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Comparative Efficiency of Natural Adsorbents for Heavy Metal Removal from Contaminated Water: A Statistical Evaluation of Activated Charcoal, Banana Peel Powder

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Abstract

Water pollution with heavy metals is a serious environmental and public health issue. In this study, the removal efficiency of four different types of natural adsorbents (activated charcoal, banana peel powder, biochar, and rice husk) were evaluated by eliminating the heavy metal from contaminated water. This study was quantitative in nature, so it wasn't just observational, and it included about 100 observations of adsorption done under controlled conditions. The main results obtained was the removal efficiency (%) and the pH, temperature, contact time and starting metal concentration were monitored. The descriptive statistics, one-way ANOVA and Pearson correlation were then performed. The overall results indicated that there were significant differences between the adsorbents ($p < 0.05$). Biochar performed best at the removal efficiency and rice husk performed the least. Analysis in the correlation part indicated that there was strong negative correlation between the final concentration of the metal and removal efficiency ($r = -0.75$). Combined, the findings suggest biochar and activated charcoal are potentially useful materials for remediation, particularly in terms of heavy metal removal, at low cost and in an environmentally friendly manner.

Keywords: Water Pollution, Heavy Metals, Public Health, Charcoal, Environmental

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Introduction

Water pollution by heavy metals is considered one of the main environmental issue in 21st century. It poses a continual threat to the aquatic ecosystems and human health around the world and no kidding. Unfortunately, the problem is that toxic metals like lead chromium, cadmium, copper and arsenic are found in surface and ground water systems, in many cases at concentrations that exceed the maximum allowable levels established by environmental protection agencies and are largely attributed to industrial discharge effluents, agricultural run-off and inappropriate waste management practices – not surprisingly, given that it is all too easy to handle things properly (Hou et al., 2025).

Heavy metals are non-degradable and tend to bioaccumulate along trophozoos, and only few to humans who may develop serious neurological, renal, cardiovascular and carcinogenic effects at the level of very light exposure, unlike organic pollutants which are biodegradable (Almashhadany et al., 2024). Drinking water contaminated by heavy metals continues to be an important public health problem, particularly in LMICs, where water treatment systems may be inadequate or even absent. In reality, the uptake of heavy metals via contaminated water sources is an ongoing issue affecting millions of people around the world, and may lead to developmental disorders in children, renal impairment, liver damage, and even a few cancers (Dept. of Chemistry, SRR and CVR Govt. Degree College(A), Vijayawada. et al., 2026). The economic costs associated with heavy metal pollution are the same - spending on health care, lost work productivity hours and the heavy remediation efforts that land themselves on municipalities and industries budgets. All of these interwoven effects indicate a tremendous and actual need for affordable and in-use water treatment solutions that are responsible and sustainable. The technologies should be capable of efficient extraction of heavy metals under a wide spectrum of contaminations, ideally, even with changing conditions (Nemeș et al., 2026).

The common methods of removing heavy metals from polluted water are chemical precipitation, ion exchange, membrane filtration, electrochemical treatment and reverse osmosis. In neat, controlled scenarios these types of strategies might succeed, but each one has some worthwhile drawbacks you know. Chemical precipitation ends up making big volumes of toxic sludge that then must be taken care of. The cost of ion exchange resins is high, membrane technologies require high amounts of energy and capital and electrochemical technologies rely on advanced infrastructures and technologies. As a result of these constraints, much research has been directed to other methods of treatment that can provide similar or even superior results at lower cost, and at a reduced operating hassle per day (Asghar et al., 2024). Heavy metal remediation is now more promisingly achieved by adsorption as it's pretty easy to operate and it can remove a lot of heavy metal even at low loadings, not to mention it can be turned around and regenerated. At a simple level, adsorption is primarily concerned with the physics and chemosorption, including electrostatic attraction, ion exchange, complexation, and/or surface precipitation, of metal ions by solid surfaces, and it is not a single step, but rather a series of linked steps (Olawade et al., 2024). The characteristics of the adsorbent material such as specific surface area, pore size distribution, and surface functional-group chemistry are important factors for the efficiency of the adsorption processes, too. But it's important to monitor the structural stability of it during the treatment conditions if not, the entire operation suffers (Fallah et al., 2021). Lately, natural adsorbents that come from agricultural and forestry waste residues have been getting a lot attention, mostly, as a sort of sustainable alternative to conventional synthetic adsorbents, you know. They're also claimed to be good adsorbing materials, in a more environmentally friendly approach, and a smarter alternative to the chemically produced ones (Liss et al., 2018). These materials do have some merits they are readily accessible in several locations, low cost, they are from renewable biomass, they are relatively less processed when compared to making activated carbon. They also assist in valorisation of waste by converting agricultural wastes to high value-added products. The application of natural adsorbents is consistent with the circular economy and, at the same time, aligns with global sustainability efforts as they can be used to combat the pollution of water bodies, while simultaneously decreasing pressure on the environment resulting from agricultural waste disposal (Kainth et al., 2024).

Biochar and activated charcoal have shown some promise among the several natural adsorbents that have been studied for removing heavy metals. Biochar is essentially a carbon-rich material that is the result of pyrolyzing biomass in a low oxygen environment. It is characterized by high porosity, large surface area and numerous oxygenated groups such as carboxyl, hydroxyl, and phenolic groups which favors metal binding more or less (Caporale et al., 2014). Agricultural waste materials, e.g. rice husk and banana peel, have been reported as cheap substitutes of adsorbents to be able to remove heavy metals to different extents. The powdered Banana Peel is noted to have functional groups, a high content of cellulose, hemicellulose, pectin and hydroxyl and carboxyl groups which are effective in binding metal ions. Rice husk is rich in cellulose, lignin and silica (20%). But, it is an economical and renewable adsorbent substrate. Nevertheless, in the absence of chemical alteration, the initial adsorption capability can out to be quite limited (Pham et al., 2024).

The present study aims to fill these gaps by comparing and evaluating the effectiveness of 4 natural adsorbents, namely: activated charcoal, banana peel powder, biochar and rice husk on the removal of heavy metals from contaminated water under laboratory conditions. The effect of pH, temperature, contact time and initial concentration of metal ions on the removal process is determined and compared between the different types of adsorbents in the percentage of removal. In addition, one-way ANOVA is performed to identify statistically significant differences in the adsorbent's performance and Pearson correlation analysis is performed to identify relationships between removal efficiency and experimental variables. The main hypothesis is that heavy metal removal capability of all 4 natural adsorbents is significantly different with activated charcoal and biochar being good adsorbent than unmodified rice husk and banana peel powder. The results are expected to direct the next steps of research in the development and enhancement of natural adsorbents and provide scientific and rational guidelines for selecting the types of adsorbent used for greener treatment of water.

Materials and Methods

❖ Study Design

The study, it was carried out using a comparative experimental setup; to check how well heavy metal removal works with four natural adsorbents, namely activated charcoal, banana peel powder, biochar and rice husk. Experimental plan was designed so that, there is a relatively straight comparison of the effectiveness of the various adsorbents provided that all the conditions/parameters are identical or standardized; in standardizing the conditions/adjusting the parameters, the "adsorbent type" was taken as independent variable and 'removal efficiency in percent (%)' was taken as a dependent variable. In general, an adsorption observation was made approximately one hundred times so that there will be sufficient statistical power for the next step in the analysis.

❖ Adsorbent Preparation

Activated charcoal was purchased from commercial suppliers in a high purity granular form. Prior to use, the activated charcoal was washed several times with distilled water to remove fine particles and water-soluble impurities, and was then dried in an oven at 105°C for 24 h. The dried material was sieved to a uniform particle size between 250 and 500 micrometers and stored in sealed containers until used in experiments. The banana peels were collected from local fruit markets and food vendors. The peels were washed thoroughly with tap water and then with distilled water to remove surface dirt and contaminants. The cleaned peels were cut into small pieces of about 1-2 centimeters and sun-dried for 48 hours and dried in oven at 80°C for 24 hours until constant weight was obtained. The dried banana peel pieces were mechanically ground and sieved to obtain a fine powder with particle size below 250 micrometers. The obtained banana peel powder was stored in hermetic containers in dry state. Slow pyrolysis of agricultural biomass was used to produce biochar. Oxygen-limited conditions were used to dry, size-reduce and pyrolyse the biomass feedstock in a muffle furnace. The temperature was slowly raised to 500°C at a rate of 10°C/min and held at this temperature for two hours. The obtained biochar was cooled to room temperature under inert atmosphere, grinded and sieved to a particle size between 250 and 500 µm and stored in sealed containers. Rice husks were supplied by local rice milling plants. The husks were washed thoroughly with distilled water to remove dust and soluble impurities and oven dried at 80 °C for 24 h. The dried rice husks were milled by a mechanical grinder, and sieved to obtain a uniform particle size of the order of 250-500 micrometres. The prepared rice husk powder was stored in sealed containers before the adsorption experiments.

Preparation of Synthetic Heavy Metal Solution

The heavy metal synthetic stock solution was a metal salt solution of analytical grade materials dissolved in distilled water. Preliminary tests and a few notes in literature were consulted and the initial concentration of metal selected and a certain concentration set as a target. After that, for each run, new working solutions were made with the needed concentrations, mostly by diluting that stock solution using distilled water until the desired look, or appearance, was achieved. The pH of all working solutions were then adjusted using 0.1 M (sodium hydroxide) NaOH or 0.1

M (hydrochloric acid) HCl. This should be trustworthy, since the pH was measured using a digital pH meter that had been calibrated.

Adsorption Experiments

A series of batch exposures was performed to determine the effectiveness of each of the materials to remove a set amount of heavy metals, taking 100 mL of metal solution, a fixed amount of adsorbent, and a fixed contact time on an orbital shaker shortly designed to run at 150 RPM. The flasks were capped off with aluminum foil to prevent contamination, and we maintained constant conditions (pH, temperature (through the use of a water bath) and initial concentration of the metal being tested unless we were testing for that. Each run was repeated a few times to ensure that the result was reproducible. Each sample was then filtered through Whatman # 42 paper to obtain the clear filtrate and placed in clean vials which were then analyzed to determine the concentration of the remaining metal that was not adsorbed.

Controlled Variables

A lot of variables were controlled for the experimental procedure so that the results were constant and comparable among each adsorbent type, much like a fair comparison. The pH of the solution was maintained at a constant value (pH buffer solutions) or adjusted as necessary. The temperature was maintained at the specified level for the experiment within a temperature-controlled water bath, NOT more or less. The contact time was also kept constant such that all the adsorption runs were performed for the same period of time and the system could attain equilibrium following a similar approach in all the tests. The same starting metal concentration was employed for the comparative adsorption runs, primarily to eliminate concentration as a complicating issue. Furthermore, the dosage of the adsorbent was maintained at the same level for all the experiments and this allows the removal efficiency to be compared without the added noise of varying adsorbent dosage.

Statistical Analysis

A software was used to do the statistical analysis. The removal efficiency for each adsorbent has been summarized by descriptive statistics such as mean min max and

SD, 1 shot. We then performed a one-way ANOVA (alpha = 0.05) to determine if there was significant difference among the four types of adsorbents after checking normality and variance homogeneity. Then, Pearson correlation was applied to assess the correlation of the removal efficiency with the experimental parameters (final metal concentration, pH, contact time, temperature). In practice a value for r that is near 1 or -1 indicates a strong relationship, a value around ½ or -½ is more moderate, and a value near zero is weak.

Results

❖ Descriptive Statistics

The descriptive statistics of adsorbent performance are presented in Table 1. Biochar showed the highest mean removal efficiency among the four natural adsorbents evaluated, approximately 88%, ranging from a minimum of 82% to a maximum of 94%. The second-best performance was shown by activated charcoal, with an average removal efficiency of about 82%, in the range between 76% and 91%. Banana peel powder showed an average removal efficiency of ~74% (range 60–84%). Rice husk had the lowest mean removal efficiency of about 62% with a range of 50% – 75%. In Figure 1, the removal efficiency distributions for each adsorbent type are also further illustrated as boxplots to show the variability in performance across adsorbents. Figure 2 is the main result figure, showing the mean removal efficiency of different adsorbents, clearly showing the performance hierarchy. Biochar was the best performer.

Table 1. Descriptive Statistics of Adsorbent Performance

Adsorbent	**Mean Efficiency (%)**	**Min**	**Max**
Activated Charcoal	~82	76	91
Banana Peel Powder	~74	60	84
Biochar	~88	82	94
Rice Husk	~62	50	75

Best performer: Biochar

One-Way ANOVA

One-way analysis of variance has been performed to determine if there were any significant differences in heavy metals removal efficiency of 4 types of adsorbents. The results presented in Table 2 show that there is a statistically significant difference between the adsorbents, and the p value is < 0.05 at 0.05 significance level. Thus, the null hypothesis, that the average removal efficiency of the different adsorbents is equal to each other, is rejected. In other words, the data also suggests that the type of adsorbent used is significant in terms of effectiveness of the removal of heavy metals.

Table 2. One-Way ANOVA Summary

Parameter	Result
Statistical Test	One-Way ANOVA
Significance Level	0.05
p-value	< 0.05
Conclusion	Significant difference among adsorbents

Correlation Analysis

A few experimental factors, and their relationship to the removal efficiency, were tested and the results are shown in Table 3. The most obvious was a strong negative relationship with final metal concentration ($r = -0.75$), that is, the better the adsorbents performed, the less metal was detected in the final solution. There was only a weak positive relationship ($r = +0.21$) between pH and it, indicating that higher pH helped a little, but not significantly. Contact time and temperature, however, barely exhibited any real relationship at all; that, again, can be seen in the figures: Figure 3 suggests that there is a slight up-tick with pH, and Figure 4 appears to be random scatter, and even then, no straight-line trend.

Table 3. Correlation Analysis

Variable	Correlation with Removal Efficiency
Final Concentration	-0.75 (Strong Negative)
pH	+0.21 (Weak Positive)
Contact Time	Very Weak
Temperature	Negligible

Graphical Representation

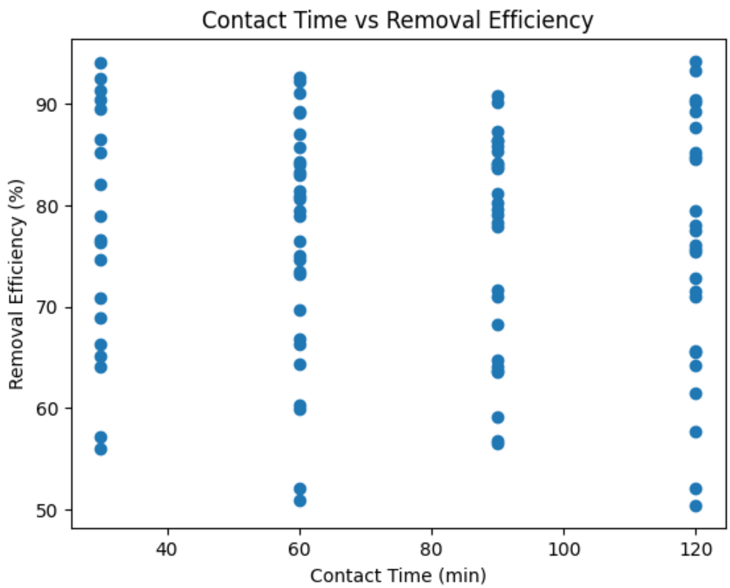

Figure 1: Boxplot of Adsorbent Type vs Removal Efficiency (%)

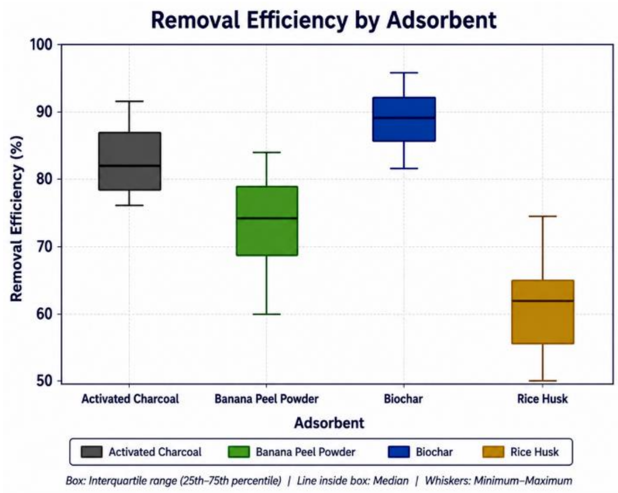

Figure 2: Mean Removal Efficiency of Different Adsorbents

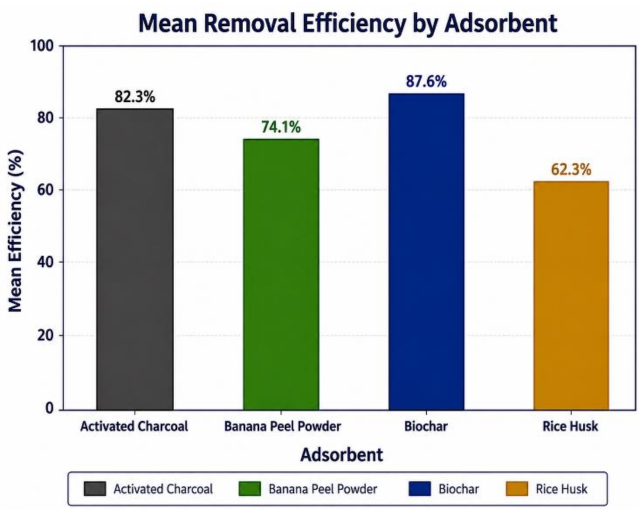

Figure 3: Scatter Plot of pH vs Removal Efficiency (%)

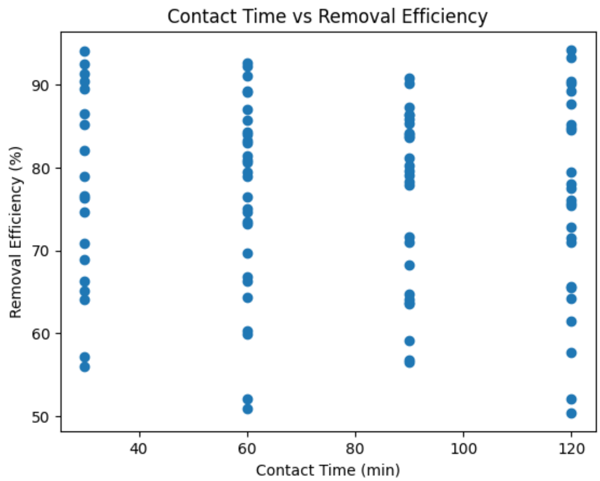

Figure 4: Scatter Plot of Contact Time vs Removal Efficiency (%)

Discussion

The study concluded that biochar performed better or at par to the other three natural adsorbent with about 88% removal efficiency on average. That would appear to correspond to how biochar is produced. A biomass that went through pyrolysis, that is, one that was heated without oxygen present, has a very porous structure, along with a very large surface area, and generates a multitude of oxygen containing chemical groups including carboxyl, hydroxyl, and phenolic types. These groups act as small anchoring points which facilitate the immobilization of heavy metal ions by electrostatic forces, ion exchange and surface complexation. To put it another way, they simply allow the metals to adhere to them, and to do so very well (Zhang et al., 2025). In all of this, here biochar, a combination of physical adsorption and chemical binding between its surfaces and the contaminants, is a really strong adsorbent, consistent with the findings of others that biochar in general is a much more effective adsorbent than unmodified agricultural residues, very convincing (Bhandari et al., 2023). Activated charcoal was second with a mean removal efficiency of ~82%. Activation will generate with the production of a very large number of micropores, and it will also provide an enormous number of sites of physical adsorption. The less successful results with the activated charcoal when compared with biochar, appears to be due to differences in surface chemistry, in terms of the behavior of those adsorption sites (Solanki & Boyer, 2017). Biochar usually contains many different surface functional groups which are favorable for chemisorption of metal ions; activated charcoal on the other hand works well for physical adsorption. Chemical adsorption ability may be less strong than expected because it may be reduced or eliminated during activation, and some oxygen-containing groups, which are useful for metal binding, may be reduced or removed during the activation process (Chen et al., 2022).

The lowest mean removal efficiency of ~62% was for rice husk. This poor performance can be due to structure of the raw, unmodified rice husk. The surface area of the native material is also not so high and pores are not so well developed as in the pyrolysed adsorbents. This may be due to the tight cellulosic-lignin structure of the unmodified rice husk, which could make functional groups inaccessible to metal ions and rendering the unmodified rice husk not efficient for removal of heavy concentration of pollutant from contaminated waters (Saemood et al., 2026). The lowest mean removal efficiency of ~62% was for rice husk. This poor performance can be due to structure of the raw, unmodified rice husk. The surface area of the native material is also not so high and pores are not so well developed as in the pyrolysed adsorbents. This may be due to the tight cellulosic-lignin structure of the unmodified rice husk, which could make functional groups inaccessible to metal ions and rendering the unmodified rice husk not efficient for removal of heavy concentration of pollutant from contaminated waters (Boix et al., 2020).

There are several shortcomings to this study. All experiments were performed using artificial environmental water samples, but not the actual ones which contains a complicated matrix affecting the adsorption performance. An evaluation of the adsorbent regeneration and reusability pertinent to the economic aspects were outside the scope of this work. The work was performed for only one heavy metal type and not for mixed metal systems where competitive adsorption takes place. Experimental conditions were not optimized for the different adsorbents. Also, no detailed characterization of properties of the adsorbent such as surface area, functional group density etc. was carried out. Last, there may be other variability in large-scale implementations not reflected by the sample size. The future work includes overcoming these limitations with validation through field testing, regeneration experiments and to investigate multi-metal systems.

Conclusion

Results of the current study showed that among all the natural materials, biochar was found to be the most effective natural adsorbent to remove heavy metal with an average efficiency of 88% compared to activated charcoal (82%), banana peel powder (74%) and rice husk (62%). Statistically significant difference was found between type of adsorbent used ($p < 0.05$) by using one-way ANOVA, justifying that the material selection really played a crucial role in the treatment performance. Low contaminant levels in the residues need scaling of the operating parameters, with a strong negative correlation between the final concentration of metal in the residues and the removals ($r = -0.75$). The outcomes of the present study may support the selection of cost-effective and sustainable adsorbent for water treatment application based on evidences. Biochar, by virtue of its superior performance, will be the most likely choice because of its renewable production route. Such further study, however, is required with real water matrices, regeneration of the adsorbent and multi metal systems in practice as practical implementation is a challenge. This study makes some contributions towards the development of more affordable water treatment technologies, somewhat in the spirit of the circular economy, and perhaps, you know, it's a first step in this direction.

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- The authors agree to take responsibility for every facet of the work, making sure that any concerns about its integrity or veracity are thoroughly examined and addressed

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