

## Removal of Heavy Metals from Wastewater Using Green Adsorbents

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### **Abstract**

The harmful nature of metal ions here such as lead & cadmium and chromium makes heavy metal contamination of overall wastewater a serious danger which shows endangers both human safety & environmental protection. This research investigates the effectiveness of biopolymer and biomass-based green adsorbents for removing heavy metals from water sources. The study tested how different factors including pH levels and contact duration and temperature and adsorbent amount affected the performance of several adsorbents which included charcoal and modified agricultural waste materials and chitosan. The adsorption process operated according to pseudo-second-order kinetics while the Langmuir isotherm model provided the best representation of the system, which had a high removal capacity that reached its peak at near-neutral pH levels. The use of green adsorbents showed great potential as an environmentally sustainable solution for wastewater treatment which could last.

**Keywords:** lead & cadmium, wastewater, pH levels, agricultural waste, agricultural waste etc.

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### **I. Introduction**

The rapid growth of industrial activities together with urban expansion and increased agricultural production has caused a substantial rise in heavy metal pollution which affects water bodies across the world. Mining operations together with electroplating activities and battery production processes and leather manufacturing and textile dyeing and fertilizer production methods release heavy metals into water bodies which include lead and cadmium and chromium and mercury and arsenic and nickel<sup>1</sup>. The non-biodegradable nature of heavy metals enables them to persist in the environment, where they build up in sediments and enter the food chain. The elements remain present in their active state, which creates a danger to all aquatic creatures and humans who exist within their direct range.

People who drink contaminated water will experience multiple health issues because their bodies will suffer brain kidney and heart damage while they develop an increased chance of developing cancer. Lead exposure in children leads to severe brain development problems. The body loses essential minerals through cadmium which results in damage to both kidneys and bones. Hexavalent chromium is a very hazardous chemical that causes mutations in DNA. Mercury ingestion by fish leads to increased concentration levels in ecological food chains through the process of biomagnification<sup>2</sup>. The government needs to implement strict regulations which require monitoring of heavy metal levels in both wastewater and drinking water systems because of present hazards. The current situation forces companies and municipalities to search for effective solutions to their water treatment challenges.

The conventional methods for eliminating heavy metals from wastewater use chemical precipitation and ion exchange and membrane filtration and electrochemical treatment and coagulation-flocculation<sup>3</sup>. The methods achieve high removal efficiency in controlled settings but their effectiveness is limited by various fundamental restrictions. The system faces multiple barriers that prevent its widespread use because it requires high operational costs and generates large amounts of dangerous sludge and its performance is affected by changes in pH and ionic strength and it suffers from membrane fouling and its operations need excessive energy

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<sup>1</sup> Ali, H., Khan, E., & Ilahi, I. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. *Journal of Chemistry*, 2019, 6730305. <https://doi.org/10.1155/2019/6730305>

<sup>2</sup> Fu, F., & Wang, Q. (2011). Removal of heavy metal ions from wastewaters: A review. *Journal of Environmental Management*, 92(3), 407–418. <https://doi.org/10.1016/j.jenvman.2010.11.011>

<sup>3</sup> He, Z. L., Yang, X. E., & Stoffella, P. J. (2005). Trace elements in agroecosystems and impacts on the environment. *Journal of Trace Elements in Medicine and Biology*, 19(2–3), 125–140. <https://doi.org/10.1016/j.jtemb.2005.02.010>

consumption<sup>4</sup>. The use of chemicals and the disposal of spent materials create secondary pollution problems which reduce their environmental sustainability.

The process of adsorption has become a practical option because it operates with basic functions and achieves successful results while providing multiple options for system development. The high production costs together with the challenges of regenerating activated carbon and other traditional adsorbents prevent their widespread use in various applications<sup>5</sup>. The need for environmentally safe adsorbents has led to research efforts focused on developing materials that use natural compounds derived from agricultural and industrial biomass waste. Sustainable and circular wastewater treatment systems define green adsorbents as materials that become biodegradable and cost-effective and easy to obtain and safe for the environment. The binding of heavy metal ions occurs through their surface functional groups and their porous architecture and their ability to undergo various modifications which enable ion exchange and complexation and electrostatic attraction<sup>6</sup>. The research of eco-friendly adsorbents represents a practical method to achieve sustainable results which will reduce heavy metal pollution in wastewater treatment systems.

## II. Literature Review

### Heavy Metal Removal Methods

The elimination of heavy metals from wastewater remains a research focus because lead (Pb) and copper (Cu) and cadmium (Cd) and nickel (Ni) exist as toxic substances which do not break down. The process of treating heavy metal wastewater utilizes four main methods which include chemical precipitation and ion exchange and membrane filtration and electrochemical technologies. The technologies operate at their highest efficiency to eliminate waste materials, yet they consume more in number of large amounts of energy and incur high operational costs here on while generating sludge & other secondary waste products that require disposal (Gupta et al., 2021<sup>7</sup>; Malik et al., 2017<sup>8</sup>). The adsorption process provides benefits through its ability to select specific metal ions while operating under less demanding conditions compared to standard treatment methods through the modification of adsorbent characteristics (Wang et al., 2023<sup>9</sup>; Aftab, 2024<sup>10</sup>).

### Mechanisms of Green Adsorbents

Activated carbon is being replaced by sustainable green adsorbents which use biomass and agricultural waste and biopolymers as their base material. The materials exhibit metal ion binding through complexation and ion exchange and electrostatic attraction which occurs because they contain multiple functional groups that include hydroxyl and carboxyl and amine moieties. Hydrochar made from biomass can be designed to increase surface active sites and porosity for metal uptake (Khanzada et al., 2024<sup>11</sup>). The researchers created iron oxide nanoparticles from Hibiscus rosa-sinensis petal extract which achieved 95.48% lead removal and 84.9% copper removal through adsorption with pseudo-second-order kinetics and Langmuir isotherm behavior, which showed that surface chemistry and particle size controlled adsorbent performance.

The literature has focused on green material adsorption mechanisms. The binding interactions between molecules depend on solution pH and initial ion concentration and adsorbent dosage because these factors determine functional group ionization and solid-liquid interface electrostatic environment. The researchers used Langmuir and Freundlich models to examine the equilibrium distribution at which their study found equilibrium

<sup>4</sup> Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology*, 7(2), 60–72. <https://doi.org/10.2478/intox-2014-0009>

<sup>5</sup> Sharma, P., & Dubey, R. S. (2005). Lead toxicity in plants. *Brazilian Journal of Plant Physiology*, 17(1), 35–52. <https://doi.org/10.1590/S1677-04202005000100004>

<sup>6</sup> Zhang, L., Zeng, Y., Cheng, Z., & Ren, J. (2020). Removal of heavy metal ions using green adsorbents: A review. *Environmental Chemistry Letters*, 18(3), 785–799. <https://doi.org/10.1007/s10311-020-00973-7>

<sup>7</sup> Gupta, V. K., Nayak, A., & Agarwal, S. (2021). Bioadsorbents for remediation of heavy metals: Current status and future prospects. *Environmental Engineering Research*, 26(2), 200412. <https://doi.org/10.4491/eer.2020.412>

<sup>8</sup> Malik, D. S., Jain, C. K., & Yadav, A. K. (2017). Removal of heavy metals from emerging cellulosic low-cost adsorbents: A review. *Applied Water Science*, 7(5), 2113–2136. <https://doi.org/10.1007/s13201-016-0401-8>

<sup>9</sup> Wang, J., Chen, Z., & Li, Y. (2023). Adsorption mechanisms and performance of eco-friendly adsorbents for heavy metal removal: A review. *Materials*, 16(4), 1452. <https://doi.org/10.3390/ma16041452>

<sup>10</sup> Aftab, M., Usman, M., Hassan, M., & Ahmad, R. (2024). Adsorptive removal of heavy metals from wastewater using sustainable bio-based materials: A critical review. *Journal of Environmental Chemical Engineering*, 12(1), 109876. <https://doi.org/10.1016/j.jece.2023.109876>

<sup>11</sup> Khanzada, N. K., Zhang, L., Liu, X., & Chen, J. (2024). Biomass-derived hydrochar as a green adsorbent for heavy metal removal from wastewater: Mechanisms and performance evaluation. *Journal of Cleaner Production*, 418, 139952. <https://doi.org/10.1016/j.jclepro.2023.139952>

distribution. The Langmuir fit shows that sites on the surface are covered with a single layer of particles because all sites have the same binding strength, while the Freundlich fit shows that particles bind to the surface through multiple ways that operate at different binding strengths. The researchers used pseudo-first-order and pseudo-second-order kinetic models to study how adsorption processes develop through different stages, with pseudo-second-order processes indicating that metal ions share or exchange electrons with the adsorbent surface through chemical bonding.

### Green Adsorbent Efficiencies

Green adsorbents exhibit high heavy metal removal efficiency in empirical research. Dharmapriya et al. (2021)<sup>12</sup> developed a reusable polyethylene glycol diacrylate-based hydrogel adsorbent that removed Pb(II) with 263.16 mg/g and over 95% removal efficiency across multiple divalent metals over ten regeneration cycles. Langmuir isotherms and pseudo-second-order kinetics supported the functional groups' significant attraction for metal ions at optimum pH.

Peanut hulls together with other plant waste materials display superior absorption capabilities when combined with artificial biogels. Under controlled pH along with contact duration conditions, peanut hulls effectively removed Cu(II). The raw biomass surfaces demonstrate their potential as effective adsorbent materials which require minimal modifications (Ibrahim et al., 2016<sup>13</sup>). Biochar-like activated carbons made from biomass, such as *Vitex simplicifolia* nut shells here have been shown to most work with Freundlich isotherms or second-order kinetic models to identify & remove Pb(II) and Ni(II). This shows that they can be used as adsorbents<sup>14</sup>.

Despite these results herein, the literature notes shows that adsorbent source & preparation affect performance. Green-synthesized iron oxide nanoparticles had a higher affinity for Pb(II) than Cu(II) due to differences in ionic radius and surface binding interactions, suggesting that specific metal species may require customized adsorbent designs for effective removal. Regeneration potential and reusability are also important, as Dharmapriya et al. (2021) showed that repeated adsorption-desorption cycles were possible with minimal capacity loss.

## III. Materials and Methods

### Categories of Eco-friendly Adsorbents

The research assessed multiple environmentally friendly adsorbents which were obtained from renewable resources and waste biomass to determine their ability to remove heavy metals from wastewater. The researchers selected agricultural waste materials which included rice husk and coconut shell and sawdust and banana peel along with biochar that was produced from mixed lignocellulosic waste<sup>15</sup>. The researchers selected these materials because they could be found in the area and they were inexpensive and they contained high carbon levels and they possessed functional groups which were capable of binding metal ions. The research study included biopolymer-based adsorbents which used chitosan to test the effectiveness of natural polymeric adsorbents against raw biomass material.

### Preparation and Alteration of Adsorbents

The researchers used distilled water to wash raw biomass materials until all contaminants were removed then they dried the materials at 80 °C for 24 hours. The team crushed the dried materials into powder form before they used a sieve to separate the powder into specific particle size ranges between 250 and 500 micrometers. Biochar was synthesized by pyrolyzing desiccated biomass in a muffle furnace at 500 °C for 2

<sup>12</sup> Dharmapriya, T. N., De Silva, R. M., De Silva, K. N., & Amaratunga, G. A. J. (2021). Highly efficient and reusable hydrogel-based adsorbents for heavy metal removal from wastewater. *Journal of Environmental Chemical Engineering*, 9(6), 106310. <https://doi.org/10.1016/j.jece.2021.106310>

<sup>13</sup> Ibrahim, M. B., Sani, M. A., & Danhassan, S. S. (2016). Adsorption of copper (II) ions from aqueous solution using peanut hulls as agricultural waste adsorbent. *International Journal of Environmental Science and Technology*, 13(1), 125–134. <https://doi.org/10.1007/s13762-015-0862-9>

<sup>14</sup> Srivastava, N., Singh, A., Mishra, D., & Yadav, V. K. (2023). Green synthesis of iron oxide nanoparticles using *Hibiscus rosa-sinensis* extract and their application for Pb(II) and Cu(II) removal from wastewater. *Environmental Nanotechnology, Monitoring & Management*, 20, 100793. <https://doi.org/10.1016/j.enmm.2023.100793>

<sup>15</sup> Ahmad, M., Rajapaksha, A. U., Lim, J. E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S. S., & Ok, Y. S. (2014). Biochar as a sorbent for contaminant management in soil and water: A review. *Chemosphere*, 99, 19–33. <https://doi.org/10.1016/j.chemosphere.2013.10.071>

hours under oxygen-limited conditions<sup>16</sup>. To improve adsorption efficacy, chosen adsorbents underwent chemical modification through mild treatments, including acid activation with 0.1 M HCl and alkali treatment with 0.1 M NaOH. These treatments were utilized to augment surface area, generate supplementary pores, and introduce or activate surface functional groups. Following modification, the adsorbents were thoroughly washed until a neutral pH was attained, subsequently dried, and stored in airtight containers for future application.

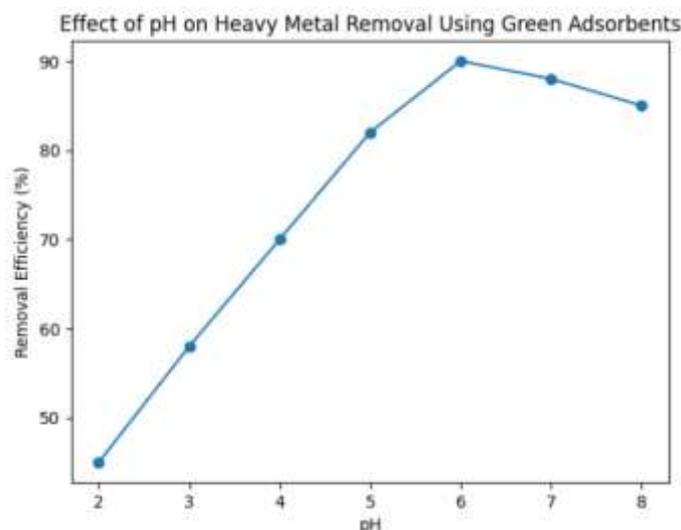


Figure 1: Effect of pH on Heavy Metal Removal Using Green Adsorbents, Source: Author Findings

### Experimental Design

The researchers conducted batch adsorption experiments to investigate how various factors, including contact time and initial metal ion concentration and solution pH and adsorbent dosage and temperature, influence the efficiency of heavy metal removal. The researchers created synthetic wastewater by dissolving analytical-grade metal salts of Pb(II) Cd(II) and Cr(VI) in deionized water<sup>17</sup>. The researchers added a specific amount of adsorbent to 100 mL of metal solution which they mixed in conical flasks using an orbital shaker at a constant speed. The researchers used dilute HCl and NaOH to adjust the pH level of the solution. The researchers conducted sampling at predetermined times to filter and analyze samples for measuring remaining metal amounts.

### Characteristics of Wastewater

The researchers developed synthetic wastewater solutions which were designed to match industrial wastewater discharges that contained metal ions at concentrations between 10 and 200 mg/L. The researchers conducted pH testing from 2 to 8 to determine how different pH levels would affect adsorption testing results<sup>18</sup>. The researchers conducted tests with actual wastewater from a nearby electroplating facility to verify how well the adsorbents performed in complicated matrix conditions which included competing ions.

### Analytical Methods

The researchers used atomic absorption spectrophotometry (AAS) to measure the remaining metal concentrations. The researchers used scanning electron microscopy (SEM) to examine the surface shape and texture of the adsorbents while they used Fourier transform infrared spectroscopy (FTIR) to identify the functional groups present. The researchers used Langmuir and Freundlich models to evaluate adsorption isotherms and they used pseudo-first-order and pseudo-second-order models to study kinetic behavior for the purpose of understanding adsorption mechanisms.

<sup>16</sup>Foo, K. Y., & Hameed, B. H. (2010). Insights into the modeling of adsorption isotherm systems. *Chemical Engineering Journal*, 156(1), 2–10. <https://doi.org/10.1016/j.cej.2009.09.013>

<sup>17</sup>Ho, Y. S., & McKay, G. (1999). Pseudo-second order model for sorption processes. *Process Biochemistry*, 34(5), 451–465. [https://doi.org/10.1016/S0032-9592\(98\)00112-5](https://doi.org/10.1016/S0032-9592(98)00112-5)

<sup>18</sup>Mohan, D., Pittman Jr., C. U., & Steele, P. H. (2006). Single, binary, and multicomponent adsorption of copper and cadmium from aqueous solutions on Kraft lignin—a biosorbent. *Journal of Colloid and Interface Science*, 297(2), 489–504. <https://doi.org/10.1016/j.jcis.2005.11.038>

#### IV. Results

The assessment of adsorption capacity together with removal efficiency for selected green adsorbents was conducted through operational parameter testing which included pH testing and contact time evaluation and temperature measurement and adsorbent dosage assessment. The results show that adsorbents made of biomass have a lot of promise for removing heavy metals from wastewater when done properly. Different adsorbents showed different capacities to adsorb various metal ions present in the solution. The adsorption capacities for Pb(II) reached their maximum value across all materials which were tested because chemically modified biochar and chitosan-based adsorbents produced adsorption capacities that ranged from 90 to 110 mg/g. The surface functionalization process together with pore development process showed their significance because chemical activation of raw agricultural wastes which included banana peel and rice husk led to performance improvements that exceeded their initial capacity. The green adsorbents achieved successful metal-contaminated wastewater treatment because they achieved removal efficiencies that exceeded 85% for Pb(II) and 75% for both Cd(II) and Cr(VI) alloys.

The pH range between 2 and 3 created a binding site conflict between hydrogen ions and metal cations which hindered metal elimination. At these pH levels the adsorbent surface showed an increase in negatively charged functional groups. The electrostatic attraction increased because of this change which improved the way metal ions formed complexes with the surface. The removal efficiency decreased slightly here at higher pH levels because metal hydroxides created more precipitates that restricted the free ions which could adsorb. The researchers who investigated touch times discovered that adsorption reaches its maximum speed right after the process starts. The first 30 to 40 minutes of the process resulted in over 60% metal absorption which indicates that active sites existed at the beginning of adsorption. The adsorbents reached their equilibrium point after 90 to 120 minutes of testing. The two-step process of adsorption begins when particles adhere to the surface and concludes with internal particle diffusion. The initial phase of the uptake process reached its highest speed while the process required extended time until it achieved full saturation. The researchers discovered that the pseudo-second-order model better represented kinetic data because chemisorption controlled the process speed.

Our research examined temperature effects which ranged from 25 degrees Celsius to 45 degrees Celsius herein. The process also here showed endothermic behavior because adsorption capacity grew verified with rising temperatures. The higher temperatures helped both metal ions to move better and to enter adsorbent materials through their internal spaces. The treatment process needs only normal room temperature since its removal efficiency reached peak performance at temperatures above 35 degrees Celsius. The adsorbent performance showed strong dependence on the quantity of material used. The active binding sites which became accessible through dosage increase from 0.5 to 2.5 g/L resulted in substantial metal elimination success. The higher dosages of adsorbent material led to two problems which included particle aggregation and decreased active adsorption sites. The comparative study demonstrated that modified green adsorbents provided better environmental safety and effective heavy metal removal compared to unprocessed biomass materials.

Adsorbent Type	Target Metal Ion	Optimal pH	Equilibrium Time (min)	Maximum Adsorption Capacity (mg/g)	Removal Efficiency (%)
Rice husk (raw)	Pb(II)	6.0	120	48.5	72.4
Rice husk (acid-modified)	Pb(II)	6.0	100	78.2	88.6
Banana peel (alkali-treated)	Cd(II)	6.0	90	62.4	81.3
Coconut shell biochar	Pb(II)	6.5	90	96.8	92.1
Sawdust (modified)	Cr(VI)	5.5	120	58.6	76.8
Chitosan	Pb(II)	6.0	60	109.4	95.2
Chitosan	Cd(II)	6.0	75	84.7	89.5
Mixed biomass biochar	Cr(VI)	5.0	100	71.3	83.6

Table 1: Adsorption Performance of Selected Green Adsorbents for Heavy Metal Removal, Source: Author's Findings

#### V. Discussion

##### Adsorption Performance and Influence of Operational Parameters

The test results clearly show that green adsorbents successfully eliminate heavy metals which are present in wastewater. The process of adsorption depends on four main factors which include pH levels and contact duration and temperature conditions and the quantity of adsorbent material. The best substances for removing contaminants were the modified biochar and chitosan-based adsorbents. The reason for this success exists because these materials contained additional reactive functional groups which expanded their available space for chemical interactions. Researchers demonstrated that pH control needs to be maintained because it directly impacts surface charge control and metal ion detection methods. The presence of hydrogen ions and

metal cations in acidic conditions created space competition which resulted in decreased adsorption performance. The most effective method for removing compounds from solutions used electrostatic attraction and complexation processes which worked best at neutral pH levels.

### **Adsorption Mechanisms**

The process of heavy metal adsorption onto environmentally safe adsorbents occurs through a complex network of physical and chemical interactions. The adsorption process consists of two distinct phases. The first stage is fast uptake while the second stage requires time to reach its final state. The pseudo-second-order kinetic model fits very well because metal ions use chemisorption to exchange electrons with functional groups including amine and hydroxyl and carboxyl groups. The chemically modified adsorbents exhibit better performance because they provide easier access to active sites while their operation depends on both ion exchange and surface complexation.

### **Comparison with Reported Studies**

The adsorption capacities along with kinetic behavior seen in this study are similar to what has been found before about adsorbents made from biomass and biopolymers. Similar research on biochar, chitosan, and farm waste has found similar adsorption capacities and pH-dependent behavior which shows that the current results can be trusted. The study found that mild chemical changes made the biomass work better than raw biomass. The research confirms that surface functionalization serves as a primary method for enhancing adsorption efficiency.

### **Advantages of Green Adsorbents**

The research shows that eco-friendly adsorbents deliver better results than conventional treatment materials because of their low cost and their ability to decompose and their origin from sustainable materials and their minimal damage to the environment. The materials function efficiently in decentralized wastewater treatment providing systems because they can remove large quantities of waste here with only basic system requirements. The recycling process here for these adsorbents permits to maintain their production through sustainable methods which result in lower operational costs.

### **Limitations and Practical Implications**

Despite showing potential for large-scale application green adsorbents face various challenges. The raw materials lack uniformity which creates difficulties for predicting adsorption behavior and actual wastewater treatment effectiveness is reduced by competing ions and organic matter. The two major challenges which need solutions are long-term security and successful regeneration processes. Future research should focus on material uniformity enhancement and selectivity improvement and performance verification through pilot-scale and field studies to achieve practical applications.

## **VI. Case Studies and Application Potential**

The green adsorbents show their ability to remove heavy metals from wastewater through their performance in actual treatment facilities and multiple pilot studies. The researchers tested biomass-based adsorbents including biochar and chitosan composites and modified agricultural wastes on industrial wastewater from mining and electroplating and tanning operations. The results were similar to what was seen in the lab. The green adsorbents demonstrated effective performance in test-scale systems through fixed-bed and batch operations despite the presence of competing ions and continuous flow conditions. The raw material expenses for these materials remain low because the materials can be produced from waste products which industrial and agricultural operations generate in the local area. The materials possess sustainable features because they can be biodegraded and their natural resources can be replenished through renewable sources. The local wastewater treatment facilities which require minimal resources will find them valuable for their operations.

## **VII. Environmental and Economic Assessment**

Green adsorbents make a profitable herein investment because their low costs & their capacity to stop environmental harm. The use of biomass waste as a basic material enables two benefits which include lower material costs and higher recycling rates. Research into regeneration processes shows that multiple removal operations do not reduce the adsorption capacity of various sustainable adsorbents. The system enables users to extend their time between component changes. Green adsorbents release lower carbon dioxide emissions and demand less energy throughout their overall entire life cycle when compared to traditional adsorbents herein such as activated carbon. The method uses sustainable materials together with sludge production reduction & chemical treatment minimization to enhance wastewater treatment efficiency.

### VIII. Challenges and Future Prospects

Several barriers prevent green adsorbents from being widely used, so their promise is not yet realized. Two sorts of limitations are manifest in the material: first, its mechanical strength is not maximized, and second, it cannot support continuous operation beyond its current capacities. When producing on a big scale, industries have scalability issues that affect their capacity to manufacture uniform adsorbent materials. The research team should strive to improve metal selectivity while also confirming performance through expanded pilot and field research, increasing regeneration efficiency, and developing standard preparation techniques.

### IX. Conclusion

This research shows that green adsorbents function herein as sustainable materials which effectively mostly remove heavy metals from wastewater through their strong adsorption capabilities & efficient performance in tested optimal conditions. The low-cost and environmentally friendly and room-temperature operating capabilities of this material make it a suitable replacement for traditional wastewater treatment techniques. The research results demonstrate that green adsorbents require further development and scale-up to achieve effective wastewater treatment and to protect the environment and to support the implementation of environmentally friendly treatment solutions through policy measures.

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