Removal of Heavy Metal Ions (Copper) from Industrial Wastewater

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***Abstract*— Heavy metal contamination in wastewater, particularly copper, threatens ecosystems and human health, necessitating sustainable and biosafe treatment solutions. This study evaluates low-cost, eco-friendly adsorbents—chalk powder, eggshells, and coconut husk—for copper removal, emphasizing biosafety by minimizing secondary pollution and utilizing waste materials. Experiments under alkaline conditions revealed that chalk powder significantly reduced copper concentrations, demonstrating its potential as a safer alternative to conventional methods like activated carbon. Partial results indicate that these adsorbents effectively lower copper levels while avoiding toxic byproducts, aligning with biosafety and circular economy principles. The findings highlight the promise of such materials for small-scale industrial applications, offering a balance between efficacy, affordability, and environmental safety.**

***Index Terms*—Biosafety, copper removal, low-cost adsorbents, sustainable wastewater, heavy metals.**

I. INTRODUCTION

The discharge of untreated or poorly treated wastewater from industrial activities such as battery production, tanneries, mining, and chemical manufacturing poses a significant threat to environmental and human biosafety. Heavy metals present in such effluents are non-biodegradable and can persist in ecosystems, accumulating in soil, water, and living organisms. When these toxic elements enter the food chain, they can cause severe health risks including neurological disorders, organ failure, and developmental issues, particularly in vulnerable populations. Copper is toxic to plants and aquatic organisms, with safe water levels for aquatic life being 2-4 ppb and for humans, 10 mg/L. Addressing this issue is critical not only from an environmental engineering perspective but also from a biosafety and public health standpoint, as exposure to heavy metal-contaminated water has been linked to increasing rates of chronic illness in affected communities.

Conventional wastewater treatment technologies—such as chemical precipitation, membrane filtration, and electrochemical methods—have long been used to remove heavy metal ions. However, these techniques often involve high capital and operational costs, complex infrastructure, and secondary pollution due to chemical by-products. Furthermore, they are not always effective at removing metals at low concentrations, which are still toxic from a biosafety viewpoint. In contrast, adsorption and biosorption techniques offer safer, more sustainable alternatives. These processes use natural or waste-derived adsorbents to capture and immobilize heavy metal ions, reducing biological exposure pathways. Such approaches align with the global move toward low-impact, resource-efficient, and health-conscious water treatment solutions.

Recent advances in materials science have identified several promising adsorbents for copper removal from wastewater, including activated carbon, chitosan, zeolites, magnetic nanoparticles, and agricultural wastes such as eggshells and rice husk. These biosorbents not only provide effective heavy metal removal but also promote circular economy principles by valorizing waste streams. From a biosafety perspective, the ability to mitigate metal-induced toxicity using low-cost, regenerable materials is highly valuable, especially in resource-constrained or densely populated regions. This paper explores the biosorption potential of various materials for copper ion removal, with a focus on safeguarding ecological and human health while supporting sustainable wastewater treatment practices.

II. PROBLEM DEFINITION

The presence of heavy metals, particularly copper, in industrial wastewater poses significant environmental and public health risks. Despite stringent regulations, conventional treatment methods such as chemical precipitation and activated carbon adsorption remain costly, energy-intensive, and often generate hazardous sludge, raising biosafety concerns. Additionally, the limited availability and high expense of commercial adsorbents restrict their use in small-scale industries, especially in developing regions. This study addresses these challenges by exploring low-cost, biodegradable alternatives—chalk powder, eggshells, and coconut husk—for copper removal. By repurposing waste materials, the approach not only enhances biosafety by minimizing secondary pollution but also aligns with circular economy principles, offering a sustainable and scalable solution for industrial wastewater remediation.

The objectives of this project are:
1. To identify the most effective adsorbent for removal of heavy metal ion copper from industrial wastewater.
2. To provide a viable, cheap and effective alternative to industrial-grade adsorbents like activated carbon, silica and alumina.

III. METHODOLOGY

A. Approach

The quantitative analysis of copper present in artificially simulated industrial wastewater was done before and after the addition of aforementioned adsorbents. Various concentrations of adsorbent were added to a fixed quantity of simulated e-waste water, and the resultant copper concentration was measured using the principle of colorimetry, to identify the most effective adsorbent at room temperature and alkaline pH.

B. Materials and Analytical Methods

The experimental setup utilized standard laboratory equipment, including 50 mL polyethylene beakers for sample containment, graduated measuring spoons (±0.1 mL accuracy) for precise adsorbent dosing, and glass stirring rods for homogenization. Artificially contaminated wastewater was prepared using analytical grade $CuSO_4 \cdot 5H_2O$ dissolved in deionized water. Three biosorbent materials were evaluated: reagent-grade chalk powder ($CaCO_3$ ≥98%), eggshell powder, and coconut husk powder. Adsorption studies were conducted following established protocols. The colorimetric quantification of copper employed a digital colorimeter operating at 620 nm - the characteristic λmax for aqueous Cu^{2+} complexes - using pre-calibrated quartz cuvettes (1 cm path length). Filtration through Whatman Grade 1 cellulose membranes ensured complete phase separation post-adsorption. All measurements were conducted in triplicate to ensure statistical reliability, with system blanks accounting for potential matrix interference. The adsorption mechanism was characterized through surface complexation modeling, considering the alkaline conditions (pH 9.0±0.2 maintained with NH_4OH/NH_4Cl buffer) promoted electrostatic interactions between negatively charged adsorbent surfaces ($CaCO_3$, pHzpc ≈9.5) and cationic Cu^{2+} species. Colorimetric data interpretation incorporated Beer-Lambert law correlations (R^2>0.99 calibration curve) to quantify residual copper concentrations with ±2% instrumental accuracy.

C. Procedures

The adsorption experiments were conducted using batch processing at ambient temperature (25±2°C). Artificially simulated industrial wastewater was prepared by dissolving copper sulphate in deionized water to achieve a 12 ppm Cu^{2+} concentration, with pH adjusted to alkaline conditions (9.0±0.2) using ammonium hydroxide. Ten 50 mL aliquots of this solution were distributed into polyethylene beakers for comparative testing. Four samples received chalk powder at incremental doses (0.5, 1.0, 1.5, and 2.0 teaspoons), while three samples each were treated with either coconut husk powder or eggshell powder (0.5, 1.0, and 1.5 teaspoons). After sealing, the mixtures underwent 132 hours of static incubation to ensure adsorption equilibrium. Post-incubation, each solution was vacuum-filtered through Whatman No. 1 filter paper to separate the adsorbents, as shown in Figure 1. The filtrates were analysed using a digital colorimeter at 620 nm wavelength, with absorbance values compared against a calibration curve to determine residual copper concentrations. Untreated wastewater served as the control for baseline measurements. This systematic approach enabled quantitative comparison of adsorption efficiencies across different biomaterials and dosages.

Fig 1. Filtering of the solutions with the respective adsorbents using filter paper.

IV. PARTIAL RESULTS

A. Initial Findings

The initial experiments involved treating 50 mL of simulated industrial wastewater containing 12 ppm of copper as shown in Figure 2(absorbance = 0.50) with three different adsorbents—chalk powder, eggshell powder, and coconut husk—each at a mean concentration of 1 teaspoon. The colorimeter measurements indicated varying degrees of copper adsorption efficiency. Chalk powder demonstrated the highest efficacy, reducing copper concentration to 3.12 ppm as shown in Figure 3, followed by eggshell powder (5.04 ppm) and coconut husk (9.60 ppm). Notably, the maximum permissible copper concentration in drinking water, as per regulatory standards, is 1.3 ppm, while levels exceeding 3 ppm are considered toxic for human consumption. These preliminary results suggest that chalk powder may be the most promising adsorbent among those tested.

Fig 2. Original Solution without adsorbents (containing 12 ppm copper)

Fig 3. Chalk powder solution with 1 teaspoon of chalk powder added initially, and then filtered out (containing 3.12 ppm copper)

B. Iterative Improvements

To optimize copper adsorption, further experiments were conducted by varying adsorbent concentrations around the mean value (1 teaspoon) while maintaining room temperature to ensure industrial applicability. Additionally, the wastewater was alkalized using ammonia solution to enhance adsorption efficiency, as copper adsorption is known to be more effective under alkaline conditions.

For chalk powder, reducing the dosage to ½ teaspoon significantly improved performance, lowering copper concentration to 0.96 ppm—below the permissible limit (as shown in Figure 4). However, increasing the dosage to 1.5 and 2 teaspoons resulted in higher residual copper levels (10.32 ppm and 9.60 ppm, respectively), indicating that excessive adsorbent may hinder effective adsorption.

In the case of coconut husk, a ½ teaspoon dosage reduced copper concentration to 5.28 ppm as shown in Figure 6, while a 1.5 teaspoon dosage showed no improvement, with copper levels remaining at the initial 12 ppm. This suggests that coconut husk may have limited adsorption capacity regardless of dosage adjustments.

Conversely, eggshell powder exhibited an inverse trend: a ½ teaspoon dosage was ineffective (11.04 ppm residual copper), whereas a 1.5 teaspoon dosage drastically improved adsorption, reducing copper concentration to 2.4 ppm (as shown in Figure 5)—close to the toxic threshold but still above the permissible limit. These findings highlight the importance of dosage optimization, with chalk powder emerging as the most viable adsorbent under the tested conditions.

Fig 4. Chalk powder solution with 0.5 teaspoon of chalk powder added initially, and then filtered out (containing 0.96 ppm copper)

Fig 5. Eggshell powder solution with 1.5 teaspoon of eggshell powder added initially, and then filtered out (containing 2.4 ppm copper)

Fig 6. Coconut husk solution with 0.5 teaspoon of coconut husk added initially, and then filtered out (containing 5.28 ppm copper)

V. RESULTS AND DISCUSSIONS

A. Adsorption Efficiency of Different Adsorbents

The study evaluated the efficacy of three adsorbents—chalk powder (calcium carbonate), eggshell powder (primarily $CaCO_3$), and coconut husk (carbon-based)—in removing copper ions from simulated industrial wastewater. Initial experiments at a fixed adsorbent concentration (1 teaspoon per 50 mL) revealed significant variations in adsorption performance. Chalk powder demonstrated the highest efficiency, reducing copper concentration from 12 ppm to 3.12 ppm (73.3% removal), followed by eggshell powder (5.04 ppm, 58% removal) and coconut husk (9.60 ppm, 20% removal). Further optimization through adsorbent dosage adjustments yielded critical insights:

Chalk powder at ½ teaspoon achieved the most effective adsorption, reducing copper concentration to 0.96 ppm—below the WHO permissible limit of 1.3 ppm for drinking water. However, increasing the dosage beyond this threshold (1.5–2 teaspoons) led to reduced efficiency, likely due to particle aggregation or saturation effects. Eggshell powder exhibited optimal performance at 1.5 teaspoons, lowering copper concentration to 2.4 ppm—below the toxicity threshold (3 ppm) but still unsuitable for potable use. Coconut husk showed limited adsorption capacity, with residual copper levels remaining high (5.28 ppm at ½ teaspoon) and no observable improvement at higher dosages (12 ppm at 1.5 teaspoons). These observations are charted in Table 1.

Adsorbent (Powdered)	Quantity (teaspoon)	Absorbance Value	Copper conc. of filtered soln. (ppm)	Quantity of copper adsorbed (ppm)
Original soln	-	0.50	12.00	-
Chalk	1/2	0.04	0.96	11.04
	1	0.13	3.12	8.88
	3/2	0.43	10.32	1.68
	2	0.40	9.60	2.40
Eggshells	1/2	0.46	11.04	0.96
	1	0.21	5.04	6.96
	3/2	0.10	2.40	9.60
Coconut husk	1/2	0.22	5.28	6.72
	1	0.40	9.60	2.40
	3/2	0.50	12.00	-

Table 1. Displays quantity of copper adsorbed by different adsorbents

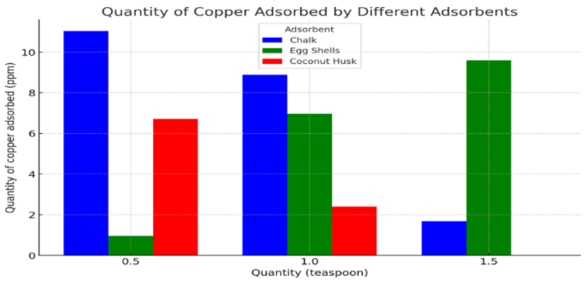

Fig 7. Compares quantity of copper adsorbed by different quantities of various adsorbents

B. Influence of pH and Temperature

Adsorption experiments were conducted under alkaline conditions (pH ~9–10) using ammonia solution, as copper (Cu^{2+}) ions exhibit higher affinity for adsorbents in alkaline media due to reduced solubility and enhanced electrostatic interactions. Room temperature (25 ± 2°C) was maintained to simulate cost-effective industrial conditions, ensuring scalability without additional energy input.

C. Mechanistic Insights into Adsorption

The superior performance of chalk powder ($CaCO_3$) can be attributed to:

1. Ion Exchange Mechanism: Ca^{2+} ions in calcium carbonate readily exchange with Cu^{2+} in solution, facilitating chemisorption.
2. Surface Complexation: The high surface area and alkaline nature of $CaCO_3$ promote the formation of copper-carbonate complexes (e.g., malachite, $Cu_2(OH)_2CO_3$).
3. Precipitation: At alkaline pH, copper ions may precipitate as hydroxides or carbonates, further enhancing removal efficiency.

Eggshell powder, composed of ~94% $CaCO_3$, exhibited similar but less efficient adsorption due to impurities (e.g., proteins, $MgCO_3$) that may block active sites. Coconut husk, being primarily carbon-based, lacked sufficient functional groups for effective copper binding, resulting in poor performance.

D. Comparative Analysis with Commercial Adsorbents

While commercially activated carbon (CAC) remains the gold standard for heavy metal removal, its high cost and non-renewability limit large-scale applications. This study demonstrates that chalk powder, despite its lower adsorption capacity compared to CAC, offers a cost-effective, sustainable alternative for small-scale wastewater treatment. Its widespread availability and minimal processing requirements make it particularly viable for decentralized systems in resource-limited settings.

E. Environmental and Practical Implications

Chronic exposure to elevated copper levels (>3 ppm) can cause liver/kidney damage, gastrointestinal distress, and neurodegenerative effects. The optimized chalk powder treatment (0.96 ppm) ensures compliance with WHO safety standards, eliminating these risks. At concentrations <1 ppm, copper exhibits minimal toxicity to aquatic life (e.g., algae, fish), preventing bioaccumulation and disruption of freshwater ecosystems. This aligns with EPA guidelines for surface water quality. The treated effluent (0.96 ppm) remains below the 2.5 ppm level associated with DNA damage in mammalian cell studies, ensuring no mutagenic hazards.

VI. CONCLUSION

This study systematically evaluated the efficacy of low-cost, naturally derived adsorbents—chalk powder ($CaCO_3$), eggshell powder, and coconut husk—for removing copper ions from simulated industrial wastewater. Our findings demonstrate that chalk powder at an optimal dosage of ½ teaspoon per 50 mL effectively reduces copper concentrations from 12 ppm to 0.96 ppm, achieving compliance with WHO drinking water standards (≤1.3 ppm) and significantly mitigating biosafety risks. The superior performance of calcium carbonate-based adsorbents over carbonaceous materials aligns with theoretical predictions, attributable to ion exchange, surface complexation, and alkaline precipitation mechanisms. From an environmental sustainability perspective, chalk powder emerges as a scalable, economically feasible alternative to commercial activated carbon (CAC), offering comparable efficacy without the associated costs or supply-chain limitations. Future work should focus on column adsorption systems, adsorbent regeneration, and multi-metal wastewater treatment to assess long-term industrial applicability. These findings contribute to the growing demand for green remediation technologies, providing a scientifically validated, eco-friendly solution for copper-laden wastewater management.

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