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Analysis of Soil Heavy Metal Absorption with the Application of Biochar Based on Oil Palm (*Elaeis guineensis* Jacq.) Frond Waste

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Abstract

Soil contamination by heavy metals such as cadmium (Cd) and lead (Pb) is an environmental issue that degrades soil quality and poses risks to the health of living organisms. One strategy to reduce heavy metal mobility in soil is the use of biochar derived from biomass waste. This study aimed to analyze the uptake of Cd and Pb in soil following the application of biochar produced from oil palm frond waste via pyrolysis. The biochar was produced at temperatures of 350–400°C for 4 hours, then applied to the soil and incubated for one month. We analyzed heavy metal content using wet digestion, followed by measurements via atomic absorption spectrophotometry (AAS) and ICP-MS. The results demonstrated that the application of oil palm frond biochar reduced Cd and Pb concentrations in the soil through mechanisms such as adsorption, ion exchange, surface complexation, and precipitation. Key biochar characteristics—specifically high surface area, high porosity, and high cation exchange capacity—play a crucial role in immobilizing heavy metals, thereby reducing their bioavailability in the soil. The advantage of this research is that biochar from oil palm frond waste has proven to be highly effective in absorbing up to 100% of cadmium and also successfully reducing lead levels, using inexpensive, readily available, and environmentally friendly materials. This research also introduced innovation in the form of activating the biochar with eco-enzymes to enhance its absorption capacity. In addition to absorbing heavy metals, this biochar also improves soil fertility, providing dual benefits and supporting more sustainable agriculture. The analytical results were compared against the standards set by the International Biochar Initiative (IBI) to evaluate the safety of using the biochar as a soil amendment. The study indicates that oil palm frond biochar can serve as an eco-friendly adsorbent for remediating heavy metal-contaminated soil while offering a sustainable alternative for managing oil palm biomass waste.

Keywords: Biochar, Cadmium (Cd), Ecoenzyme, Lead (Pb), Pyrolysis

1. Introduction

Soil is a crucial factor that determines the growth and yield of cultivated crops. It serves as a growing medium for plants and acts as a reservoir and supplier of nutrients. Based on its particle size, soil is a mixture of sand, silt, and clay. Finer particles result in a larger surface area per unit weight. Therefore, clay is the soil fraction with the largest surface area compared to the other two fractions. It is on the surface of these particles that various chemical reactions occur, which then affect soil fertility (Budidaya et al., 2024).

The mechanism by which biochar restores (remediates) soil contaminated with heavy metals is greatly influenced by soil type, the presence of cations in the soil, and the composition of the biochar itself. Previous studies have shown that biochar plays a role in stabilizing heavy metals by increasing the soil's adsorption capacity and binding metal ions through interactions with minerals such as phosphate and carbonate (Panjaitan et al., 2025).

Oil palm fronds are an abundant biomass waste from the palm oil plantation sector in Indonesia. This waste is usually left in plantation areas as ground cover, but in reality, these fronds have great potential for further utilization. Oil palm frond waste has not been optimally

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utilized. As the world's largest palm oil producer, Indonesia generates large amounts of frond waste (approximately 3 tons per hectare per year). However, so far, it has often been left to pile up or openly burned in plantations, despite its potential to be processed into useful biochar.

A notable research gap is that previous studies have focused on the general effectiveness of biochar adsorption but have not comprehensively analyzed whether biochar derived from oil palm fronds is safe to use—specifically, whether it is free from heavy metal residues inherent in the raw materials. In one hectare of oil palm land, the annual production of fronds is quite significant; if left untreated, it can cause environmental disturbances. Oil palm fronds contain high levels of lignocellulose, making them a potential raw material for various products such as biochar, compost, bioethanol, and even paper pulp. (Ahmad, A., Amri, I., & Nabilah, 2020)

Pyrolysis is a thermal decomposition process that occurs in the absence of oxygen and converts biomass into more stable products such as biochar, bio-oil, and pyrolytic gas. Research by Yanti, Ratnaningsih, and Ikhsani (2022) shows that pyrolysis products from palm oil waste, particularly shells and fronds, have great potential to be developed into biochar that can be used as an alternative fuel in the form of bio-briquettes. Their research emphasized the importance of pyrolysis temperature and time in determining the final quality of the biochar (Yanti et al., 2022).

Zamzami (2023), in his study, proved that the pyrolysis method is effective in producing biochar from oil palm fronds, which is then applied to the soil. Researchers highlighted that biochar characteristics changed significantly depending on the temperature and pyrolysis time used. When used in planting media, biochar can increase soil water capacity and stimulate plant growth, indicating promising agronomic potential (Zamzami, 2023).

Biochar is charcoal produced by the pyrolysis of organic materials such as agricultural waste, wood, or other biomass under oxygen-limited conditions. This process produces a carbon-rich product with a porous structure widely recognized as a soil amendment capable of improving the physical, chemical, and biological qualities of the soil. Various studies have shown that biochar from waste such as rice husks, palm oil waste, and corncobs has great potential as a soil ameliorant in marginal or ex-mining areas (Muslimah, 2022).

According to Hidayat & Pramuga (2024), heavy metals are a group of metallic elements with high densities and toxic characteristics that harm the environment and human health. Elements such as lead (Pb), cadmium (Cd), mercury (Hg), and chromium (Cr) fall into this category and are non-biodegradable, so they accumulate easily in organismal tissues and soil environments. Heavy metal contamination generally originates from industrial activities, agriculture, and poorly managed domestic waste. The application of FABA to former tin mining sites is expected to enrich macro- and micronutrients, thereby optimizing the growth of plants cultivated there. To determine the effect of FABA application on soil lead (Pb) content and heavy metal uptake by peanut plants through their pods, as an indicator of food security in former tin mining sites, research is needed to assess heavy metal uptake in various FABA application compositions (Khodijah et al., 2026).

According to research (Aulia et al., 2024), Saccharomyces cerevisiae packaged in calcium alginate capsules is effective in removing Cd 2+ from contaminated water with an absorption capacity of 15.4 g/capsule (Montfort, 2016). Given this potential, Saccharomyces cerevisiae can be used as a remediation material for soil contaminated with heavy metals, particularly cadmium. Furthermore, it can assist in soybean cultivation on contaminated soil and promote the absorption of cadmium to prevent its accumulation in plant seeds.

Currently, Indonesia has no National Standard (SNI) that specifically sets limits on heavy metal content in biochar used as a soil conditioner. Therefore, many biochar studies in Indonesia refer to the IBI standard or the European Biochar Certificate (EBC) as international benchmarks for evaluating biochar quality.

In this study, of compared the Cd and Pb results to the IBI standard, one of the most widely used international benchmarks for biochar certification. The International Biochar Initiative (IBI) sets maximum limits for heavy metal content in biochar used as a soil amendment.

2. Material and Methods

Biochar production was carried out on the campus of the Indonesian Palm Oil Technology Institute (ITSI), located on Jalan William Iskandar (Jalan Pancing), Medan, North Sumatra 20371. The coordinates are at 3 °35'44.9"N (North Latitude) and 98 °42'28.3"E (East Longitude). This area has an average elevation of around 25 meters above sea level. Oil palm fronds and soil were obtained from the Indonesian Palm Oil Technology Institute plantation.

2.1. Tools and materials

The tools used in this study were an oven, dryer, 60 mesh sieve, sample grinder, analytical balance, hot plate, Erlenmeyer flask, beaker, measuring flask, porcelain cup, dropper pipette, glass funnel, filter paper, plastic clip for sample storage, Atomic Absorption Spectrophotometer (AAS), and ICP-MS (Inductively Coupled Plasma Mass Spectrometry) instruments.

Materials included dry oil palm fronds, soil, oil palm plants, ecoenzymes, nitrogen gas, standard heavy metal solutions (for tool calibration), and distilled water.

This research was conducted for 3 months, from April to June, with several stages, including the first stage of preparing raw materials from oil palm frond waste. The

pyrolysis process was carried out to obtain biochar, the main raw material in this research, and the biochar was activated to open the pores and provide nutrients. Apply the biochar to the soil and make observations. The application duration was 1 month.

Before applying biochar to the soil samples, soil analysis was carried out to establish the control baseline. The soil samples that had been taken were analyzed at the Palm Oil Research Center (PPKS) Laboratory for control data analysis.

2.1.1. Sample Preparation

Palm fronds are dried to remove moisture, then cut into small, uniform pieces and stored in a closed container before pyrolysis.

2.1.2. Pyrolysis Process

Oil palm fronds are fed into a pyrolysis reactor. The pyrolysis process is carried out at 350-400°C for four hours in low-oxygen conditions. The resulting biochar is then collected, cooled, and stored in a sealed container at room temperature.

2.1.3. Application to soil and Laboratory Analysis

The cooled biochar is sieved into smaller particle sizes. Before applying it to the soil, mix the biochar with ecoenzyme and water in a ratio of 300 ml of water, 30 ml of ecoenzyme, and 60 grams of biochar. Then, mix in one container and stir every 3 hours so that the ecoenzyme solution is evenly mixed in the pores of the biochar. After that, sprinkle the biochar on the soil being studied and make observations.

The soil samples were then analyzed in the GIS Laboratory for data analysis. Observation parameters included the heavy metals cadmium (Cd) and lead (Pb).

2.2. Observation Parameters

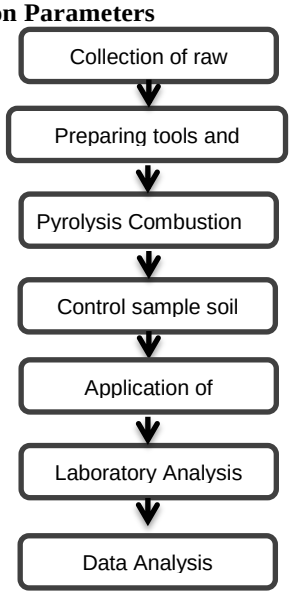


Figure 1. Research Diagram

2.3. Heavy metal

The rapid progress of the times has increased human needs. Increasing human needs also drive industry to expand its activities to meet them. Various activities in the metal mining, metal plating and alloying, oil, pigment, pesticide manufacturing, and leather tanning industries can produce waste containing heavy metals (Bonor et al., 2023).

Neutral soil pH conditions cause the movement of elements in the soil to be hampered and immobile, so that soil Pb will remain continuously in the soil (Sherene, 2010) states that all types of heavy metals will show low mobility at neutral to slightly alkaline pH values and will increase again if there is a decrease in soil pH. The addition of dolomite fertilizer, manure, and compost to the land where waste is dumped serves to increase the pH value of the soil.

The mechanism of toxicity of heavy metals released by mining activities (e.g. Pb, Cd, As, Hg, Zn, Cu) explains how such pollution threatens agricultural productivity and public health. In soil, heavy metals can accumulate in the topsoil horizon and become available for uptake by plant roots; at physiological levels, they disrupt photosynthesis, cause chlorosis, reduce cell division and root growth, and inhibit important enzymes, reducing crop yields. For humans, exposure through contaminated food, drinking water, and dust can cause bioaccumulation and chronic effects, such as nervous system and cognitive impairment in children (Pb), kidney disorders and carcinogenicity (Cd, As), as well as hepatotoxic or neurotoxic effects depending on the element—thus creating a significant public health risk. A summary of the literature review indicates a pattern of high concentrations of heavy metals in topsoil around mine sites and nearby agricultural land, with a proportion of land/market garden samples exceeding safety thresholds for Cu, Zn, Cd, and others in several case studies in contaminated agricultural areas. Implicit in this evidence is the urgency of assessing soil/water quality monitoring and mitigation interventions to protect land productivity and the health of affected residents (Adnan et al., 2022). (Félicien Mununga Katebe 1, 2,* et al., 2023) .

Therefore, using the experimental quantitative method to measure the levels of heavy metals Cd and Pb in the soil before and after biochar application, the analysis process begins with taking composite soil samples, which are then crushed and sieved to make them homogeneous, followed by extraction using the wet digestion method (HNO_3 /HCl solvent) according to SNI and IBI standards. The resulting digestion solution is then analyzed using Atomic Absorption Spectrophotometry (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to measure Cd and Pb concentrations accurately. The data are then processed descriptively and quantitatively by comparing metal levels before and after treatment against SNI and International Biochar Initiative (IBI) standard thresholds,

and calculating the level of reduction effectiveness using the percentage removal efficiency formula ($C_0 - Ce$) / $C_0 \times 100\%$. The tools and supporting materials in this process include dry oil palm fronds, ecoenzymes, nitrogen gas, heavy metal standard solutions, and distilled water as the main ingredients, as well as drying ovens, grinders, analytical scales, hot plates, Erlenmeyer flasks, beakers, porcelain cups, micropipettes, glass funnels, filter paper, 60 mesh filters, and pyrolysis reactors as laboratory equipment, so that they can be used as adsorption materials for both liquid and organic substances.

3. Results and Discussion

This research aimed to determine the ability of oil palm frond waste-based biochar to reduce the heavy metal content of Cadmium (Cd) and Lead (Pb) in soil. Initial analysis was carried out on control soil to determine the heavy metal content before treatment. Next, biochar was applied to the soil and incubated for one month before retesting.

Biochar is a carbon-rich material produced through the pyrolysis of biomass under oxygen-limited conditions. Its characteristics, including high surface area, high porosity, and the presence of active functional groups, enable it to adsorb various contaminants, including heavy metals. Furthermore, biochar can increase soil pH and cation exchange capacity, thereby reducing the mobility of heavy metals in soil (IBI, 2013).

Laboratory analysis revealed that the control soil sample before biochar application contained heavy metals such as cadmium (Cd) of 0.05 ppm and lead (Pb) of 0.34 ppm. While the concentrations of both heavy metals are generally considered quite high, they are still below the safe threshold required by the International Biochar Initiative (IBI) standards. However, the presence of heavy metals in plantation land can negatively affect plant physiology and productivity. Therefore, we carried out remediation efforts by adding activated biochar. The application of biochar aims to bind (immobilize) heavy metal compounds in the soil, so that the availability of these pollutants can be reduced and soil conditions become safer to support plant growth.

Based on the analysis results, this test was conducted on a composite soil sample taken from several representative points around the planterbag area, with two repeat measurements, namely Simplo (first measurement) and Duplo (repeat/duplicate measurement), to ensure the consistency and validity of the analysis results. The analysis was carried out using the 18-13-1/MU method with an ICP-OES (Inductively Coupled Plasma - Optical Emission Spectroscopy) instrument, an emission spectrometry technique capable of detecting heavy metal concentrations at very low levels. The Limit of Detection (detection limit of the tool) for the Cadmium (Cd) parameter is 0.00011 mg/kg, so a "Not Detected" result for Cd indicates that the concentration is below the detection threshold of the tool, not that it is truly zero. For the purposes of calculating the effectiveness of heavy metal reduction in this study, the value used as the final result is the Duplo value (Pb = 0.29 mg/kg), because it is a repeat result that serves as confirmation of the Simplo results. The Cd and Pb values obtained were below the IBI threshold for oil palm frond biochar, which is categorized as safe for use as a soil conditioner and does not pose an additional risk of pollution.

Heavy Metals: Cadmium (Cd) and Lead (Pb). The analysis results show that the application of biochar also causes a decrease in Cd and Pb content in the soil. Cadmium (Cd) is a heavy metal that is relatively easy to dissolve and move, especially in acidic soil conditions. Therefore, biochar application can increase pH and reduce Cd solubility, making its presence more stable in the soil. In addition to increasing pH, biochar's porosity and high cation exchange capacity also influence Cd adsorption. Cd^2 ions can bind to the biochar surface through ion exchange and surface complexation, reducing the available Cd concentration in the soil solution (IBI, 2013).

The decrease in Lead (Pb) indicates that oil palm frond biochar can bind Pb^2 ions, reducing their availability in the soil. Biochar's ability to adsorb Pb is influenced by its high surface area and the presence of hydroxyl (-OH), carboxyl (-COOH), and phenolic functional groups that can form complex bonds with heavy metal ions. Furthermore, the increase in soil pH due to biochar application causes Pb to precipitate more easily in the form of insoluble compounds, thus reducing its mobility (IBI, 2013).

These results indicate that oil palm frond biochar has good potential as a remediation material to reduce Cd pollution in soil and as an environmentally friendly natural adsorbent in the remediation of heavy metal-contaminated soil.

The effectiveness of biochar in reducing heavy metal concentrations can be calculated using the formula:

$$\text{Effectiveness} = \frac{C_0 - C_e}{C_0} \text{x } 100\%$$

Information:

C_0 = Initial concentration of heavy metals in the sample before being given biochar (mg/L or ppm).

C_e = Final concentration (equilibrium) of heavy metals after the contact/filtration process with biochar is complete (mg/L or ppm).

Effectiveness of Cadmium (Cd)

$$(\text{Cd}) = \frac{0{,}05 - 0}{0{,}05} \text{x } 100\% = 1 \text{ x } 100\% = 100\%$$

Cadmium (Cd) showed a very significant reduction with 100% effectiveness, with the Cd concentration decreasing from 0.05 ppm to undetectable after biochar application. This finding indicates that biochar is very effective in immobilizing Cd^2 ions through adsorption

mechanisms on active functional groups and precipitation due to increased soil pH.

Effectiveness of Lead (Pb)

$$(Pb) = \frac{0,34-0,29}{0,34} x\ 100\% = \frac{0,05}{0,34} = 0.147 \text{ x } 100\% = 14.71\ \%$$

Pb (Lead) decreased by 14.71 %, from 0.34 ppm to 0.29 ppm. This value is lower than Cd because Pb^{2+} ions are larger, so adsorption requires longer incubation time and a higher biochar dosage. Nevertheless, the decrease was still significant, indicating that biochar plays an active role in reducing the mobility and bioavailability of Pb in the soil through cation exchange mechanisms and carboxylate group complexation.

The reduction percentage obtained indicates the biochar's success rate in adsorbing heavy metals. The effectiveness of Pb reduction in this study (14.71%) is lower than the effectiveness of Cd in the same study. It is also relatively low compared to the Pb reduction claimed in the study by Rahayu et al. (2021), who used activated palm oil biochar in liquid waste. This finding is consistent with the nature of the Pb^{2+} ion, which is larger in size, so that it requires a longer incubation time and a higher dose of biochar to achieve maximum effectiveness. This study was significantly superior for Cd reduction, even with a relatively short incubation time. However, for Pb, its effectiveness is still below the optimal performance achieved by other studies, indicating that there is room for further development in terms of biochar dosage, incubation duration, and the level of ecoenzyme activation used. Therefore, a higher effectiveness value indicates greater biochar ability to mobilize heavy metals in soil. The success of biochar in absorbing heavy metals is influenced by:

1. Biochar surface area
2. Number of micro and macro pores
3. Organic carbon content
4. Cation exchange capacity
5. The pH of biochar tends to be alkaline.

These characteristics cause Pb and Cd ions to bind more easily to the surface of biochar than in soil solution (IBI, 2013).

Table 1. IBI Standards for Heavy Metals

Parameter	Maximum limit (mg kg^{-1})
CD	≤39
Pb	≤300

Source: IBI Biochar Standards Version 1.1. (IBI, 2013)

The IBI standard table shows that the levels of heavy metals Cd and Pb decreased after the application of oil palm frond biochar, when compared with the International Biochar Initiative standard *(IBI, 2013). The initial* levels of both metals were actually below the maximum threshold set (Cd levels ≤ 39 mg kg^{-1} and Pb ≤ 300 mg kg^{-1}). After the remediation process, the quality of biochar became better and safer to use as a soil conditioner because the concentration of heavy metals was increasingly moving away from the maximum threshold of the quality standard, with a reduction effectiveness of 100% for Cd and 14.71 % for Pb, respectively."

Table 2. Laboratory Analysis Results of Cd and Pb

Parameter	Unit	Before	After	Comparison	Decrease %	Information
CD	ppm	0.05	-	-	100%	Decline
Pb	ppm	0.34	0.29	0.05	14.71%	Decline

Based on the research results in the table, the application of biochar based on oil palm frond waste has been shown to reduce the content of heavy metals Cd and Pb in the soil. Before treatment, the initial concentration of Cd in the soil was 0.05 ppm. After biochar application, the Cd content decreased significantly to the point of no longer being detectable. Meanwhile, for Pb, the initial concentration of 0.34 ppm was successfully reduced to 0.29 ppm after treatment, indicating a decrease of 0.05 ppm.

Overall, the results of this study demonstrate that biochar derived from oil palm fronds is highly effective as an ameliorant (soil conditioner) for the remediation of land contaminated with heavy metals. This reduction mechanism occurs because biochar can adsorb and immobilize heavy metals in the soil, significantly decreasing the concentration of these hazardous substances. Notably, biochar's adsorption capacity was much more effective in reducing cadmium (Cd), achieving a 100% reduction, than for lead (Pb), which showed a 14.71% reduction.

The difference in effectiveness levels is influenced by the unique characteristics of each metal, such as ion size, affinity to the biochar surface, and soil chemical conditions that affect the retention of these heavy metals. The concentrations of Cd and Pb after the application of oil palm frond biochar were confirmed to be below the thresholds set by the IBI. Therefore, this palm oil waste-based soil conditioner is categorized as very safe for use in agriculture and land restoration, as it has been proven to improve soil quality without posing risks of additional pollution or contamination to the surrounding environment.

4. Conclusion

Based on the research results, oil palm frond waste-based biochar demonstrates superiority in reducing heavy metals in soil: cadmium (Cd) decreased from 0.05 ppm to

"undetectable" (100% removal efficiency). In comparison, lead (Pb) decreased from 0.34 ppm to 0.29 ppm (14.71% reduction). Based on these findings, oil palm frond biochar is recommended for farmers and plantation operators as an alternative soil conditioner for land contaminated with heavy metals. The main advantage of this biochar lies in its ability to immobilize heavy metals through mechanisms such as adsorption, ion exchange, surface complexation, and increased soil pH, making it an inexpensive and environmentally friendly remediation solution.

Compared to previous studies, the 100% reduction of Cd in this research is notably high, even surpassing the effectiveness of biochar derived from coal lignite waste in a fixed-bed column system, which achieved a 99.83% reduction. It also outperforms the study by Prasetyo (2021), which used unactivated palm frond biochar to reduce manganese (Mn) in peat water, with a reduction of 78% (though involving a different metal). Conversely, the 14.71% reduction in Pb observed in this study is relatively lower than the results reported by Rahayu et al. (2021), who used activated palm biochar in liquid waste.

Overall, biochar made from oil palm frond waste has the potential to serve as an environmentally friendly soil remediation material and an alternative use for oil palm plantation waste. In addition to reducing heavy metal content, the biochar used in this study meets safety standards, as measured heavy metal levels remain below the maximum limits set by the International Biochar Initiative (IBI).

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