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# PHYSICOCHEMICAL CHARACTERIZATION AND COMPARATIVE EVALUATION OF BIOCHAR MATERIALS FOR HEAVY METAL ADSORPTION

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**ABSTRACT**

Due to its attractive physicochemical characteristics and production from various biomass feedstocks, biochar has shown potential as a sustainable adsorbent for heavy metal remediation. But, due to the differences between feedstock and pyrolysis conditions, significant differences in adsorption performance are obtained, indicating the need of systematic comparative evaluation. The present study compared the physicochemical properties of various biochar materials and examined the correlation between the physicochemical properties and the adsorption performance of Pb and Cd by biochar by using a secondary open access data set. A compiled data set of adsorption records of Pb and Cd, as well as physicochemical properties, pyrolysis conditions, and adsorption performance indicators were analysed quantitatively. Descriptive statistics, comparative analysis, correlation analysis and multiple linear regression were used to evaluate the effect of physicochemical properties on the adsorption of heavy metals. Results indicated a significant variation among the materials in pyrolysis temperature, specific surface area, pore characteristics, elemental composition and biochar pH. Similarly, adsorption capacity and removal efficiency for both Pb and Cd were greatly different depending on different biochar feedstocks. The regression analysis revealed that the initial concentration of the metal was the best predictor of adsorption capacity, and the other variables (physicochemical properties) also influenced the adsorption capacity. Conclusively, systematic physicochemical characterization is important to choose efficient biochar materials for removing heavy metals. The results offer insights for further development of the biochar-based adsorbents and the utilization in sustainable water treatment and environmental remediation.

**KEYWORDS**
Biochar; Heavy metal adsorption; Physicochemical characterization; Lead; Cadmium.

## 1. INTRODUCTION

Rapid industrialization, mining, urbanization, agricultural intensification and inadequate disposal of industrial effluents have led to heavy metal contamination, which has become one of the most entrenched environmental issues. Of particular concern are toxic metals like lead (Pb) and cadmium (Cd), as they accumulate in the environment and the food chain and are not biodegradable. The traditional remediation technologies such as chemical precipitation, ion exchange, membrane filtration, coagulation, etc. are usually high operating cost, secondary pollution, and not suitable for low concentration contamination. Hence, the design of adsorbents that are environmentally friendly, economically viable and highly effective is now a priority for the present-day environmental chemistry research. Biochar has received significant attention among the available alternatives because of its ready availability, low producing cost, renewable nature, and excellent adsorption potential towards various heavy metals in aqueous environments (Bayar et al., 2024; Hashmi et al., 2024).

Biochar is a porous material rich in carbon produced by thermochemical treatment of biomass under oxygen limited conditions. Physicochemical properties such as surface area, pore structure, mineral composition, surface functional groups, elemental composition and alkalinity control its adsorption efficiency. These characteristics impact adsorption site availability and several removal mechanisms including electrostatic attraction and ion exchange, pore filling, complexation, and surface precipitation. Furthermore, some modification methods have been suggested to further improve the adsorption capacity of biochar by adding more functional groups or mineral phases that can selectively adsorb heavy metals. Previous studies have consistently shown that both pristine and modified biochars have impressive adsorption capacities for Pb (II), Cd (II), and toxic metal ions, which highlights the potential of biochars as sustainable adsorbents in wastewater treatment processes (Lee & Shin, 2021; Liu et al., 2022; Wang et al., 2024).

The physico-chemical characteristics of biochar greatly depend on biomass feedstock characteristics and production conditions, especially the pyrolysis temperature. Generally, higher pyrolysis temperatures favor carbonization, aromaticity, pore formation, and surface area, along with the presence of oxygen functional groups and mineral components (Mulyanto et al., 2026; Almanassra et al., 2024)). Therefore, it is expected that biochars produced from different feedstocks are often very different in terms of adsorption capacity under the same experimental conditions. Many studies have reported substantial correlation between the physicochemical properties and the removal efficiencies of the heavy metals, and the systematic characterizations are vital before assessing the adsorption behaviour (Cuixia et al., 2020; Xu et al., 2022).

In spite of increasing experimental studies, the comparative assessment of different biochar materials is difficult, due to the different feedstock sources, preparation procedures, characteristics, and experimental conditions used (Van Hien et al., 2020). Comparative evaluations are thus necessary to determine the properties that most affect the adsorption efficiency and to assist in selecting appropriate biochar materials for practical applications in the environment. Our previous comparative research has shown that the adsorption capacity of different types of biochar is significantly influenced by their biomass sources, activation methods, and physical and chemical properties, with no single biochar consistently outperforming others under all conditions (Chaudhary et al., 2024; Thue et al., 2022).

In addition, recent progress in statistical modelling and quantitative analytical methods has further improved the understanding of adsorption mechanisms of heavy metals, allowing to identify critical physicochemical variables that govern the adsorption performance of a number of biochar materials (Iamsaard et al., 2026; Zeng et al., 2025). These methods enable strong comparative studies and offer useful insights for improving biochar production and application in the environment (Al-Zyoud et al., 2026).

However, there is a lack of detailed evaluations that combine physico-chemical evaluation with comparative adsorption performance for a range of biochar materials. In the present study, an open access data set has been used to assess the physicochemical properties of various biochar materials and the relationships between this and the adsorption of lead and cadmium. The results are hoped to assist creation of scientifically based selection of efficient biochar adsorbents and development of sustainable heavy metal remediation technologies.

### Research objectives:

- To comparatively characterize the physicochemical properties of different biochar materials used for heavy metal adsorption.
- To evaluate and compare the adsorption performance of different biochar materials for the removal of lead (Pb) and cadmium (Cd).
- To investigate the relationships between key physicochemical characteristics of biochar and their heavy metal adsorption performance through comparative analysis.

## 2. Materials and Methods

### 2.1 Study Design

The research design was secondary data analysis using quantitative approach to compare the physicochemical properties of the different biochar materials and their heavy metal adsorption capacities. The study was aimed at the identification of the biochar variations and the effect of these variations on lead (Pb) and cadmium (Cd) adsorption. No laboratory experiments were conducted or samples collected, as an existing open access data set was used. The analytical method was focused on comparative assessment of the biochar materials derived from different biomass feedstocks and pyrolysis conditions using standardised analytically relevant parameters related to their physicochemical properties and adsorption.

### 2.2 Data Source

The adsorption data of lead (Pb) and cadmium (Cd) by various biochar materials was obtained from an open access supplementary data set to perform the analysis (Yue, 2024). The data source consisted of two separate data sheets, Pb Adsorption Data and Cd Adsorption Data, with the physicochemical characteristics of the adsorbent and adsorption performance data obtained from experimental studies and previously published data. The generated database contained several types of biochar made from different biomass feedstocks and generated under different pyrolysis conditions and thus served as a good source for comparison of biochar adsorption behaviour.

### 2.3 Data Processing and Management

The data set was thoroughly checked before statistical analysis to ensure that it is complete, consistent, and adequate for comparative evaluation. The two worksheets were analysed separately with the same analytical approach, representing the datasets for the adsorption of lead and cadmium. The variables were filtered to select the physicochemical and adsorption relevant parameters, and records with the relevant parameters were kept for analysis. Where necessary, variable names were harmonized to allow for comparisons to be made between the two data sets, but the original measurement values reported in the data source database were not changed. The cleaned data were then categorized into the following themes: biomass characteristics, biochar physic-chemical properties, pyrolysis conditions, wastewater characteristics, and biochar adsorption performance indicators.

### 2.5 Comparative Evaluation

Comparative evaluation was conducted to compare the differences between the biochar materials in terms of their physicochemical properties and adsorption capacity. Comparisons were made between the various biomass feedstocks, production situations and the different adsorption results for lead and cadmium. The focus was on the different physicochemical properties of the materials that could affect the adsorption efficiency, and the characteristics of materials that could remove the heavy metal more efficiently. Comparative analysis also helped to determine the similarities and differences in the adsorption behaviour of the constituent elements (lead and cadmium) among the collected biochar materials.

### 2.6 Statistical Analysis

Descriptive data analysis was conducted to provide a summary of the chemical and physical properties and adsorptive capacity of the biochar studied. Continuous variables were presented as appropriate descriptive measures mean, standard deviation, minimum and maximum. Comparative studies were conducted to investigate the differences between the biochar materials and adsorption efficiency to lead/cadmium. Correlation analysis was performed to study the relationship between the selected physicochemical properties and adsorption capacity. In addition, the multiple linear regression analysis was conducted to determine the physic-chemical factors that had significant contribution towards the adsorption performance of heavy metals. Appropriate statistical software was used to carry out all statistical data analyses and graphical visualisations were carried out, with a p-value of $<0.05$ regarded as statistically significant.

## 3. Results

### 3.1 Dataset Characteristics

The database had 716 adsorption data, including 422 adsorption data for lead (Pb) and 294 adsorption data for cadmium (Cd). The Pb dataset contained biochar feedstocks from 11 different sources, while the Cd dataset contained biochar feedstocks from 7 different sources. For the 356 Pb records and 174 Cd records, the adsorption capacity was available. All 422 observations of Pb were 100% efficient and 243 observations of Cd were available. The data set varied widely in the number of physicochemical variables available, including biochar pH and pyrolysis temperature (Table 1).

**Table 1. Characteristics and completeness of the compiled biochar adsorption dataset**

| Dataset characteristic | Pb dataset | Cd dataset |
|---|---|---|
| Total records | 422 | 294 |
| Unique biochar feedstocks | 11 | 7 |
| Records with adsorption capacity, Qe | 356 | 174 |
| Records with removal efficiency | 422 | 243 |
| Records with pyrolysis temperature | 415 | 185 |
| Records with specific surface area | 422 | 243 |
| Records with pore volume | 422 | 243 |
| Records with pore diameter | 422 | 243 |
| Records with elemental carbon | 398 | 219 |
| Records with biochar pH | 422 | 127 |

## 3.2 Physicochemical Characteristics of the Biochars

A very wide range of biochar properties were recorded physicochemical properties. The average pyrolysis temperature for Pb-associated biochars was 514.70 ± 136.20°C, and for Cd-associated biochars was 527.84 ± 119.08°C. The mean specific surface area of the Cd-associated biochars was higher than that of the Pb-associated biochars, while the mean pore volume of the biochars was similar. The average elemental carbon concentration for the two datasets was around 64%. Significant variations in surface area, pore diameter, elemental composition, ash content and biochar pH were observed as shown in Table 2.

**Table 2. Descriptive statistics of selected physicochemical characteristics**

| Characteristic | Metal | Valid n | Mean ± SD | Minimum–maximum |
|---|---|---|---|---|
| Pyrolysis temperature (°C) | Pb | 415 | 514.70 ± 136.20 | 300.00–800.00 |
| | Cd | 185 | 527.84 ± 119.08 | 300.00–800.00 |
| Volatile matter (%) | Pb | 88 | 36.87 ± 1.54 | 31.30–38.20 |
| | Cd | 51 | 38.75 ± 2.80 | 35.42–42.21 |
| Fixed carbon (%) | Pb | 88 | 34.41 ± 7.00 | 32.00–58.90 |
| | Cd | 51 | 41.75 ± 1.10 | 40.61–43.21 |
| Ash (%) | Pb | 88 | 25.74 ± 6.07 | 6.00–28.00 |
| | Cd | 132 | 15.64 ± 1.82 | 12.79–17.37 |
| Elemental carbon (%) | Pb | 398 | 64.70 ± 16.63 | 16.46–84.00 |
| | Cd | 219 | 64.07 ± 10.47 | 9.68–79.21 |
| Elemental nitrogen (%) | Pb | 398 | 1.04 ± 1.12 | 0.02–4.31 |
| | Cd | 219 | 1.31 ± 0.33 | 0.32–2.30 |
| Specific surface area ($m^2/g$) | Pb | 422 | 108.41 ± 109.35 | 0.32–374.20 |
| | Cd | 243 | 163.34 ± 109.47 | 2.63–312.30 |
| Total pore volume ($cm^3/g$) | Pb | 422 | 0.109 ± 0.039 | 0.001–0.200 |
| | Cd | 243 | 0.104 ± 0.048 | 0.005–0.194 |

| | | | | |
|---|---|---|---|---|
| Pore diameter (nm) | Pb | 422 | 4.07 ± 1.93 | 1.75–12.47 |
| | Cd | 243 | 3.58 ± 1.43 | 1.38–9.81 |
| Biochar pH | Pb | 422 | 8.43 ± 1.19 | 1.13–11.40 |
| | Cd | 127 | 8.34 ± 2.13 | 2.05–12.44 |

### 3.3 Lead and Cadmium Adsorption Performance
The mean Pb adsorption capacity was 61.78 ± 76.24 mg/g, compared with 48.53 ± 96.19 mg/g for Cd. The difference in mean adsorption capacity was not statistically significant, however, according to Welch's independent-samples t test, $t = 1.59$, $p = 0.113$. Likewise, there was no significant difference between the percentage of Pb and Cd removed ($t = 1.00$, $p = 0.318$). The medians were significantly lower than the means for all the above, showing that the distributions were positively skewed, with high values affecting the means. The distribution of Qe is shown in Figure 1 and the adsorption conditions and performance measures are given in Table 3.

**Table 3. Comparative adsorption conditions and performance for Pb and Cd**

| Parameter | Pb | Cd | Comparative test |
|---|---|---|---|
| Adsorption capacity, Qe (mg/g) | 61.78 ± 76.24; n = 356 | 48.53 ± 96.19; n = 174 | t = 1.59, p = 0.113 |
| Median Qe (range), mg/g | 32.00 (0.00–376.32) | 17.11 (0.82–397.98) | — |
| Removal efficiency (%) | 45.88 ± 32.37; n = 422 | 43.27 ± 32.60; n = 243 | t = 1.00, p = 0.318 |
| Median removal efficiency (%) | 36.30 | 34.22 | — |
| Solution pH | 4.79 ± 0.84 | 4.94 ± 1.10 | — |
| Initial metal concentration (mg/L) | 87.50 ± 82.69 | 379.92 ± 587.48 | — |
| Adsorption temperature (°C) | 26.72 ± 5.72 | 25.12 ± 2.71 | — |
| Adsorption time (min) | 647.97 ± 598.83 | 1013.58 ± 852.56 | — |
| Biochar dosage (mg) | 78.21 ± 108.72 | 124.01 ± 93.88 | — |

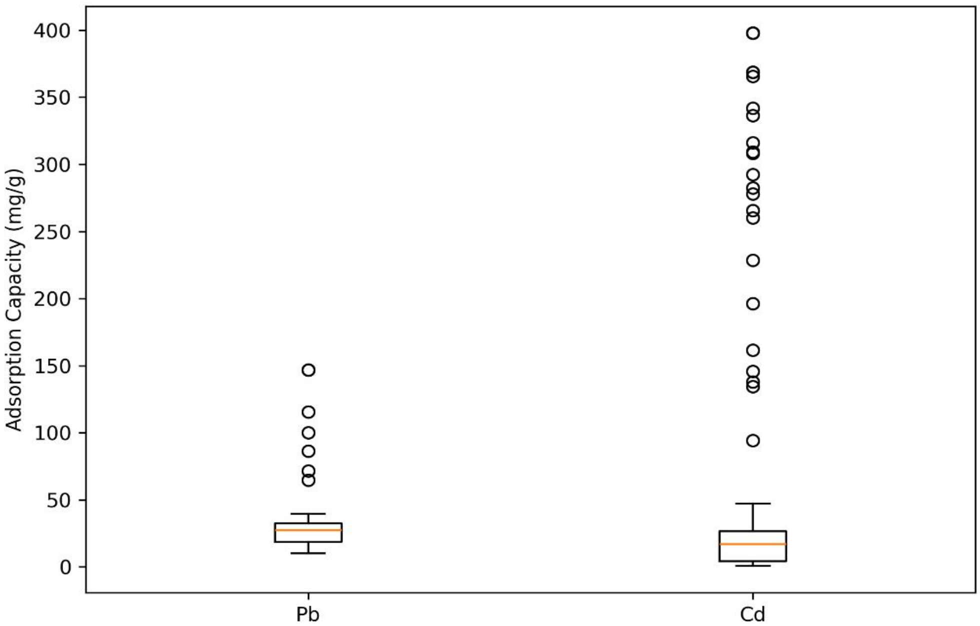


**Figure 1. Distribution of adsorption capacity for Pb and Cd**

### 3.4 Feedstock-Based Adsorption Performance
Significant variations in adsorption capacity were found for the feedstock-derived biochars. The charcoal made from sycamore branch showed the highest mean Qe value, which is 314.82 ± 73.72 mg/g followed by

Paulownia leaf charcoal (232.86 ± 77.41 mg/g) and poplar wood-chip biochar (158.73 ± 5.21 mg/g) in the Pb dataset. The available Qe values indicated that pig-manure biochar had the lowest mean Pb adsorption capacity. The mean adsorption capacities of Paulownia bark, wood charcoal and leaf-litter biochars were the highest for Cd. The mean Qe of cassava-pomace biochar was comparatively low (4.08 ± 1.82 mg/g) but the mean removal efficiency was high (81.73 ± 17.91%). Results for the various feedstocks are shown in Table 4 and illustrated in Figure 2.

**Table 4. Adsorption performance according to biochar feedstock**

| Metal | Feedstock | Qe n | Mean Qe ± SD (mg/g) | Mean removal efficiency ± SD (%) |
|---|---|---|---|---|
| Pb | Sycamore branch charcoal | 6 | 314.82 ± 73.72 | 21.30 ± 18.43 |
| Pb | Paulownia leaf charcoal | 6 | 232.86 ± 77.41 | 41.79 ± 19.35 |
| Pb | Poplar wood chip | 65 | 158.73 ± 5.21 | 11.82 ± 2.89 |
| Pb | Bagasse | 68 | 46.29 ± 69.13 | 39.55 ± 28.30 |
| Pb | Straw | 64 | 29.11 ± 13.10 | 65.82 ± 17.80 |
| Pb | Pine needles | 28 | 25.28 ± 22.65 | 25.98 ± 20.43 |
| Pb | Pecan slice | 28 | 21.80 ± 22.01 | 41.06 ± 29.17 |
| Pb | Spanish moss | 28 | 21.08 ± 21.47 | 43.11 ± 30.07 |
| Pb | Sludge | 28 | 20.56 ± 21.19 | 46.14 ± 31.07 |
| Pb | Pig manure | 28 | 9.25 ± 15.16 | 79.98 ± 28.79 |
| Pb | Kiwi twig | 0 | Not reported | 90.92 ± 16.84 |
| Cd | Paulownia bark | 7 | 302.37 ± 103.01 | 35.52 ± 18.72 |
| Cd | Wood charcoal | 7 | 295.16 ± 80.88 | 34.28 ± 18.05 |
| Cd | Leaf litter | 7 | 244.56 ± 68.25 | 31.54 ± 18.54 |
| Cd | Silkworm excrement | 15 | 22.69 ± 9.10 | 22.94 ± 22.44 |
| Cd | Poplar wood chip | 65 | 20.80 ± 6.15 | 11.56 ± 3.42 |
| Cd | Cassava pomace | 66 | 4.08 ± 1.82 | 81.73 ± 17.91 |
| Cd | Kiwi twig | 0 | Not reported | 32.54 ± 9.27 |

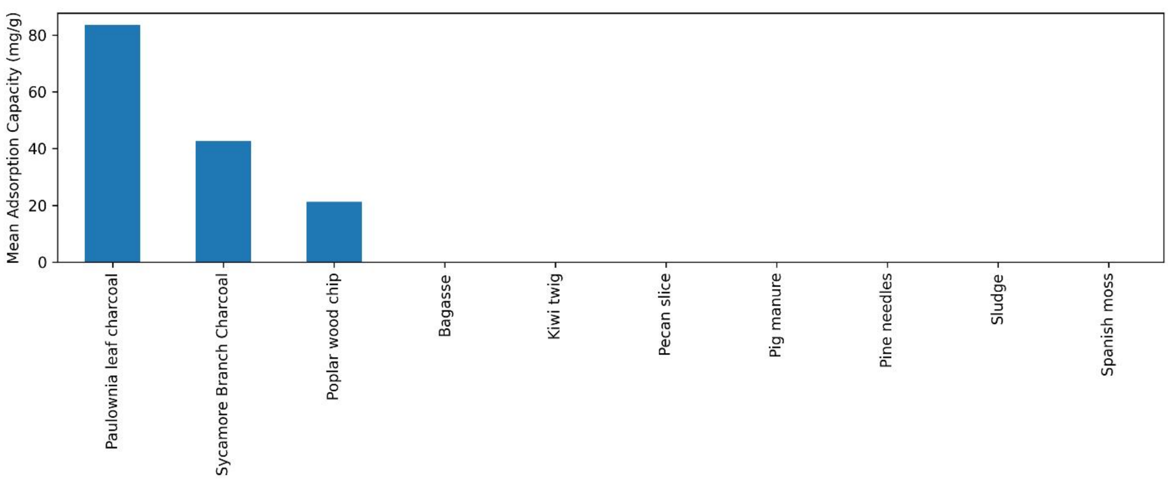


**Figure 2. Mean adsorption capacity according to biochar feedstock and heavy metal**

### 3.5 Correlation Between Biochar Properties and Adsorption Capacity

The Pearson correlation analysis showed the highest correlation for the initial heavy metal concentration and the adsorption capacity for both Pb and Cd. The initial concentration was significantly positively correlated to Qe for Pb ($r = 0.931$, $p < 0.001$). The adsorption capacity also exhibited weak positive correlation with pyrolysis temperature, elemental carbon, specific surface area, pore volume, biochar pH and adsorption time. Initial concentration was strongly correlated with Qe for Cd ($r = 0.830$, $p < 0.001$). Moderate positive correlation was noted for pyrolysis temperature and specific surface area. The pH of the biochar also revealed a significant positive correlation while elemental carbon and adsorption time revealed weak negative correlation. The detailed coefficients are given in Table 5 and shown in Figures 3.

**Table 5. Pearson correlations between selected variables and adsorption capacity**

| Variable | Pb: n | Pb: r | Pb: p | Cd: n | Cd: r | Cd: p |
|---|---|---|---|---|---|---|
| Pyrolysis temperature | 349 | 0.123 | 0.021 | 146 | 0.543 | <0.001 |
| Elemental carbon | 356 | 0.232 | <0.001 | 174 | −0.174 | 0.022 |
| Specific surface area | 356 | 0.186 | <0.001 | 174 | 0.541 | <0.001 |
| Total pore volume | 356 | 0.111 | 0.036 | 174 | 0.022 | 0.774 |
| Pore diameter | 356 | −0.048 | 0.367 | 174 | −0.138 | 0.069 |
| Biochar pH | 356 | 0.104 | 0.050 | 88 | 0.345 | 0.001 |
| Solution pH | 356 | −0.033 | 0.540 | 174 | 0.044 | 0.568 |
| Initial concentration | 356 | 0.931 | <0.001 | 174 | 0.830 | <0.001 |
| Adsorption time | 356 | 0.132 | 0.013 | 174 | −0.157 | 0.038 |

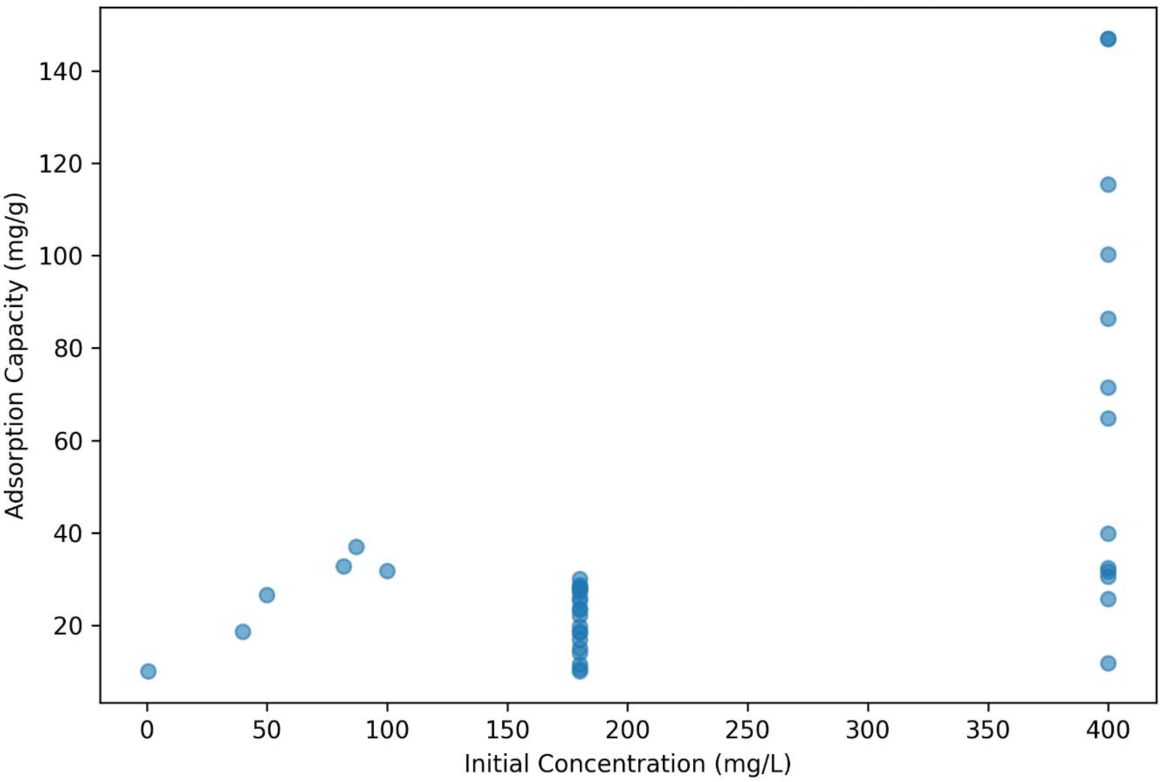


**Figure 3. Relationship between initial heavy metal concentration and adsorption capacity**

### 3.6 Multivariable Predictors of Adsorption Capacity

Complete observations were used for multiple linear regression for Pb and Cd, separately. The Pb model accounted for 92.0% of the variance in adsorption capacity, with an adjusted $R^2$ value of 0.918 and an overall p value of $< 0.001$ and included 349 records. Initial concentration was the best positive predictor of the adsorption capacity of Pb with standardized $\beta = 0.951$ ($p < 0.001$). In addition, pyrolysis temperature and specific surface area were significant positive predictors. After accounting for the other model variables, pH of the biochar and solution pH were significant negative predictors. The model Cd contained 81 complete records and accounted for 78.3% of the variance in adsorption capacity with adjusted $R^2 = 0.759$ and overall $p < 0.001$. Only initial concentration had a conventional level of statistical significance ($\beta = 0.227$, $p = 0.014$). Elemental carbon had a borderline negative adjusted association, and pyrolysis temperature showed a positive but not significant association. The regression results are displayed in Table 6.

**Table 6. Multiple linear regression models predicting adsorption capacity**

| Predictor | Pb standardized β | Pb p | Cd standardized β | Cd p |
|---|---|---|---|---|
| Pyrolysis temperature | 0.177 | <0.001 | 0.461 | 0.077 |
| Elemental carbon | 0.039 | 0.148 | −1.078 | 0.053 |
| Specific surface area | 0.128 | <0.001 | 0.203 | 0.322 |
| Pore diameter | 0.027 | 0.091 | 0.100 | 0.773 |
| Biochar pH | −0.209 | <0.001 | −0.304 | 0.400 |
| Solution pH | −0.044 | 0.010 | 0.033 | 0.557 |
| Initial metal concentration | 0.951 | <0.001 | 0.227 | 0.014 |
| Adsorption time | 0.001 | 0.949 | −0.051 | 0.442 |
| Complete-case sample size | 349 | — | 81 | — |
| $R^2$ | 0.920 | — | 0.783 | — |
| Adjusted $R^2$ | 0.918 | — | 0.759 | — |
| Overall model significance | <0.001 | — | <0.001 | — |

## 4. Discussion

The present study comparatively evaluated the physicochemical characteristics of different biochar materials and their adsorption performance for lead (Pb) and cadmium (Cd). There were significant differences in pyrolysis temperature, specific surface area, porosities, elemental composition, pH and adsorption capacity. These differences suggest a significant effect of feedstock and production conditions on biochar performance. Similar results were observed for both pruning biochars and modified biochars, where surface chemistry, functional groups, and physicochemical properties played a key role in the adsorption of Pb and Cd (Rabiee Abyaneh et al., 2024; Saha et al., 2025). Characterization parameters, process optimization, and regeneration potential are also among the significant factors to determine the removal efficiency of heavy metals (Sireesha et al., 2025).

Physicochemical analysis revealed that the surface area, carbon content, pore structure, and pyrolysis temperature were significantly different between the biochar materials. These variations are within the expected range as they are directly related to the composition of the feedstocks and the thermal processing itself, and are related to the carbonization, porosity, mineral content and surface functional groups. A comparative study of carbonaceous adsorbents also reported that the sorption performance depends on the activation methods and the materials used as the precursors (Wang et al., 2020). Optimization of pyrolysis conditions can help enhance the stability of the carbon, the development of pores, and the adsorption capacity, and the difference between hydrochar and biochar further highlights the significance of thermochemical processing in determining the characteristics of the materials (Ramisetty et al., 2025; Alipoursarbani et al., 2026).

The results showed that initial concentration of metal was the most significant factor in the adsorption capacity of both metals, Cd and Pb. The results indicated that the adsorption process is controlled by the biochar intrinsic properties and the experimental conditions. Similarly, the performance of biochar in removing contaminants has been compared to that of bone char and traditional sorbents, revealing that both contaminant concentration and operating conditions significantly influence the removal process (Biswas et al., 2026). The same results were observed for MgO-based adsorbents, rice husk biochar, and activated carbon, which showed varying adsorption efficiencies depending on the synthesis techniques, characteristics of the wastewater, and type of pollutants (Chan et al., 2025; Okoya et al., 2020; Remmani et al., 2024).

There were a number of physicochemical properties that showed correlation with the adsorption capacity, but the extent and direction of the correlation varied for Pb and Cd. Such metal-specific behavior suggests that there are various mechanisms for adsorption, such as ion exchange, electrostatic attraction, surface complexation, precipitation, and pore filling. Engineered sewage sludge biochar also has been found to exhibit adsorption mostly influenced by mineral composition, surface functional groups and structural characteristics (Elkhlifi et al., 2023). Additionally, biochar's ability to immobilize heavy metals has been compared to mineral adsorbents, reinforcing the notion that the mechanism involved is a combination of various physicochemical factors (Derstila et al., 2026).

The results also emphasize the environmental significance of using agricultural and biomass wastes as good adsorbents. These valorisations can be used for wastewater treatment, sustainable waste management, soil remediation and circular use of resources. Comparative analysis of native biomass, hydrochar and biochar has also highlighted their potential for environmental remediation applications (Simić et al., 2026; Yaseen & Alhalimi, 2025).

The study was limited, however, due to the heterogeneity of the secondary data set, differences in feedstocks, experimental protocols, metal concentrations, and adsorption conditions. As such, the results are associations from studies that have been compiled, and not direct causation. Future studies are needed to use standardized experimental conditions and advanced predictive methods for better selection and optimization of biochars with high performance. Machine learning models can be particularly useful for determining the physicochemical properties which most strongly influence heavy metal adsorption efficiency.

## 5. Conclusion

A large secondary data set was used here to compare the adsorption performance of various biochar materials for lead (Pb) and cadmium (Cd) and their physicochemical characteristics. Results showed that there was significant variation in the biochar characteristics due to biomass feedstocks and production conditions, such as pyrolysis temperature, specific surface area, pore characteristics, elemental composition, and pH. Such differences led to variations in the capacity of adsorption and removal efficiency of heavy metal in the studied biochar materials. Correlation and regression analyses also showed that adsorption performance depends on the interactions of intrinsic physicochemical properties and experimental conditions, and that the initial metal concentration is the most significant adsorption affecting factor. Comparisons of the biochars for different feedstocks also showed that those biochars with greater adsorption capacity did not necessarily remove the highest percentage of contaminants, as this is a complex adsorption phenomenon. In conclusion, the study shows that systematic physicochemical characterization is necessary for the use of appropriate biochar materials for removing heavy metal and to understand the factors affecting adsorption behaviour. The use of secondary experimental data facilitated the general comparative evaluation of different types of biochar, offering insights for the selection of sustainable adsorbents and environmental applications. The results should be interpreted, however, with regards to the differences in experimental protocol and data available among the compiled studies. Future studies are recommended to include standard experimental methods and more advanced methods of predicting biochar production and use for sustainable water treatment and heavy metal removal technologies.

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