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Effectiveness of sawdust-derived biochar in reducing lead contamination and enhancing soil quality parameters

Sri Slamet Mulyati, Nurul Hidayah, Ade Kamaludin, Muhamad Iqbal, Salma Aripin*

Environmental Health Department, Bandung Health Polytechnic, Cimahi, Indonesia

Abstract

Background: Biochar has emerged as a sustainable and cost-effective amendment for remediating heavy metal-contaminated soils. This study investigated the effectiveness of sawdust-derived biochar in reducing lead (Pb) contamination, improving soil pH and organic matter, and its impact on seed germination in Pb-contaminated soil.

Methods: A laboratory-scale experiment using a post-test control design was conducted with soils treated with 1%, 4%, and 7% biochar concentrations. Measured parameters included Pb concentrations, pH levels, organic matter content, and germination rates of mung bean seed.

Results: Biochar application reduced Pb concentration by up to 98.19% and increased soil pH from 6.2 to 7.45. Organic matter content reached 62.92% at 7% biochar. However, seed germination rates declined at higher concentrations, with the highest germination rate (81.67%) observed at 1% biochar. Differences among treatments were statistically significant ($P < 0.05$).

Conclusion: Sawdust-derived biochar effectively reduces Pb contamination and improves soil pH and organic content, offering a sustainable remediation solution. However, higher application rates may negatively affect seed germination, indicating the need for optimized dosage in future applications.

Keywords: Biochar, Heavy metal remediation, Lead, Soil pH, Organic matter

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***Correspondence to:**
Salma Aripin,
Email: salma.aripin@gmail.com

Introduction

Biochar, a carbon-rich by-product generated through the pyrolysis of organic materials under limited oxygen, has emerged as a promising material for soil remediation. It has been extensively studied for its ability to immobilize heavy metals, particularly cadmium (Cd) and lead (Pb), through various mechanisms, such as adsorption, ion exchange, and complexation. In addition to reducing the mobility and bioavailability of heavy metals, biochar is known to improve soil properties by increasing pH, enhancing organic matter content, and promoting microbial activity (1).

Contaminated soils, particularly those located near industrial areas, former mining sites, and old landfills, are often enriched with heavy metals such as Pb, Cd, Mn, Hg, Cu, and Cr, all of which are toxic even at low concentrations. These pollutants persist in the environment, accumulate in plants and animals, and interfere with essential biological functions such as photosynthesis and growth, leading to ecosystem imbalance and health risks to nearby populations (2). Heavy metals in soil are resistant to natural degradation, posing significant risks to plant growth and ecosystem balance. These pollutants accumulate in soil and plants, disrupting photosynthesis and development (3,4). Sorption and desorption processes influence the mobility of contaminants in soil and groundwater, emphasizing the need for tailored remediation strategies for different contamination scenarios (5). Therefore, remediation is a vital component of soil management, which requires a systematic approach including risk assessment, method selection, and continuous monitoring (6,7).

Biochar application has shown significant potential in improving the quality of soils contaminated with heavy metals. Studies have reported that biochar enhances soil pH and organic matter, which in turn decreases the solubility and mobility of metals like Pb and Cd (8,9). Moreover, the combination of biochar with organic amendments such as compost can further improve soil nutrient content and structure, leading to better crop productivity (10). However, many previous studies have focused on narrow conditions—either on a single feedstock type or specific contamination levels—making it difficult to generalize the optimal conditions for biochar use in remediation efforts.

Another critical consideration that remains

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underexplored is the phytotoxicity of biochar at higher application rates. While biochar is generally regarded as beneficial, excessive application may have unintended negative effects on seed germination or plant growth due to factors such as pH shifts or the release of toxic compounds during pyrolysis (11). This duality of effect—beneficial versus potentially harmful—is one of the key challenges in applying biochar effectively.

The novelty of this study lies in its focus on evaluating the effects of sawdust-derived biochar at multiple concentrations (1%, 4%, and 7%) on Pb-contaminated soil. While most research has either used very low or singular doses of biochar, this study sought to provide a comparative perspective across a range of application levels. The study also explored both soil improvement parameters (pH, organic matter content) and biological response (mung bean seed germination) as indicators of remediation success.

To this end, sawdust-derived biochar was prepared through pyrolysis and modified to improve Pb sorption. The study was conducted using a post-test control group design with artificial Pb contamination. Parameters observed included changes in Pb concentration, soil pH, organic matter, and mung bean (Vigna radiata) germination rates (12-14). These comprehensive evaluations aim to identify not only the effectiveness but also the limitations of biochar under different conditions, providing practical insights into its safe and efficient use for lead remediation in agricultural soils.

Materials and Methods

In this study, a laboratory-scale experimental approach with a post-test control group design was used to evaluate the effects of sawdust-derived biochar on soil contaminated with lead (Pb). The population in this research referred to all soil media mixed with biochar, and the samples were specific portions of soil artificially contaminated with Pb.

The sample size was determined based on preliminary testing to ensure a valid statistical analysis. Each treatment group—0% (control), 1%, 4%, and 7% biochar—was replicated six times based on the result of Gomez and Gomez's formula for experimental repetition (15). This resulted in a total of 24 experimental units.

The concentrations of 1%, 4%, and 7% biochar were selected based on previous studies, indicating the effectiveness of low to moderate biochar application rates in improving soil properties and reducing heavy metal mobility. Specifically, these levels enable the evaluation of both minimal and relatively higher application rates without exceeding the range typically used in similar soil remediation studies (4,14). This range also aimed to identify potential trade-offs between remediation effectiveness and phytotoxic effects on seed germination, which is an important consideration in practical field applications.

Biochar Production and Modification

Biochar was produced from sawdust through slow pyrolysis under limited oxygen conditions using a pyrolysis furnace at 800°C for 25 minutes. The sawdust was tightly wrapped in an aluminium foil to restrict airflow and ensure incomplete combustion. After pyrolysis, the biochar was cooled at room temperature, then ground and sieved through a 2 mm mesh. The pyrolysis mechanism involved thermal decomposition of organic matter into a stable carbon matrix with high surface area and functional groups, including carboxyl and hydroxyl moieties.

Soil Contamination and Treatment Design

For contamination, 1 kg of clean soil was mixed with 10 g of $Pb(NO_3)_2$ and left to stabilize for two weeks. After stabilization, biochar was added at different concentrations: 1%, 4%, and 7% by weight. Specifically, 99 g of contaminated soil was mixed with 1 g of biochar, 96 g with 4 g, and 93 g with 7 g. Each mixture was thoroughly blended until it became homogeneous.

Germination Test

A germination test was performed using 20 healthy mung bean (Vigna radiata) seeds per replicate. Seeds were placed in Petri dishes containing the treated soil samples and kept at a constant temperature of 25 ± 2°C with a 12-hour light/dark cycle. Germination was observed over 7 days. A seed was considered germinated when its radicle reached at least 2 mm. Germination rate was calculated as the percentage of germinated seeds out of the total.

Soil Analysis

Soil pH was measured using a digital pH meter (Hanna Instruments HI 2211) in a 1:2.5 soil-to-water mixture. Organic matter content was determined using the Loss-on-Ignition (LOI) method, following Nelson and Sommers (16). In this method, soil samples were first dried at 105°C for 24 hours, then ignited at 550°C in a muffle furnace for 4 hours. The percentage of organic matter was calculated based on the weight loss after ignition.

Method Validation and Equipment Calibration

Lead concentration in the soil was analyzed using an Atomic Absorption Spectrophotometer (PerkinElmer AAnalyst 400), with a detection limit of 0.001 mg/L. Soil samples were digested using acid following the U.S. EPA Method 3050B (17). Calibration was done using certified standard solutions to ensure measurement accuracy.

Statistical Analysis

For statistical analysis, data were first tested for normality. The Kruskal–Wallis test was used for non-parametric data such as Pb concentration and soil pH. One-way ANOVA followed by Tukey's HSD test was used to analyze differences in organic matter content and seed germination rates. All analyses were conducted at a 95% confidence level using IBM SPSS Statistics version 25.

Results

Measurement Results of Soil Pb Content with Variation of Biochar Concentration

The Pb content in soil before and after treatment with various biochar concentrations is presented in Table 1.

The data distribution deviated from normality, necessitating the use of a non-parametric statistical test, namely the Kruskal-Wallis test. The analysis conducted to assess the levels of Pb content in soil across different variations in biochar concentration yielded statistically significant differences. The statistical test produced a P value of 0.001 (<0.05). The findings indicated a positive correlation between the concentration of biochar and the extent of heavy metal Pb removal from the soil. Table 1 shows biochar significantly reduced soil Pb levels, with removal efficiencies of 94.75% (1%), 97.54% (4%), and 98.19% (7%).

Soil pH Measurement Results with Variations in Biochar Concentration

Soil pH in the control and after treatment with the addition of *biochar* concentration variations is presented in Table 2.

The dataset exhibited a departure from normal distribution, necessitating the use of a non-parametric statistical test, specifically the Kruskal-Wallis test. Significant differences were demonstrated in the non-parametric tests used to assess alterations in soil pH across different biochar concentrations. The statistical test results yielded a P value of 0.000 (<0.05). The study's findings revealed a positive correlation between the concentration of biochar and the increase in soil pH, particularly within the neutral range of pH values (≥ 7). Table 2 showed biochar significantly reduced soil Pb levels, with removal efficiencies of 94.75% (1%), 97.54% (4%), and 98.19% (7%).

Table 1. Soil Pb Content with Variation of *Biochar* Concentration

Repetition	Control (mg/Kg)	1% Concentration (mg/Kg)	4% Concentration (mg/Kg)	7% Concentration (mg/Kg)
1	0.061	0.0030	0.0015	0.0010
2		0.0056	0.0015	0.0012
3		0.0024	0.0013	0.0010
4		0.0016	0.0015	0.0010
5		0.0031	0.0016	0.0011
6		0.0034	0.0014	0.0010
Average		0.0032	0.0015	0.0011
Allowance		94.75%	97.54%	98.19%

Table 2. Soil pH with Variations in *Biochar* Concentration

Repetition	Control	1% Concentration	4% Concentration	7% Concentration
1	6.2	6.9	7.2	7.5
2		6.8	7.1	7.4
3		6.8	7.2	7.4
4		6.9	7.3	7.4
5		6.7	7.3	7.5
6		6.8	7.2	7.5
Average		6.82	7.22	7.45

Measurement Results of Soil Organic Content with Variations in Biochar Concentration

Soil organic content in the control and after treatment with various biochar concentrations is presented in Table 3.

The data exhibited a normal distribution, necessitating the use of a one-way analysis of variance (ANOVA) test. The ANOVA conducted to examine the variations in soil organic content across different levels of biochar concentration yielded statistically significant differences. The statistical test results yielded a P value of 0.000 (<0.05). The findings indicated a positive correlation between the concentration of biochar and the organic content of the soil. Table 3 showed that soil pH increased from 6.2 (control) to 6.82 (1%), 7.22 (4%), and 7.45 (7%).

Results of Seed Germination Calculation (Germination Rate) on Soil with Variation of Biochar Concentration

A seed germination experiment was performed wherein 20 mung bean seeds were sown into soil containing Pb contamination at a concentration of 0.061 mg/kg. The subsequent growth of the sprouts was observed. Table 4 presents the observed seed germination rates on soil polluted with Pb after treatment involving the addition of different quantities of biochar.

The data had a normal distribution, prompting the use of a one-way ANOVA test. The ANOVA conducted to examine the impact of different concentrations of biochar on seed germination in soil revealed no statistically significant differences. The statistical test results yielded a P value of 0.155 (>0.05). The findings indicated that an increased biochar concentration in the soil occasionally enhanced sprout growth in the contaminated soil.

Table 3. Soil Organic Content with Variation of *Biochar* Concentration

Repetition	Control (%)	1% Concentration (%)	4% Concentration (%)	7% Concentration (%)
1	16.69	26.39	46.12	50.27
2		31.12	57.46	52.46
3		26.30	42.03	63.90
4		30.82	57.22	74.67
5		20.67	49.36	62.62
6		31.65	41.38	73.60
Average		27.82	48.93	62.92

Table 4. Seed Germination in Soil with Variation of Biochar Concentration

Repetition	1% Concentration (%)	4% Concentration (%)	7% Concentration (%)
1	80	75	90
2	95	85	65
3	65	70	70
4	85	90	60
5	100	75	50
6	65	50	55
Average	81.67	74.17	65

Discussion

This study demonstrates the high efficiency of unmodified sawdust-derived biochar in remediating lead (Pb)-contaminated soil, achieving a removal rate of up to 98.19%. This performance is notably higher than that of several previously reported methods. For instance, biochar derived from straw and modified with thiol groups removed only 8.6%–11.1% of Pb under similar experimental conditions (18,19), while chitosan-thiol modified straw biochar achieved 89% Cd removal from water (6). Although those studies applied advanced chemical modifications to enhance surface functionality, our results show that even without modification, sawdust biochar can achieve superior performance in Pb immobilization. This suggests that the effectiveness of biochar depends not only on surface chemistry but also on the feedstock type, pyrolysis conditions, and application dosage.

In comparison to other studies focusing on biochar pH behavior, our findings also indicate consistent and effective soil pH enhancement. A 1% application of sawdust biochar increased the pH from 6.2 to 6.82, while a 7% concentration increased the pH to 7.45. These results align with those reported by Park (9), who identified 4% biochar as optimal for pH adjustment, and Widowati et al (13), who observed reduced heavy metal mobility at higher biochar concentrations. Furthermore, our observed pH increase exceeded that reported in another study using 2% straw biochar, which increased pH from 5.48 to 6.11 (20), further highlighting the potential of sawdust biochar as a more potent soil amendment (21).

The effectiveness of biochar also varies across pollutant types and environmental conditions. Prior research has shown that biochar derived from grapefruit peel using chemical and magnetic treatments achieved 80% Bisphenol A (BPA) removal at a lower pH range of 3–6 (22), while our biochar achieved higher Pb removal at a more neutral pH (6.7–7.5). This comparison highlights that optimal pH conditions for pollutant removal depend heavily on the type of contaminant involved. Moreover, studies have indicated that while vapor activation may have limited benefits, chemical modification generally enhances biochar's adsorption potential (21,22). However, our results suggest that certain feedstocks like sawdust, when subjected to pyrolysis alone, can still yield highly functional biochar capable of significant remediation without the need for chemical enhancers (23).

Beyond heavy metal removal, this study confirms the role of biochar in improving soil quality, particularly by increasing organic matter content and influencing heavy metal mobility. Additionally, our research observed that higher biochar concentrations correlated with higher organic matter content and greater Pb removal, suggesting a synergistic relationship between carbon inputs and contaminant immobilization. This is further supported by studies showing the rapid migration of Zn and Ni in soils enriched with biochar-derived organic matter (24,25).

Despite these strengths, some limitations must be acknowledged. This study did not investigate microbial community responses, which are known to influence the degradation of organic pollutants such as PAHs (21,26). The omission of microbial profiling limits our understanding of biochar's full ecological impact. Moreover, while our germination tests showed an increase in mung bean seed germination up to 81.67%, higher biochar concentrations appeared to suppress germination, likely due to the lignin content inherent in sawdust biochar (27,28). This indicates potential phytotoxic effects at elevated dosages, which must be carefully considered in practical applications.

Conclusion

Significant variations in biochar concentrations of 1%, 4%, and 7% were observed to have notable effects on reducing Pb levels, improving pH, and enhancing organic matter content in the soil. However, the seed germination of mung bean seeds in the soil with various concentrations of biochar did not exhibit any statistically significant differences. Biochar can immobilize and retain heavy metals, resulting in their binding to biochar and a subsequent reduction in soil concentration. The presence of Pb pollutants led to a pH that tended to approach neutrality with the addition of biochar. Furthermore, the use of sawdust biochar as a source of organic matter effectively facilitated the migration and mobilization of the heavy metal Pb. However, the application of biochar at higher rates corresponded with an increase in the growth medium's pH, which ultimately reduced seed germination rates.

This study demonstrates that sawdust-derived biochar effectively enhances soil quality by reducing Pb contamination and increasing pH and organic matter content. While higher biochar concentrations resulted in better remediation outcomes, they adversely affected seed germination rates. These findings underscore the potential of biochar as a sustainable remediation tool, particularly in addressing heavy metal contamination in agricultural soils. Future research should explore the long-term effects of biochar application and its interaction with other soil amendments. Practical implications include its use in rehabilitating degraded lands and mitigating heavy metal risks to food security and environmental health.

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Authors' contributions

Conceptualization: Sri Slamet Mulyati.
Data curation: Sri Slamet Mulyati.
Formal analysis: Sri Slamet Mulyati.
Funding acquisition: Sri Slamet Mulyati.
Investigation: Sri Slamet Mulyati.
Methodology: Nurul Hidayah.
Project administration: Sri Slamet Mulyati.
Resources: Sri Slamet Mulyati.
Software: Ade Kamaludin.
Supervision: Muhamad Iqbal.
Validation: Muhamad Iqbal.
Visualization: Ade Kamaludin.
Writing–original draft: Sri Slamet Mulyati.
Writing–review & editing: Salma Aripin.

Competing interests

None.

Ethical issues

This research does not raise any ethical issues.

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