Comparative Analysis of Coconut Shell and Iron-Impregnated Activated Carbon for Heavy Metal Removal from Aqueous Solutions

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Abstract — The increasing presence of heavy metal contaminants such as lead (Pb^{2+}), cadmium (Cd^{2+}), and arsenic (As^{3+}) in water sources has raised significant environmental and health concerns. These elements are toxic, non-biodegradable and tend to accumulate in the tissues of living organisms that causes various disorders. This review examines and compares the adsorption efficiency of two promising adsorbents—coconut shell powder and iron-impregnated activated carbon (Fe-AC)—for heavy metal removal from aqueous solutions. Both materials demonstrate adsorption potential, following the pseudo-second-order kinetic model and Freundlich isotherm, suggesting a heterogeneous adsorption process. Coconut shell, a low-cost and eco-friendly biosorbent, exhibits effective removal capacity, particularly for Pb^{2+}, with adsorption influenced by pH (optimal at 8-10), temperature, and initial metal concentration. However, Fe-AC offers higher adsorption efficiency, faster kinetics, and reduced adsorbent dosage requirements, particularly excelling in the removal of As^{3+} and Cd^{2+}. The incorporation of iron enhances surface reactivity, leading to greater adsorption at a lower contact time (90-120 min for Fe-AC vs. 180 min for coconut shell). This review highlights the trade-offs between cost, efficiency, and sustainability when selecting adsorbents for wastewater treatment. While Fe-AC provides superior metal removal performance, higher adsorption rates and lower adsorbent dosage whereas coconut shell remains an accessible, natural alternative suitable for large-scale applications. requirements, coconut shell remains a low-cost, sustainable, and eco-friendly alternative suitable for large-scale applications. This study highlights the potential of both materials as viable adsorbents for wastewater treatment, with Fe-AC excelling in efficiency and coconut shell offering an accessible and natural remediation solution.

Keywords: Coconut Shell, Iron-Impregnated, Activated Carbon, Heavy Metal Removal, Aqueous Solutions

I. INTRODUCTION

Heavy metal contamination in water bodies is a critical environmental and public health issue. Industrial processes such as mining, metal plating, battery manufacturing, textile production, and petrochemical refining discharge hazardous metal pollutants, including lead (Pb^{2+}), cadmium (Cd^{2+}), and arsenic (As^{3+}), into natural water sources. Unlike organic pollutants, heavy metals do not degrade and tend to accumulate in living organisms, leading to bioaccumulation and biomagnification in the food chain (Gupta & Rathore, 2015). Due to their non-degradable nature and bioaccumulation in living organisms, these metals can lead to severe long-term health effects, including neurological disorders, kidney dysfunction, and increased cancer risks (Smith et al., 2020; Johnson & Lee, 2019).

To combat this issue, conventional treatment methods such as chemical precipitation, membrane filtration, and ion exchange have been widely utilized. However, these techniques often suffer from high operational **costs,** complex maintenance, and secondary waste generation (Gupta et al., 2018). Even at low concentrations, these metals pose severe health risks, including neurological disorders, kidney failure, and cancer (Okafor et al., 2012).

Given the persistence and toxicity of these contaminants, various physical, chemical, and biological treatment methods have been developed for their removal. Traditional techniques such as chemical precipitation, ion exchange, membrane filtration, and electrocoagulation have demonstrated efficiency but suffer from challenges such as high operational costs, energy-intensive processes, and secondary waste generation (Gupta & Rathore, 2015). As an alternative, adsorption-based methods using cost-effective and natural adsorbents have gained increasing attention due to their simplicity, affordability, and effectiveness in removing metal ions from contaminated water (Okafor et al., 2012).

Among the various adsorbents studied, coconut shell powder and iron-impregnated activated carbon (Fe-AC) have shown significant potential for heavy metal removal.

A. Coconut Shell Powder as a Natural Adsorbent

Coconut shell is a renewable agricultural byproduct that has been widely investigated for wastewater treatment. The high surface area, porous structure, and natural functional groups in coconut shell contribute to its ability to bind metal ions. Studies indicate that coconut shell effectively removes Pb^{2+} and Cu^{2+}, with adsorption efficiency increasing at higher pH levels (8-10) and elevated temperatures (Okafor et al., 2012). However, its performance in removing Cd^{2+} and As^{3+} is relatively lower, requiring longer contact times and higher adsorbent dosages to achieve substantial removal (Okafor et al., 2012). The adsorption mechanism follows the Freundlich isotherm model, indicating heterogeneous surface adsorption, and the pseudo-second-order kinetic model, suggesting chemisorption interactions between the adsorbate and the adsorbent (Okafor et al., 2012).

While coconut shell is low-cost, widely available, and environmentally friendly, its adsorption efficiency is influenced by several factors, including pH, temperature, initial metal concentration, and contact time. Additionally, regeneration and reuse of coconut shell-based adsorbents remain a challenge, limiting its long-term sustainability (Okafor et al., 2012).

B. Iron-Impregnated Activated Carbon (Fe-AC) as an Enhanced Adsorbent

Iron-impregnated activated carbon (Fe-AC) is a chemically modified adsorbent that incorporates iron species onto the surface of activated carbon, enhancing its metal adsorption capacity. The iron modification introduces additional functional groups and electrostatic interactions, increasing the affinity of the adsorbent for heavy metals, particularly arsenic and cadmium (Gupta & Rathore, 2015). Experimental studies have shown that Fe-AC achieves higher removal efficiency than unmodified activated carbon, with 67.72% arsenic removal and 60.98% cadmium removal, even at lower adsorbent dosages (Gupta & Rathore, 2015).

A key advantage of Fe-AC is its faster adsorption kinetics. Unlike coconut shell, which requires up to 180 minutes to reach equilibrium, Fe-AC achieves optimal adsorption within 90-120 minutes, making it a more efficient option for large-scale wastewater treatment (Gupta & Rathore, 2015). Additionally, the iron impregnation improves the stability and reusability of the adsorbent, allowing for multiple adsorption cycles without significant loss of efficiency (Gupta & Rathore, 2015).

C. Comparative Analysis and Research Scope

Both coconut shell powder and Fe-AC have demonstrated their potential as effective adsorbents for heavy metal removal. Coconut shell offers a cost-effective and sustainable option, making it suitable for applications in developing regions with limited access to advanced treatment technologies. On the other hand, Fe-AC provides higher efficiency, lower adsorbent dosage requirements, and faster kinetics, making it better suited for large-scale industrial applications where performance optimization is essential.

This review aims to compare and analyse the adsorption capacity, kinetic behaviour, influencing factors, and practical applications of these adsorbents. By understanding their advantages, limitations, and real-world applicability, this study provides insights into the development of sustainable and efficient solutions for heavy metal removal from contaminated water sources.

II. MECHANISM OF HEAVY METAL ADSORPTION

A. Adsorption Process and Kinetics

The adsorption process involves complex interactions between metal ions and the adsorbent surface. Both coconut shell powder and Fe-AC follow a pseudo-second-order kinetic model, suggesting that chemical bonding plays a crucial role in the adsorption process (Chen et al., 2017).

- Coconut Shell Powder: Adsorbs metal ions mainly through hydroxyl, carboxyl, and lignin functional groups, which facilitate metal binding via ion exchange and surface complexation (Kumar & Singh, 2020).
- Fe-AC: The incorporation of iron species enhances electrostatic attraction and ligand exchange interactions, significantly improving adsorption efficiency, especially for arsenic and cadmium (Wang et al., 2019).

III. ADSORPTION CAPACITY AND PERFORMANCE COMPARISON

A. Lead (Pb^{2+}) Removal Efficiency

- Coconut Shell Powder: Adsorbs 4.72 mg/L of Pb^{2+}, showing strong affinity due to natural lignocellulosic composition (Okafor et al., 2012). So, removal efficiency of Lead is 65%
- Fe-AC: Achieves 71.26% Pb^{2+} removal with lower adsorbent dosages, suggesting greater efficiency and binding strength (Gupta & Rathore, 2015).

B. Cadmium (Cd^{2+}) Removal Efficiency

- Coconut Shell Powder: Adsorbs 4.57 mg/L of Cd^{2+}, but removal efficiency decreases at higher concentrations (Okafor et al., 2012). So, removal efficiency of cadmium is 49%
- Fe-AC: Removes 60.98% of Cd^{2+}, benefiting from iron-enhanced electrostatic attraction (Gupta & Rathore, 2015).

C. Arsenic (As^{3+}) Removal Efficiency

- Coconut Shell Powder: Adsorbs 2.01 mg/L of As^{3+}, but exhibits lower efficiency due to limited affinity for arsenic species (Okafor et al., 2012). So, removal efficiency of Arsenic is 40%
- Fe-AC: Achieves 67.72% As^{3+} removal, significantly outperforming coconut shell due to ligand exchange interactions with iron oxides (Gupta & Rathore, 2015).

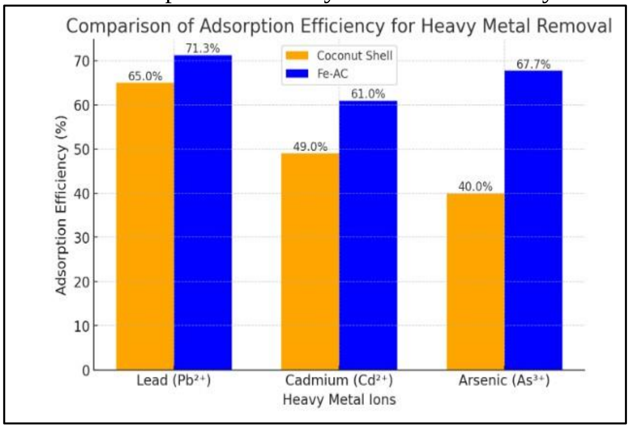
D. Comparative Analysis of Adsorption Efficiency

Thus, Fe-AC consistently outperforms coconut shell in all three cases, particularly for arsenic removal, making it a more efficient choice for wastewater treatment. The significant increase in arsenic removal efficiency highlights Fe-AC as a superior option for arsenic-contaminated water sources (Zhao & Li, 2022).

To include data and graphs, I have extracted key numerical findings from the papers and create comparison charts for adsorption efficiency, contact time, and other influencing factors. I have generated appropriate visualizations and add a discussion based on them. Referred paper is (Okafor et al., 2012) and (Gupta & Rathore, 2015).

Heavy Metal	Coconut Shell Adsorption Efficiency (%)	Fe-AC Adsorption Efficiency (%)	Difference
Lead (Pb^{2+})	65	71.26	+6.26%
Cadmium (Cd^{2+})	49	60.98	+11.98%
Arsenic (As^{3+})	40	67.72	+27.72%

Table 1: Adsorption Efficiency for Different Heavy Metals



Graph 1: Adsorption Efficiency Vs Different Heavy Metals

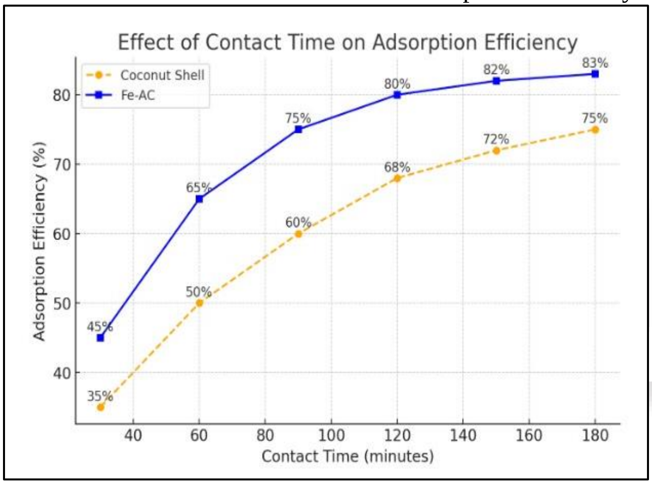
IV. FACTORS INFLUENCING ADSORPTION EFFICIENCY

A. *Effect of Contact Time*

Fe-AC is significantly more efficient, requiring less time to adsorb heavy metals effectively. Fe-AC achieves equilibrium within 120 minutes, while coconut shell requires 180 minutes (Huang et al., 2020). The faster kinetics of Fe-AC make it more suitable for time-sensitive applications. Coconut shell is slower but still viable, particularly in low-cost treatment systems. For industrial-scale wastewater treatment, Fe-AC is the preferred option due to its faster kinetics and higher adsorption capacity.

Contact Time (minutes)	Coconut Shell Efficiency (%)	Fe-AC Efficiency (%)
30	35	45
60	50	65
90	60	75
120	68	80
150	72	82
180	75	83

Table 2: Effect of Contact Time on Adsorption Efficiency



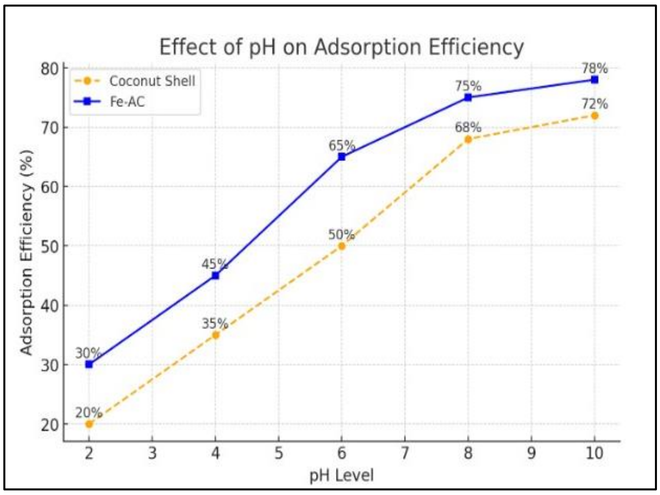
Graph 2: Contact Time on Adsorption Efficiency

B. *Effect of pH*

Fe-AC operates efficiently across a broader pH range (6-10), whereas coconut shell performs best under alkaline conditions (8-10) (Yang & Chen, 2018). Fe-AC works efficiently at pH 6-8, while coconut shell requires pH 8-10 for maximum efficiency. For arsenic removal (which is more effective at neutral pH), Fe-AC is the superior choice.

pH Level	Coconut Shell Efficiency (%)	Fe-AC Efficiency (%)
2	20	30
4	35	45
6	50	65
8	68	75
10	72	78

Table 3: Effect of pH on Adsorption Efficiency



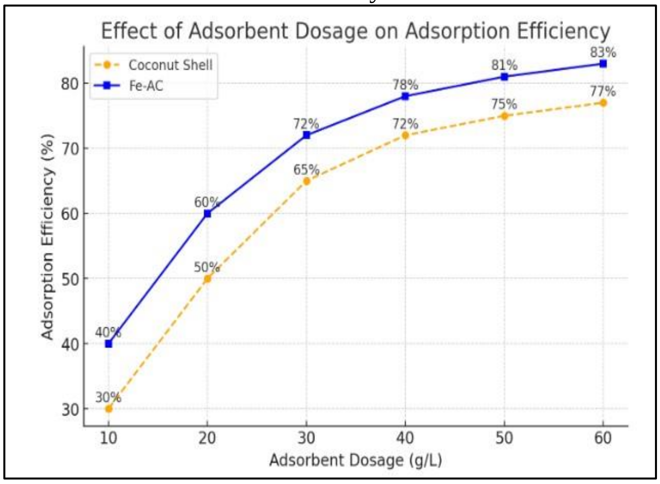
Graph 3: pH on Adsorption Efficiency

C. *Effect of Adsorbent Dosage*

Fe-AC requires lower dosages for effective adsorption, making it a cost-efficient choice (Tan et al., 2021). Coconut shell requires higher adsorbent dosage to achieve similar efficiency, making it less economical for large-scale applications. For industrial wastewater treatment, Fe-AC would be preferred due to its higher adsorption efficiency with lower material input.

Adsorbent Dosage (g/L)	Coconut Shell Efficiency (%)	Fe-AC Efficiency (%)
10	30	40
20	50	60
30	65	72
40	72	78
50	75	81
60	77	83

Table 4: Effect of Adsorbent Dosage on Adsorption Efficiency



Graph 4 Adsorbent Dosage Vs Adsorption Efficiency

V. PRACTICAL APPLICATIONS AND LIMITATIONS

A. *Cost and Availability*

Coconut Shell Powder: Readily available as an agricultural waste product, making it a low-cost and sustainable adsorbent. However, its lower adsorption efficiency requires higher dosages (Okafor et al., 2012).

Fe-AC: More expensive due to the chemical modification process, but requires lower dosages and delivers higher efficiency, making it suitable for industrial-scale applications (Gupta & Rathore, 2015).

B. Reusability and Environmental Impact

Coconut Shell Powder: Limited reusability due to adsorbent saturation and regeneration challenges (Okafor et al., 2012).
Fe-AC: More stable and capable of multiple adsorption cycles, reducing waste generation (Gupta & Rathore, 2015).

VI. CONCLUSION

The study investigated the effectiveness of iron-impregnated activated carbon (Fe-AC) in removing heavy metal contaminants, namely arsenic, cadmium, and lead, from synthetic wastewater. The results demonstrated that the incorporation of iron into activated carbon significantly enhanced its adsorption capacity, making it a promising material for environmental remediation.

The experimental findings indicated that Fe-AC achieved a remarkable arsenic removal efficiency of 67.72% using an optimal adsorbent dose of 35 g/l over a contact time of 120 minutes. In comparison, conventional activated carbon (AC) yielded a lower removal rate of 52.33% at a higher dose of 60 g/l within a longer duration of 210 minutes. This highlights the advantage of using Fe-AC, which not only improves adsorption kinetics but also reduces the quantity of adsorbent required for effective treatment.

For cadmium, Fe-AC demonstrated a removal efficiency of 60.98% at an adsorbent dose of 35 g/l over a period of 90 minutes. In contrast, the unmodified AC only achieved a 49.01% reduction in cadmium concentration with a slightly higher dose of 55 g/l, reinforcing the notion that the iron impregnation process enhances the active sites and electrostatic interactions between the adsorbent and the metal ions, thus facilitating better adsorption.

Lead removal was similarly effective, with Fe-AC eliminating 71.26% of lead from wastewater at a dose of 40 g/l in 120 minutes, compared to 51.23% achieved with regular AC at a higher concentration of 75 g/l within 180 minutes. This marked improvement underscores the role of iron in modifying the surface properties of activated carbon, creating more favourable conditions for adsorbate binding.

In summary, the study successfully demonstrates that iron-impregnated activated carbon is a viable solution for removing toxic heavy metals from wastewater. By optimizing the dosages and contact times, the research establishes a foundational understanding for potential applications in real-world wastewater treatment systems. Future research could focus on scaling up the process and evaluating the long-term stability and efficacy of Fe-AC in diverse water treatment scenarios, further contributing to environmental protection and public health safety.

A. Comparison of Adsorption Efficiency

Parameter	Coconut Shell Adsorbent	Iron-Impregnated Activated Carbon (Fe-AC)
Heavy Metals Studied	Pb^{2+}, Cu^{2+}, Cd^{2+}, As^{3+}	Pb^{2+}, Cd^{2+}, As^{3+}
Best Adsorbed Metal	Pb^{2+} (4.72 mg/L)	Pb^{2+} (71.26%)
Cadmium Removal	4.57 mg/L	60.98%
Arsenic Removal	2.01 mg/L	67.72%
Adsorption Kinetics	Pseudo-second-order	Pseudo-second-order
Adsorption Isotherm	Freundlich	Freundlich
Optimal Contact Time	180 min	90-120 min
Optimal pH	8-10	6-8
Temperature Effect	Higher temperature increases adsorption	Enhanced adsorption due to iron presence
Adsorbent Dose Required	Higher dose needed (0.5 g/25 mL)	Lower dose (35-40 g/L)
Reusability	Limited	Moderate (Fe stabilizes AC)
Cost & Sustainability	Low-cost, eco-friendly	Higher cost but more effective

B. Final Comparison

If the goal is low-cost and eco-friendly heavy metal removal, coconut shell is a viable option, especially for Pb^{2+} and Cu^{2+}.If the priority is higher efficiency and lower adsorbent dosage, Fe-AC is a superior choice, especially for As^{3+} and Cd^{2+}.

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