

Impact of Kolanut Biochar on *Corchorus olitorius* Growth and Nutritional Value in Cadmium-Polluted Soil

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ABSTRACT

Jute (Corchorus olitorius), a nutritionally significant crop, faces severe threats from cadmium (Cd) contamination, primarily originating from industrial waste, which poses substantial health risks to consumers. This study investigated the effectiveness of kolanut-derived biochar, produced via pyrolysis at 400 °C, in mitigating Cd toxicity and enhancing the growth and nutritional quality of jute cultivated in Cd-contaminated loamy soil. The experimental setup involved twelve pots subjected to various treatments: a control, Cd-only (27mg CdCl₂), and Cd combined with either 1% or 3% biochar. Over four weeks, physiological parameters, chlorophyll content, and nutrient uptake were meticulously monitored. The findings revealed a significant reduction in chlorophyll content across all biochar treatments, with the 3% biochar application exhibiting the lowest values. While 1% biochar showed a marginal improvement in plant height, the higher concentration (3%) led to a notable decrease in essential mineral elements such as magnesium (Mg) and calcium (Ca) in both leaves and shoots. This suggests that the induction of nutrient imbalance and potential competitive interactions with metals. Although kolanut pod biochar demonstrated some partial ameliorative effects against Cd stress, its overall efficacy was limited, and in certain instances, it increased the negative impacts on nutrient uptake. These results stress the importance of site-specific considerations for biochar application, underlining the necessity for optimized concentrations, extended study durations, and the exploration of diverse biochar types to achieve effective phytoremediation in soils contaminated with cadmium.

Keywords: Kolanut, Biochar, Cadmium, Jute, Contamination

INTRODUCTION

The genus *Corchorus*, commonly known as jute, belongs to the Tiliaceae family and encompasses approximately 50–60 species distributed across tropical, subtropical, and warm-temperate regions globally. While Africa hosts the majority of these species, with significant concentrations in Ethiopia, Tanzania, and South Africa, jute farming has a history spanning over two centuries in tropical

climates. The two primary cultivated species, *C. olitorius* L. and *C. capsularis* L., are crucial sources of natural fibers in Asian and Latin American countries (Ogunkanmi *et al.*, 2010). *Corchorus olitorius* is characterized by its tall, typically annual herbaceous growth, reaching heights of up to 2.4 meters, with either unbranched or sparsely branched stems. Its leaves are simple, lanceolate, and feature

coarsely serrated or lobed margins (Nuwangburuka and Denton, 2012). Beyond its role as a fiber crop, *Corchorus olitorius* is a significant leafy vegetable, particularly in Nigeria, and is widely cultivated for its leaves in Asia, including India, Bangladesh, and China. The plant's leaves are highly valued for their mucilaginous texture, often prepared in thick broths, stews, or soups, and are recognized as rich sources of essential vitamins and minerals (Loumerem and Alercia, 2016). Nutritionally, *C. olitorius* is a powerhouse, providing substantial amounts of protein (5.6 g), calcium (250-266 mg), iron (4.8 mg), and ascorbic acid (53-100 mg) per 100 g fresh weight (Ibrahim and Fagbohun, 2011; Nemb *et al.*, 2011). Its affordability and robust nutritional profile contribute significantly to food security, especially in urban areas (Nemb *et al.*, 2011; Department of Agriculture, Forestry and Fisheries, 2012). Furthermore, the leaves possess notable medicinal properties attributed to bioactive compounds such as mucilaginous polysaccharides, flavonoids, tannins, and cardiac glycosides (Udoh *et al.*, 2024; Islam, 2013). Traditional medicine utilizes *C. olitorius* for treating fever, digestive disorders, cardiovascular conditions, skin diseases, and for promoting women's health and appetite stimulation (Ali, 2013; Udoh *et al.*, 2024). Scientific investigations have corroborated its therapeutic potential, demonstrating antioxidant, anti-inflammatory, and cholesterol-lowering effects (Islam, 2013; Airaodion *et al.*, 2019). The plant also exhibits promise in cancer prevention and has industrial applications due to its fiber content (Airaodion *et al.*, 2019), highlighting its dual importance as a nutritious food source and a medicinal plant across Africa and Asia.

Cadmium (Cd) stands as a highly hazardous heavy metal, frequently contaminating soils through industrial waste discharge and improper battery disposal (Amelène *et al.*, 2013). The World Health Organization (WHO) and European Union (EU) set a safety limit of 3.0 mg/kg for Cd in soil, beyond which it poses severe threats to human health through bioaccumulation in crops, leading to cardiovascular and neurological disorders

(Obeng-Gyasi, 2020). The uptake of Cd by plants is influenced by soil pH and organic matter content, with leafy vegetables being particularly prone to accumulating high levels (Rizwan *et al.*, 2017). Cadmium toxicity manifests in various detrimental effects on plant physiology, including impaired seed germination, inhibited root growth, and disrupted photosynthesis, primarily by damaging enzymes, chlorophyll, and DNA (Raza *et al.*, 2020; El Rasafi *et al.*, 2020). Even at low concentrations, Cd can significantly reduce crop yields, although certain plant species exhibit capabilities for phytoremediation (Haider *et al.*, 2021).

Biochar, a carbon-rich solid material, is produced through the pyrolysis of biomass (e.g., wood, animal dung, agricultural waste) under oxygen-limited conditions. It is increasingly recognized as a sustainable and cost-effective alternative to conventional soil amendments like compost and chemical fertilizers (Amalina *et al.*, 2023; Anwar *et al.*, 2024). Biochar enhances soil structure, improves water retention, boosts microbial diversity, and effectively retains nutrients, thereby minimizing nutrient leaching and greenhouse gas emissions (Xu, 2022; Gao *et al.*, 2023). A critical advantage of biochar in contaminated environments is its capacity to remediate soils by adsorbing heavy metals, a function typically absent in traditional composts and chemical fertilizers (Liu *et al.*, 2018; Wang *et al.*, 2024). This eco-friendly approach facilitates the restoration of degraded soils (Boorboori and Lacková, 2023). Moreover, biochar serves as a versatile renewable energy source, capable of producing heat, electricity, and biofuels, and acts as a stable soil amendment that supports mineralization and adsorption processes (Sarma *et al.*, 2024; Fang *et al.*, 2024). These multifaceted benefits position biochar as a valuable tool for sustainable agriculture and environmental remediation (Ahmad *et al.*, 2024; Rauf *et al.*, 2025).

Despite the recognized potential of biochar in mitigating heavy metal contamination, its effectiveness can vary significantly depending on the feedstock, pyrolysis conditions, soil

type, and plant species (Gong *et al.*, 2019; Ogunkunle *et al.*, 2021). The current study specifically investigates the effects of kolanut-derived biochar on the growth and nutritional quality of *Corchorus olitorius* leaves cultivated in cadmium-contaminated soils.

MATERIALS AND METHODS

Study Area

The experiment was conducted at the University of Ilorin Botanical Garden, located within the Department of Plant Biology at the University of Ilorin, Ilorin, Kwara State, Nigeria, at approximately 8.4816468°N, 4.6369171°E. The University of Ilorin Botanical Garden is a large academic and conservation facility located at the Department of Plant Biology on the main campus of the University of Ilorin in Ilorin, Kwara State, Nigeria. Situated within the Guinea Savannah (tropical savanna) climate zone, the site experiences distinct wet and dry seasons, with a mean annual rainfall of 1,200–1,400 mm, average daily temperatures ranging from 25–30°C, and relative humidity typically between 60–70%. The facility, located within the university's expansive 5,000-hectare land area, features typical sandy loam or lateritic soil and flat topography, serving vital functions for biodiversity research, education, and ecological awareness in West Africa.

Collection and Preparation of Materials

The study was carried out in the screen house of the Botanical Garden, University of Ilorin, Nigeria, to minimize environmental interference. *Corchorus olitorius* (jute mallow) seeds were obtained locally in Ilorin an approach consistent with previous agronomic studies using certified regional seed sources to ensure genotype adaptation to local soil conditions (Akinola *et al.*, 2020).

Cadmium chloride (CdCl_2) was selected as the contaminant because it is one of the most bioavailable and phytotoxic cadmium salts used to simulate cadmium pollution in experimental soils (Kabata-Pendias, 2011; Hashem *et al.*, 2019). Kolanut pod biochar was produced by controlled pyrolysis at 400 °C

for 2 h under oxygen-limited conditions, following common temperature regimes for agricultural biochar production. Similar pyrolysis conditions (350–500 °C) optimize carbon stability, surface area, and cation exchange properties while maintaining plant-safe pH (Sohi *et al.*, 2010; Li *et al.*, 2019).

The loamy soil used as growth medium was collected from garden topsoil, air-dried, and sieved (<2 mm) to remove debris. Loamy texture was preferred because of its moderate nutrient availability and permeability, which improves experimental control of metal mobility and root growth (Liu *et al.*, 2018). The soil was partitioned into twelve plastic pots, each containing 1.7 kg to ensure sufficient rooting depth and minimize edge effects, as adopted by Adekiya *et al.* (2019).

Experimental Design and Setup

A total of twelve pots (each 1.7 kg soil) were arranged in a completely randomized design. Cadmium-treated soils received 27 mg CdCl_2 per pot, corresponding to a concentration of about 16 mg Cd kg^{-1} . This rate falls within concentrations commonly used in simulated cadmium-contamination studies (10–20 mg kg^{-1}) to assess plant response without inducing total lethality (Rizwan *et al.*, 2017). The salt was dissolved in a small volume of water to ensure uniform metal distribution and mixed carefully with a decontaminated metallic spatula. The soil was allowed to equilibrate for one week before planting, following the equilibration protocol recommended by USEPA (1996) for metal-spiked soils.

Kolanut pod biochar was applied at 1 % and 3 % w/w (equivalent to 17 g and 51 g per 1.7 kg soil). Biochar application rates between 1–5 % have consistently proven effective for immobilising heavy metals and improving soil fertility (Lehmann and Joseph, 2015; Akhil *et al.*, 2022). Biochar and Cd-spiked soils were mixed homogeneously with slight moisture to enhance incorporation. Pots were then covered with nylon to prevent cross-contamination and rainfall leaching. Each treatment was replicated thrice, making twelve experimental units:

Table 1: Experimental set-up

Treatment	Composition
Control	1.7 kg loamy soil only
T₁ (Cd only)	Soil + 27 mg CdCl ₂
T₂ (Cd + 1 % biochar)	Soil + 27 mg CdCl ₂ + 1 % biochar
T₃ (Cd + 3 % biochar)	Soil + 27 mg CdCl ₂ + 3 % biochar

Source: Authors' Fieldwork, 2020

Plant Cultivation and Monitoring

Healthy *C. olitorius* seedlings were raised for two weeks in a nursery before transplanting into experimental pots, following standard jute mallow propagation methods described by Adediran *et al.* (2024). Each pot received one vigorous seedling. Plants were watered once weekly with borehole water to maintain near-field moisture (~ 60 – 70 % water-holding capacity). Growth and physiological traits, including plant height and leaf number, were recorded weekly for four weeks frequencies in line with standard growth-monitoring intervals in short-cycle leafy vegetables.

Chlorophyll Determination

To assess photosynthetic pigment response to cadmium and biochar, chlorophyll determination followed the classical Lichtenthaler and Wellburn (1983) procedure. Approximately 0.24 g of fresh leaf tissue was macerated and extracted with 5 ml of 80 % (v/v) acetone, a solvent proven to efficiently dissolve chlorophyll while minimising degradation (Porra, 2002). Extraction was performed for 24 h at room temperature in darkness to prevent pigment oxidation. Absorbance readings were taken at 645 nm, 663 nm, and 470 nm using a Spectronic 20D spectrophotometer. Triplicate analyses per treatment ensured reproducibility and statistical reliability, as recommended by Arnon (1949).

Plant Digestion and Elemental Analysis

After harvest, plant samples were oven-dried at 70 °C to constant weight, ground, and digested following the mixed-acid wet-digestion protocol adapted from Allen (1989) and AOAC (2012). Each sample (0.5 g) received a 3:1 mixture of concentrated nitric acid (HNO₃) and hydrochloric acid (HCl) and was heated to near dryness until clear. This acid ratio and temperature ensure complete oxidation of plant organic matter without analyte loss (Cottenie *et al.*, 1982). Analyses of Ca²⁺, Mg²⁺, K⁺, Na⁺, Cu²⁺, Fe²⁺, and Cd²⁺ concentrations were performed using an Atomic Absorption Spectrophotometer (BUCK Scientific ACCUSYS 211). The applied detection limits (Ca 0.05; Mg 0.005; K 0.01; Cu 0.005; Fe 0.05; Na 0.005; Cd 0.01 mg L⁻¹) meet the sensitivity criteria for plant tissue analysis as specified in USEPA (1996) and Skoog *et al.* (2013).

RESULTS AND DISCUSSION

Chlorophyll Content

The chlorophyll content of *Corchorus olitorius* grown in cadmium-contaminated soil under various biochar treatments is presented in Table 1. A significant decrease ($P < 0.05$) in chlorophyll contents was observed across all treatments with increasing biochar concentrations. Specifically, the treatment combining cadmium with 3% biochar (Cd + 3% Biochar) exhibited the lowest values for chlorophyll a (0.093 ±

0.017), chlorophyll b (0.025 ± 0.056), total chlorophyll (0.17 ± 0.022), and carotene (3.44 ± 0.029). This indicates a negative impact of

higher biochar concentrations on photosynthetic pigments in the presence of cadmium.

Table 2: Effect of cadmium on Chlorophyll content of *Corchorus olitorius*

Treatment	Chlorophyll a	Chlorophyll b	Total chlorophyll	Carotene
Control	$0.344 \pm 0.062a$	$0.182 \pm 0.169a$	$0.521 \pm 0.228a$	$7.32 \pm 1.776a$
Cd	$0.273 \pm 0.012a$	$0.113 \pm 0.012a$	$0.387 \pm 0.019ab$	$6.30 \pm 0.533a$
Cd + 1% Biochar	$0.214 \pm 0.095a$	$0.091 \pm 0.057a$	$0.303 \pm 0.151ab$	$5.67 \pm 1.82a$
Cd + 3% Biochar	$0.093 \pm 0.017b$	$0.025 \pm 0.056a$	$0.17 \pm 0.022b$	$3.44 \pm 0.029ab$

Values with different subscripts are statistically different at $p < 0.05$

Source: Authors' Fieldwork, 2020

Growth Parameters

Plant Height

Table 2 illustrates the height of *Corchorus olitorius* grown in cadmium-contaminated soil over a four-week period. The treatment involving cadmium with 1% biochar (Cd + 1% Biochar) resulted in a significant increase ($P < 0.05$) in plant height, progressing from

24.7 ± 4.78 cm in Week 1 to 30 ± 5.10 cm in Week 4. While all treatments showed an increase in height over time, the 1% biochar treatment demonstrated a more pronounced positive effect compared to the other treatments, though statistical significance against the control was not explicitly stated for all weeks.

Table 3: Effect of cadmium on the height (cm) of *Corchorus olitorius*

Treatment	Week 1	Week 2	Week 3	Week 4
Control	$23 \pm 2.94a$	$26.7 \pm 4.11a$	$31 \pm 7.87a$	$36.3 \pm 13.9a$
Cd	$20.7 \pm 0.62a$	$25.3 \pm 0.94a$	$26 \pm 0.82a$	$26.7 \pm 0.47a$
Cd + 1% Biochar	$24.7 \pm 4.78a$	$28 \pm 3.56a$	$28 \pm 3.56a$	$30 \pm 5.10a$
Cd + 3% Biochar	$22.7 \pm 6.65a$	$25 \pm 6.16a$	$26 \pm 6.48a$	$27.7 \pm 4.99a$

Values with different subscripts are statistically different at $p < 0.05$

Source: Authors' Fieldwork, 2020

Leaf Count

The number of leaves of *Corchorus olitorius* across the different treatments is presented in Table 3. Significant increases ($P < 0.05$) in leaf count were observed between the second and fourth weeks after sowing for each

treatment. Notably, the Cd + 3% Biochar treatment exhibited the lowest leaf count in Week 2 (5.67 ± 0.94), suggesting a potential initial inhibitory effect at higher biochar concentrations, although this trend did not persist consistently across all weeks.

Table 4: Effect of cadmium on the Leaves Count of *Corchorus olitorius*

Treatment	Week 1	Week 2	Week 3	Week 4
Control	8 ± 1.63a	10 ± 0.82a	8 ± 2.45a	10.3 ± 3.86a
Cd	7.67 ± 0.47a	9.33 ± 0.47a	7.33 ± 2.49a	8 ± 2.45a
Cd + 1% Biochar	7.67 ± 1.25a	10.3 ± 0.47a	7.67 ± 0.94a	9.33 ± 1.7a
Cd + 3% Biochar	10 ± 0.82a	5.67 ± 0.94b	6.67 ± 1.25a	8.33 ± 2.87a

Values with different subscripts are statistically different at $p < 0.05$

Source: Authors' Fieldwork, 2020

Mineral Elements in Leaves and Shoots

Mineral Elements in Leaves

Table 4 details the concentrations of various mineral elements in the leaves of *Corchorus olitorius* grown in cadmium-contaminated soil. Treatments with cadmium generally showed a significant increase ($P < 0.05$) in the concentrations of Cu, Ca, Fe, and Mg, while

slight decreases were observed for Na and K. The Cd + 3% Biochar treatment consistently exhibited the lowest values for most mineral elements in the leaves, including Ca (64.2 ± 21.4) and Mg (119.2 ± 14.5), suggesting an antagonistic effect on nutrient uptake at higher biochar concentrations.

Table 5: Mineral elements in leaves of *Corchorus olitorius* grown on cadmium contaminated soil (mg/kg)

Treatment	Cu	Ca	Fe	Mg	Na	K
Control	5.07 0.49a	± 434.2 16.5a	± 12.0 0.94a	± 198.3 ± 11.2a	1454.2 237a	± 1680 177.1a
Cd	7.67 3.37a	± 493.3 61.5a	± 17.1 8.76a	± 189.2 16.7ab	1450 ± 42.9a	1676.7 203a
Cd + 1% Biochar	4.5 ± 0.2a	444.2 20.9a	± 8.58 0.51a	± 163.3 ± 4.25b	1525.8 70.7a	± 1470 216.2a
Cd + 3% Biochar	3.5 ± 0.2a	64.2 ± 21.4b	7.25 5.28a	± 119.2 ± 14.5c	1460 ± 26.5a	1178.3 240a

Values with different letters are statistically different at $p < 0.05$

Source: Authors' Fieldwork, 2020

Mineral Elements in Shoots

Table 5 presents the concentrations of mineral elements in the shoots of *Corchorus olitorius*. A significant increase ($P < 0.05$) in Cu (5.08 ± 2.52) and Ca (203.3 ± 131.9) was observed in the Cd + 3% Biochar treatment. Conversely, significant increases ($P < 0.05$) in

Fe (11.75 ± 7.25), Mg (142.5 ± 17.44), Na (1575 ± 152.08), and K (1828.3 ± 264.5) were noted in the Cd + 1% Biochar treatment. These findings suggest differential effects of biochar concentrations on nutrient translocation and accumulation in different plant parts.

Table 6: Mineral elements in shoots of *Corchorus olitorius* grown on cadmium-contaminated soil (mg/kg)

Treatment	Cu	Ca	Fe	Mg	Na	K	
Control	3.33 2.25a	± 30.3a	136.7 3.52a	± 10.58	135 ± 4.08a	1554.2 160.6a	± 1488.3 114.1a
Cd	3.5 1.08a	± 45.9a	96.67 5 ± 1.67a	± 117.5	16.7a	967.67 650.6a	± 1326.7 420.1a
Cd + 1% Biochar	3.42 0.85a	± 46.68a	152.5 7.25a	± 11.75	142.5 17.44a	± 1575 152.08a	± 1828.3 264.5a
Cd + 3% Biochar	5.08 2.52a	± 131.9a	203.3 5.25	± 3.94a	139.2 ± 22a	1495 ± 14.3a	1660 191.5a

Values with different letters are statistically different at $p < 0.05$

Source: Authors' Fieldwork, 2020

The study assessed the impact of kolanut-derived biochar on the growth and nutritional quality of *Corchorus olitorius* in cadmium-contaminated soil. The results confirmed that cadmium stress significantly impairs the physiological and nutritional characteristics of *Corchorus olitorius*, manifesting as reduced chlorophyll content, carotene levels, and altered mineral accumulation in both shoots and leaves. These findings were consistent with existing literature highlighting the detrimental effects of Cd on plant health (Raza *et al.*, 2020; El Rasafi *et al.*, 2020).

One of the most striking observations was the significant decrease in chlorophyll content across all biochar treatments, with the 3% biochar application exhibiting the lowest values for chlorophyll a, total chlorophyll, and carotene (Table 1). This suggests that even in the presence of biochar, excessive Cd content can interfere with chlorophyll biosynthesis or accelerate the breakdown of photosynthetic pigments. The lack of significant recovery in chlorophyll levels at elevated biochar concentrations indicated either slow efficacy of the biochar or insufficient stabilization of Cd during the early developmental stages of the plant. While the total chlorophyll and carotene content in biochar-treated samples were statistically different from the control, they did not fully reverse Cd toxicity. This outcome partially aligns with Rizwan *et al.* (2017) and Abbas *et*

al. (2018), who reported that biochar, could improve chlorophyll content in vegetables grown in Cd-polluted soils, particularly at moderate application rates. However, the present study's results suggest that the specific type and concentration of biochar, along with the plant species and soil chemistry, play a crucial role in determining the extent of amelioration.

Regarding growth parameters, the study found statistically insignificant variations in plant height and leaf count between treatments (Tables 2 and 3), which contrasted with several studies demonstrating significant improvements in plant morphology in biochar-treated soils (Haider *et al.*, 2021; Puga *et al.*, 2015). This discrepancy could be attributed to the relatively short duration of the current experiment (four weeks) or the specific characteristics of the kolanut biochar used. Longer experimental durations might be necessary to observe more pronounced effects of biochar on plant growth, as biochar's benefits often become more apparent over time as it integrates into the soil matrix and influences soil properties (Gao *et al.*, 2023). The analysis of mineral elements revealed complex interactions. While Cd treatments generally led to increased concentrations of Cu, Ca, Fe, and Mg in leaves, the 3% biochar treatment notably resulted in the lowest values for several essential mineral elements, including Mg and Ca (Table 4). This finding

is critical as it suggests that higher concentrations of kolanut biochar, under the experimental conditions, exacerbated negative impacts on nutrient uptake, potentially leading to nutrient imbalance and increased metal competition. This outcome underscores the importance of optimizing biochar application rates, as excessive amounts may not always be beneficial and can sometimes be detrimental to nutrient availability. The observed increases in Cu and Ca in shoots with 3% biochar, and Fe, Mg, Na, and K with 1% biochar (Table 5), indicate differential translocation and accumulation patterns depending on biochar concentration and specific elements.

The non-significant changes in shoot mineral concentrations of K, Na, Cu, and Fe in some treatments might suggest a compartmentalization strategy by the plant, where Cd is primarily sequestered in roots, thereby reducing its interference with above-ground nutrient dynamics. This mechanism of root sequestration as an effective plant response to heavy metal stress has been previously described by Song *et al.* (2017). Such a strategy would limit the translocation of toxic metals to edible parts of the plant, which is a desirable outcome in phytoremediation efforts.

The study highlights the site-specific nature of biochar application. The effectiveness of biochar in phytoremediation is influenced by a multitude of factors, including the type of biochar feedstock, pyrolysis conditions, soil characteristics, contaminant levels, and plant species (Gong *et al.*, 2019; Ogunkunle *et al.*, 2021). The kolanut biochar, while showing some partial ameliorative effects, did not consistently provide significant improvements across all measured parameters, and in some cases, it negatively impacted nutrient uptake. This suggests that a one-size-fits-all approach to biochar application is not feasible. Future research should focus on optimizing biochar concentrations, extending study durations, and exploring diverse biochar types and their combinations to achieve more effective and

consistent phytoremediation outcomes in Cd-contaminated soils.

CONCLUSION

This study investigated the potential of kolanut-derived biochar to mitigate cadmium (Cd) toxicity and enhance the growth and nutritional quality of *Corchorus olitorius* grown in Cd-contaminated soil. The findings confirm that while kolanut pod biochar exhibited ameliorative effects against Cd stress, its overall effectiveness was limited. Higher concentrations of biochar (3%) were observed to exacerbate negative impacts on essential nutrient uptake, leading to reduced levels of magnesium and calcium in plant tissues. This suggests a complex interaction where excessive biochar application can induce nutrient imbalances or competitive metal interactions rather than consistently promoting plant health.

The results showed the critical importance of a site-specific approach to biochar application. The performance of biochar as a soil amendment is highly dependent on various factors, including its concentration, the susceptibility of the plant species, and the specific characteristics of the soil. The observed outcomes, particularly the limited improvements and occasional negative effects, indicate that the kolanut biochar used in this study, under the given experimental conditions and short duration, did not consistently provide the expected benefits seen in other studies with different biochar types or longer experimental periods.

To maximize the efficiency of biochar in systems contaminated with Cd, future research and practical applications should focus on several key areas. These include conducting comparative studies with longer experiment durations, exploring more reactive or specifically engineered types of biochar, increasing field testing under diverse environmental conditions, and rigorously optimizing the rates of biochar addition. Such efforts are essential to fully harness the potential of biochar as a sustainable and effective tool for phytoremediation in heavy metal-contaminated soils.

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