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Immobilization of Cadmium (CD) in Soil from the Talang Gulo Landfill Using Palm Shell Biochar

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Abstract
Introduction: *Cadmium (Cd) levels in well water near the Talang Gulo Landfill (TPA) reached 0.064 mg/L, approximately 19 times higher than the clean water quality standards set by the Minister of Health Regulation No. 02 of 2023. Cd concentrations decreased with increasing distance from the landfill, indicating the mobilization of Cd from the landfill soil into the surrounding environment. Given the toxic and highly mobile nature of Cd, mitigation efforts are needed to suppress the movement of this heavy metal.* ***Objective:*** *This study aims to evaluate the effectiveness of palm oil shell biochar in immobilizing cadmium (Cd) in landfill soil through changes in solubility under water extraction and simulated acidic conditions.* ***Methods****: This study used a laboratory experimental method with the addition of palm oil shell biochar to the Talang Gulo landfill soil at doses of 0%, 5%, and 10% and an incubation time of up to 60 days.* ***Results and Discussion:*** *The addition of biochar can increase soil pH and significantly reduce Cd mobility, with immobilization efficiency increasing with increasing biochar dose and incubation period.* ***Conclusion:*** *Palm oil shell biochar has the potential to be used as an environmentally friendly ameliorant solution for the remediation of cadmium-contaminated soil.*

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Introduction

Jambi City currently relies on a single Final Disposal Site (TPA), the Talang Gulo Landfill, located on the South Ring Road, Kenali Asam Bawah Village. Since its operation in 1997, the landfill has accumulated waste beyond its original capacity. Covering an area of 10 hectares with a 20% slope, it operates using an open dumping system and receives approximately 1,000–1,400 m³ of waste per day. As of 2020, the landfill was reported to be 90% full and overloaded. A new section spanning 21.3 hectares, supported by KfW Germany, is being developed to adopt a sanitary landfill system, intended to reduce environmental pollution and accommodate future waste accumulation more sustainably.

The open dumping system used previously has led to severe environmental concerns, particularly the leaching of heavy metals into surrounding soil and groundwater (Yusmaman, W. M., Widiyanto, H., Rohmah, S. N., & Akbarsyah, M. A., 2023). Among these, cadmium (Cd) is of serious concern due to its high mobility in acidic soils and toxicity at low concentrations (Kadim, N., 2023). Cd contamination near the landfill has been linked to various household and electronic waste sources, and concentrations in nearby dug wells have been reported far above safe limits (up to 0.064 mg/L, compared to the regulatory standard of 0.003 mg/L). Cd enters the environment through the breakdown of solid waste, forming leachate that infiltrates the soil and contaminates groundwater, as confirmed by multiple studies (Limia, 2024; Mitra et al., 2022; Puspitarini et al., 2023).

To address soil and water contamination, various studies have investigated the use of biochar, a carbon-rich material derived from biomass pyrolysis, as a low-cost and effective adsorbent for heavy metal immobilization. Biochar's porous structure, surface functional groups, and negative surface charge make it particularly effective at binding Cd, reducing its mobility and bioavailability. Prior research has demonstrated significant reductions in Cd mobility in soil and water when treated with biochar derived from agricultural waste, such as sugarcane bagasse and lignite (Zahedifar, 2020; Prasetyo, 2021; Wang et al., 2021). However, biochar application directly into contaminated water has not yet succeeded in meeting drinking water standards (Limia, 2024), suggesting that soil-based immobilization approaches may offer better control over Cd movement before it reaches groundwater.

Despite these promising findings, there has been no evaluation of cadmium (Cd) immobilization in soil from the Talang Gulo Landfill using palm oil shell biochar, particularly through a dissolved extraction method combined with acidic simulation to mimic leachate conditions. This presents a crucial knowledge gap, especially considering the urgent need to remediate landfill-affected soils in Jambi. Therefore, this study aims to examine the immobilization of cadmium from landfill soil using palm oil shell biochar as a potential mitigation strategy.

Method

This study employed an experimental method with acid extraction followed by laboratory analysis using Atomic Absorption Spectrophotometry (AAS). The research used a quantitative approach, which converts measurement data into numerical form and may include descriptive, correlational, or associative analysis based on relationships between variables (Ali et al., 2022). Soil samples were mixed with biochar at doses of 0% (control), 5%, and 10%, then homogenized. Approximately 500 g of treated soil was placed in incubation bottles, adjusted to 50% water-holding capacity, and incubated for

60 days under laboratory conditions. After incubation, cadmium (Cd) levels in the soil were analyzed in accordance with Indonesian National Standard SNI 06-6992.4-2024 for heavy metal testing in soil using AAS

Results and Discussion

Heavy Metal and Carbon Content in Soil

The soil characteristics obtained were composite soil samples from the Old Talang Gulo Landfill. Before being treated with biochar addition and the soil incubation process, an initial soil characteristic analysis was conducted at the Integrated Laboratory Academic Support Unit of the University of Lampung using the ICP OES Varian 715-ES method to determine the concentrations of Al, Cd, and Na. Organic matter was determined using the Lenton/UAF 16/1 Furnace method. Initial soil total N and pH testing was conducted at the Integrated Basic Laboratory of the University of Jambi. Based on the results of the initial soil analysis before being treated in this study, they are presented in the following table.

Table 1

Initial soil characteristics before treatment

No	Initial Soil Parameters	Analysis Results
1	Cd (mg/kg)[a]	17.9
2	Al (mg/kg)[a]	5702.4
3	Na (mg/kg)[a]	41.3
4	Organic Ingredients (%)[a]	6.67
5	N-Total (%)[b]	0.19
6	pH (1:5)[b]	5.4

Source: Test results data from the University of Lampung Laboratory in 2025 (a) and the University of Jambi Laboratory (2025) (b).

Based on the initial soil analysis in Table 1, the total Cd content was 17.9 mg/kg; Al 5702.4 mg/kg; Na 41.3 mg/kg; Organic matter 6.67%; N 0.19% and soil pH 5.4 as measured with a pH meter at a ratio of (1:5 (w/v)). The initial soil analysis results from the Talang Gulo landfill contained 17.9 mg/kg of Cd; indicating that the soil texture and its physical characteristics allow for the long-term accumulation of heavy metals from leachate. This indicates that leachate not only moves rapidly through the soil, but also is retained and interacts with the silt and clay fractions, causing Cd accumulation. The 17.9 mg/kg of Cd is much higher than the normal Cd content in soil of around 1 mg/kg (Anjelina et al., 2021). The Cd content is very high, exceeding the standard of 0.003 mg/L, indicating serious heavy metal contamination and is highly hazardous to human health and the environment. Cadmium is the only metal found above the threshold limit in soil (Boostani et al., 2024). The high Cd content in the landfill may originate from poorly managed electronic waste, batteries, and metal-coated plastics that enter the landfill (Boostani et al., 2024).

The Al content in the soil, at 5702.4 mg/kg, is considered high. Aluminum in soil is generally found in the form of clay minerals and oxides. Although Al is a common soil constituent, high levels can indicate certain mineralization or industrial/natural residues. However, at high pH (alkaline), the availability of Al to plants tends to be low, so it does not cause toxicity to plants. Aluminum metal in soil is usually a problem at low pH (acidic) due to the dissolution of toxic and toxic Al3+. At pH 8, dissolved Al tends to be significantly lower, but the high total content warrants attention due to potential mobilization potential if the pH changes. This is consistent with research conducted by

Hailegnaw et al., 2020, which showed that increasing pH and CEC (cation exchange capacity) can reduce the availability of Al, Cd, Zn, and Mn in soil.

Furthermore, the measured total Na value of 41.3 mg/kg indicates that sodium content can also significantly affect the soil's ability to immobilize metals. Na ions can play a role in ion exchange processes that occur on the surface of soil particles, which in turn can facilitate the increase of heavy metals. Zhou et al. (2024) stated that biochar-based material modification can assist in the adsorption of heavy metals such as Cd, through an effective ion exchange mechanism, in which Na ions in the soil play a role. High Na levels can affect water and nutrient availability, which in turn can affect plant growth and the soil's capacity to retain nutrients optimally. Therefore, the presence of Na requires special attention, as it can interact with other elements and affect the bioavailability of heavy metals in the soil. The organic matter content is relatively high at 6.67% and plays a crucial role in the cadmium immobilization process through the formation of organic complexes, increasing cation exchange capacity, and reducing dissolved Cd in the soil. Organic matter acts as a binding agent for heavy metals, which can then reduce their availability in the soluble phase of the soil (Gusri et al., 2024). The organic matter content in landfills has the potential to play a role in heavy metal immobilization, especially when combined with biochar treatment, which has been shown to be effective in stabilizing heavy metals (Jova et al., 2020).

Biochar Characterization with FTIR

Biochar was analyzed using Fourier transform infrared spectroscopy (FTIR). FTIR analysis aims to determine the presence of functional groups in the biochar used. The FTIR results of the biochar are shown in Figure 1.

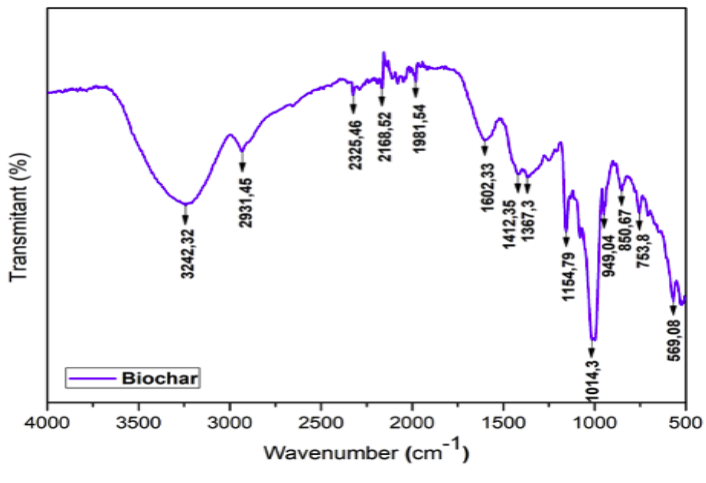

Figure 1. FTIR Spectrum of Biochar

The FTIR spectrum of biochar produced by SCPR (Damris et al., 2024) was recorded in transmission mode between 4000 and 500 cm-1 (Figure 4.1). As seen from the FTIR spectrum and results (Table 4.2), the biochar used in this study has aromatic and aliphatic functional groups (Ray et al., 2020). Based on the principle of infrared radiation absorption by molecules at certain frequencies that correspond to the vibrational energy of atomic bonds. Each functional group has a unique absorption pattern that can be used as a chemical characterization of the biochar surface. The FTIR spectrum results in Figure 4.1 are presented in the form of wavenumbers in the range of 4000 - 500 cm-1. This analysis aims to determine the chemical components and active functional groups that play a role in the adsorption and immobilization of heavy metal Cd in the soil. In the FTIR spectrum, several main absorption peaks are seen at wavenumbers 3,242.32 cm-1; 2,931.45 cm-1; 2,325.46 cm-1; 2,168.52 cm-1; 1,981.54 cm-1; 1,602.33 cm-1; 1,412.35 cm-1; 1,367.3 cm-1; 1,154.79 cm-1; 1,014.3 cm-1; 949.04 cm-1; 850.67 cm-1; 753.8 cm-1; and 569.08 cm-1. Each peak indicates the presence of a specific vibration of a particular functional group present on the surface of the biochar.

Table 2
Waveforms from FTIR

No	Wave Number (cm^{-1})	Functional Group
1	3200-3600	-OH
2	2931	-CH
3	2325	C≡C
4	2168	C≡C
5	1981	C=C
6	1602	C-C; COO^-
7	1412	-CH
8	1367	-CH
9	1154	C-O
10	1014	C-O
11	949	C-O
12	850	Carbon-related functional groups

FTIR analysis, which includes wavenumbers (cm-1), can provide in-depth information about the presence of various functional groups in a compound. Based on the data in Table 2, there are various wavenumbers that indicate the presence of certain functional groups. At wavenumbers 3,200-3,600 cm-1, absorption was found indicating the presence of -OH groups, which are generally associated with alcohols or phenols. Several previous studies have shown that absorption peaks in this range can be attributed to hydroxyl group vibrations. Biochar exhibits a broad absorption band function around 3,242 cm-1, which corresponds to the -OH stretch associated with hydroxyl groups and adsorbed water, indicating the presence of hydrophilic functional groups in the sample (Nandiyanto et al., 2023). Strikingly, biochar displays a broad and intense -OH band, indicating the presence of hydrogen-bonding functional groups.

The peak around 2,931 cm-1 is associated with the -CH stretching vibrations of aliphatic groups, which typically originate from lignocellulosic residues that were not fully decomposed during pyrolysis (Scroccarello et al., 2023). These vibrations are typically associated with hydrocarbon compounds, providing a clear indicator of the presence of aliphatic hydrocarbon chains. This peak frequently appears in FTIR analysis of carbon-based compounds. The presence of alphatic tends to reduce the polarity of biochar but contributes to its adsorption capacity through hydrophobic interactions with organic pollutants. In the biochar spectrum, two peaks are observed at wavenumbers 2,325 cm-1 and 2,168 cm-1, which correspond to C≡C stretching vibrations. At wavenumber 1,981 cm-1, it indicates the presence of C=C bonds. In lignocellulosic biochar, this peak often appears due to the formation of conjugated carbon compounds during pyrolysis. This is characteristic of compounds with aromatic or alkene structures (Duan et al., 2024).

The peaks at wavenumbers 1,602 cm-1 and 1,412 cm-1, respectively, are identified with C-C and COO- vibrations, indicating the presence of carboxylic salts or acidic compounds. At peak 1,367 cm-1, the assimilated -CH vibrations strengthen the presence of aliphatic groups in the compound. The higher the pyrolysis temperature, the stronger the aromatic band. Separate peaks at 1,154 cm-1, 1,014 cm-1, and 949 cm-1, which correspond to C-O stretching vibrations, indicate the presence of residual polysaccharide structures (cellulose/lignin) that have not been fully decomposed. The region between 1,050 cm-1 and 1,100 cm-1 shows peaks related to C-O-C and C-O stretching vibrations, which are typical for polysaccharide structures (Ardiani et al., 2025), and the peak at wave number 850 cm-1 indicates carbonate functional groups. The presence of these bands confirms that biochar contains inorganic components that are important for adsorption and increasing soil pH. This indicates that these compounds have structures related to carbonate ions or salts of carbonic acid (Nicholas et al., 2023).

Biochar Characterization with SEM

Biochar surface morphology is a structural parameter that significantly determines its ability in environmental applications, particularly in the adsorption and immobilization of heavy metals such as Cd2+ in soil. Biochar produced from lignocellulosic materials such as palm kernel shells, coconut shells, or other hard biomass generally exhibits distinctive morphological patterns, such as a hollow surface or pores, including macro, meso, and micropores formed during the pyrolysis process, as well as pore wall density, which plays a crucial role in interactions with metals. All of these characteristics are closely related to the initial biomass composition and pyrolysis conditions. Scanning Electron Microscopy (SEM) analysis was performed to determine the surface morphology of the biochar. The results of the SEM analysis are presented in Figure 2.

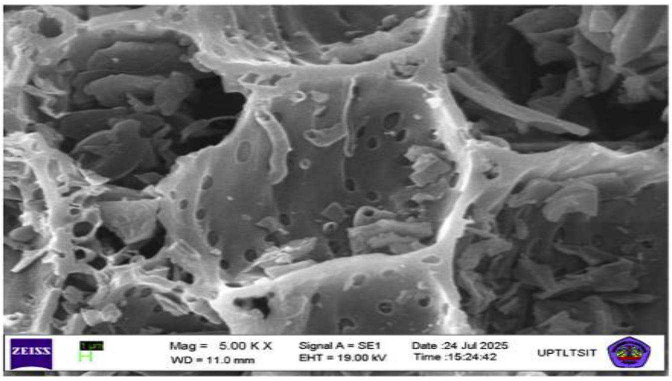

Figure 2. SEM results of biochar

Figure 2 shows the porous and fibrous surface morphology, identifying the pore structure, active surface, and changes in biochar texture that significantly impact the immobilization of the heavy metal Cd in soil. The biochar retains some of the fibrous structure of the original feedstock, with macro- and micropores visible throughout the surface. These pores form due to the release of volatile compounds during pyrolysis, creating tall, irregular voids and a rough surface (Ray et al., 2020). The pyrolysis process of biomass such as palm kernel shells tends to produce biochar with high structural resilience, supporting effective Cd adsorption through both macropores and functional groups on the pore walls, thus preventing pore wall collapse. SEM images confirm that the biochar has a complex and heterogeneous porous framework. The voids visible in the SEM images indicate the degree of biochar devolatilization, which affects the biochar's density and porosity (Kalina et al., 2022). The analyzed biochar has physical and structural qualities that are highly favorable for use in the remediation of Cd-contaminated soil. The characteristics of porosity, cracks, and layered structure indicate that biochar not only has a large surface area but also provides sufficient reactivity space to bind heavy metals. Biochar with these morphological characteristics can function as an effective adsorbent, improving soil physical properties, increasing cation exchange capacity, and reducing metal toxicity to plants.

Initial pH of Soil Sample

Initial soil pH is a crucial parameter in understanding soil quality and chemical conditions, particularly in areas impacted by anthropogenic activities, such as the Talang Gulo landfill. Talang Gulo, a long-standing waste disposal site in Jambi City, has soil that experiences significant ecological stress due to organic material decomposition, leachate movement, heavy metal contamination, and sulfide oxidation. Soil pH can influence soil chemical properties; typically, a lower pH increases the availability of heavy metals, while a higher pH decreases the availability of heavy metals. After measuring using a pH meter, the soil from the old Talang Gulo landfill site had a pH of 5.4, which is considered strongly acidic, typically found in fine- to medium-textured soils rich in organic matter.

Under these conditions, leachate entering the soil tends to increase the dissolution of heavy metals, including Cd and Al, thereby increasing the potential for contaminant mobility. Acidic soil conditions at landfill sites occur due to soil contamination by domestic solid waste containing organic matter, which causes a decrease in soil pH (Negi and Meena 2025). Long-term accumulation of waste produces organic matter that undergoes an incomplete humification process. Unstable organic matter produces many acidic carboxylic acid (-COOH) groups. When these groups decompose, H+ ions are released into the soil solution, lowering the pH. High soil acidity plays a significant role in the mobility of heavy metals, including Cd. Under low pH conditions, Cd2+ ions become more soluble and move into the soil liquid phase, thereby increasing the availability of Cd in the soil solution and its potential for plant uptake. Talang Gulo soil is known to be contaminated with metals such as Cd, Pb, and Zn. In addition, landfills such as the old Talang Gulo landfill produce CO2 from the landfill and root respiration, which can dissolve in soil moisture and release H+ ions into the soil. Protons can replace basic cations such as Ca2+, Mg2+, K+, and Na+ that are bound to soil particles, causing an increase in soil acidity (Yao et al., 2025; Huang et al., 2023).

pH Biochar

The biochar used in this study was produced from palm kernel shells using a modified Segmented Chamber Pyrolysis Reactor (Damris et al., 2024). The biochar pH of 9.4 is still within the commonly reported biochar pH range and is stated to comply with the European Biochar Certificate (EBC) and International Biochar Initiative (IBI) standards, indicating high alkali characteristics, which generally originate from medium to high temperature pyrolysis (500-700 0C) and tend to have higher ash and mineral content (Geng et al., 2022; Damris, 2019). The pH of biochar produced from palm kernel shells is in the pH range of 9.2-12.00 (Kong et al., 2023). The degree of alkalinity of biochar is influenced by temperature and raw materials (Damris, 2019; Oliviera et al., 2018). Feedstocks with high ash content, such as crop residues and grasses, generally have a higher pH than woody biomass, which typically has a lower ash content (Yao et al., 2025; Nguyen, 2025).

The feedstock influences the pH of biochar primarily due to its natural chemical composition, particularly its ash and mineral content (He et al., 2024). Different feedstocks exhibit varying levels of alkali and alkaline earth metals, which influence the amount of alkaline substances, such as carbonates, oxides, and hydroxides, present in biochar ash. Therefore, selecting the right feedstock and pyrolysis temperature can produce biochar with desired characteristics (He et al., 2024; Kong et al., 2019). During the biochar production process, hydrogen, oxygen, nitrogen, and carbon atoms in the organic feedstock are released in an unbalanced manner (Oliviera et al., 2018). The loss of these atoms is more pronounced than that of carbon atoms, resulting in a decrease in the ratios of carbon to hydrogen, carbon to oxygen, and carbon to nitrogen in the biochar product (Damris, 2019; Oliviera et al., 2018). Consequently, the stability, porosity, aromaticity, and alkalinity of the biochar increase. Furthermore, this also affects the surface area and functional groups of the biochar (Zhang et al., 2022).

Ash is the inorganic fraction remaining after carbon combustion. The ash content of high-pH biochar typically reaches 10-30%, depending on the biomass type. Ash contains basic minerals such as K2CO3, CaCO3, and metal oxides CaO and MgO, which are highly reactive to H+ ions. These minerals play a significant role in increasing the biochar's pH. High ash content significantly affects the alkalinity of biochar. Alkali minerals, including Ca, Mg, K, and Na, are mostly present in the form of carbonates, oxides, and hydroxides, which release hydroxide ions (OH-) upon contact with soil moisture (Septiana et al., 2018). Biochar with high alkalinity and significant inherent mineral content generally exhibits higher ash content (Zhang et al., 2022; Reyhanitabar et al., 2022). Temperature significantly affects the physical and chemical properties of biochar (He et al., 2024; Zhang et al., 2022). Increasing the pyrolysis temperature of high-ash feedstock produces more alkaline biochar. The type of feedstock and ash content, along with temperature, are important factors influencing biochar properties (Reyhanitabar et al., 2023).

Initial Effect of Biochar on Soil pH

The soil pH on day 0 in the treatment without biochar or the control was measured at 5.4, still relatively low due to the acidic effects of the extraction process. Acidic soil conditions cause Cd2+ to remain in soluble form, thus suboptimal immobilization efficiency. However, in the 5% and 10% biochar treatments, the pH increased to 5.6 (3.7%) and 5.7 (5.6%), respectively (Figure 4.3). This indicates that biochar begins to act as an initial adsorbent by providing an active surface for the adsorption of metal ions. This demonstrates that the addition of biochar has been shown to increase soil pH. The addition of biochar demonstrates the soil's buffering capacity in neutralizing the alkalinity of the biochar (Nguyen, 2025; Dvoracek et al., 2022).

This phenomenon is particularly evident in acidic soils (Yao et al., 2025) and occurs through the neutralization of hydrogen ions (H+) by the carbonates, oxides, and hydroxides present in the biochar (Nyugen, 2025). A more significant increase in soil pH was observed in acidic soils compared to neutral and alkaline soils, where the effect may be smaller or insignificant. Under acidic conditions, such as those found in the soil at the Old Talang Gulo Landfill, interactions between Al and Fe oxides may also play a role; however, toxic ions may be released (Dvoracek et al., 2022). The Al concentration in the soil at the Old Talang Gulo Landfill, measured at 5,702.4 mg/kg, is much lower than the normal range found in soil, which is approximately 10,000 to 30,000 mg/kg (EPA, 2003). Given these concentration levels, toxic Al release in the soil at the Old Talang Gulo Landfill is unlikely.

The Effect of Incubation Time and Biochar on Soil pH

The effect of incubation time and the use of palm kernel shell biochar on soil pH can be seen in Figure 3, where the pH of the control soil, or soil without biochar, did not show a significant increase during the incubation period. This indicates that the soil has a buffering capacity, which helps prevent continued pH fluctuations over time (Nguyen, 2025). Furthermore, microbial activity and chemical processes may not produce significant alkalinity or sufficient neutralization reactions to increase soil pH in the future (Dvoracek et al., 2022).

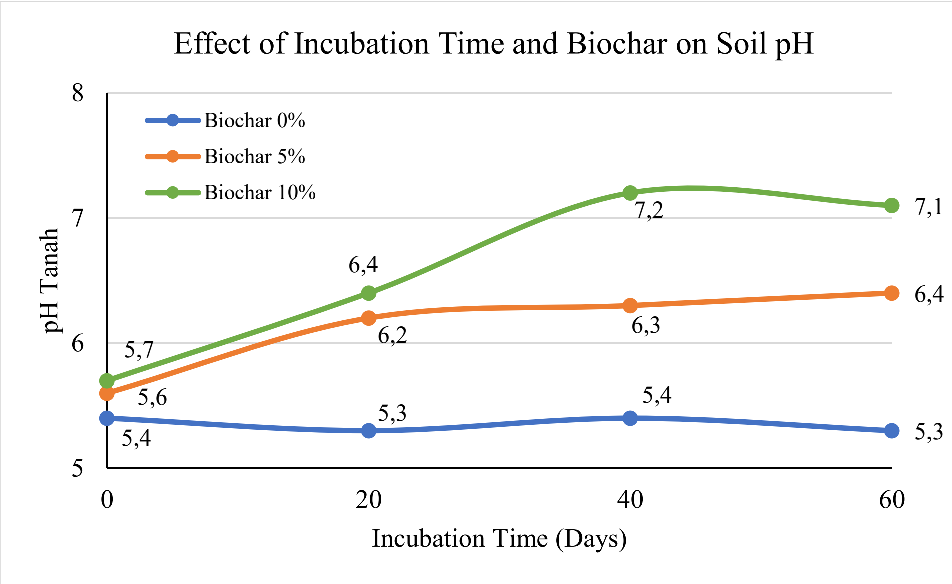

Figure 3. Effect of biochar and incubation time on soil pH

The initial soil pH was 5.4 before being treated with the addition of biochar. The addition of 5% and 10% biochar significantly increased the soil pH, especially seen on the 20th and 40th days of incubation (Figure 4). The addition of 5% biochar increased the soil pH from 5.6 to pH 6.2, reflecting a 10.71% increase, and to 6.3 (a 1.61% increase). 10% biochar showed a 12.28% increase, on the 20th day with a pH of 6.4 and on the 40th day of 7.2 (a 12.5% increase) and on the 40th day of incubation. After the 40th day of incubation, there was no increase in pH for the addition of 5% and 10% biochar. The soil treated with 10% biochar showed a consistently higher pH level compared to the control group (0%) and the addition of 5% biochar. The increase in soil pH after biochar application can be attributed to the alkaline nature of biochar, which includes basic cations such as Ca, Mg, K, and Na in the form of oxides and carbonates. These compounds reduce soil acidity by reacting with H+ and Al3+ ions (Sun et al., 2022). Biochar's surface functional groups, including (-COO-) and (-O), contribute to the neutralization of H+ ions, thereby increasing soil pH (Liu et al., 2025). The increase in soil pH is closely correlated with the biochar application rate (Yao et al., 2024; Abdella et al., 2024). The increase in pH strengthens the precipitation process of heavy metals in the form of Cd(OH)2 and CdCO3.

Under these conditions, the soil system has reached a new equilibrium, where most of the Cd is no longer in a readily mobile dissolved form. Biochar's alkaline nature and porous structure play a crucial role in maintaining this stability by providing active sites for metal binding and maintaining a neutral pH. Increasing biochar application rates generally lead to an increase in soil pH levels, with results influenced by pyrolysis temperature and feedstock type (Yoa et al., 2025; Geng et al., 2022). Long-term biochar use is associated with maintaining high soil pH levels, which is due to its persistent alkalinity, buffering capacity (Abdella et al., 2024), and resistance to decomposition. Recent studies confirm that the dual mechanisms consisting of chemical neutralization, physical adsorption, and hydrodynamic modification illustrate the synergistic potential of biochar in acidic soil remediation (Liu et al., 2025; Bolan et al., 2023).

Initial Effect of Biochar on the Immobilization Efficiency of Cd Metal

The effect of biochar on the immobilization efficiency of Cd metal shows the relationship between the percentage of biochar (0%, 5% and 10%) and the efficiency of metal immobilization in two solvent conditions: water (neutral pH) and HCl acid solution pH 4 presented in Figure 4.

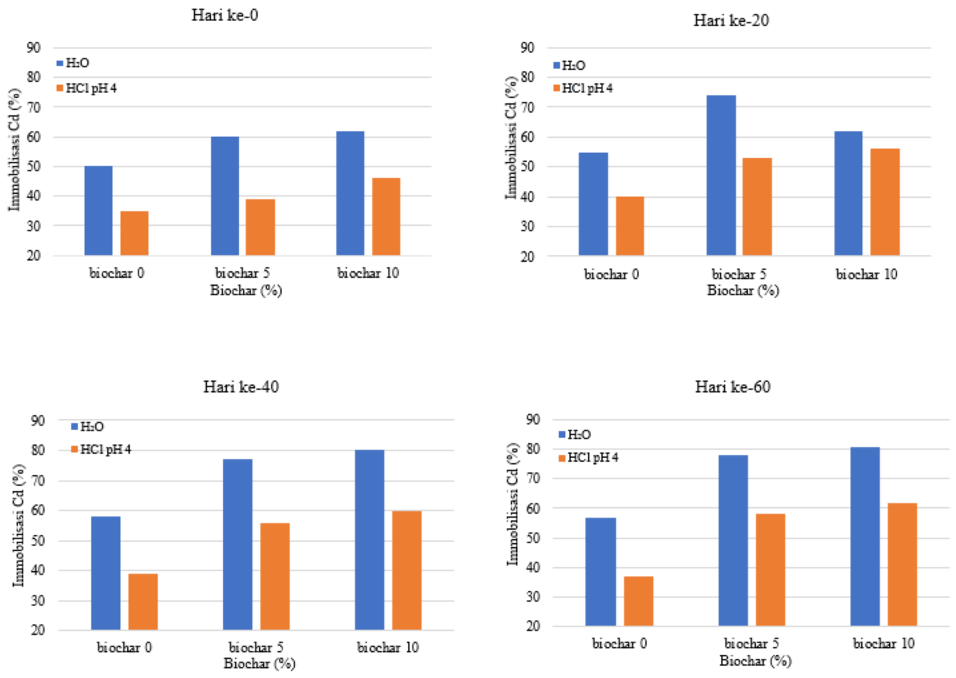

Figure 4. The effect of biochar on the efficiency of instant Cd immobilization extracted with water (H2O) and HCl pH 4.

Water extraction was performed to represent the soluble Cd fraction that could potentially contaminate groundwater, while HCl pH 4 extraction was used to simulate acidic conditions and evaluate the stability of Cd binding in the soil after biochar treatment. The use of HCl pH 4 is relevant considering that previous studies at the Talang Gulo Landfill reported that the leachate and surrounding soil exhibit moderately acidic characteristics, with pH values ranging from 4.3 to 5.2 (Limia, 2024). Acidic soil and leachate conditions can enhance metal solubility and mobility, making the pH 4 simulation appropriate for evaluating Cd stability under environmental stress.

Figure 4.5 shows that the initial addition of biochar significantly increased the soil's ability to immobilize heavy metals. The direct impact of biochar on Cd immobilization was tested using mineralized water and a pH 4 HCl solution. On day 0, the untreated soil showed Cd immobilization of approximately 50.00% in water and 35% in acidic conditions. The application of 5% biochar increased immobilization to 60% in water and 39% in pH 4 HCl solution, while 10% biochar further increased immobilization to 62% (water) and 46% (HCl). These early improvements suggest that biochar addition increases soil pH, thereby reducing Cd solubility. The rise in pH likely leads to the precipitation of Cd as $CdCO_3$ (cadmium carbonate) and enhances electrostatic adsorption due to increased negative surface charge on soil particles.

On the 20th day of incubation, immobilization increased in all treatments: 55% in water and 40% in HCl pH 4 without biochar; 74% in water and 53% in HCl with 5% biochar; and 62% in water and 56% in HCl with 10% biochar. The pattern continued at day 40, where immobilization reached 58% (water) and 39% (HCl) in the control, 77% (water) and 56% (HCl) with 5% biochar, and 80% (water) and 60% (HCl) with 10% biochar. These results support the findings of Lehman & Joseph (2015), who stated that acidic conditions reduce the soil's immobilization capacity due to protonation of surface functional groups and reduced electrostatic attraction for cations.

The ability of biochar to overcome this limitation lies in its high cation exchange capacity (CEC) and buffering capacity. According to Yuan et al. (2011) and Ahmad et al. (2014), biochar rapidly activates its CEC upon contact with soil, enabling exchange reactions with Cd^{2+} ions. In addition, pH buffering and carbonate formation from biochar contribute to transforming Cd from soluble/exchangeable forms into more stable carbonate- or oxide-bound forms. These mechanisms are further supported by carbonate precipitation pathways, which become dominant in neutral to slightly alkaline conditions induced by biochar addition.

By day 60, the Cd immobilization reached 57% (water) and 37% (HCl) in the untreated soil, 78% (water) and 58% (HCl) with 5% biochar, and 81% (water) and 62% (HCl) with 10% biochar. These improvements confirm that biochar not only alters soil pH but also provides reactive surfaces and functional groups for Cd complexation (Chu et al., 2018), allowing effective reduction of dissolved Cd fractions (Chen et al., 2024). The higher immobilization seen in water compared to HCl pH 4 suggests that while biochar performs well under neutral conditions, acidic stress still poses a challenge, albeit reduced with higher biochar doses.

In conclusion, increasing the biochar dosage and extending the incubation time enhanced Cd immobilization efficiency, with better results in neutral water extraction than in simulated acidic conditions. This indicates that biochar effectively binds Cd in the soluble fraction and improves long-term stability, particularly under conditions similar to those found at the Talang Gulo landfill.

The Effect of Incubation Time and Biochar on Cd Immobilization Efficiency

In accessing the dissolved Cd fraction from the soil, pure water and hydrochloric acid with pH 4 were used as extraction agents. The remaining cadmium in the solid phase was analyzed using GF-AAS. Figure 5 illustrates the effect of incubation time and biochar addition on the Cd immobilization efficiency after extraction of the dissolved Cd fraction using water (a) and HCl pH 4 (b). The results showed a moderate increase in Cd immobilization efficiency along with increasing incubation time. Incubation partially converts soil cadmium from the exchangeable fraction to a less stable fraction (Yang et al., 2019) and increases the cadmium immobilization efficiency.

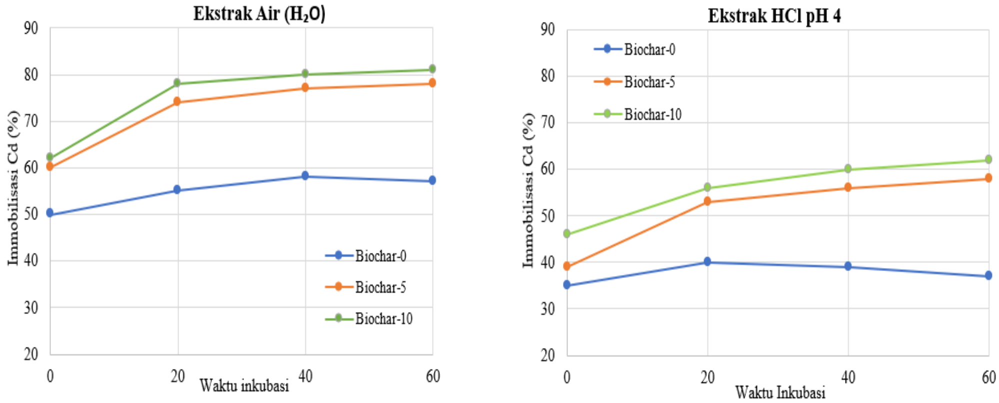

Figure 5. Impact of incubation time and biochar on the efficiency of Cd immobilization after extraction with water (A) and HCl pH 4 (B)

Application of 5% and 10% biochar increased Cd immobilization in the soil. The efficiency of 5% biochar increased from 60% to 74% (a 14% increase) on the 20th day of incubation, from 74% to 77% on the 40th day of incubation, and at the end of the incubation period, on the 60th day, the effect of 5% biochar increased to 78%. The 10% biochar effect on the 20th day was 78%, increasing to 80% on the 40th day and 81% on the 60th day. Cd immobilization increased rapidly in the first 20 days of incubation and then stabilized until the 60th day, indicating that biochar is effective in reducing Cd availability, especially at the beginning of incubation. The 5% biochar treatment using HCl solution at pH 4 increased from 39% to 53% on day 20, then to 56% on day 40, and to 58% on day 60. The 10% biochar treatment increased from 46% to 56% on day 20, then to 60% on day 40, and to 62% on day 60. This allows more time for chemical, physical, and biological processes to stabilize Cd in the soil, including increasing soil pH, which reduces metal solubility, ion exchange, and complexation with acidic functional groups on the biochar surface, physical adsorption on the porous structure of the biochar, and precipitation as insoluble compounds (Boostani et al., 2024; Rahim et al., 2022).

Increasing the incubation time provides more opportunity for the biochar to interact with metal ions and soil components, resulting in the formation of stronger, more dissolution-resistant Cd-biochar complexes. Biochar plays a crucial role in increasing the efficiency of Cd immobilization through interrelated mechanisms (Boostani et al., 2024; Bolan et al., 2022; Rahim et al., 2022). The higher the biochar dose, the greater the number of active sites and adsorptive surface area available to bind Cd2+ ions. Liu et al., (2022) demonstrated that increasing the biochar dose from 1% to 5% reduced Cd availability by more than 80% in contaminated soil through a combination of adsorption mechanisms and metal-organic complex formation. The increasing trend in Cd immobilization over time and biochar dose indicates that biochar functions not only as a neutralizer of soil acidity but also as an active adsorbent and chemical stabilizer for heavy metals in the soil.

The increase in soil pH due to biochar application causes metals to shift to less soluble hydroxide and carbonate forms. Furthermore, the increased cation exchange capacity and large surface area of biochar facilitate Cd immobilization through specific and non-specific interactions (Juraszek and Piasecka, 2020). Biochar can enhance Cd immobilization through the interaction of environmental parameters such as soil pH, redox potential, and biochar's inherent properties such as adsorption, functional groups, porous structure, and high stability, which are characteristic of biochar as a promising amendment to reduce heavy metal toxicity and enhance heavy metal immobilization.

Conclusion

Cd immobilization in the soil of the Old Talang Gulo Landfill increased with the addition of 5% and 10% biochar. A 60-day incubation experiment showed that Cd immobilization increased with increasing incubation time and biochar concentration. Water (H2O) extraction treatment showed more optimal biochar performance, while extraction using HCl pH 4 under acidic conditions decreased immobilization capacity. Nevertheless, the biochar-treated soil still had a higher Cd-retaining capacity than the control soil without biochar.

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