Vol 10 No. 2 (2025) 106-115 ISSN (Online) : 2502-0943

Jurnal Katalisator

ADSORPTION STUDY OF LEAD (Pb^{2+}) IONS USING CASSAVA PEEL BIOCHAR: EFFECT OF pH AND CONTACT TIME

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Detail Artikel

Diterima : 17 Oktober 2025
Direvisi : 30 Oktober 2025
Diterbitkan : 31 Oktober 2025

Kata Kunci

cassava peel biochar
Pb^{2+} adsorption
solution pH
contact time
NaOH activation

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A B S T R A C T

*This study evaluates the adsorption performance of NaOH-activated cassava peel biochar (*Manihot esculenta *Crantz) for the removal of Pb^{2+} ions from aqueous solutions, with particular focus on the effects of solution pH and contact time. Cassava peel biochar was produced via pyrolysis at 180–350 °C and chemically activated using 0.1 M NaOH. Surface functional groups and morphology were characterized using Fourier Transform Infrared Spectroscopy (FTIR) and Scanning Electron Microscopy–Energy Dispersive X-ray (SEM–EDX). Batch adsorption experiments were conducted by varying solution pH (3–8) and contact time (30–120 min), while Pb^{2+} concentrations before and after adsorption were analyzed using Atomic Absorption Spectroscopy (AAS). The results showed that solution pH significantly affected Pb^{2+} adsorption, with the highest adsorption capacity of 9.94 mg/g achieved at pH 5. Contact time also influenced adsorption performance, and the optimum condition was obtained at 90 min, yielding a maximum adsorption capacity of 9.94 mg/g. These findings indicate that NaOH-activated cassava peel biochar exhibits stable and effective Pb^{2+} adsorption under slightly acidic*

http://doi.org/10.22216/jk.v5i2.5717
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conditions and moderate contact time, highlighting its potential as a low-cost and environmentally friendly adsorbent for Pb^{2+} removal from contaminated wastewater.

INTRODUCTION

Heavy metal contamination in aquatic environments has become an increasingly serious environmental problem due to the rapid growth of industrial, mining, and domestic activities (Elfia, 2019). Among various heavy metals, lead (Pb) is of particular concern because of its high toxicity, persistence, non-biodegradable nature, and tendency to accumulate in living organisms. The presence of Pb^{2+} ions in water bodies poses significant risks to human health, including neurological disorders, kidney damage, and developmental impairments in children. Therefore, effective removal of Pb^{2+} from wastewater prior to environmental discharge is essential (Kumkum & Kumar, 2024).

Various treatment methods have been developed to remove heavy metals from wastewater, including chemical precipitation, ion exchange, membrane filtration, and adsorption (Abdullah et al., 2019). Among these techniques, adsorption is widely applied due to its operational simplicity, high removal efficiency, and flexibility in practical applications. However, the use of commercial adsorbents such as activated carbon and synthetic resins is often limited by high production and regeneration costs. This limitation has encouraged the development of alternative adsorbents derived from abundant, low-cost, and environmentally friendly biomass wastes (Zhang et al., 2020).

Biochar is a carbon-based material produced through the pyrolysis of biomass under limited oxygen conditions. It has attracted considerable attention as an effective adsorbent for heavy metal removal due to its porous structure, relatively large surface area, and abundant surface functional groups that facilitate physical and chemical interactions with metal ions (Shalchian et al., 2025). The adsorption performance of biochar is strongly influenced by the type of biomass, pyrolysis conditions, and activation treatments. Chemical activation using strong bases such as NaOH has been reported to enhance biochar porosity and increase oxygen-containing functional groups, thereby improving its adsorption capacity toward heavy metal ions (Premchand et al., 2024).

Cassava peel (*Manihot esculenta* Crantz) is an abundant agricultural waste in Indonesia, including Bengkulu Province, generated as a by-product of cassava processing industries. Its utilization remains limited, and improper disposal may cause environmental problems. Due to its high lignocellulosic content, cassava peel is a promising precursor for biochar production. Converting cassava peel into biochar not only helps reduce biomass waste but also produces value-added materials for wastewater treatment applications.

In addition to adsorbent characteristics, operational parameters play a crucial role in determining adsorption efficiency. Solution pH significantly affects the surface charge of the adsorbent and the speciation of Pb^{2+} ions in solution, while contact time influences mass transfer rates and the attainment of adsorption equilibrium. Therefore, investigating the effects of pH and contact time is essential for evaluating the adsorption performance of cassava peel biochar (Rabiee Abyaneh et al., 2024).

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Based on the above considerations, this study aims to evaluate the adsorption capability of NaOH-activated cassava peel biochar for the removal of Pb^{2+} ions from aqueous solutions, with particular emphasis on the effects of solution pH and contact time. The results of this study are expected to provide insight into the optimum adsorption conditions and support the development of low-cost, sustainable biochar-based adsorbents for heavy metal-contaminated wastewater treatment.

MATERIALS AND METHODS

Sample Collection

Cassava peel (*Manihot esculenta* Crantz) waste was randomly collected from Panca Mukti Village, North Bengkulu Regency, Bengkulu Province, Indonesia. The site was selected due to the high availability of cassava peel residues generated from local agricultural processing activities. The collected samples were immediately transported to the laboratory for subsequent preparation and analysis.

Biochar Production from Cassava Peel by Pyrolysis

The collected cassava peels were thoroughly rinsed with tap water to remove surface impurities and then sun-dried for 1–3 days. Approximately 1 kg of dried material was loaded into a sealed pyrolysis reactor equipped with temperature control. Pyrolysis was carried out at temperatures between 180 and 350 °C for about 3 days until biochar formation was completed. After cooling to ambient temperature, the obtained biochar was ground using a blender and sieved through a 100-mesh screen to ensure uniform particle size. The fine biochar fraction was further dried in an oven at 105 °C for 1 h to eliminate residual moisture prior to characterization and adsorption experiments (Nzediegwu et al., 2021).

Chemical Activation of Cassava Peel Biochar

Biochar activation was conducted using sodium hydroxide (NaOH) as the chemical activating agent. Fifty grams of dried biochar were mixed with 250 mL of NaOH solution, resulting in a biochar-to-solution ratio of 1:5 (w/v). The mixture was stirred continuously for 2 h using a magnetic stirrer to promote effective interaction between the biochar and the activating agent. Subsequently, the suspension was covered and allowed to stand at room temperature for 24 h to complete the activation process. The activated biochar was then separated by filtration using Whatman No. 42 filter paper and washed repeatedly with deionized water until the filtrate reached neutral pH (≈7), indicating the removal of excess alkali. The washed biochar was dried and stored in sealed containers for further use (Premchand et al., 2024).

Adsorption Experiments

Batch adsorption experiments were performed to assess the capacity of cassava peel biochar to remove Pb^{2+} ions from aqueous solutions. The investigated parameters included solution pH, initial Pb^{2+} concentration, and contact time. After adsorption, the suspensions were filtered, and the remaining Pb^{2+} concentration in the filtrate was quantified using Atomic Absorption Spectroscopy (AAS) (Sepryani et al., 2017).

Effect of Solution pH

To examine the influence of solution pH, 0.1 g of biochar was added to 20 mL of Pb^{2+} solution with an initial concentration of 50 mg/L. The pH of the solution was adjusted to 3, 4, 5, 6, and 8 using appropriate amounts of HCl or NaOH. The mixtures were agitated at room temperature for 60 min. Following filtration, the residual Pb^{2+} concentration was measured using AAS to identify the optimum pH for adsorption (Elfia, 2019).

Effect of Contact Time

For contact time evaluation, 0.1 g of biochar was introduced into 20 mL of Pb^{2+} solution at the previously determined optimum pH. The adsorption process was conducted for varying contact times of 30, 60, 90, and 120 min. After each adsorption period, the solutions were filtered, and the remaining Pb^{2+} concentration was analyzed using AAS to determine the optimum contact time for Pb^{2+} removal (Elfia, 2019).

Data Analysis

The Pb^{2+} adsorption capacity was calculated based on the difference between the initial and equilibrium Pb^{2+} concentrations before and after the adsorption process using the following equation (Nguyen et al., 2025):

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

where qe (mg/g) is the adsorption capacity at equilibrium, C0 (mg/L) is the initial Pb^{2+} concentration, Ce (mg/L) is the equilibrium Pb^{2+} concentration, V (L) is the volume of the solution, and m (g) is the mass of the adsorbent. The effects of pH and contact time on adsorption performance were analyzed descriptively to determine the optimum adsorption conditions.

RESULTS AND DISCUSSION

Effect of Solution pH on Pb^{2+} Adsorption Capacity

The effect of solution pH on the adsorption capacity of Pb^{2+} ions by cassava peel biochar is presented in Figure 1 and Table 1. Based on the experimental results, the Pb^{2+} adsorption capacity ranged from 9.83 to 9.94 mg/g within the pH range of 3–8. At pH 3, the adsorption capacity was recorded at 9.84 mg/g, followed by a slight decrease to 9.83 mg/g at pH 4.

An increase in adsorption capacity was observed at pH 5, where the maximum value of 9.94 mg/g was achieved, indicating the optimum pH condition for Pb^{2+} adsorption by cassava peel biochar. This enhancement suggests that at this pH level, interactions between Pb^{2+} ions and the active functional groups on the biochar surface occur more effectively.

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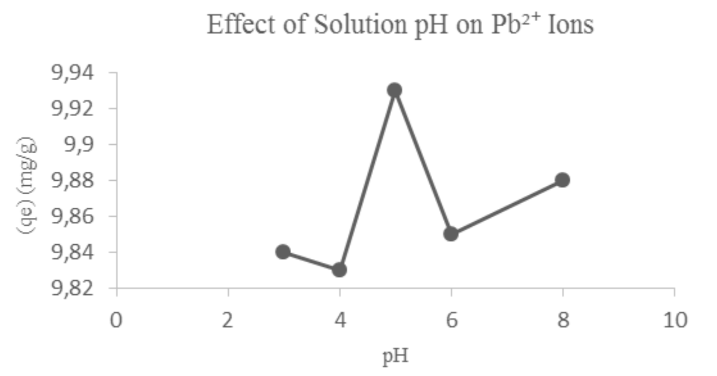

Figure 1. Effect of solution pH on the adsorption capacity of Pb^{2+} ions by cassava peel biochar activated with NaOH.

At pH 6 and pH 8, the adsorption capacities decreased to 9.85 mg/g and 9.88 mg/g, respectively. Although fluctuations in adsorption capacity were observed at pH values above the optimum condition, the differences were relatively small. This indicates that cassava peel biochar maintains a stable Pb^{2+} adsorption performance over the tested pH range; however, maximum adsorption efficiency is achieved under a specific pH condition.

Table 1. Effect of solution pH on the adsorption capacity of Pb^{2+} ions by NaOH-activated cassava peel biochar.

pH	Co (ppm)	Ce (ppm)	V (ml)	m (gr)	Qe (mg/g)
3	50	0,811	20	0,1	9,84
4	50	0,846	20	0,1	9,83
5	50	0,303	20	0,1	9,94
6	50	0,748	20	0,1	9.85
8	50	0,573	20	0,1	9,88

From a chemical perspective, the effect of pH on Pb^{2+} adsorption is closely related to the surface charge of the adsorbent and ionic competition in the solution. At low pH values, a high concentration of H^+ ions competes with Pb^{2+} ions for active binding sites on the biochar surface, resulting in a reduced adsorption capacity (Hou et al., 2025). In contrast, at near-neutral pH conditions, the competition from H^+ ions decreases, allowing more effective interactions between Pb^{2+} ions and the adsorbent surface. However, at higher pH levels, possible changes in Pb^{2+} speciation in the solution may limit further enhancement of adsorption capacity (Herath et al., 2021). This trend is consistent with previous studies reporting that the optimum pH for Pb^{2+} adsorption by biomass-based adsorbents generally occurs under slightly acidic to near-neutral conditions (Sepryani et al., 2017).

Effect of Contact Time on Pb^{2+} Adsorption Capacity

The results of the contact time effect on Pb^{2+} adsorption capacity by cassava peel biochar are presented in Figure 2 and Table 2. Based on the experimental data, the Pb^{2+} adsorption capacity ranged from 17.96 to 19.90 mg/g for contact times between 30 and 120 min. At a contact time of 30 min, the adsorption capacity reached 19.90 mg/g, indicating that Pb^{2+} adsorption occurred rapidly during the initial stage due to the availability of a large number of active sites on the biochar surface.

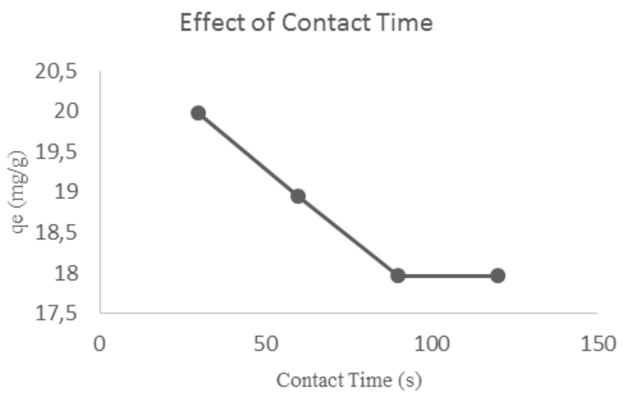

Figure 2. Effect of contact time on the adsorption capacity of Pb^{2+} ions by NaOH-activated cassava peel biochar.

Increasing the contact time to 60 min resulted in an adsorption capacity of 18.95 mg/g, which did not show a significant difference compared to the contact time of 30 min. This indicates that most of the active sites on the biochar surface were occupied within a relatively short period. The lowest adsorption capacity was obtained at a contact time of 90 min, with a value of 17.96 mg/g, suggesting that the adsorption system had approached equilibrium conditions.

At a longer contact time of 120 min, the adsorption capacity slightly increased to 17.96–17.97 mg/g; however, this increase was relatively small and insignificant. This behavior indicates that extending the contact time beyond equilibrium does not substantially enhance adsorption capacity (da Silva et al., 2022). The decrease in adsorption capacity at longer contact times may be attributed to the saturation of active sites and the possible desorption of Pb^{2+} ions from the adsorbent surface.

http://doi.org/10.22216/jk.v5i2.5717
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Table 2. Effect of contact time on the adsorption capacity of Pb^{2+} ions by NaOH-activated cassava peel biochar.

Contact Time (s)	Co (ppm)	Ce (ppm)	V (mL)	m (gr)	Qe (mg/g)
30	100	0,095	20	0,1	19,981
60	100	1,268	20	0,1	18,946
90	100	0,129	20	0,1	17,964
120	100	0,115	20	0,1	17,957

Overall, these results indicate that Pb^{2+} adsorption by cassava peel biochar occurs rapidly and reaches near-equilibrium conditions within a relatively short contact time. In this study, the optimum contact time was practically set at 60 min, as it provided a high and stable adsorption capacity, making it more efficient for wastewater treatment applications (Rabiee Abyaneh et al., 2024).

Performance Evaluation of Cassava Peel Biochar as a Pb^{2+} Adsorbent

The performance of cassava peel biochar as a Pb^{2+} adsorbent was evaluated based on adsorption results obtained under varying solution pH and contact time conditions. In general, cassava peel biochar exhibited relatively stable Pb^{2+} adsorption performance across different operational conditions, with adsorption capacities ranging from 9.83 to 9.94 mg/g. This narrow range demonstrates that cassava peel biochar is capable of maintaining consistent adsorption efficiency despite changes in pH and contact time (Amelia, 2025).

The experimental results revealed that the optimum Pb^{2+} adsorption condition was achieved at pH 5 and a contact time of 90 min, yielding the highest adsorption capacity. This condition reflects a balance between the surface charge characteristics of the adsorbent and the availability of active sites that facilitate interactions with Pb^{2+} ions. At excessively low pH values, competition with H^+ ions can reduce adsorption efficiency, whereas at higher pH levels, changes in Pb^{2+} speciation may limit further enhancement of adsorption capacity . In terms of contact time, the adsorption process was relatively fast and approached equilibrium within a short duration, consistent with previous findings (Rabiee Abyaneh et al., 2024) (Bąk et al., 2022).

The relatively stable adsorption performance under various conditions indicates that cassava peel biochar is tolerant to fluctuations in operational parameters. This characteristic is particularly advantageous for practical wastewater treatment applications, where solution pH and contact time often vary. Moreover, the utilization of cassava peel biochar provides added value to abundant agricultural waste that is otherwise underutilized (Rabiee Abyaneh et al., 2024).

Based on this evaluation, cassava peel biochar can be classified as an effective adsorbent with strong potential for further development in Pb^{2+} removal from aqueous solutions. Its satisfactory adsorption performance, readily available raw material, and relatively simple preparation process make cassava peel biochar a promising low-cost and environmentally friendly alternative adsorbent for the treatment of heavy metal-contaminated wastewater (Nandiyanto et al., 2025).

CONCLUSIONS

Based on the results and discussion, it can be concluded that cassava peel biochar exhibits good adsorption capability for the removal of lead ions (Pb^{2+}) from aqueous solutions. Solution pH and contact time were confirmed to significantly influence the Pb^{2+} adsorption performance of cassava peel biochar.

The optimum solution pH for Pb^{2+} adsorption was found to be pH 5, at which a maximum adsorption capacity of approximately 9.94 mg/g was achieved. In terms of contact time, the adsorption process occurred rapidly and reached optimum performance at a contact time of 90 min, also yielding a maximum adsorption capacity of approximately 9.94 mg/g. Prolonging the contact time beyond this point did not result in a significant increase in adsorption capacity.

Overall, cassava peel biochar demonstrated relatively stable Pb^{2+} adsorption performance under various operational conditions, indicating its potential as a low-cost and environmentally friendly alternative adsorbent for the treatment of wastewater contaminated with heavy metals, particularly Pb^{2+} ions.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Faculty of Mathematics and Natural Sciences, University of Bengkulu, for financial support and laboratory facilities through the RBA FMIPA Research Development Scheme 2025 (Contract No. 4556/UN30.12/HK/2025).

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