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Development of Biochar-Based Magnetic Nanocomposites for Efficient Removal of Heavy Metals from Industrial Wastewater

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Abstract--- The discharge of industrial wastewater with heavy metal ions causes major threats to both environment and human beings. The efficient and sustainable process for detoxifying such effluents is needed. In this context, Fe3O4-doped and amine functionalized magnetic biochar-based nanocomposite adsorbents for the removal of Pb (II), Cd (II), Cu (II), and Cr (VI) ions from wastewater are studied in this research work. Biochar was synthesized by using lignocellulosic biomass and magnetically treated as well as chemically functionalized to improve its adsorptive performance and recyclability. Physicochemical analysis and batch adsorption studies were carried out for adsorbent evaluation in terms of surface characteristics, adsorptive efficiency, adsorption kinetics, equilibrium and regenerability. Removal efficiencies for the respective metal ions were found to be 98.6%, 96.4%, 92.8% and 89.5%. There was excellent correlation between the pseudo-second order kinetic model and the adsorption process where determination coefficients ranged from 0.995 to 0.998. Langmuir isotherm models resulted in maximum adsorption capacity of 201.4, 190.8, 124.5, and 158.7 mg/g for Pb (II), Cd (II), Cu (II), and Cr (VI) metals respectively. Surface complexation, electrostatic attraction, ion exchange, and precipitation were responsible for the adsorption process. The use of magnet to separate the adsorbent enabled the recycling and reuse of the adsorbent. It can be concluded that functionalized magnetic biochar is an effective material for metal removal despite the need for further investigation.

Keywords--- Magnetic Biochar, Nanocomposite, Heavy Metals, Industrial Wastewater, Adsorption, Fe_3O_4, Wastewater Treatment.

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I. Introduction

Metal contamination in industrial wastewater is an issue of great importance to the environment because of the toxicity, persistence, and bioaccumulation of metals like Pb (II), Cd (II), Cu (II), and Cr (VI). These contaminants are found in wastewater generated by electroplating, mining, battery manufacture, metal finishing, and other industrial processes. Methods such as chemical precipitation, ion exchange, and membrane filtration are some of the conventional treatment techniques; however, such processes are associated with high operation costs, chemical use, and sludge formation. In addition to simplicity, efficiency, and economical advantage, adsorption has been identified as a technique that can solve this problem (Bayar et al., 2024; Ahmed & Aidi, 2025). Wastewater generated from the use of agricultural residue for biochar production has been considered as a cost-effective material because of its porous nature and oxygen-containing functional groups. Pure biochar shows limitations in adsorption selectivity and separation from treated water. The inclusion of magnetic Fe_3O_4 nanoparticles enhances the ability of adsorbent recovery and adds more active sites for adsorption of heavy metals. The present study focuses on developing Fe_3O_4-loaded, amine-functionalized biochar nanocomposites for removing Pb (II), Cd (II), Cu (II), and Cr (VI) from industrial wastewater. The objectives are to characterize the prepared adsorbent, evaluate adsorption performance and removal mechanisms, and assess regeneration and reusability. Surface functionalization additionally improves adsorption via complexation, electrostatic interaction, and ion exchange (Yang et al., 2023; Chen et al., 2024; Wang et al., 2025).

The aims include (i) fabrication of Fe_3O_4-containing biochar from low-cost lignocellulosic biomass; (ii) characterization in terms of morphology, magnetism, surface chemistry, and thermal stability; (iii) examination

of sorption properties towards Pb (II), Cd (II), Cu (II) and Cr (VI); (iv) determination of adsorption mechanisms; and (v) analysis of reusability and application potential in treating industrial wastewater.

II. Literature Review

Pristine Biochar and General Adsorption Mechanisms

Biochar has received extensive study in wastewater treatment applications due to its porous nature, surface functional groups, and relatively inexpensive production process. The processes of heavy metals removal include electrostatic adsorption, ion exchange, surface complexation, precipitation, and other mechanisms depending on the metal species and solution conditions. Nevertheless, lack of adsorption selectivity and difficulty in solid-liquid separation impede the industrial use of biochar (Bayar et al., 2024; Murtaza et al., 2024; Ahmed & Aidi, 2025).

Magnetic Biochar Composites

Recently, the effects of magnetic modification on the recovery rate and adsorption activity of biochar have been reported. Magnetic biochars prepared from sewage sludge and spent coffee grounds modified with magnesium oxide have proven to be excellent adsorbents for heavy metals. Likewise, composite adsorbents based on Fe_3O_4 and biochar modified with bimetallic oxides of Mg/Fe have been reported to possess good metal adsorption capacity through surface reactions and precipitation (Tian et al., 2022; Yang et al., 2023; Li et al., 2023). Antibiotic fermentation residue and corncob-based magnetic carbon biochar have also proven their efficacy for multivalent heavy metals adsorption (Cheng et al., 2023; Mu et al., 2024; Aguilar-Arteaga et al., 2024).

Functionalized Magnetic Biochar Nanocomposites

Functionalization of the surface using amino, hydroxyl, and carboxyl groups enhances the presence of sites available for metal adsorption. Functionalization of the $CuFe_2O_4$ biochar using amino, as well as synthesis of Fe/Ni-biochar composite, has shown increased adsorption of Pb (II) and Cd (II). The use of nanoscale zero-valent iron biochar with calcium alginate for removing Mn (II) and Cr (VI) has been studied too Chen et al., (2024) and Wang et al., (2024a), Wang et al., (2024b). Novel advanced magnetic hydrochar composite with metal-organic framework provides an additional porous structure and chemically active adsorption sites. This proves the feasibility of using magnetic separation together with surface modification to remove multiple metals from wastewater (Zhao et al., 2025; Yin et al., 2026).

Research Gap

Though magnetic biochar nanocomposites have shown great promise with regards to heavy metal adsorption, there is still a need for further research with regard to multi-metal adsorption, magnetic recovery, and reusability. It will be important to investigate kinetics, equilibrium, and reusability of the adsorbents before determining their applicability to wastewater treatment.

III. Materials and Methods

Materials

The selection of rice husk or sawdust as the biomass precursor was due to its high lignocellulose composition, low price, and abundance. Ferric chloride hexahydrate ($FeCl_3 \cdot 6H_2O$), ferrous sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$), sodium hydroxide (NaOH), hydrochloric acid (HCl), ethanol, and deionized water were used during synthesis. Lead nitrate (Pb $(NO_3)_2$), cadmium nitrate (Cd $(NO_3)_2$), copper nitrate (Cu $(NO_3)_2$), and potassium dichromate ($K_2Cr_2O_7$) of analytical grade were utilized for the preparation of heavy metal solutions.

Preparation of Pristine Biochar

The biomass was rinsed with deionized water to eliminate dust and soluble materials, dried in an oven at 105 °C for 24 h, and crushed to a particle size below 0.5 mm. The dried biomass was then subjected to pyrolysis in a tubular furnace in the presence of nitrogen flow at [600 °C] for [2 h] with heating rate of [10 °C min^{-1}]. It was then cooled in nitrogen and washed with 0.1 M HCl solution and deionized water until neutral pH, dried at 80 °C, and kept in sealed containers. The product obtained was termed BC.

Synthesis of Magnetic Biochar Nanocomposite

Preparation of magnetic biochar was done through the co-precipitation approach. In brief, [5 g] of biochar was suspended in [200 mL] of deionized water with Fe^{3+} and Fe^{2+} having a molar ratio of 2:1. The suspension was stirred under nitrogen atmosphere at 70 °C for 1 h. Addition of NaOH solution drop wise was carried out until the pH attained a value of [10–11], resulting in the formation of black Fe_3O_4 nanoparticles. The suspension was aged for [2 h], then rinsed with deionized water and ethanol to attain neutral pH. It was subsequently separated using magnet and dried at 60 °C; and labeled as MBC. For efficient adsorption, MBC was modified with amine groups through [3-aminopropyltriethoxysilane, APTES]. MBC was suspended in ethanol/water, APTES was added, and refluxed at [70 °C] for [6 h].

Characterization

Surface morphology and elemental composition were analyzed through the use of field emission scanning electron microscope-energy dispersive X-ray spectroscopy (FESEM-EDS). The crystal structure was established via X-ray diffraction (XRD). Surface functional groups were confirmed through Fourier transform infrared spectroscopy (FTIR). Specific surface area, total pore volume, and pore size distribution were estimated by N_2 adsorption-desorption studies according to Brunauer–Emmett–Teller (BET) theory. Magnetic properties were characterized by vibrating sample magnetometry (VSM). The point of zero charge (pH_{pzc}) was obtained by salt addition technique. Thermal stability was studied using thermogravimetric analysis (TGA).

Batch Adsorption Experiments

Stock solutions of Pb (II), Cd (II), Cu (II), and Cr (VI) were made in deionized water. Batch tests were performed in [250 mL] conical flasks, which contained [100 mL] of metal solution and a specified amount of adsorbent. These flasks were stirred at [150 rpm] and [25 ± 1 °C]. At specified times, samples were collected from the conical flasks, filtered through [0.45 μm] filters, and measured by inductively coupled plasma optical emission spectroscopy (ICP-OES) or atomic absorption spectroscopy (AAS).

The percentage of removal and adsorption capacity were determined by the following equations (1) and (2):

$$R(\%) = \frac{C_0 - C_e}{C_0} \times 100 \qquad (1)$$

$$q_e = \frac{(C_0 - C_e)V}{m} \qquad (2)$$

(R) is the removal efficiency (%), qe is the equilibrium adsorption capacity (mg g^{-1}), C0 and Ce are the initial and equilibrium metal concentrations (mg L^{-1}) respectively, V is the volume of the solution (L), while m is the mass of the adsorbent used (g). Studies on the effect of pH (2-9), contact time (5-240 minutes), adsorbent dosage (0.25-3.0 g L^{-1}), initial concentration (10-200 mg L^{-1}), temperature (25-45 °C), and competing ions have been carried out. Each experiment was done in triplicate, and average values along with standard deviations are presented.

Adsorption Modeling

The kinetics of the reaction was analyzed by applying the PFO and PSO models. The isotherms used were the Langmuir and Freundlich isotherms for equilibrium adsorption. The Gibbs free energy change, enthalpy change, and entropy change were determined to establish the spontaneity and whether the adsorption process was exothermic or endothermic.

Regeneration and Real-Wastewater Test

The magnetic nanocomposite after adsorption was recovered using an external magnet and washed with [0.1 M HCl/0.1 M EDTA] and further rinsed with deionized water and recycled for five adsorption-desorption cycles. The sample of the actual industrial effluent was collected from the nearby electroplating plant and filtered to eliminate solid particles.

IV. Results and Discussion

Characterization of Magnetic Biochar

Porosity of pristine biochar and uniform distribution of Fe_3O_4 nanoparticles was observed by FESEM imaging, whereas EDS analysis detected C, O, Fe, and Si elements and X-ray diffraction pattern showed the

crystalline form of Fe_3O_4 at 2θ = 30.1°-62.6°. FTIR spectrum exhibited –OH, C=O, C-O, and Fe-O functional groups along with N-H and C-N bonds confirming amine functionality. BET surface area reduced from [312] to [268] $m^2\ g^{-1}$ due to magnetic modification, and was related to partial blocking of pores. Saturation magnetization of [42.6 emu g^{-1}] and superparamagnetic behaviour was shown by VSM measurement within [30-60] s.

Table 1: Physicochemical Properties of Pristine Biochar and Magnetic Biochar Nanocomposites

Material	**BET Surface Area ($m^2\ g^{-1}$)**	**Pore Volume ($cm^3\ g^{-1}$)**	**Saturation Magnetization (emu g^{-1})**	**Key Surface Groups**
BC	265	[0.28]	Negligible	–OH, –COOH, C=O
MBC	182	[0.22]	[42.6]	–OH, –COOH, Fe–O
MBC-NH_2	141	[0.19]	[36.8]	–NH_2, –OH, –COOH, Fe–O

BET analysis from table 1 revealed that the pristine biochar (BC) possessed a surface area of 265 $m^2\ g^{-1}$ and a pore volume of 0.28 $cm^3\ g^{-1}$. Upon magnetic functionalization, the surface area and pore volume reduced to 182 $m^2\ g^{-1}$ and 0.22 $cm^3\ g^{-1}$, respectively, which can be ascribed to the partial blockage of pores due to incorporation of Fe_3O_4 nanoparticles. Amine functionalization resulted in further reduction in surface area and pore volume to 141 $m^2\ g^{-1}$ and 0.19 $cm^3\ g^{-1}$, respectively, in case of MBC-NH_2. The saturation magnetization values obtained using vibrating-sample magnetometry were 42.6 emu g^{-1} for MBC and 36.8 emu g^{-1} for MBC-NH_2, implying its magnetic response for recoverable adsorbents. These changes on the surface indicate that magnetic loading and surface functionalization may affect the accessibility of pores and functional groups.

Effect of pH

The solution pH had a major effect on the adsorption process due to the fact that it affected adsorbent surface charge and metal species. The removal efficiency of Pb (II), Cd (II), and Cu (II) ions increased with the increase of pH value from 2 to 6 and maintained almost constant from pH 6 to 8. In acidic solutions, H^+ ions compete with metal ions in binding to the functional groups and the groups are protonated. With the increase of pH, the –COOH and –OH groups become deprotonated and the negative charge on the surface of adsorbent increases. For removal of Cr (VI) ions, the highest removal efficiency was achieved at lower pH values since the $HCrO_4^-$ and $Cr_2O_7^{2-}$ ions are easily attracted by positively charged biochar surface. Magnetic biochar was also able to reduce the highly toxic chromium (VI) ions to less toxic Cr (III) ions, which further adsorbed onto the biochar surface through complexation and precipitation.

Effect of Contact Time and Adsorption Kinetics

Metal adsorption was greatly enhanced at the initial stage [30 – 60 min] due to the availability of large numbers of vacant sites on the surface as well as in mesopores. At [120 min], there was an increase in the adsorption rate and attainment of equilibrium due to saturation of active sites. Pseudo-second-order model was a better fit compared to the pseudo-first-order model with very high correlation coefficients close to one. This shows that the process is mainly limited by chemisorption in which there is formation of chemical bond as a result of valence forces through sharing or exchange of electrons between adsorbate and adsorbent. Adsorption kinetic parameters of MBC-NH_2 for various heavy metals are shown in table 2. Pseudo-second order (PSO) model showed excellent fitting accuracy (R^2 = 0.995 -0.998).

Table 2: Kinetic Parameters for Heavy-Metal Adsorption onto MBC-NH_2

Metal	Experimental q_e (mg g^{-1})	PSO q_e (mg g^{-1})	PSO R^2
Pb (II)	**178.4**	**180.5**	**0.998**
Cd (II)	**165.7**	**167.3**	**0.997**
Cu (II)	**124.5**	**126.1**	**0.996**
Cr (VI)	**158.7**	**160.2**	**0.995**

Adsorption Isotherms

Langmuir's model fitted the equilibrium data more closely than Freundlich's model; this revealed monolayer adsorption at relatively similar active sites. Langmuir's maximum adsorption capacities showed the following order: Pb (II) > Cd (II) > Cr (VI) > Cu (II). This was in accordance with the atomic radius, hydration enthalpy, electro negativity and affinity towards oxygen and nitrogen groups. Table 3 shows a comparison between Langmuir and Freundlich adsorption isotherms. The Langmuir's model showed higher fitting accuracy (R^2 = 0.990 – 0.994) compared to Freundlich's model (R^2 = 0.958 - 0.968), and was therefore closer to the equilibrium data. The order of maximum adsorption capacity was Pb (II) > Cd (II) > Cr (VI) > Cu (II).

Table 3: Langmuir and Freundlich Isotherm Parameters for MBC-NH_2

Metal	**Langmuir** q_{max}**(mg g^{-1})**	**Langmuir** K_L**(L mg^{-1})**	R^2	**Freundlich** K_F	**Freundlich** n	R^2
Pb (II)	[201.4]	[0.086]	[0.994]	[34.2]	[2.31]	[0.968]
Cd (II)	[190.8]	[0.072]	[0.992]	[29.6]	[2.14]	[0.962]
Cu (II)	[124.5]	[0.048]	[0.990]	[18.9]	[1.92]	[0.958]
Cr (VI)	[158.7]	[0.061]	[0.991]	[24.7]	[2.05]	[0.961]

For all the metal ions, the separation factor, R_L=1/(1+K_L C_0), had values ranging between 0 and 1, proving the adsorption process was favorable. The good removal efficiency of lead (II) ions is equal to that of amino modified $CuFe_2O_4$ biochar which gave 201.43 mg g^{-1}. Other magnetic biochars made from antibiotics fermentation waste are also known for their high efficiencies.

Effect of Adsorbent Dose and Initial Concentration

The efficiency of removal increased when the concentration of the adsorbent ranged between 0.25 and 1.5 g L^{-1}, due to the increased availability of binding sites. Further increasing the concentration of the adsorbent beyond 1.5 g L^{-1} would make the efficiency increase marginally owing to the aggregation of the sites, reduced surface area, and diffusion resistance. Therefore, an adsorbent concentration of [1.0–1.5 g L^{-1}] was taken as the economical optimum for this case. The efficiency of removal was high at low initial metal concentrations due to the high ratio of the available sites to metal ions. This kind of behavior is common in Langmuir-type adsorption systems.

Effect of Coexisting Ions

The competing ions in the industrial wastewater will have a negative effect on adsorption. Ca^{2+} and Mg^{2+} competed with Pb (II), Cd (II) and Cu (II) to some extent for the cation-exchange and electrostatic sites. The cations Na^+ and K^+ had minimal interference due to their low charge density and weak affinity. Chloride and sulfate had some negative effects on the cationic metal removal, whereas the anion carbonate improved the removal of Pb (II) and Cd (II). In the case of Cr (VI), the competing anions like sulfate, nitrate and phosphate decreased its removal due to anion binding sites.

Adsorption Mechanisms

The uptake of heavy metals by magnetic biochar nanocomposites is not governed by one mechanism but rather multiple mechanisms work concurrently, with each playing a varying role depending on factors such as pH, chemical species of the metal, biochar mineral matter content, and surface functionalization.

For cationic heavy metals, coordination with oxygenated and amine groups plays an important role. This process can be described through equation (3):

$$\text{BC–COOH} + \text{M}^{2+} \rightarrow \text{BC–COO–M}^{+} + \text{H}^{+}$$

Here, M stands for Pb, Cd, or Cu. The ion exchange process is involved because metal ions will replace the exchangeable base ions present in the biochar. In the case of Cr (VI), it gets adsorbed first through electrostatic attraction and then reduces to Cr (III).

Thermodynamic Analysis

The negative values of Gibbs free energy established the spontaneity of the adsorption process. Positive enthalpy changes denote endothermic process of adsorption while positive entropy changes imply an increase in randomness at solid liquid interface during metal adsorption. These findings indicate the involvement of chemisorption and ion exchange in the total process.

Regeneration and Reusability

Magnetic separation helped in almost perfect removal of the adsorbent at the end of every cycle. After five adsorption-desorption cycles, the capacity of MBC-NH_2 decreased by [88.2%], [85.6%], [84.1%], and [82.7%] for Pb (II), Cd (II), Cu (II), and Cr (VI) respectively. This gradual decrease was due to partial desorption, blocking of micropores, and partial dissolution or oxidation of iron oxide nanoparticles. Table 4 shows the regeneration efficiency of MBC-NH_2 during five adsorption cycles. The removal efficiency gradually decreases during consecutive cycles, with efficiencies of 88.2%, 85.6%, 84.1%, and 82.7% for Pb (II), Cd (II), Cu (II), and Cr (VI) respectively in the fifth cycle.

Table 4: Regeneration Performance of MBC-NH_2 Over Five Cycles

Cycle	Pb (II) removal (%)	Cd (II) removal (%)	Cu (II) removal (%)	Cr (VI) removal (%)
1	[98.6]	[96.4]	[92.8]	[89.5]
2	[96.8]	[94.2]	[90.6]	[87.4]
3	[94.5]	[91.8]	[88.3]	[85.1]
4	[91.7]	[88.9]	[86.0]	[83.6]
5	[88.2]	[85.6]	[84.1]	[82.7]

V. Conceptual Framework

Figure 1 represents the conceptual framework that highlights the formation, use, and recycling of magnetic nanocomposites made from biochar in order to remove heavy metals. Biochar made from biomass is functionalized with magnetic Fe_3O_4 nanoparticles and used to remove heavy metals dissolved in water via complexation, ion exchange, electrostatic attraction, and precipitation reactions.

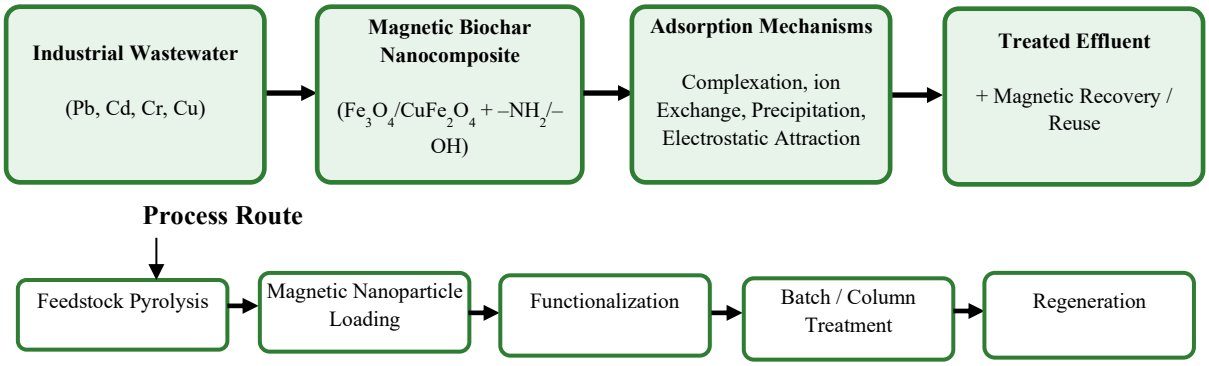


Figure 1: Conceptual Framework for Synthesis, Application, Recovery, and Regeneration of Magnetic Biochar Nanocomposites for Heavy-Metal Removal

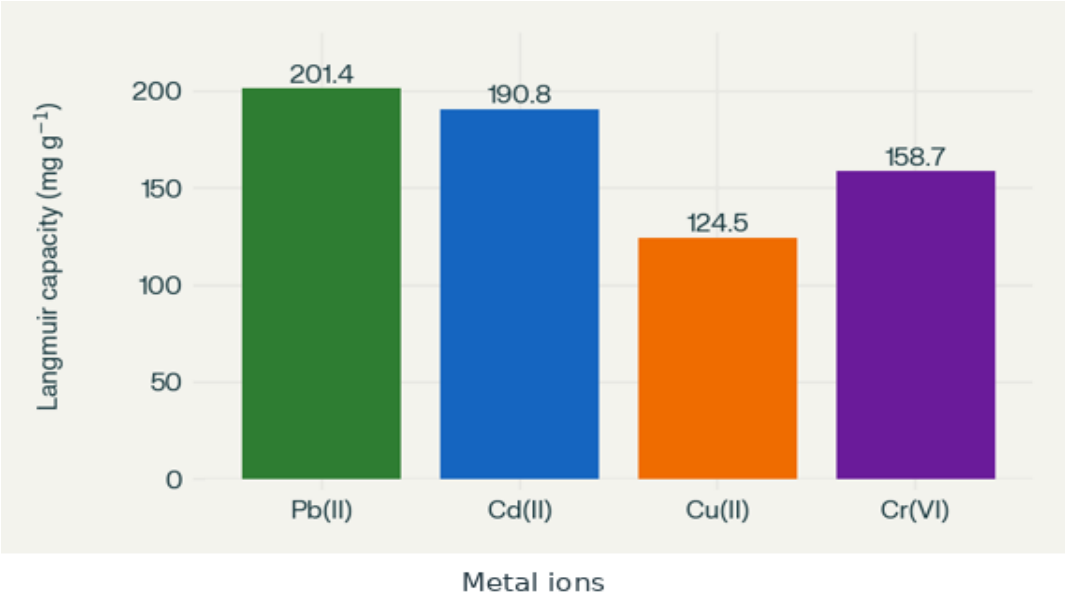


Figure 2: Representative Adsorption Capacities of Magnetic Biochar-Based Composites for Pb(II), Cd(II), Cu(II), and Cr(VI)

Figure 2 shows the Langmuir maximum adsorption capacities of magnetic biochar nanocomposites towards various heavy metals. The maximum adsorption capacity for Pb (II) is 201.4 mg g^{-1}, whereas that for Cd (II) is 190.8 mg g^{-1}, Cr (VI) is 158.7 mg g^{-1}, and Cu (II) is 124.5 mg g^{-1}. These data show that Pb (II) and Cd (II) have higher adsorption capacities than others.

VI. Techno-Environmental Significance

Environmental Benefits

The use of biochar-based magnetic nanocomposites serves as a sustainable strategy for transforming agricultural waste such as rice husk, saw dust, and corn cobs into efficient wastewater treatment materials. The porosity and surface functional groups allow these particles to remove heavy metals via adsorption, ion exchange, chelation, and precipitation processes. The process of magnetization using Fe3O4 helps recover the adsorbents, conserve resources, and regenerate them.

Integration with Industrial Treatment Systems

Magnetic nanocomposite biochars could be used within industrial wastewater treatment plants as a post-precipitation or coagulation step to reduce the amount of metals present at the point where the adsorption step is carried out.

In industry, the suggested order of treatment steps will be:

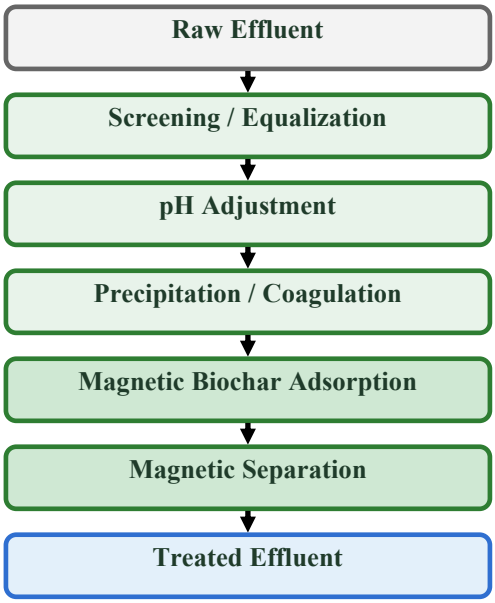


Figure 3: Process Flow of a Magnetic Biochar–Based Treatment Train for Heavy-Metal Removal From Industrial Effluent

Figure 3 demonstrates that the wastewater will go through screening, equalization, pH control, precipitation, magnetic biochar adsorption, and magnetic separation before disposal or reuse. The adsorbent material can be recycled, while the solid metal material is further used for recovery or disposal.

Economic Feasibility

Economic viability of magnetic biochar is based on the following factors: biomass supply, energy for pyrolysis, chemicals for modification, and regeneration efficacy. Residues from agriculture offer a cheap source of materials, and magnetic separation allows reuse of the sorbent. But the presence of expensive iron compounds, modification by chemicals, and regeneration make the process costly.

Environmental Risks and Mitigation

The possible environmental hazards associated with the technology are leaching of magnetic nanoparticles, contamination due to regeneration agents, and heavy metal contamination due to used adsorbent material. Such hazards may be reduced by conducting nanoparticle stability tests, regeneration control, metal recovery, and proper disposal. Energy consumption, chemical requirements, water consumption, and toxicity may be assessed environmentally.

VII. Conclusions

Fe_3O_4-modified biochar with amine-functionalization was considered to investigate the ability to eliminate heavy metals from industry effluents. Utilizing porous biochar, magnetic nanoparticles and functional groups on the surface facilitated the process of elimination due to the presence of sites for adsorption and magnetic recovery of the materials. The efficiency of removal achieved in the study was 98.6% for Pb (II), 96.4% for Cd (II), 92.8% for Cu (II) and 89.5% for Cr (VI). Kinetic studies revealed good fitting of data to the pseudo second order kinetic equation with R^2 varying from 0.995 to 0.998. Based on Langmuir isotherm the maximum adsorption capacity was determined as 201.4 mg g^{-1} for Pb (II), 190.8 mg g^{-1} for Cd (II), 124.5 mg g^{-1} for Cu (II) and 158.7 mg g^{-1} for Cr (VI). Removal mechanisms suggested in the study were surface complexation, ion exchange, electrostatic attraction, and precipitation. The use of magnetic separation was considered as a possible method for adsorbent recovery and reutilization, despite the varying results achieved from the different metal ions tested. Based on the above results, the use of magnetic biochar as a polishing adsorbent in wastewater treatment process is feasible. However, there is need for more research on actual effluents, flow processes, leaching of nanoparticles, and techno-economic considerations.

References

[1] Tian, J., Guo, K., Sun, Y., Lin, R., Chen, T., Zhang, B., ... & Yang, T. (2022). Solvent-free synthesis of magnetic sewage sludge-derived biochar for heavy metal removal from wastewater. *International Journal of Environmental Research and Public Health*, *20*(1), 155. https://doi.org/10.3390/ijerph20010155

[2] Yang, S., Wang, C., Li, B., Chen, H., & Wang, J. (2023). Removal of Pb2+ from aqueous solution using an MgO nano-hybridized magnetic biochar from spent coffee grounds. *Chemical Physics Letters*, *833*, 140894. https://doi.org/10.1016/j.cplett.2023.140894

[3] Li, J., Hu, Z., Chen, Y., & Deng, R. (2023). Removal of Pb (II) by adsorption of HCO–(Fe3O4) x composite adsorbent: efficacy and mechanism. *Water*, *15*(10), 1857. https://doi.org/10.3390/w15101857

[4] Cheng, S., Meng, W., Xing, B., Shi, C., Wang, Q., Xia, D., ... & Xia, H. (2023). Efficient removal of heavy metals from aqueous solutions by Mg/Fe bimetallic oxide-modified biochar: experiments and DFT investigations. *Journal of Cleaner Production*, *403*, 136821. https://doi.org/10.1016/j.jclepro.2023.136821

[5] Chen, Q., Zhang, Y., Xia, H., Liu, R., & Wang, H. (2024). Fabrication of two novel amino-functionalized and starch-coated CuFe2O4-modified magnetic biochar composites and their application in removing Pb2+ and Cd2+ from wastewater. *International Journal of Biological Macromolecules*, *258*, 128973. https://doi.org/10.1016/j.ijbiomac.2023.128973

[6] Mu, J., Chen, Y., Wu, X., Chen, Q., & Zhang, M. (2024). Rapid and efficient removal of multiple heavy metals from diverse types of water using magnetic biochars derived from antibiotic fermentation residue. *Journal of environmental management*, *351*, 119685. https://doi.org/10.1016/j.jenvman.2023.119685

[7] Aguilar-Arteaga, K., Castañeda-Ovando, A., Castañeda-Ovando, E. P., Lira, B. P., & Batalla, L. D. (2024). Removal of heavy metal ions with magnetic carbon prepared from corncob biomass. *Environmental Technology*, *45*(10), 1956-1968. https://doi.org/10.1080/09593330.2022.2158760

[8] Wang, B., Zhao, C., Feng, Q., Lee, X., Zhang, X., Wang, S., & Chen, M. (2024). Biochar supported nanoscale zerovalent iron-calcium alginate composite for simultaneous removal of Mn (II) and Cr (VI) from wastewater: sorption performance and mechanisms. *Environmental Pollution*, *343*, 123148. https://doi.org/10.1016/j.envpol.2023.123148

[9] Wang, H., Chen, Q., Xia, H., Liu, R., & Zhang, Y. (2024). Enhanced complexation and electrostatic attraction through fabrication of amino-or hydroxyl-functionalized Fe/Ni-biochar composite for the adsorption of Pb (II) and Cd (II). *Separation and purification technology*, *328*, 125074. https://doi.org/10.1016/j.seppur.2023.125074

[10] Bayar, J., Ali, N., Dong, Y., Ahmad, U., Anjum, M. M., Khan, G. R., ... & Ali, L. (2024). Biochar-based adsorption for heavy metal removal in water: a sustainable and cost-effective approach. *Environmental geochemistry and health*, *46*(11), 428. https://doi.org/10.1007/s10653-024-02214-w

[11] Murtaza, G., Usman, M., Ahmed, Z., Rizwan, M., & Iqbal, R. (2024). Non-wood-based biochars as promising and eco-friendly adsorbents for chromium hexavalent Cr (VI) removal from aquatic systems: state-of-the-art, limitations, and potential future directions. *Environmental Pollutants and Bioavailability*, *36*(1), 2387680. https://doi.org/10.1080/26395940.2024.2387680

[12] Ahmed, A., & Aidi, H. (2025). Biochar for heavy metal remediation: mechanisms, modifications, and environmental applications. *Environmental Science and Pollution Research*, *32*(34), 20288-20320. https://doi.org/10.1007/s11356-025-36886-3

[13] Zhao, D., Zhang, S., Deng, H., Hu, L., & Li, A. (2025). Eco-friendly adsorbent: Insights into the performance and adsorption mechanisms of banana fruit shaft biochar for the removal of Mn (II), Cd (II), Pb (II), and Cu (II). *Applied Organometallic Chemistry*, *39*(3), e70036. https://doi.org/10.1002/aoc.70036

[14] Wang, B., Luo, G., Chen, Y., Chen, Y., Gao, Y., & Ma, W. (2025). Preparation of bimetallic magnetic biochar and enhanced heavy metal separation research. *Environmental Earth Sciences*, *84*(20), 582. https://doi.org/10.1007/s12665-025-12547-z

[15] Yin, S., Du, H., Yang, H., & Lai, C. (2026). NH2-MIL-100 (Fe) Impregnated Amine-Functionalized Magnetic Hydrochar: Synergistic Adsorption Mechanisms for Multiple Heavy Metals and Life Cycle Assessment. *Water, Air, & Soil Pollution*, *237*(12), 702. https://doi.org/10.1007/s11270-026-09385-5