International Journal of Engineering Research and Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 21, Issue 5 (May 2025), PP 254-259

Adsorption of Heavy Metals from Synthetic Wastewater Using Rice Husk as A Biosorbent

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Abstract: *Heavy metal contamination in water bodies poses a serious threat to ecosystems and human health. This study investigates the potential of rice husk, an agricultural waste product, as a low-cost and sustainable biosorbent for the removal of lead (Pb^{2+}), copper (Cu^{2+}), and zinc (Zn^{2+}) from synthetic wastewater. Two forms of rice husk—Grounded Rice Husk (GRH) and Carbonized Rice Husk (CRH)—were prepared and evaluated for their adsorption capacity under varying conditions. Characterization was performed using SEM and XRF analyses to assess morphological and elemental properties. Batch adsorption experiments assessed the influence of pH, initial metal concentration, contact time, and temperature. The results demonstrated that CRH exhibited superior adsorption efficiency due to increased porosity and surface functionality, achieving maximum adsorption capacities of 2.04 mg/g for Pb^{2+}, 2.012 mg/g for Cu^{2+}, and 2.015 mg/g for Zn^{2+}. Adsorption followed pseudo-second-order kinetics and Langmuir isotherm behavior. This study supports the potential of rice husk—especially in carbonized form—as an effective and scalable biosorbent for eco-friendly wastewater treatment.*

Keywords: *Rice husk, heavy metals, adsorption, wastewater treatment, biosorbents, carbonization, sustainability*

Date of Submission: 11-05-2025 Date of acceptance: 22-05-2025

I. Introduction

Heavy metal contamination in aquatic environments is a critical environmental issue that poses significant threats to human health and ecological systems. Among the various pollutants, heavy metals such as lead (Pb), copper (Cu), and zinc (Zn) are particularly dangerous due to their non-biodegradable, persistent, and bioaccumulative nature (Wan Ngah & Hanafiah, 2008). These metals primarily originate from industrial effluents, electroplating, mining activities, battery manufacturing, and agricultural runoff. Once discharged into water bodies, they tend to accumulate in sediments and living organisms, thereby entering the food chain and exerting long-term toxic effects (Kumar et al., 2012). Lead, for example, is known to affect neurological development in children and can cause kidney dysfunction and cardiovascular issues in adults, while excessive copper can lead to liver damage and gastrointestinal distress, and high levels of zinc have been associated with immunosuppression and nausea (El-Sayed et al., 2011; Jiménez-Cedillo et al., 2013).

Conventional techniques for removing heavy metals from wastewater include chemical precipitation, membrane filtration, ion exchange, and electrochemical treatments. While these methods can be effective, they are often associated with high operational costs, energy consumption, and the generation of secondary waste, making them less suitable for large-scale or low-resource settings (Bailey et al., 1999). In contrast, adsorption has emerged as a widely accepted and economically viable alternative due to its operational simplicity, minimal sludge generation, and potential for regenerability (Yan & Viraraghavan, 2001). Activated carbon, the most common adsorbent, offers high removal efficiency but is cost-prohibitive for widespread use, especially in developing regions (Puranik & Paknikar, 1997).

Recent research has focused on identifying low-cost and eco-friendly adsorbents derived from natural and agricultural waste materials. These include sawdust, coconut shells, fruit peels, and rice husk—each demonstrating promising adsorption properties due to their functional groups and porous structures (Matheickal & Yu, 1999; Boota et al., 2009). Among them, rice husk has gained particular attention due to its abundant availability, high surface area, and chemical composition rich in silica, cellulose, lignin, and hemicellulose. These components provide active binding sites such as hydroxyl (-OH), carboxyl (-COOH), and silanol (-SiOH) groups that facilitate metal ion binding through complexation, ion exchange, and electrostatic attraction (Marshall et al., 1999; Gaballah & Kilbertus, 1998). Rice husk accounts for approximately 20% of paddy weight and is often considered an agricultural waste product, thereby offering both economic and environmental advantages when utilized as a biosorbent (Khalid et al., 1999).

This study explores the potential of rice husk—both in grounded and carbonized forms—as an effective adsorbent for the removal of Pb^{2+}, Cu^{2+}, and Zn^{2+} from synthetic wastewater. Carbonization of rice husk is hypothesized to enhance its surface characteristics, such as porosity and functional group exposure, thereby improving its adsorption performance. The research involves comprehensive chemical and morphological characterization of the adsorbents, systematic variation of experimental parameters such as pH, contact time, and initial metal concentration, and evaluation of adsorption behavior through isotherm and kinetic modeling. The findings aim to contribute to the development of cost-effective, sustainable, and scalable solutions for heavy metal remediation in wastewater treatment systems.

II. Materials and Methods

2.1 Adsorbent Preparation

The primary adsorbent used in this study was rice husk, an abundant lignocellulosic agricultural by-product obtained a local rice mill. The raw rice husk was initially washed multiple times using distilled water to eliminate dust particles, dirt, and any residual organic or inorganic impurities that could interfere with adsorption performance. Following the cleaning process, the material was air-dried for 48 hours under ambient conditions and subsequently oven-dried at 105°C for 24 hours to remove any remaining moisture.

The dried husk was divided into two parts to produce two distinct adsorbents: Grounded Rice Husk (GRH) and Carbonized Rice Husk (CRH). For GRH, the rice husk was mechanically ground using a laboratory blender and sieved through a 355 µm mesh sieve to ensure uniform particle size, which enhances surface area and promotes consistent adsorption performance. For CRH, a separate portion of the sieved rice husk was subjected to thermal treatment (pyrolysis) in a muffle furnace at 500°C for 3 hours in an oxygen-limited environment to avoid combustion. The resulting charred material, characterized by a darker color and increased brittleness, was then cooled in a desiccator to prevent moisture uptake, ground to a fine powder, and stored in airtight polyethylene containers to preserve its adsorption properties for experimental use.

This preparation process aimed to evaluate the effect of carbonization on the adsorption efficiency of rice husk by comparing the performance of GRH and CRH under identical experimental conditions.

2.2 Synthetic Wastewater Preparation

To simulate real-world heavy metal contamination in water, synthetic wastewater samples were prepared in the laboratory using analytical-grade chemicals without any further purification. Solutions of lead (Pb^{2+}), copper (Cu^{2+}), and zinc (Zn^{2+}) ions were created by dissolving the respective salts—lead nitrate [$Pb(NO_3)_2$], copper sulfate pentahydrate [$CuSO_4\cdot 5H_2O$], and zinc sulfate heptahydrate [$ZnSO_4\cdot 7H_2O$]—in deionized water. Stock solutions were initially prepared at concentrations of 1000 mg/L for each metal ion and were subsequently diluted to obtain working concentrations ranging from 1 mg/L to 21 mg/L, based on experimental requirements.

The pH of the synthetic wastewater was adjusted using either 0.1 M hydrochloric acid (HCl) or 0.1 M sodium hydroxide (NaOH), and a digital pH meter was used for accurate monitoring. The pH range for the experiments was selected between 2.0 and 6.0 to prevent the precipitation of metal hydroxides, which could interfere with the adsorption mechanism.

2.3 Adsorption Experiments

Batch adsorption experiments were conducted to evaluate the efficiency of GRH and CRH in removing Pb^{2+}, Cu^{2+}, and Zn^{2+} from synthetic wastewater under various physicochemical conditions. Each adsorption trial was performed in a 300 mL Erlenmeyer flask containing 100 mL of metal solution and a pre-weighed amount (1.0–2.0 g) of the adsorbent. The flasks were sealed and agitated using an electromagnetic stirrer at a constant speed of 250 revolutions per minute (rpm) to ensure uniform mixing and enhanced mass transfer between adsorbate and adsorbent particles. The experimental temperature was maintained at 40 ± 1°C using a thermostatic water bath to replicate typical warm-climate effluent conditions.

The effect of contact time was studied by withdrawing samples at regular intervals (0.5, 1, 3, 6, 12, and 24 hours). After each interval, the samples were filtered using Whatman No. 42 filter paper to separate the spent adsorbent from the treated solution. The residual concentrations of Pb^{2+}, Cu^{2+}, and Zn^{2+} in the filtrate were analyzed using an Atomic Absorption Spectrophotometer (AAS, Perkin-Elmer Analyst 200) calibrated with standard metal solutions to ensure precision. Blanks and duplicate samples were run in parallel to validate the accuracy and reproducibility of the measurements.

2.4 Characterization of Adsorbents

To understand the adsorption behavior of GRH and CRH, detailed physicochemical characterization was carried out. The surface morphology of the adsorbents was examined using Scanning Electron Microscopy (SEM) at magnifications of 100x and 500x. This provided visual insights into the textural changes introduced by grinding and carbonization, including pore development, surface roughness, and fiber degradation.

Elemental analysis was performed using X-ray Fluorescence (XRF) spectroscopy to determine the relative concentrations of key elements such as silica (Si), carbon (C), and trace inorganic compounds. These elements are critical for understanding the interaction mechanisms between metal ions and surface functional groups on rice husk. The comparative analysis between GRH and CRH highlighted the chemical transformation induced by thermal treatment, which is central to enhanced adsorption performance.

2.5 Data Analysis and Modeling

Following each batch experiment, the Perkin-Elmer Model Analyst 200 AAS was used to filter the treated water samples and measure the remaining concentrations of Pb(II), Cu(II), and Zn(II). The results obtained were employed to compute the adsorption capacity (Qe, in mg/g) by using the following equation:

$$Q_e = \frac{(c_i - c_f) \times V}{m} \quad (1)$$

where c_i and c_f are initial and final metal ion concentrations (mg/L), V is the solution volume (L), and mm is adsorbent mass (g). The removal percentage of every metal was also calculated. The graphs were plotted for visualization of the metal removal in relation to parameters like pH, contact time, and concentration. Comparative studies between GRH and CRH were conducted to assess which form exhibited better adsorption performance. The findings from experiments were further explained with the help of adsorption isotherms and kinetic models in order to illustrate the mechanisms of adsorption and predict behavior under real-world applications

Graphical analysis was performed using Microsoft Excel and Origin Pro software. Statistical validation of model fits (R^2 values) was used to determine the most suitable models for describing the adsorption process.

III. Results

3.1 Characterization of Adsorbents

The physicochemical characteristics of the adsorbents were assessed using Scanning Electron Microscopy (SEM) and X-ray Fluorescence (XRF). SEM analysis revealed that Carbonized Rice Husk (CRH) had a more porous, rough, and irregular surface texture compared to Grounded Rice Husk (GRH), which exhibited relatively smoother surfaces with fewer visible pores. This increase in surface porosity upon carbonization indicates a larger available surface area and more active adsorption sites, thereby enhancing the metal ion binding capacity.

XRF results further supported these findings by revealing higher silica (SiO_2) and carbon content in CRH than in GRH. As shown in Table 1, silica increased from 18% in GRH to 32% in CRH, and carbon increased from 30% to 40%. Meanwhile, the content of cellulose and lignin—organic polymers that can block active sites—was significantly reduced in CRH due to thermal degradation. This shift in composition favors the exposure of functional groups such as –OH, –COOH, and –SiOH, which facilitate ion exchange and complexation with metal ions.

Table 1. ***Chemical Composition of Rice Husk***

Component	**GRH (%)**	**CRH (%)**
Cellulose	45	28
Lignin	25	15
Silica (SiO_2)	18	32
Carbon	30	40

3.2 Effect of pH

The pH of the aqueous solution plays a critical role in influencing the surface charge of the adsorbent and the speciation of metal ions. The experimental results demonstrated that at pH 2, adsorption was least effective due to the high concentration of H^+ ions, which compete with metal cations (Pb^{2+}, Cu^{2+}, Zn^{2+}) for available binding sites on the adsorbent surface.

Maximum adsorption efficiency for all three metal ions was observed in the pH range of 4–5, where the deprotonation of surface functional groups enhanced the electrostatic attraction between the negatively charged adsorbent surface and the positively charged metal ions. However, at pH > 6, a decline in adsorption was noted, likely due to the precipitation of metal hydroxides, which made it difficult to differentiate between adsorption and chemical precipitation.

3.3 Effect of Contact Time

The influence of contact time was studied to understand the kinetics of metal ion uptake by GRH and CRH. The results showed a rapid increase in adsorption during the first few hours, attributed to the high availability of unoccupied active sites on the adsorbent surface. As the reaction progressed, the rate of adsorption slowed down and eventually plateaued at around 18 hours, suggesting the system had reached adsorption equilibrium.

This pattern indicates that the adsorption process is time-dependent, and sufficient contact time is necessary to maximize removal efficiency. The CRH reached equilibrium faster than GRH, owing to its higher surface porosity and accessibility of binding sites.

3.4 Effect of Initial Concentration

Varying the initial metal ion concentration revealed its impact on adsorption capacity (Qe) and percentage removal. As the initial concentration increased, the adsorption capacity (Qe) also increased due to a higher mass transfer driving force that facilitated the diffusion of ions to the adsorbent surface. However, the percentage removal began to decline slightly at higher concentrations due to the saturation of available binding sites.

This trend is captured in Table 2, which shows that for a 21 mg/L initial concentration, CRH exhibited much higher Qe values than GRH for all three metal ions. Specifically, Pb^{2+} adsorption capacity increased from 0.4531 mg/g in GRH to 2.040 mg/g in CRH, reflecting the significant performance boost due to carbonization

Table 2. ***Adsorption Capacities at 21 mg/L Initial Concentration***

Metal Ion	**GRH (Qe mg/g)**	**CRH (Qe mg/g)**
Pb^{2+}	0.4531	2.040
Cu^{2+}	0.3793	2.012
Zn^{2+}	0.4005	2.015

IV. Discussion

The comparative evaluation between GRH and CRH clearly indicates that CRH is a superior adsorbent. This superiority is attributed to its enhanced porosity, higher surface area, and greater exposure of functional groups, all of which contribute to an increased number of available binding sites for metal ion attachment.

The adsorption process followed pseudo-second-order kinetics, suggesting that the rate-limiting step was chemisorption, involving valency forces and sharing of electrons between adsorbent and adsorbate. Furthermore, equilibrium data fitted well to the Langmuir isotherm model, as illustrated in Figure 1, confirming the assumption of monolayer adsorption on a homogenous surface.

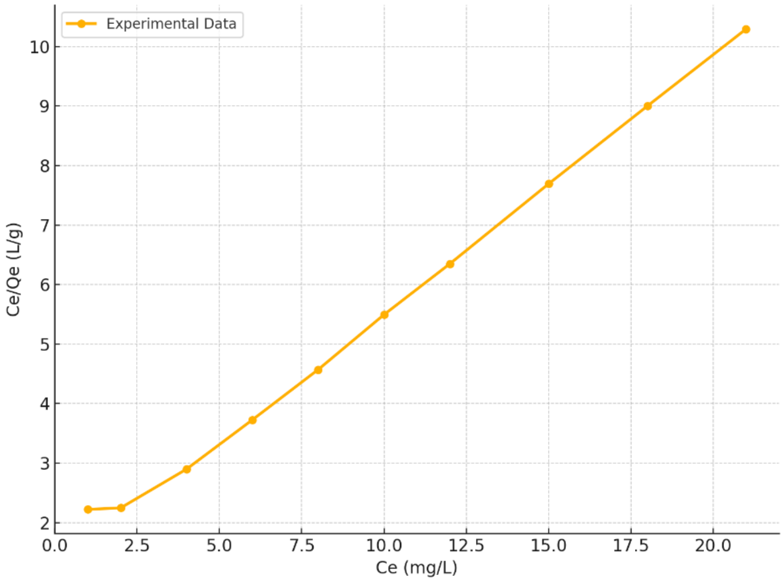

Figure 1. ***Langmuir Isotherm Plot for Pb^{2+} Adsorption on CRH***

The comparison of Qe values across metals, presented in Figure 2, demonstrates the relative affinity of CRH for different ions. Pb^{2+} showed the highest uptake, which can be attributed to its larger ionic radius and higher polarizability, allowing stronger electrostatic and complexation interactions with active sites.

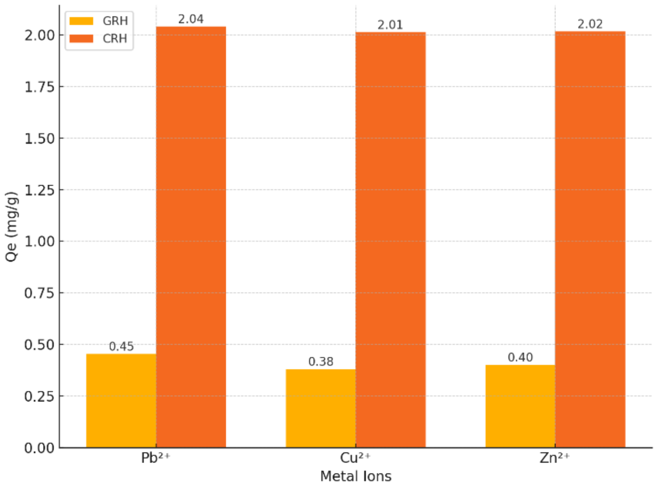

Figure 2. ***Comparison of Qe for GRH vs CRH at 21 mg/L***

The optimal pH of 4–5 across all tested metals further supports existing literature, which identifies this pH range as favorable for maximizing surface charge effects without inducing metal hydroxide precipitation. The current study's improved kinetics, higher adsorption capacity, and better isotherm fit highlight the effectiveness of the carbonization process in optimizing rice husk as a sustainable and high-performance biosorbent.

V. Conclusion

This study presents a systematic and comparative evaluation of Grounded Rice Husk (GRH) and Carbonized Rice Husk (CRH) as low-cost, sustainable biosorbents for the removal of heavy metals—specifically Pb^{2+}, Cu^{2+}, and Zn^{2+}—from synthetic wastewater. The research employed a combination of chemical characterization (via SEM and XRF), batch adsorption experiments under varying operational conditions (pH, contact time, initial concentration), and adsorption modeling using kinetic and isotherm frameworks.

The findings unequivocally demonstrate the superior adsorption performance of CRH over GRH. The carbonization process significantly enhanced the physicochemical properties of rice husk by increasing surface porosity, silica and carbon content, and the availability of active functional groups. This transformation resulted in markedly higher adsorption capacities, with CRH achieving maximum values of 2.040 mg/g for Pb^{2+}, 2.012 mg/g for Cu^{2+}, and 2.015 mg/g for Zn^{2+} at 21 mg/L initial concentration, as compared to substantially lower capacities exhibited by GRH.

Experimental results confirmed that the adsorption mechanism adhered to pseudo-second-order kinetics, indicating chemisorption, and the equilibrium behavior conformed well to the Langmuir isotherm model, suggesting monolayer adsorption on a homogenous surface. The optimum pH for maximum removal efficiency across all tested metals was found to be in the range of 4–5, which corresponds to favorable conditions for electrostatic attraction and ion exchange without interference from metal hydroxide precipitation.

Overall, the study substantiates the viability of using rice husk, particularly in its carbonized form, as an effective and scalable solution for the remediation of heavy metal-laden wastewater. Its high removal efficiency, economic feasibility, and environmentally friendly nature make CRH a promising candidate for incorporation into real-world wastewater treatment systems, especially in regions where agricultural waste is abundant and affordable solutions are essential.

Future research should aim to extend this work to multi-metal systems, explore adsorbent regeneration techniques, and validate performance using actual industrial effluents. Life cycle and techno-economic analyses are also recommended to assess the sustainability and commercial scalability of CRH-based adsorption systems.

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