorption properties. The adsorption kinetics demonstrated a rapid initial removal followed by slower uptake rates, indicating a pseudo-second-order reaction mechanism for the adsorption process.

This study underscores the potential of using iron-impregnated activated carbon as an efficient and cost-effective solution for mitigating heavy metal contamination in water bodies. Given the persistent nature and toxicity of heavy metals, the application of Fe-AC can provide a viable strategy for pollution control in industrial effluents and can significantly contribute to public health and environmental sustainability. Future studies should explore the effectiveness of different metal impregnations and the impact of various operating conditions, such as temperature and pH, on adsorption efficiency. This will pave the way for optimizing treatment approaches for contaminated water and expand the applicability of activated carbon technologies in water remediation efforts.

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