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A novel wheat straw-derived adsorbent for efficient removal of heavy metals (Cu^{2+} and Pb^{2+}) from aqueous solutions

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Abstract
Madhya Pradesh is one of the major wheat-producing states, generating a large amount of wheat straw as an agricultural residue. A significant portion of this biomass remains underutilized or is openly burned, causing environmental pollution. Heavy metal contamination of water by Cu^{2+} and Pb^{2+} poses serious environmental and health concerns. Therefore, a novel wheat straw-derived adsorbent is proposed for the removal of these metal ions from aqueous solutions. The adsorption performance will be evaluated under different experimental conditions, including pH, contact time, adsorbent dosage, and initial metal ion concentration. The natural functional groups present in wheat straw are expected to enhance metal ion adsorption and improve removal efficiency. The anticipated results may demonstrate that wheat straw-derived adsorbent is an effective, low-cost, and sustainable material for heavy metal removal, while also promoting the value-added utilization of agricultural waste for wastewater treatment.

Keywords: Wheat straw, Adsorption, Heavy metals, Copper (Cu^{2+}), Lead (Pb^{2+}), Wastewater treatment, Agricultural waste

Introduction
Water pollution caused by heavy metals has become a major environmental concern due to rapid industrialization, urbanization, and agricultural activities. Heavy metals such as lead (Pb^{2+}) and copper (Cu^{2+}) are non-biodegradable and tend to accumulate in living organisms, causing serious health and environmental problems. Excessive exposure to lead may result in neurological disorders and kidney damage, while high concentrations of copper can affect the liver and gastrointestinal system [1, 2]. Therefore, the removal of heavy metals from contaminated water is essential for protecting human health and aquatic ecosystems.
Various methods, including chemical precipitation, ion exchange, membrane filtration, and electrochemical treatment, have been employed for heavy metal removal. However, these techniques often suffer from limitations such as high operational costs and sludge generation [3]. Among the available technologies, adsorption has gained considerable attention because of its simplicity, cost-effectiveness, and high efficiency [4]. Agricultural wastes have emerged as promising adsorbent materials, with wheat straw being one of the most abundant residues rich in cellulose, hemicellulose, and lignin containing functional groups capable of binding metal ions [5]. Madhya Pradesh generates large quantities of wheat straw every year, making it a readily available and low-cost resource [6]. Therefore, a novel wheat straw-derived adsorbent is proposed for the removal of Cu^{2+} and Pb^{2+} ions from aqueous solutions, and its adsorption performance will be evaluated under different experimental conditions.

Literature Review
The use of low-cost agricultural wastes as adsorbents for heavy metal removal has received considerable attention in recent years due to their abundance, environmental compatibility, and adsorption potential. Carbonized wheat straw demonstrated significantly higher adsorption capacity for Pb^{2+} ions compared to natural wheat straw due to the development of a porous structure and increased active adsorption sites [7]. Biomass-derived adsorbents were also found to be effective in removing toxic metal ions through mechanisms such as ion exchange, surface complexation, and electrostatic interactions [8]. Agricultural residues including wheat straw, rice husk, and other lignocellulosic materials exhibited considerable adsorption efficiencies for heavy metals such as Cu^{2+} and Pb^{2+}, highlighting their potential as low-cost and environmentally friendly alternatives to conventional adsorbents [9].
Furthermore, biochar produced from agricultural wastes showed enhanced adsorption performance owing to its high surface area, porous nature, and abundance of oxygen-containing functional groups [10]. Recent studies reported that carbonization and surface modification significantly improved the adsorption behavior of biomass-based adsorbents by increasing the availability of active binding sites and strengthening metal ion interactions [11, 12]. Collectively, these findings suggested that wheat straw-derived adsorbents possess significant potential for the efficient removal of Cu^{2+} and Pb^{2+} ions and can be utilized as sustainable materials for wastewater treatment applications.

Materials and Methods
Materials used and methods employed for the preparation of wheat straw adsorbent and the adsorption of Cu^{2+} and Pb^{2+} ions from aqueous solutions are described.

1. Adsorbent and Chemicals
Wheat straw was used as the adsorbent for the removal of Pb^{2+} and Cu^{2+} ions from aqueous solutions. Lead nitrate [$Pb(NO_3)_2$] and copper sulfate pentahydrate [$CuSO_4 \cdot 5H_2O$] were used for the preparation of Pb^{2+} and Cu^{2+} ion solutions, respectively. Distilled water was used throughout the study, while hydrochloric acid (HCl) and sodium hydroxide (NaOH) were used for pH adjustment whenever required. The different stages of wheat straw preparation are shown in Figures 1–3.

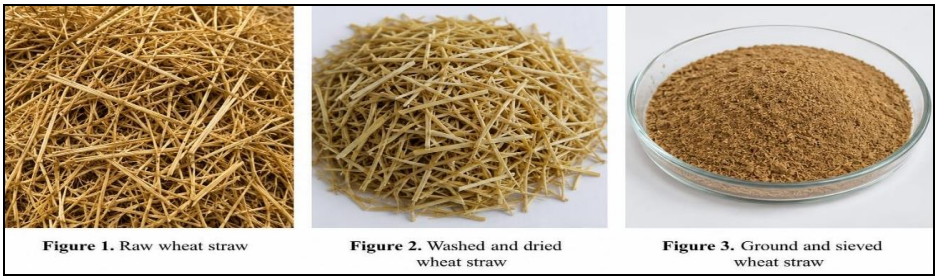


Figure 1. Raw wheat straw

Figure 2. Washed and dried wheat straw

Figure 3. Ground and sieved wheat straw

2. Experimental Methodology

The wheat straw was collected and thoroughly washed with distilled water to remove dust and impurities. It was then dried at room temperature, ground into fine powder, and sieved to obtain uniform particle size for adsorption studies.

Stock solutions (1000 mg/L) of Pb^{2+} and Cu^{2+} ions were prepared by dissolving lead nitrate [$Pb(NO_3)_2$] and copper sulfate pentahydrate [$CuSO_4 \cdot 5H_2O$] in distilled water.

Dissociation of salts in aqueous medium is represented as:

$Pb(NO_3)_2\ (aq) \rightarrow Pb^{2+}\ (aq) + 2NO_3^-\ (aq)$

$CuSO_4 \cdot 5H_2O\ (aq) \rightarrow Cu^{2+}\ (aq) + SO_4^{2-}\ (aq) + 5H_2O\ (l)$

Working solutions of different concentrations (10, 20, 30, and 40 mg/L) were prepared by appropriate dilution of the stock solutions.

For batch adsorption experiments, 100 mL of metal ion solution was taken in a conical flask and a known amount of wheat straw adsorbent was added. The pH of the solution was adjusted using dilute HCl or NaOH. The mixture was shaken for a fixed contact time to achieve adsorption equilibrium.

The adsorption process occurs due to interaction between metal ions and functional groups (–OH and –COOH) present in cellulose, hemicellulose, and lignin of wheat straw. These groups act as active binding sites for metal ions:

Wheat Straw–OH + $Pb^{2+} \rightarrow$ Wheat Straw–O–Pb

Wheat Straw–COOH + $Cu^{2+} \rightarrow$Wheat Straw–COO–Cu + $2H^+$

General ion-exchange mechanism:

Wheat Straw + $M^{2+} \rightarrow$Wheat Straw–M complex

Where M^{2+} represents Pb^{2+} or Cu^{2+} ions.

After adsorption, the mixture was filtered to separate the adsorbent from the solution. The residual concentration of metal ions in the filtrate was determined using standard analytical methods.

The percentage removal of metal ions was calculated using:

$$\% = Removal = \frac{c_0 - c_e}{c_0} \times 100$$

Where C_0 = initial concentration (mg/L) and C_e = equilibrium concentration (mg/L).

Results and Discussion

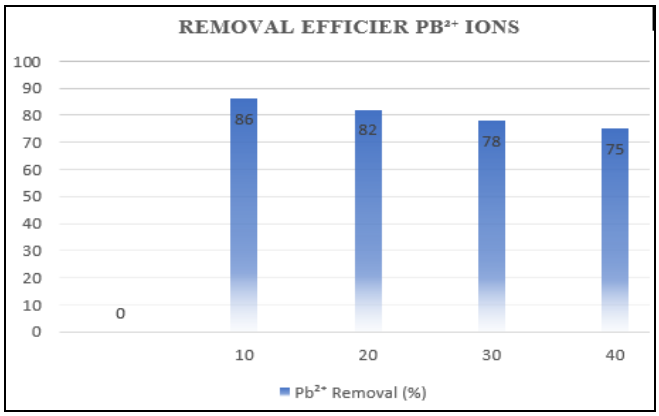
In this section, the experimental data obtained have been analyzed, and the adsorption behavior of Pb^{2+} and Cu^{2+} ions using wheat straw has been explained. It briefly presents the effect of different experimental conditions and the overall adsorption trend observed in the study.

1. Adsorption of Pb^{2+} Ions

The experimental values obtained for the adsorption of Pb^{2+} ions are presented in Table 4.1, and their graphical representation is shown in Graph 4.1 (Concentration vs Removal Efficiency). This reserch explains the effect of initial concentration on the adsorption performance of wheat straw.

Table 1: Adsorption Data of Pb^{2+} Ions

Initial Concertration (mg/L)	Removal Efficier
10	86
20	82
30	78
40	75
50	71



The adsorption results of Pb^{2+} ions indicate that wheat straw acts as an effective biosorbent for heavy metal removal. The maximum removal efficiency (86%) is observed at the lowest concentration (10 mg/L), while it decreases to 71% at 50 mg/L.

2. Adsorption of Cu^{2+} Ions

The experimental values obtained for the adsorption of Cu^{2+} ions are presented in Table 2, and their graphical representation is shown in Graph 2 (Concentration vs Removal Efficiency). This study explains the effect of initial concentration on the adsorption performance of wheat straw for Cu^{2+} ions.

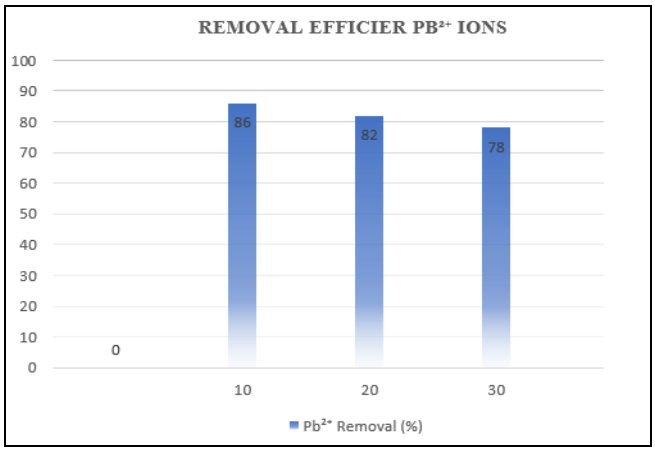


Table 2: Adsorption Data of Cu^{2+} Ions

Initial Concentration (mg/L)	Removal Efficiency (%)
10	85
20	81
30	77
40	73
50	69

The adsorption behavior of Cu^{2+} ions shows a similar trend to Pb^{2+} ions, where the removal efficiency decreases with an increase in initial concentration. The highest removal efficiency (85%) is observed at 10 mg/L, which decreases to 69% at 50 mg/L.

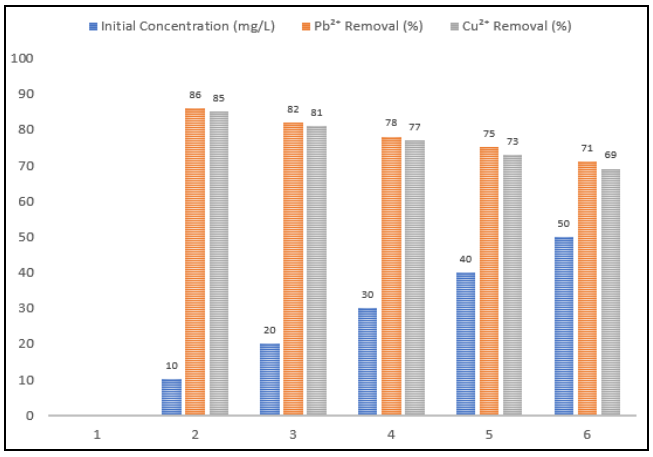
This reduction in adsorption efficiency is due to the saturation of active binding sites on the surface of wheat straw at higher concentrations. At lower concentrations, sufficient active sites are available for metal ion binding, resulting in higher adsorption. The graph clearly indicates a decreasing trend, confirming that Cu^{2+} adsorption also follows a surface adsorption mechanism using wheat straw as a biosorbent.

3. Comparative Analysis of Pb^{2+} and Cu^{2+} Ions

The comparative study of Pb^{2+} and Cu^{2+} ions adsorption is presented in Table 4.3, and its graphical representation is shown in Graph 4.3 (Comparison of Removal Efficiency). This section evaluates the adsorption performance of wheat straw for both metal ions under identical experimental conditions.

Table 3: Comparison of Pb^{2+} and Cu^{2+} Adsorption

Initial Concentration (mg/L)	Pb^{2+} Removal (%)	Cu^{2+} Removal (%)
10	86	85
20	82	81
30	78	77
40	75	73
50	71	69



The comparative analysis shows that Pb^{2+} ions exhibit higher adsorption efficiency than Cu^{2+} ions at all studied concentrations. This indicates that wheat straw has a comparatively greater affinity towards Pb^{2+} ions. The difference may be due to variations in ionic properties such as hydration energy and interaction with surface functional groups.

Conclusion

Wheat straw has been found to be an effective, low-cost, and environmentally friendly biosorbent for the removal of heavy metal ions (Pb^{2+} and Cd^{2+}) from aqueous solutions. This study demonstrates that agricultural waste materials can serve as a useful alternative for environmental remediation applications. The adsorption behaviour shows that removal efficiency decreases with an increase in initial metal ion concentration, mainly due to the saturation of active sites available on the surface of the biosorbent. Functional groups such as –OH and –COOH present in wheat straw play an important role in the binding of metal ions. The comparative study indicates that Pb^{2+} ions exhibit slightly higher adsorption efficiency than Cd^{2+} ions, suggesting a greater affinity of wheat straw towards lead ions. For future improvement, the adsorption capacity of wheat straw can be enhanced through chemical modification, and further studies can be carried out on its application in various types of industrial wastewater.

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