International Journal of Design & Nature and Ecodynamics
Vol. 21, No. 2, February, 2026, pp. 511-518
Journal homepage: http://iieta.org/journals/ijdne

Citronella (*Cymbopogon nardus*) Distillation Waste-Derived Biochar for Immobilization of Lead and Cadmium in Contaminated Soil

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https://doi.org/10.18280/ijdne.210219

Received: 13 December 2025
Revised: 18 February 2026
Accepted: 26 February 2026
Available online: 28 February 2026

Keywords:
biochar, citronella waste, heavy metals, Pb, Cd, soil remediation

ABSTRACT

Soil contamination by heavy metals such as lead (Pb) and cadmium (Cd) poses significant environmental and health risks due to their toxicity, persistence, and bioaccumulative properties. Biochar derived from agricultural and industrial biomass waste has shown promise as a low-cost and sustainable remediation material. This study investigates the effectiveness of biochar produced from citronella (*Cymbopogon nardus*) distillation waste in immobilizing Pb and Cd in contaminated soils. Biochar was prepared through pyrolysis at a temperature of 200 °C for 10 min under limited oxygen conditions and characterized for its physicochemical properties. Soil samples contaminated with Pb and Cd were treated with varying doses of biochar (0%, 10%, 20%, 30%, 40% and 50%). Changes in the bioavailable Pb and Cd fractions were quantified using atomic absorption spectrophotometry (AAS), together with measurements of soil pH. The results showed that biochar application significantly reduced the bioavailability of Pb and Cd and increased soil pH. The highest reduction efficiency was achieved at 40% biochar dosage, with removal efficiencies ranging from 73% to 82% for Pb and 74% to 86% for Cd. These findings demonstrate the potential use of citronella distillation waste biochar as an environmentally friendly and sustainable remediation material for managing heavy metal-contaminated soil.

1. INTRODUCTION

Industrialization and agricultural intensification have led to the accumulation of heavy metals such as lead (Pb) and cadmium (Cd) in soils, posing serious risks to human health and ecological stability [1]. Heavy metals are persistent, non-biodegradable, and can easily enter food chains, resulting in bioaccumulation and biomagnification across trophic levels [2]. Soil contamination by Pb and Cd not only disrupts soil fertility and plant productivity but also threatens environmental and food safety [3]. Furthermore, the persistence of these metals in soil systems limits natural attenuation, leading to long-term contamination that is difficult to remediate using conventional methods [4, 5]. Consequently, the development of sustainable and cost-effective strategies to mitigate heavy metal pollution in soil has become a crucial focus in environmental research and management.

Traditional methods for heavy metal remediation, such as soil washing, chemical stabilization, and phytoremediation, have shown varying degrees of effectiveness but often come with high costs and environmental drawbacks [6]. Chemical methods can cause secondary pollution due to reagent residues, while physical remediation is frequently energy-intensive and limited in large-scale applications. Phytoremediation, though eco-friendly, typically requires long timeframes and is influenced by plant species and site conditions [7]. Hence, the limitations of these conventional approaches have prompted researchers to explore alternative remediation materials that are both environmentally sustainable and economically viable.

Among various emerging technologies, biochar has gained significant attention for its ability to immobilize and adsorb heavy metals in contaminated soils [8]. Biochar is a carbon-rich, porous material produced through the pyrolysis of biomass under limited oxygen conditions [9]. Its high surface area, cation exchange capacity (CEC), and functional groups enable strong interactions with metal ions through mechanisms such as complexation, precipitation, and electrostatic attraction [10]. In addition to improving soil structure and nutrient retention, biochar contributes to long-term carbon sequestration, aligning with global climate mitigation goals [11].

The effectiveness of biochar in immobilizing heavy metals is largely influenced by its physicochemical properties, which are determined by the feedstock type and pyrolysis temperature. Biochar produced at low pyrolysis temperatures (around 200 °C) generally retains a higher CEC and more oxygen-containing functional groups, which enhance heavy metal immobilization through ion exchange and surface complexation mechanisms. However, biochar produced at higher temperatures typically has greater structural stability, higher carbon content, and improved carbon sequestration potential. Therefore, selecting an appropriate pyrolysis temperature is important to optimize biochar performance for heavy metal immobilization in soils [12].

Citronella (*Cymbopogon nardus*) distillation waste, a by-product of the essential oil industry, represents a promising raw material for biochar production. Large quantities of this fibrous residue are often discarded or burned, contributing to environmental pollution and resource wastage. Converting citronella waste into biochar provides an opportunity to valorize industrial by-products while creating a functional adsorbent for soil remediation [13]. Studies suggest that biochars derived from aromatic plant residues, including citronella, contain abundant silica and carbon, which enhance their metal adsorption capacity and stability under field conditions.

However, limited studies have specifically investigated the application of biochar derived from citronella (*Cymbopogon nardus*) distillation waste for the immobilization of Pb and Cd in contaminated soils. Compared with biochars from other feedstocks, citronella residue may have advantages such as higher ash content, silica content, alkalinity, and the presence of functional groups that can enhance heavy metal immobilization through adsorption, ion exchange, and surface complexation mechanisms.

Therefore, this study aims to evaluate the effectiveness of biochar derived from citronella distillation waste in remediating soils contaminated with Pb and Cd. The evaluation focuses on adsorption efficiency, determination of optimal biochar dosage, and changes in soil pH after biochar application. This study is expected to provide scientific evidence on the potential use of citronella waste-derived biochar as a sustainable and low-cost material for heavy metal soil remediation, while also promoting the circular economy through the valorization of agricultural and industrial waste.

2. MATERIALS AND METHODS

2.1 Citronella distillation waste collection

Citronella (*Cymbopogon nardus*) distillation waste was collected from a local essential oil industry located in Alahan Panjang, West Sumatra. The biomass residue, consisting mainly of fibrous plant material remaining after oil extraction, was air-dried for 72 hours to remove surface moisture and then oven-dried at 105 °C for 24 hours to ensure uniform dryness before biochar production.

2.2 Soil sampling and preparation

Soil samples were collected from the vegetable production center area of Nagari Alahan Panjang, Danau Kembar District, Solok Regency, West Sumatra, Indonesia. The soil was taken from the topsoil layer (0–20 cm), air-dried, and sieved through a 2 mm sieve before use. The initial concentrations of Pb and Cd in the soil were measured and found to be 7.32 mg/L and 1.14 mg/L, respectively. The soil contamination was relatively uniform as the samples were homogenized before the experiment. The basic soil properties, including pH, CEC, texture, and organic matter content, were analyzed following standard procedures (e.g., US EPA Method 3050B for heavy metal digestion). This method involves the oxidation of organic matter and dissolution of environmentally available metals through successive heating with nitric acid (HNO_3), hydrochloric acid (HCl), and hydrogen peroxide (H_2O_2) at approximately 95 °C, providing a reliable estimation of bioavailable metal fractions rather than total metal content.

2.3 Chemicals and reagents

Analytical-grade lead nitrate ($Pb(NO_3)_2$) and cadmium nitrate ($Cd(NO_3)_2 \cdot 4H_2O$) were used to artificially spike the soil samples. A total of 2.745 g of $Pb(NO_3)_2$ and 0.784 g of $CdSO_4 \cdot 8H_2O$ were dissolved and thoroughly mixed to ensure homogeneous distribution of metals. Soil was gradually added and continuously mixed until the total mass reached 3 kg. Based on the calculation, the initial concentrations of Pb and Cd in the contaminated soil were approximately 572 mg/kg and 83 mg/kg.

2.4 Biochar production

The dried citronella waste was converted into biochar through slow pyrolysis under limited oxygen conditions in a muffle furnace. Pyrolysis was carried out at 200 °C for 10 minutes. This temperature was selected because low-temperature pyrolysis generally produces biochar with higher CEC and more oxygen-containing functional groups, which play an important role in heavy metal adsorption and immobilization mechanisms. Biochar produced at lower temperatures also tends to have higher surface functional groups, such as carboxyl and hydroxyl groups, that enhance metal binding through ion exchange and complexation mechanisms. After cooling in an oxygen-free environment, the biochar was ground and sieved to a particle size of < 1 mm. The biochar yield (%) was calculated as the ratio of the mass of biochar obtained to the initial dry weight of the feedstock. All samples were stored in airtight polyethylene containers for further use.

2.5 Experimental setup

Batch experiments were conducted to assess the performance of citronella-derived biochar in immobilizing Pb and Cd in contaminated soil. Biochar was applied at four different rates: 0% (control), 10%, 20%, 30%, 40% and 50% (w/w). The relatively high biochar dosage (10–50% w/w) was used in this study to evaluate the maximum potential of biochar for heavy metal immobilization under controlled laboratory conditions. This dosage range was intended to observe the trend of heavy metal adsorption and soil pH changes rather than to represent field application rates. In practical field applications, lower biochar dosages are typically used. Each treatment was mixed evenly with 3 kg of soil and then incubated for 2 weeks under controlled laboratory conditions (temperature 25 ± 2 °C and humidity equivalent to 60% of field capacity). The experimental design used was a completely randomized design (CRD) with three replications for each treatment.

2.6 Sample analysis

After incubation, the soils were air-dried and sieved (2 mm) before analysis. The residual concentrations of Pb and Cd were determined by Atomic Absorption Spectrophotometry (AAS) after digestion using US EPA Method 3050B. Soil pH, organic matter content, and CEC were re-evaluated to assess changes in soil properties after biochar addition. Removal efficiency (%) and removal rate of the metals were calculated using Eq. (1) and Eq. (2), respectively.

$$\text{Removal efficiency} = \frac{(C_0 - C_t)}{C_0} \times 100\% \tag{1}$$

where, C_0 is the initial concentration of metals in the soil (mg/kg) and C_t is the concentration of metals at time *t* (mg/kg).

$$k=\frac{\ln\frac{C_0}{C_t}}{t} \tag{2}$$

where, *k* is the removal rate of metals (/day) and *t* is the duration of the experiment (days).

2.7 Statistical analysis

All experimental data were tabulated and statistically analyzed using analysis of variance (ANOVA) at a 95% confidence level ($p < 0.05$). The analysis of variance and comparison of treatment means were performed following the procedures described by Gomez and Gomez [14], when significant differences were detected among treatments, the means were separated using Duncan's Multiple Range Test (DMRT) at 95% and 99% confidence levels ($p < 0.05$ and $p < 0.01$) to identify statistically distinct groups.

The relationships between treatment variables (biochar application rate) and observed parameters (Pb and Cd concentrations in soil) were further evaluated using two-way ANOVA.

3. RESULTS AND DISCUSSION

3.1 Adsorption capacity of citronella waste biochar on Pb and Cd

The application of citronella (*Cymbopogon nardus*) distillation waste-derived biochar significantly decreased the concentration of Pb and Cd in contaminated soil. The reduction was proportional to the biochar dosage, as shown in Table 1.

The application of biochar derived from citronella (*Cymbopogon nardus*) distillation waste demonstrated a significant effect on the immobilization of Pb and Cd in contaminated soils. The results showed that increasing the biochar dosage from 10% to 50% caused a gradual decrease in the concentrations of both metals. This indicates that biochar dosage plays a significant role in determining overall adsorption performance. The results of a two-way ANOVA confirmed this finding, showing that the effect of biochar dosage was significant on the reduction of Cd concentration, while incubation time showed no significant effect.

In general, the immobilization of Pb and Cd by biochar occurs through multiple physicochemical mechanisms, including surface adsorption, ion exchange, complexation with oxygen-containing functional groups (such as COOH and OH), and precipitation of metal hydroxides or carbonates on the biochar surface. The porous structure and high specific surface area of biochar provide abundant active sites that facilitate strong interactions between metal ions and surface functional groups. Previous studies have reported that Pb^{2+} and Cd^{2+} are preferentially retained on biochar surfaces through inner-sphere complexation and electrostatic attraction, leading to a significant reduction in their mobility and bioavailability in soil systems [15].

Although the overall trend showed a decrease in Pb and Cd concentrations with increasing biochar dosage and incubation time, slight fluctuations were observed at several treatments and incubation periods. This phenomenon may be attributed to desorption of weakly bound metals, changes in soil pH, release of dissolved organic carbon from biochar, and redistribution of metals between soil solid and solution phases during incubation. Soil incubation systems are dynamic, and metal concentrations in the extract may not decrease monotonically over time due to equilibrium shifts between adsorption and desorption processes.

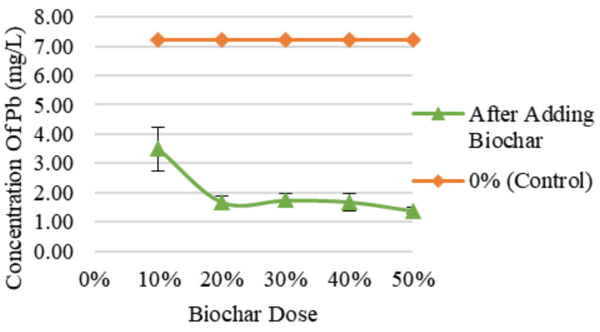
Table 1. Effect of biochar dosage and incubation time on Pb and Cd concentrations in contaminated soil

Biochar Dose (%)	Week 1	Week 2	Week 3	Week 4
Pb (mg/L)				
0% (Control)	7.23 ± 0.73	7.23 ± 0.73	7.23 ± 0.73	7.23 ± 0.73
10%	3.49 ± 0.75	2.51 ± 0.47	2.00 ± 0.66	2.24 ± 1.00
20%	1.68 ± 0.18	1.96 ± 0.47	2.11 ± 0.58	2.14 ± 1.35
30%	1.74 ± 0.21	2.18 ± 0.12	1.80 ± 0.37	1.74 ± 0.22
40%	1.68 ± 0.30	1.93 ± 0.26	1.89 ± 0.30	1.27 ± 0.51
50%	1.38 ± 0.10	1.59 ± 0.29	2.29 ± 0.25	2.08 ± 0.47
Cd (mg/L)				
0% (Control)	1.14 ± 0.10	1.14 ± 0.10	1.14 ± 0.10	1.14 ± 0.10
10%	0.61 ± 0.75	0.60 ± 0.47	0.36 ± 0.66	0.40 ± 1.00
20%	0.31 ± 0.18	0.38 ± 0.47	0.37 ± 0.58	0.34 ± 1.35
30%	0.35 ± 0.21	0.42 ± 0.12	0.33 ± 0.37	0.32 ± 0.22
40%	0.24 ± 0.30	0.25 ± 0.26	0.29 ± 0.30	0.15 ± 0.51
50%	0.29 ± 0.10	0.29 ± 0.29	0.43 ± 0.25	0.36 ± 0.47

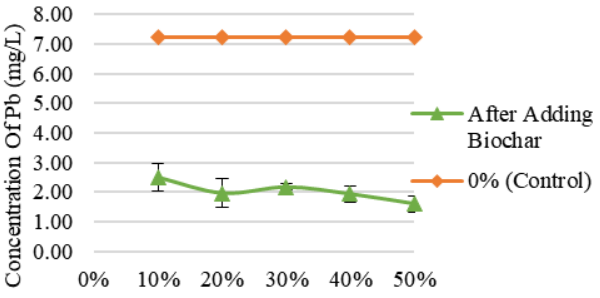
3.2 Determination of the optimum biochar dosage

Metal concentrations decreased sharply up to 40% biochar treatment, then plateaued at 50%. This indicates that the optimum dose for immobilizing Pb and Cd metals is around 40% (w/w). Pb concentrations before and after biochar addition can be seen in Figure 1.

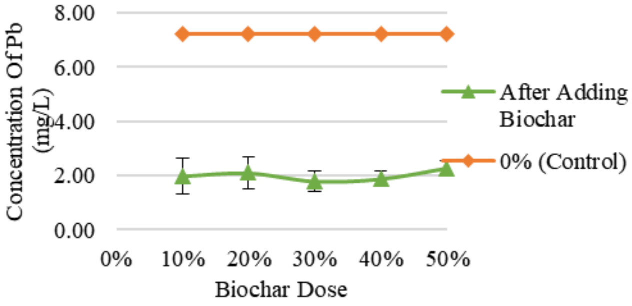
Table 2 shows the percentage reduction of Pb concentrations at different biochar doses and incubation times. The highest reduction was observed at 40% (Week 4: 82.39% ± 6.98%). Increasing the biochar dose from 40% to 50% did not consistently improve Pb reduction, suggesting that additional biochar may provide limited incremental immobilization under the tested conditions.



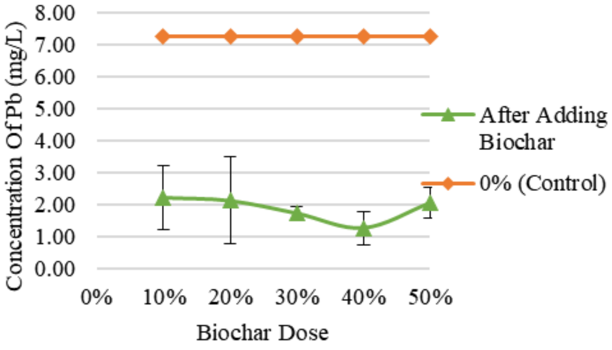
(a) Week 1



(b) Week 2



(c) Week 3



(d) Week 4

Figure 1. Concentration of Pb before and after biochar addition

Table 2. Pb reduction compared with control (0%)

Biochar Dose (%)	Week 1	Week 2	Week 3	Week 4
0% (Control)				
10%	51.69% ± 10.31%	65.31% ± 6.49%	72.42% ± 9.14%	69.05% ± 13.85%
20%	76.80% ± 2.49%	72.85% ± 6.52	70.87% ± 7.97%	70.39% ± 18.68%
30%	75.95% ± 2.90%	69.91% ± 1.59%	75.12% ± 5.10%	75.93% ± 3.02%
40%	76.73% ± 4.13%	73.27% ± 3.63%	73.91% ± 4.16%	82.39% ± 6.98%
50%	80.87% ± 1.33%	77.98% ± 4.00%	68.36% ± 3.48%	71.25% ± 6.54%

Note: Control treatment (0%) defined as 0% reduction

Two-way ANOVA was performed to evaluate the effect of biochar dosage and incubation time on Pb and Cd concentrations. The control treatment (0% biochar) was excluded from the ANOVA analysis to focus on the effect of biochar dosage levels. Therefore, the analysis included five dosage levels (10%, 20%, 30%, 40%, and 50%) and four incubation times.

Table 3. Analysis of variance (ANOVA) results for Pb

Factor	df	F-value	Sig. (p)	Description
Biochar Dose	4	6.169	< 0.001	Highly significant
Time	3	0.266	0.849	Not significant
Dose × Time	12	2.403	0.130	Not significant

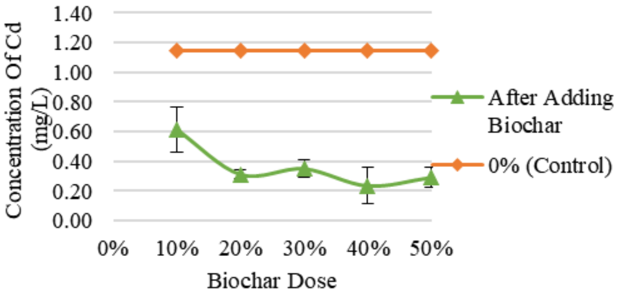
Table 4. Duncan's Multiple Range Test (DMRT) results for Pb (α = 0.05)

Biochar Dose	Average Pb (mg/L)	DMRT Letter
40%	1.69 ± 0.66	a
50%	1.83 ± 0.21	a
30%	1.86 ± 0.21	a
20%	1.97 ± 0.30	a
10%	2.55 ± 0.42	b

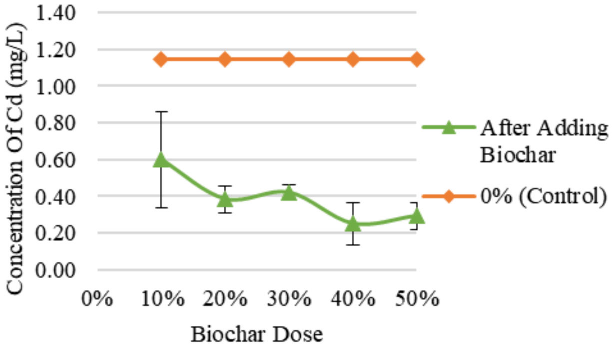
Based on the analysis of variance (Table 3), biochar treatment had a very significant effect on soil Pb levels ($p < 0.001$), while incubation time did not have a significant effect ($p = 0.849$), and the interaction between biochar and incubation time showed no significance ($p = 0.130$). Further DMRT testing at a 95% confidence level (Table 4) showed that the 40% biochar treatment produced the lowest Pb levels and was significantly different from the 10% treatment.

Table 5. Results of Pb statistical test (α = 0.05)

Biochar Dose	Mean Pb (mg/L)	Standard Error	Lower Bound	Upper Bound
40%	1.69 ± 0.66	0.273	0.728	1.820
50%	1.83 ± 0.21	0.273	1.534	2.625
20%	1.86 ± 0.21	0.273	1.596	2.688
30%	1.97 ± 0.30	0.273	1.195	2.287
10%	2.55 ± 0.42	0.273	1.693	2.784



(a) Week 1



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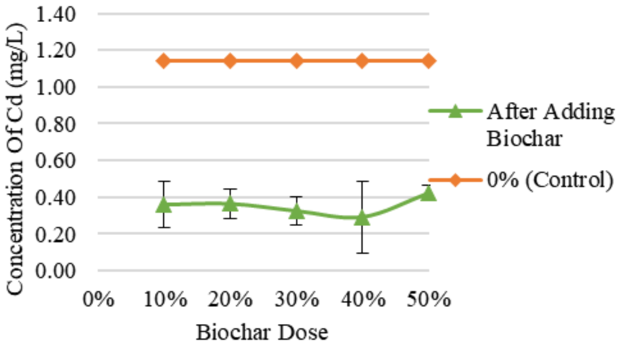
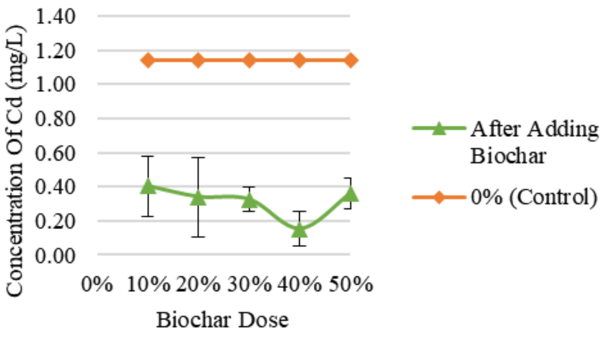


(c) Week 3



(d) Week 4

Figure 2. Concentration of Cd before and after biochar addition

Based on the statistical test results in Table 5, 40% biochar treatment also produced the smallest mean value, at 1.2735. The smaller the mean value, the more effective the dose is in reducing Pb concentrations. This means that the 40% biochar treatment resulted in the greatest reduction in Pb concentrations. Cd concentrations before and after biochar addition can be seen in Figure 2.

Table 6. Cd reduction compared with control (0%)

Biochar Dose (%)	Week 1	Week 2	Week 3	Week 4
0% (Control)				
10%	46.42% ± 13.31%	47.48% ± 22.83%	68.50% ± 10.82%	64.86% ± 15.44%
20%	72.57% ± 2.82%	66.40% ± 6.34%	68.06% ± 7.01%	70.28% ± 20.27%
30%	69.28% ± 5.31%	63.26% ± 3.55%	71.55% ± 6.74%	71.64% ± 6.10%
40%	79.27% ± 10.77%	78.19% ± 9.99%	74.59% ± 16.95%	86.57% ± 9.16%
50%	74.37% ± 5.82%	74.45% ± 6.32%	62.77% ± 3.70%	68.44% ± 7.76%

Table 6 shows the percentage reduction of Cd concentrations at different biochar doses and incubation times. At 10% - 50% biochar, Cd reduction reached 46% - 86% compared with the control. Beyond this point, further reduction tended to level off, likely due to the limited availability of active adsorption sites and the attainment of adsorption equilibrium on the biochar surface.

Based on the analysis of variance (Table 7), the biochar treatment had a highly significant effect on soil Cd concentration ($p < 0.001$), whereas the incubation time had no significant effect ($p = 0.335$). The interaction between biochar and incubation time was also not significant ($p = 0.116$). The DMRT post-hoc test at the 95% confidence level (Table 8) showed that the 40% biochar treatment resulted in the lowest Cd concentration and was significantly different from the other treatments. The 10% treatment produced the highest Cd concentration and formed a separate subset. Meanwhile, the 20%, 30%, and 50% treatments did not show significant differences from one another.

Table 7. Analysis of variance (ANOVA) results of Cd

Factor	df	F-value	Sig. (p)	Description
Biochar Dose	4	8.523	< 0.001	Highly significant
Waktu	3	1.075	0.366	Not significant
Dose x Waktu	12	1.331	0.226	Not significant

Table 8. Duncan's Multiple Range Test (DMRT) results for Cd ($\alpha = 0.05$)

Biochar Dose	Average Cd (mg/L)	DMRT Letter
40%	0.23 ± 0.13	a
50%	0.34 ± 0.03	b
20%	0.35 ± 0.04	b
30%	0.35 ± 0.06	b
10%	0.49 ± 0.06	c

Table 9. Results of the Cd statistical test ($\alpha = 0.05$)

Biochar Dose	Mean Cd (mg/L)	Standard Error	Lower Bound	Upper Bound
40%	0.23 ± 0.13	0.032	0.429	0.556
50%	0.34 ± 0.03	0.032	0.287	0.414
20%	0.35 ± 0.04	0.032	0.292	0.418
30%	0.35 ± 0.06	0.032	0.169	0.296
10%	0.49 ± 0.06	0.032	0.271	0.400

Based on the statistical test results in Table 9, 40% biochar treatment also produced the smallest mean value, at 0.23 ± 0.13. The smaller the mean value, the more effective the dose is in reducing Cd concentrations. This means that the 40% biochar treatment resulted in the greatest reduction in Cd concentrations.

Despite the observable temporal variations, statistical analysis using ANOVA revealed that incubation time from one to four weeks did not have a significant effect on Pb and Cd removal efficiency ($p > 0.05$). This finding suggests that the adsorption process reached equilibrium relatively early, and extended incubation did not substantially enhance further metal removal. The absence of a significant temporal effect supports the hypothesis that most adsorption sites were occupied during the initial phase of interaction, after which the system gradually stabilized. Similar findings were reported by Ahmad et al. [15], who observed that biochar's high surface reactivity facilitates rapid heavy metal binding, with only limited improvements during prolonged incubation. Therefore, biochar dosage had a more pronounced influence on Pb and Cd immobilization than incubation time, highlighting the importance of dosage optimization for effective remediation. The removal efficiency trends of Pb and Cd are presented in Figure 3 and Figure 4, respectively. In addition, the kinetic rate constants (k) for Pb and Cd immobilization as a function of incubation time are shown in Figure 5 and Figure 6, respectively.

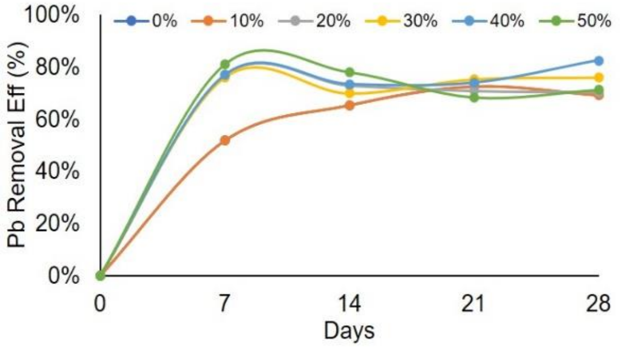


Figure 3. Removal efficiency of Pb

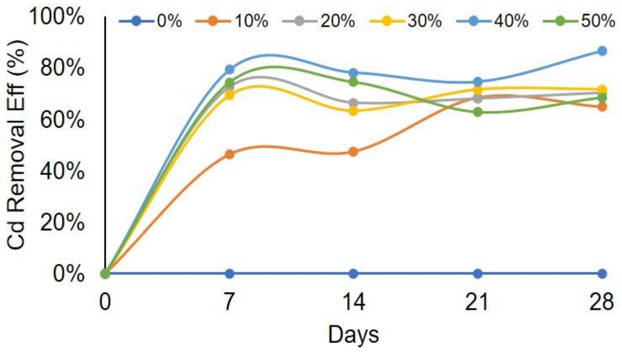


Figure 4. Removal efficiency of Cd

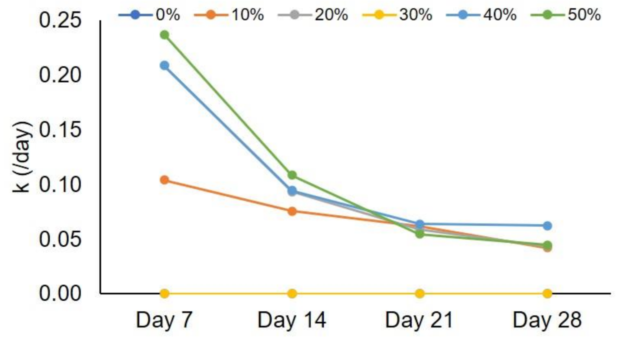


Figure 5. Kinetic rate constant k (day⁻¹) for Pb removal as a function of incubation time

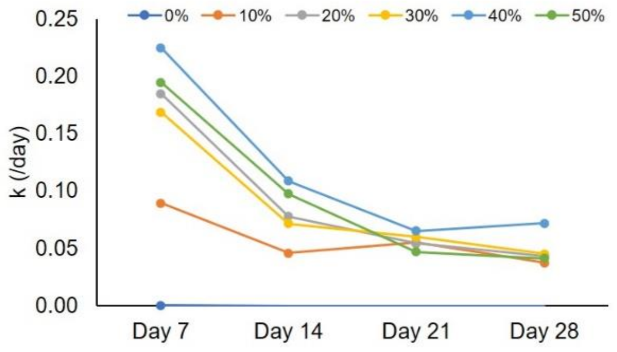


Figure 6. Kinetic rate constant k (day⁻¹) for Cd removal as a function of incubation time

3.3 Effects of biochar on soil physicochemical properties

The incorporation of citronella waste biochar improved several soil characteristics important for remediation performance. Table 10 presents the changes in soil pH after biochar addition.

Table 10. Effects of biochar on soil pH

Biochar Dose (%)	Week 1	Week 2	Week 3	Week 4
0% (Control)	7.20 ± 0.08	6.47 ± 0.05	5.80 ± 0.09	7.10 ± 0.15
10%	7.85 ± 0.12	7.54 ± 0.07	6.30 ± 0.23	7.40 ± 0.08
20%	8.20 ± 0.16	8.00 ± 0.13	7.10 ± 0.21	7.80 ± 0.17
30%	9.03 ± 0.21	8.57 ± 0.15	6.70 ± 0.16	8.40 ± 0.11
40%	9.20 ± 0.35	9.07 ± 0.24	7.50 ± 0.06	8.70 ± 0.31
50%	9.44 ± 0.11	9.34 ± 0.21	7.80 ± 0.06	8.90 ± 0.29

Soil pH was measured using a soil-to-water ratio of 1:1 (w/v) using a calibrated digital pH meter. The pH meter was calibrated using standard buffer solutions (pH 4, 7, and 10) before measurement. Soil samples were taken from the same batch and measured under the same conditions to minimize variation. Changes in pH during incubation may be influenced by microbial activity, biochar alkalinity, and CO_2 dissolution in soil moisture.

Based on the data in Table 10, the addition of biochar derived from citronella distillation waste showed a significant effect on increasing soil pH compared to the control. The soil pH increased with higher biochar doses, with the highest pH value of 9.44 observed at week 1 with a 50% biochar dose. In contrast, the control treatment showed lower and more fluctuating pH values, ranging from 5.8 to 7.2 throughout the observation period. The increase in soil pH was attributed to the alkaline nature of biochar, which contains basic cations such as Ca^{2+}, K^+, and Mg^{2+} that can neutralize H^+ and Al^{3+} ions in the soil, thereby reducing soil acidity.

The trend of pH stabilization after the third week aligns with the findings of several previous studies, which reported that biochar initially causes a sharp increase in soil pH due to the release of soluble ash components, followed by a gradual stabilization phase. In the present study, the final pH values after four weeks ranged from 7.10 in the control to 8.90 in the 50% biochar treatment, demonstrating that citronella biochar can effectively buffer soil acidity over time [16, 17].

In week 3, a slight decrease in soil pH was observed across all treatments, possibly due to the consumption of soluble basic compounds or microbial activity producing organic acids during the decomposition of organic matter. However, by week 4, the pH values increased again and tended to stabilize, indicating that a new equilibrium had been established between the biochar and soil matrix. This pH enhancement plays a crucial role in the remediation of heavy metals, as more alkaline conditions promote the precipitation of Pb and Cd into insoluble hydroxide or carbonate forms, thereby reducing their bioavailability. Thus, citronella distillation waste biochar demonstrates strong potential as a soil amendment capable of improving soil chemical properties and supporting the immobilization of heavy metals in a sustainable manner.

The increase in soil pH induced by biochar application significantly contributes to the immobilization of Pb and Cd in contaminated soils. Under more alkaline conditions, Pb^{2+} and Cd^{2+} favor the formation of insoluble compounds such as hydroxides and carbonates, which reduces their solubility and bioavailability. Additionally, biochar can alter soil nutrient balance and promote precipitation or co-precipitation reactions, shifting heavy metals from exchangeable to more stable, immobilized fractions [18-20].

4. CONCLUSION

This study evaluated the performance of citronella-distillation-waste biochar as a remediation agent for Pb and Cd-contaminated soils. The results indicate that the biochar exhibited a strong adsorption capacity toward both heavy metals, achieving removal efficiencies ranging from 51% to 82% for Pb and 46% to 86% for Cd across various application doses. These findings confirm that citronella biochar can effectively reduce the mobility and bioavailability of Pb and Cd in contaminated soils.

The optimal dosage of biochar was identified at 40%, which produced the highest metal removal while maintaining soil stability. At this dosage, Pb and Cd concentrations decreased to 1.27 mg/L and 0.15 mg/L, respectively, demonstrating the superior performance of citronella biochar compared to other dosages.

Although the overall trend showed a reduction in metal concentrations, slight fluctuations were observed at certain incubation times. This behavior reflects the dynamic nature of soil systems, where adsorption, desorption, and redistribution processes may occur simultaneously.

The immobilization mechanisms of Pb and Cd in biochar-amended soil differ due to their chemical behavior. Pb tends to form stable precipitates and strong complexes with functional groups on biochar surfaces, resulting in lower mobility. In contrast, Cd is generally more mobile and less strongly retained in soil systems. However, the significant reduction of Cd observed in this study may be attributed to the combined effects of increased soil pH, ion exchange processes, and surface complexation with oxygen-containing functional groups in biochar. The increase in soil pH following biochar application reduces the solubility of both Pb and Cd, thereby enhancing their immobilization. Although detailed mechanistic analyses such as sequential extraction or TCLP were not conducted, the observed trends suggest that biochar plays a significant role in reducing the bioavailability of both metals.

In addition to heavy metal remediation, the application of citronella biochar resulted in notable improvements in soil physicochemical properties. Post-remediation analysis showed increases in soil pH from 6.47 to 9.34, indicating enhanced soil quality and reduced metal bioavailability. These changes suggest that citronella biochar contributes not only to contaminant immobilization but also to soil pH restoration.

Although biochar application significantly reduced Pb and Cd availability, the use of high biochar dosages (40–50%) may have potential adverse effects on soil quality. Excessive biochar application can increase soil pH beyond optimal levels, which may negatively affect plant growth and microbial activity. In addition, high biochar content may increase soil salinity (electrical conductivity) and lead to nutrient imbalances. Furthermore, the release of dissolved organic carbon from biochar could enhance the mobility of certain heavy metals under specific conditions. Therefore, while higher dosages improve metal immobilization efficiency, their environmental implications and practical feasibility should be carefully considered.

Overall, this research provides scientific evidence supporting the use of citronella distillation waste biochar as an effective, environmentally friendly, and underutilized amendment for heavy-metal remediation. Given its promising performance and sustainable origin, further application and development of this biochar type are strongly recommended for future soil remediation practices.

ACKNOWLEDGMENT

The author would like to express sincere gratitude to the Institute for Research and Community Service (LPPM), Andalas University, for the research funding support under *the Early Career Faculty Research Program Batch II*, Contract No. 509/UN16.19/PT.01.03/PDP/2025 in 2025 Fiscal Year.

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