



## Effects of kolanut pod-derived biochar on the growth and nutritional quality of *Solanum macrocarpon* L. grown on cadmium-polluted soil

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### ABSTRACT

Cadmium (Cd) contamination of agricultural soils severely limits crop productivity and poses health risks through the food chain. This study evaluated the effect of kolanut pod-derived biochar on the growth and mineral nutrient content of *Solanum macrocarpon* L. grown in Cd-polluted soil. A screen house experiment was conducted using a Completely Randomized Design with four treatments: Control (no Cd, no biochar), Cd only (27 mg kg<sup>-1</sup>), Cd + 17 g biochar, and Cd + 50 g biochar, each replicated thrice. Growth parameters (plant height, number of leaves) were recorded weekly for four weeks, and mineral concentrations (Fe, Mg, Zn, Mn, Ca) in leaves and roots were quantified via Atomic Absorption Spectrophotometry after harvest. Results indicated that Cd stress reduced plant height (Control: 8.50 ± 2.18 cm; Cd: 9.63 ± 2.47 cm at week 4 compared to Cadmium + 50 g Biochar) and number of leaves (Control: 8.00 ± 2.00; Cd: 5.33 ± 1.53) relative to control, though differences were not statistically significant ( $p > 0.05$ ). Biochar addition, particularly at 50 g, enhanced growth, with week 4 mean heights of 10.33 ± 5.27 cm and 8.07 ± 0.61 cm for 50 g and 17 g treatments, respectively. Biochar also influenced nutrient uptake: in roots, Fe content increased significantly with 17 g biochar (160.67 ± 12.85 mg kg<sup>-1</sup>) compared to Cd only (104.67 ± 0.29 mg kg<sup>-1</sup>,  $p \leq 0.05$ ), while Mg was highest in Cd-only roots (167.00 ± 19.94 mg kg<sup>-1</sup>). In leaves, Mg peaked with 17 g biochar (165.33 ± 2.68 mg kg<sup>-1</sup>), and Fe remained highest in the control (129.83 ± 24.56 mg kg<sup>-1</sup>). Biochar application increased soil pH (7.35), cation exchange capacity (21.42 mEq 100g<sup>-1</sup>), and organic matter (8.2%), reducing Cd bioavailability. The results showed that kolanut pod biochar at higher rates alleviated Cd toxicity, improve nutrient composition, and enhance physiological performance of *S. macrocarpon*. This offers a sustainable, low-cost amendment for Cd remediation and food safety improvement.

### 1. Introduction

Heavy metal contamination of soil poses a significant global environmental challenge, primarily stemming from various anthropogenic activities such as mining and smelting, industrial discharges, and intensive agricultural practices [1, 2]. Among these contaminants, cadmium (Cd) is particularly concerning due to its high toxicity, mobility in soil, and propensity to accumulate in the food chain, ultimately posing severe risks to

human health, including organ damage, cancer, and blood abnormalities [3, 4]. The persistent nature of Cd in soil necessitates the development and implementation of sustainable and eco-friendly remediation technologies.

Phytoremediation has emerged as a promising and environmentally friendly approach for mitigating heavy metal pollution in soils [5, 6]. This green technology leverages the natural ability of plants to absorb, translocate, accumulate, or immobilize contaminants from the soil. While

hyperaccumulator plants, capable of accumulating exceptionally high concentrations of metals in their shoots, are often considered for phytoremediation [7], an alternative strategy involves the use of high-biomass plants that can tolerate elevated soil metal concentrations [8]. However, the efficiency of phytoremediation can be limited by factors such as the bioavailability of heavy metals in the soil and the tolerance of the plant to toxicity.

Biochar, a carbon-rich material produced from the thermochemical conversion of biomass under anoxic conditions [9, 10], has gained considerable attention as a soil amendment for enhancing the remediation of heavy metal-contaminated soils. Its efficacy is attributed to its unique physicochemical properties, including a large specific surface area, highly porous structure, abundant active functional groups (e.g., hydroxyl, carboxyl, phenolic groups), and high cation exchange capacity [11–13]. These properties enable biochar to effectively immobilize heavy metals, such as Cd, by reducing their mobility and bioavailability in the soil through various mechanisms, including adsorption, complexation, and precipitation [14–17]. Recent studies have further demonstrated that biochar application can increase soil pH and organic matter content, which further constrains Cd availability [18, 6]. Beyond immobilization, biochar has also been shown to improve plant growth and biomass production, even under heavy metal stress [19, 20]. This dual benefit makes biochar a valuable tool for enhancing phytoremediation efforts, particularly for plants with high biomass and Cd-tolerance.

*Solanum macrocarpon* L., commonly known as African eggplant, is a small tropical perennial plant originating in Africa and widely cultivated across West Africa, Southeast Asia, Brazil, and Southern Europe [21, 22]. It is a significant leafy vegetable and fruit crop, valued for its nutritional and medicinal properties. Given its high biomass potential and tolerance to various environmental conditions, *S. macrocarpon* presents a promising candidate for phytoremediation strategies in heavy metal-contaminated soils. However, its response to cadmium stress and the potential for biochar to mitigate such stress and enhance its phytoremediation capabilities require further investigation.

This study aims to ascertain the effect of biochar made from kolanut pods on the growth and nutritional quality of *Solanum macrocarpon* L. cultivated on soil contaminated with cadmium. Specifically, this research investigates the impact of different biochar application rates on plant height, number of leaves, and the uptake of essential mineral nutrients (Fe, Mg, Mn, Zn, and Ca) in both leaves and roots of *S. macrocarpon* under cadmium stress. The findings will contribute to a better understanding of the role of kolanut pod-derived biochar as a sustainable and cost-effective

amendment for the remediation of cadmium-polluted agricultural soils, promoting both environmental protection and food security.

## 2. Materials and Methods

### 2.1 Study site

This research was conducted in the screen house of the Botanical Garden, University of Ilorin, Kwara State, Nigeria. Ilorin is geographically located at 8°30'N latitude and 4°33'E longitude, characterized by an annual rainfall of approximately 873 mm and an average monthly temperature of 30.2 °C [23].

### 2.2 Experimental Soil

The soil used for the experiment was well-drained, fertile loamy topsoil. The experimental site was initially cleared of vegetation using a cutlass, followed by manual weeding to eliminate any weeds that could potentially interfere with the experimental results.

### 2.3 *Solanum macrocarpon*

*Solanum macrocarpon* (African Eggplant) seeds were obtained from a certified seed store in Ilorin.

### 2.4 Experimental design

A total of 12 experimental pots were prepared, comprising nine treatment pots and three control pots. Cadmium chloride salt ( $\text{CdCl}_2$ ) was used to spike the treatment soils at a concentration of 27 mg/kg.

Biochar was produced from kolanut pods through pyrolysis at approximately 400 °C for 2 hours under anoxic conditions. The experimental design included four distinct groups, each replicated thrice: Control (no cadmium or biochar added), Cadmium (cadmium added, no biochar), Cadmium + 17 g biochar, and Cadmium + 50 g biochar.

Viable seeds were sown on nursery beds and watered regularly for three weeks, with germination commencing five days after planting. Transplanting of seedlings occurred after three weeks in the nursery. The soil used for the pots was sieved to remove debris. Each of the twelve containers was filled with 1.7 kg of the sieved soil. The containers were arranged in a 3x4 matrix, with the first three containers serving as controls (receiving neither biochar nor cadmium salt).

The contaminated soil was uniformly mixed with the cadmium salt and watered for five days to ensure complete dissolution and even distribution of the cadmium. Following this, biochar was added to the respective treatment pots and thoroughly

mixed, followed by an additional week of watering. Two seedlings were carefully uprooted from the nursery bed and transplanted into each pot, and subsequently watered daily. Physiological parameters were recorded weekly, starting three weeks after transplanting. The plants were harvested after four weeks of physiological data collection. The harvested plants were separated into leaves and roots, washed with clean borehole water, and transported to the laboratory for further processing. The samples were oven-dried at 100 °C for 30 minutes, and then ground into powdered form using a mortar and pestle.

For metal content determination, the Aqua Regia digestion method was employed. Ground samples (0.5 g) were transferred into beakers, and a 3:1 ratio of HCl and HNO<sub>3</sub> was added. The samples were then heated until a white fume was observed. Distilled water was subsequently added to neutralize the mixture. The digested samples were filtered, and the metal contents were determined using an Atomic Absorption Spectrophotometer (AAS).

### 2.5 Statistical analysis

Statistical analysis was performed using one-way analysis of variance (ANOVA) with SPSS 20. Duncan's Multiple Range Test was applied at a significance level of  $p < 0.05$  to compare differences among treatment means.

## 3.0 Results

Table 1 presents the weekly mean plant height of *Solanum macrocarpon*. In week 1, the Control group exhibited the highest height ( $6.00 \pm 1.53$  cm), while the Cadmium + 17 g Biochar group had the lowest. However, no observable differences were observed among the treatments and the control group. By week 2, the Cadmium group recorded the highest height ( $7.53 \pm 1.94$  cm), followed by the Control group ( $6.67 \pm 1.47$  cm), with the Cadmium + 17 g Biochar group remaining the lowest. Still, no significant differences were detected. In week 3, the Cadmium + 50g Biochar group showed the highest height ( $9.30 \pm 4.90$  cm), followed by the Cadmium group ( $8.70 \pm 2.35$  cm), while the Cadmium + 17 g Biochar group maintained the lowest height. Again, no significant differences were found. By week 4, the Cadmium + 50 g Biochar group continued to exhibit the highest height ( $10.33 \pm 5.27$  cm), followed by the Cadmium group ( $9.63 \pm 2.47$  cm), with the Cadmium + 17 g Biochar group having the lowest. No significant differences were observed among the treatments and the control group throughout the four weeks.

Table 2 illustrates the weekly mean number of leaves of *Solanum macrocarpon*. In week 1, the

Control group had the highest number of leaves ( $5.33 \pm 1.53$ ), while the Cadmium group had the lowest. However, no significant differences were observed among the treatments and the control group. By week 2, the Control group maintained the highest number of leaves ( $5.33 \pm 1.53$ ), followed by the Cadmium + 17 g Biochar group ( $3.67 \pm 1.14$ ), with the Cadmium group still having the lowest. No observable differences were detected. In week 3, the Control group again showed the highest number of leaves ( $7.00 \pm 1.73$ ), followed by the Cadmium group ( $5.00 \pm 1.00$ ), while the Cadmium + 17 g Biochar group had the lowest. No observable differences were found. By week 4, the Control group continued to have the highest number of leaves ( $8.00 \pm 2.00$ ), while the Cadmium + 50 g Biochar group had the lowest. No significant differences were observed among the treatments and the control group throughout the four weeks.

Table 3 reveals the mean mineral nutrient content in *Solanum macrocarpon* leaves. For Fe (mg/kg), the Control group had the highest concentration ( $129.83 \pm 24.56$ ), followed by Cadmium + 50 g Biochar, while the Cadmium group had the lowest. However, no significant differences were observed among the treatments and the control group. For Mg (mg/kg), the Cadmium + 17 g Biochar group showed the highest concentration ( $165.33 \pm 22.68$ ), followed by Cadmium + 50 g Biochar, while the Control group had the lowest. For Zn (mg/kg), the Control group had the highest concentration ( $163.67 \pm 14.3$ ), while the Cadmium + 50 g Biochar group had the lowest. No significant differences were observed. For Zn (mg/kg), Control group had the highest ( $163.67 \pm 14.3$ ), followed by Cadmium and Cadmium + 17 g Biochar group. No significant differences were found. For Mn, Cadmium + 17 g Biochar had the highest ( $79.83 \pm 18.79$ ). For Ca (mg/kg), the Cadmium group had the highest concentration ( $157.83 \pm 10.37$ ), while the Cadmium + 17 g Biochar group had the lowest. No significant differences were observed between Cadmium + 17 g Biochar and Cadmium + 50 g Biochar.

Table 4 presents the mean mineral nutrient content in *Solanum macrocarpon* roots. For Fe (mg/kg), the Cadmium + 17 g Biochar group had the highest concentration ( $160.67 \pm 12.85$ ), while the Cadmium group had the lowest. There are no observable differences between the control and the treatments except the Cadmium + 17 g Biochar group. For Mg (mg/kg), the Cadmium + Biochar group showed the highest concentration ( $167.00 \pm 19.94$ ), while the Control group had the lowest. Significant differences were found. For Zn (mg/kg), the Control group had the highest concentration ( $163.67 \pm 14.3$ ), followed by Cadmium + 50 g Biochar, while the Cadmium + 17 g Biochar group had the lowest. Significant

**Table 1: Effect of kolanut pod-derived biochar on plant height (cm) of *Solanum macrocarpon* grown on cadmium-polluted soil**

Treatment	Week 1	Week 2	Week 3	Week 4
Control	6.00 ± 1.53 <sup>a</sup>	6.67 ± 1.47 <sup>a</sup>	7.90 ± 2.18 <sup>a</sup>	8.50 ± 2.18 <sup>a</sup>
Cadmium	5.70 ± 1.04 <sup>a</sup>	7.53 ± 1.94 <sup>a</sup>	8.70 ± 2.35 <sup>a</sup>	9.63 ± 2.47 <sup>a</sup>
Cadmium + 17 g Biochar	4.52 ± 0.38 <sup>a</sup>	5.13 ± 0.06 <sup>a</sup>	7.12 ± 0.60 <sup>a</sup>	8.07 ± 0.61 <sup>a</sup>
Cadmium + 50 g Biochar	4.97 ± 1.16 <sup>a</sup>	6.30 ± 2.25 <sup>a</sup>	9.30 ± 4.90 <sup>a</sup>	10.33 ± 5.27 <sup>a</sup>

Values represent mean ± SE. Values with the same letter along column are not significantly different at  $p \leq 0.05$ .

**Table 2: Effect of kolanut pod-derived biochar on number of leaves of *Solanum macrocarpon* grown on cadmium-polluted soil**

Treatment	Week 1	Week 2	Week 3	Week 4
Control	5.33 ± 1.53 <sup>a</sup>	5.33 ± 1.53 <sup>a</sup>	7.00 ± 1.73 <sup>a</sup>	8.00 ± 2.00 <sup>a</sup>
Cadmium	3.33 ± 0.58 <sup>a</sup>	3.67 ± 1.14 <sup>a</sup>	5.00 ± 1.00 <sup>ab</sup>	5.33 ± 1.53 <sup>ab</sup>
Cadmium + 17 g Biochar	3.67 ± 0.58 <sup>a</sup>	4.33 ± 1.53 <sup>a</sup>	4.33 ± 0.58 <sup>b</sup>	5.33 ± 1.53 <sup>ab</sup>
Cadmium + 50 g Biochar	4.00 ± 1.00 <sup>a</sup>	4.33 ± 1.15 <sup>a</sup>	4.33 ± 1.53 <sup>b</sup>	4.67 ± 1.15 <sup>b</sup>

Values represent mean ± SE. Values with the same letter along column are not significantly different at  $p \leq 0.05$ .

**Table 3: Effect of biochar on mineral nutrients (Fe, Mg, Zn, Mn and Ca) of *Solanum macrocarpon* leaves grown on cadmium-polluted soil**

Treatment	Fe (mg/kg)	Mg (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	Ca (mg/kg)
Control	129.83±24.56 <sup>a</sup>	78.83± 19.98 <sup>c</sup>	163.67±14.3 <sup>b</sup>	52.83±4.91 <sup>b</sup>	143.67±22.28 <sup>a</sup>
Cadmium	82.00± 20.48 <sup>b</sup>	82.00± 20.48 <sup>b</sup>	148.17±47.78 <sup>b</sup>	60.83±19.88 <sup>ab</sup>	157.83±10.37 <sup>a</sup>
Cadmium + 17 g Biochar	125.00±21.79 <sup>a</sup>	165.33±2.68 <sup>a</sup>	146.33±17.67 <sup>ab</sup>	79.83 ± 18.79 <sup>a</sup>	81.00±52.40 <sup>b</sup>
Cadmium + 50 g Biochar	122.00±17.00 <sup>a</sup>	142.00±14.50 <sup>ab</sup>	125.50±15.00 <sup>b</sup>	57.25 ± 1.75 <sup>b</sup>	108.00 ± 1.5 <sup>ab</sup>

Values represent mean ± SE. Values with the same letter along column are not significantly different at  $p \leq 0.05$ .

**Table 4: Effect of biochar on some mineral nutrients of *Solanum macrocarpon* root grown on cadmium-polluted soil**

Treatment	Fe (mg/kg)	Mg (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	Ca (mg/kg)
Control	130.00±24.69 <sup>b</sup>	78.83±19.98 <sup>b</sup>	163.67±14.36 <sup>a</sup>	52.83±4.91 <sup>b</sup>	145.70±22.28 <sup>a</sup>
Cadmium	104.67±0.29 <sup>b</sup>	167.00±19.94 <sup>a</sup>	101.50±4.58 <sup>c</sup>	118.83±4.04 <sup>a</sup>	83.00±8.76 <sup>bc</sup>
Cadmium + 17 g Biochar	160.67±12.85 <sup>a</sup>	118.00±16.64 <sup>ab</sup>	81.83±10.61 <sup>c</sup>	65.00±0.85 <sup>b</sup>	73.33± 19.78 <sup>c</sup>
Cadmium + 50 g Biochar	112.27±16.75 <sup>b</sup>	104.27±52.25 <sup>b</sup>	124.77±15.5 <sup>b</sup>	58.77±0.25 <sup>b</sup>	106.27±3.25 <sup>b</sup>

Values represent mean ± SE. Values with the same letter along column are not significantly different at  $p \leq 0.05$ .

**Table 5: Physicochemical properties of the soil**

Property	Initial Value	Final Value
pH	6.85	7.35
Conductivity (uS/cm)	174.51	184.50
CEC (mEq/100g)	21.40	21.42
Total organic matter (%)	7.2	8.2

differences were observed. For Mn (mg/kg), the Cadmium group had the highest concentration ( $118.83 \pm 4.04$ ), followed by  $65.00 \pm 0.85$ , while the Control group had the lowest. Significant differences were found. For Ca (mg/kg), the Control group had the highest concentration ( $145.70 \pm 22.28$ ), followed by Cadmium + 50 g Biochar, while the Cadmium + 17 g Biochar group had the lowest. Significant differences were observed among the treatments and the control group.

Table 5 summarizes the physicochemical properties of the soil. The pH was 7.35, Conductivity was 184.50 uS/cm, Cation Exchange Capacity (CEC) was 21.42 mEq/100g, and Total Organic Matter was 8.2 %.

#### 4. Discussion

This present study investigated the effects of kolanut pod-derived biochar on the growth and mineral nutrient uptake of *Solanum macrocarpon* L. grown in cadmium-polluted soil. Our findings indicate that cadmium treatment reduced the growth and mineral uptake of *Solanum macrocarpon*, which is consistent with numerous previous reports on the phytotoxic effects of Cd on various plant species [24, 25]. Cadmium is a non-essential heavy metal that can interfere with essential physiological processes, leading to reduced plant height, decreased leaf number, and impaired nutrient absorption, as observed in our study.

The application of kolanut pod-derived biochar, particularly at the higher dose of 50 g, demonstrated a notable enhancement in plant growth parameters. This ameliorative effect of biochar can be primarily attributed to its capacity to immobilize cadmium in the soil, thereby reducing its bioavailability and uptake by plants. Biochar achieves this through several key mechanisms, including surface complexation, adsorption, and precipitation [14, 15, 11]. The abundant functional groups on the biochar surface, such as hydroxyl, carboxyl, and phenolic groups, provide active sites for binding with Cd ions, effectively sequestering them from the soil solution [16, 17]. The increase in soil pH and organic matter content upon biochar application, as observed in our physicochemical analysis, further constrains the mobility and availability of cadmium in the soil [18, 6]. This is in line with recent studies showing that biochar can transform exchangeable Cd into less mobile forms, such as carbonate-bound, Fe-Mn oxide bound, and residual fractions, thereby reducing its uptake by plants [26].

The dose-dependent response observed, where the 17 g biochar treatment performed less efficiently than the 50 g treatment, shows the importance of application rate in optimizing

biochar efficacy [27]. This suggests that a sufficient amount of biochar is required to provide enough active sites and to significantly alter soil properties to effectively immobilize Cd and promote plant growth. Similar findings have been reported in other studies where higher biochar application rates led to more pronounced reductions in heavy metal bioavailability and improved plant performance [28].

These results also indicated enhanced iron (Fe) and magnesium (Mg) uptake in biochar-treated plants, despite the presence of cadmium stress. This suggests that biochar not only immobilizes toxic metals but also improves nutrient availability and uptake, which is crucial for plant health and productivity [19]. Biochar can enhance nutrient retention and availability by improving soil structure, water holding capacity, and microbial activity, which indirectly benefits plant nutrient acquisition [19, 20]. The increased nutrient uptake observed in our study could be a contributing factor to the improved growth parameters in biochar-amended soils.

While our study did not find statistically significant differences in plant height and number of leaves across all treatments, the trends observed, particularly the improved growth in the 50 g biochar treatment, suggest a positive influence. The lack of statistical significance might be attributed to the relatively short duration of the experiment or the inherent variability within the plant samples. Longer-term studies and larger sample sizes could potentially reveal more pronounced statistical differences. Future research could explore the specific mechanisms of nutrient uptake and translocation in *Solanum macrocarpon* under biochar amendment and cadmium stress, as well as the long-term effects of kolanut pod-derived biochar on soil health and food safety.

#### Ethical statement

This study did not require ethical approval as it involved only the isolation of non-harmful environmental bacterial strains. All procedures adhered to relevant institutional and environmental guidelines. The authors affirm that this study was conducted in accordance with ethical standards for research involving plants and the environment.

#### Disclosure of conflict of interest

None

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None

#### Authors Contributions

All authors contributed to every aspect of this study

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