

# Phytoremediation Potential of *Leucaena Leucocephala* on Heavy Metal and Crude Oil Polluted Soils Amended with Biochar and Compost

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## Abstract

Soil contamination from heavy metals and crude oil is a global concern globally with the challenge being felt most in developing countries where remediation options are limited. In this study, the phytoremediation potential of *Leucaena leucocephala* and the ameliorative effects of biochar and compost on plant growth in contaminated soils were investigated. Lead-contaminated soil collected from a battery waste dumpsite was mixed with normal soil to get 50% contamination level, Soil artificially spiked with crude oil at 5% w/w was used as crude oil polluted soil. Both soil types were treated with compost and biochar at four application rates (0, 2.5, 5, and 10 t/ha). The compost and biochar were applied singly or combined depending on the treatment. *Leucaena leucocephala* seeds were planted one week after application. Data were collected on plant height, number of leaves, biomass, secondary metabolites (proline and phenolics) and lead accumulation in plant tissues. Lead contamination caused stunted plant growth in unamended soil, while addition of organic amendments enhanced plant's performance despite different levels of soil contamination. On the osmolyte production, plants in untreated lead-contaminated soil produced more proline and phenolic compounds than those grown on amended soil. The translocation factor for Pb exceeded 1.0, in most treatment combinations, but the biological absorption factor was relatively low. In conclusion, *Leucaena leucocephala* could be considered as a credible candidate for phytoremediation of lead contaminated soil particularly in the presence of organic soil amendments.  
**Keywords:** Remediation: Heavy metals: Biochar: Compost: Phytoremediation: Crude oil pollution soil: *Leucaena leucocephala*.

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## Introduction

Soil degradation resulting from natural and anthropogenic sources such as industrialization, rapid urbanization, and uncontrolled waste disposal have left many agricultural and urban land heavily polluted (Yaashikaa and Kumar, 2022). All these have resulted in the poor soil fertility (Asyakina et al., 2021) and eventual yield reduction. The contamination poses threats to environmental and human health (Funtikova et al., 2023). Heavy metals such as lead (Pb), cadmium and chromium, are found deposited in many agricultural lands (Ali et al., 2022). Oil exploration and production have also caused damage to soil and

waterways. These have disrupted the farming and fishing activities of the affected communities and raised serious concerns about food safety and public health.

Cleaning up contaminated land could be burdensome. The conventional methods such as excavation and replacement strategies are costly, resource demanding and often results in ecological disruption. The use of phytoremediation, an approach that uses living plants to extract, break down, or immobilize contaminants in the soil, is being promoted as a cost-effective and environmentally friendly alternative for managing

contaminated soils. It harnesses the natural ability of plants to absorb, translocate, and sequester pollutants from contaminated media. Plants are used for phytoremediation through several pathways: direct extraction and accumulation in tissues (phytoextraction), root-zone stabilization (phytostabilization), volatilization through leaves (phytovolatilization), and microbial degradation in the rhizosphere (rhizodegradation). Among these, phytoextraction is commonly used. However, the type of plant used for this determines the efficiency. The use of leguminous and high biomass plants could offer an additional advantage through symbiotic nitrogen fixation and enough biomass for metal accumulation. Hence, *Leucaena leucocephala*, a fast-growing leguminous tree could be a good candidate for phytoremediation. It grows quickly and can reach maturity within six to seven months, generates significant above-ground biomass, and tolerates a wide range of soil conditions. All these traits qualify it for phyto-remediation.

Organic amendments, especially biochar and compost have been used severally to improve soil structure, boost nutrient availability, increase water retention and support microbial communities that benefit plant roots. Compost enhanced Biochar and phytoremediation can therefore help in addressing the problem of contamination in different ways. Apart from improving soil health by retaining nutrients, reducing soil acidity, and increasing water-holding capacity, it also promotes the growth of plants on contaminated soil. Both compost enhanced biochar and phytoremediation can work together to improve soil health, provide the nutrients and carbon needed for plants to grow and remove harmful chemicals from the soil. This can create a more sustainable and resilient remediation strategy that supports healthy plant growth while reducing the risk of environmental pollution. The interaction between these amendments and *Leucaena leucocephala* therefore needs to be tested at different combinations and application rates. This study was designed to determine the phytoremediation potentials of this leguminous plant and the roles of soil amendments in phytoremediation of heavy metal and crude oil contaminated soils. The effective rate of application of these amendments, heavy metal uptake by the tested plant and tolerance mechanisms were also investigated.

## Materials and Methods

### Experimental Site and Materials

The study was carried out at the Department of Crop

Protection and Environmental Biology, Faculty of Agriculture, University of Ibadan, Nigeria (latitude 3°55'E, longitude 7°24'N).

### Soil and Amendment Preparation

Lead-contaminated soil was collected from a battery waste dumpsite in Lalupon, Ibadan while the control soil used for crude oil pollution was collected from the departmental crop garden. These two soil types were first sieved through a 2 mm mesh before mixing them in a 1:1 ratio to achieve 50% Pb contamination. Uncontaminated soil was separately spiked with unrefined crude oil at 5% w/w. Organic amendments consisted of biochar and compost. Compost was prepared from Mexican sunflower (*Tithonia diversifolia*) and poultry manure in 3:1 ratio and biochar were prepared from dry Mexican sunflower and pyrolysed at 350°C. The compost was prepared through a three-month aerobic decomposition process with monthly turning and moisture management.

### Experimental Design and Treatment Application

The experiment employed a randomized complete block design with three replicates. Five hundred grams of soil per pot was treated with amendments at rates of 0 (control), 2.5 (C1/B1), 5 (C2/B2), and 10 (C3/B3) t/ha applied individually and in 15 combined variations, yielding 144 experimental units across three soil types: heavy metal-polluted, crude oil-polluted, and unpolluted control soil.

### Seed Treatment and Planting

Seeds of *Leucaena leucocephala* were obtained from the Teaching and Research Farm of the University of Ibadan. *Leucaena leucocephala* seeds were treated with concentrated sulfuric acid for 20 minutes for breaking dormancy, followed by double rinsing with distilled water. Seeds were sown in pots containing pre-moistened soil seven days after amendments application. Plants were maintained in the screen house with regular watering (50 ml every three days) and weeding was carried out as required.

### Data Collection and Analysis

Growth parameters (plant height and number of leaves) were measured at 2, 4, 6, and 8 weeks after sowing. Plant height was measured from soil surface to apical tip using a measuring ruler. Leaves were counted visually at each sampling date. Plants were harvested at 8 weeks after planting, separated into roots and shoots, thoroughly washed, and oven-dried



at 60°C for 48 hours before weighing. Proline content was determined using the acid ninhydrin method following homogenization in 3% aqueous sulfosalicylic acid. Total phenolic content was determined using the Folin-Ciocalteu reagent method with absorbance measured at 765 nm against a gallic acid standard curve. Soil and plant samples (1 g each) were digested in 10 mL of 2 M nitric acid by boiling for 2-3 hours. The filtrate was adjusted to 100 mL with distilled water and analysed for lead concentration using atomic absorption spectrometry (VGP210 BUCK Scientific). Biological Absorption Factor (BAF) was calculated as the ratio of total metal concentration in plant tissue to soil concentration. Translocation Factor (TF) was calculated as the ratio of shoot metal concentration to root metal concentration. Data were analysed using analysis of variance (ANOVA) with treatment means compared using Duncan Multiple Range Test at P ≤ 0.05 significance level.

## Results and Discussion

### Soil and Amendment Characterization

Pre-planting soil analysis results in table 1, revealed lead concentration of 12,095 mg/kg in the contaminated soil. Compost and biochar contained substantial levels of plant-essential nutrients, with compost demonstrating higher available phosphorus (6.36 mg/g) and potassium (13,467.56 cmol/kg) compared to biochar (2.47 mg/g and 11,719.44 cmol/kg, respectively) (Table 2).

**Table 1** Physical and chemical properties of soil used for the experiment (pre-planting analysis of contaminated soil from battery waste dumpsite)

Parameters	Contaminated Soil	Units
pH (H <sub>2</sub> O)	4.60	-
Organic Carbon	0.21	%
Acidity	6.20	Cmol/kg
Total Nitrogen	0.01	%
Available P	2.35	mg/g
Exchangeable Bases (Cmol/kg)		
K	0.94	-
Ca	2.56	-
Mg	0.75	-
Na	455.85	-
Exchangeable Micronutrients (mg/kg)		
Mn	29.03	-

Fe	385.12	-
Cu	33.11	-
Zn	200.05	-
Heavy Metal (mg/kg)		
Pb (Lead)	23,759	-

**Table 2** Physical and chemical properties of compost and biochar used as soil amendments.

Parameters	Compost	Biochar	Units
Available P	6.36–7.46	2.47–0.64	mg/g
Exchangeable Bases (Cmol/kg)			
K	13,467.56	11,719.44	-
Ca	0	0	-
Mg	2,077.27	914.41	-
Na	271.44	323.46	-
Exchangeable Micronutrients (mg/kg)			
Mn	92.74	34.31	-
Fe	759.17	163.57	-
Cu	5.99	2.76	-

### Growth Response to Treatments

Plants cultivated in heavy metal-polluted soil were generally better in growth compared to those in crude oil-polluted soil. However, addition of organic amendments enhanced plant growth in both contaminated soils. Application of biochar and compost, particularly combined treatments, significantly enhanced leaf production and plant height relative to untreated controls across all soil types. The number of leaves recorded in heavy metal-polluted soil (Table 3), was more than that of crude oil polluted soil (Table 4). The highest value was recorded in the C3B1 treatment (185 leaves) at 8 weeks, while crude oil-polluted soil had maximum values (142.67 leaves) with C3 treatment. Plant height measurements showed a progressive increase with increase in amendment application rates (Tables 5 and 6). In heavy metal-polluted soil, the plants in C3B1 treatment had 14.33 cm by 8 weeks after sowing. As observed for the number of leaves, crude oil-polluted soil demonstrated consistently lower heights, with maximum values around 11.67 cm (Table 6).

**Table 3** Effects of different levels of organic fertilizers on number of leaves of *Leucaena leucocephala* planted on crude oil-polluted soil.

Treatment	CONLW2	CONLW4	CONLW6	CONLW8
B1	18.00b	39.33b	72.0j	74.67bc

B2	23.33ab	58.67a b	68.0k	126.33ab
B3	34.33a	60.67a b	80.0h	103.00abc
C1	25.33ab	63.33a b	72.0j	114.00abc
C2	33.00ab	59.33a b	98.0c	121.33ab
C3	30.67ab	67.33a b	120.0 a	142.67a
C1B1	35.33a	57.33a b	106.0 b	108.00abc
C1B2	23.33ab	58.00a b	84.0f	106.33abc
C1B3	17.33ab	64.00a b	62.0 m	91.33abc
C2B1	17.33ab	58.67a b	96.0d	106.00abc
C2B2	26.67ab	63.33a b	92.0e	105.67abc
C2B3	32.33ab	85.33a	62.0 m	111.33abc
C3B1	14.00ab	68.67a b	78.0i	69.33bc
C3B2	22.00ab	66.00a b	82.0g	87.00abc
C3B3	6.67b	47.33a b	80.0h	70.67bc
CONTROL	30.67ab	48.67a b	66.0l	51.00c

Means followed by the same letters are not significantly different ( $P \leq 0.05$ ). CONLW = Crude Oil Number of Leaves Week; C = Compost; B = Biochar.

**Table 4** Effects of different levels of organic fertilizers on number of leaves of *Leucaena leucocephala* planted on heavy metal-polluted soil.

Treatment	HMNL W2	HMNL W4	HMNL W6	HMNL W8
B1	23.33a	78.00ab	129.33a bc	144.00a bc
B2	40.33a	87.33ab	105.33a bc	136.00a bc
B3	36.67a	85.33ab	104.00a bc	133.33a bc
C1	24.00a	97.33a	102.00a bc	88.67cd e
C2	23.33a	86.00ab	103.33a bc	37.67de
C3	24.00a	67.33ab	83.33c	10.00e

C1B1	36.00a	82.67ab	100.00a bc	39.33de
C1B2	18.00a	58.33b	105.33a bc	80.67cd e
C1B3	34.00a	89.33ab	109.33a bc	128.00a bc
C2B1	32.67a	80.00ab	124.00a bc	142.67a bc
C2B2	32.00a	70.67ab	94.00ab c	96.33bc d
C2B3	23.67a	78.67ab	131.33a bc	153.33a bc
C3B1	18.00a	76.00ab	162.67a	185.00a
C3B2	32.00a	69.33ab	156.67a b	178.00a b
C3B3	33.33a	80.33ab	88.67bc	120.67a bcd
CONTR OL	27.33a	94.00a	98.67ab c	110.33a bcd

Means followed by the same letters are not significantly different ( $P \leq 0.05$ ). HMNLW = Heavy Metal Number of Leaves Week; C = Compost; B = Biochar.

**Table 5** Effects of different levels of organic fertilizers on plant height (cm) of *Leucaena leucocephala* planted on crude oil-polluted soil.

Treatment	COPH W2	COPH W4	COPH W6	COPH W8
B1	6.00a	5.67a	5.67a	7.33a
B2	8.00a	7.67a	8.67a	10.33a
B3	7.33a	8.67a	8.67a	10.33a
C1	6.67a	8.00a	8.67a	10.33a
C2	8.00a	7.00a	8.67a	10.67a
C3	6.67a	8.33a	9.67a	11.67a
C1B1	6.67a	8.00a	8.00a	9.00a
C1B2	5.67a	7.67a	8.00a	9.00a
C1B3	7.33a	9.00a	8.67a	10.00a
C2B1	7.00a	8.33a	9.00a	10.33a
C2B2	7.33a	9.33a	9.33a	11.00a
C2B3	6.00a	8.33a	9.00a	10.67a
C3B1	6.67a	8.00a	8.33a	9.33a
C3B2	6.33a	8.00a	7.67a	9.33a
C3B3	7.33a	5.00a	5.33a	6.33a
CONTR OL	6.33a	5.67a	6.00a	7.33a

Means followed by the same letters are not significantly different ( $P \leq 0.05$ ). COPHW = Crude Oil Plant Height Week; C = Compost; B = Biochar.

**Table 6** Effects of different levels of organic fertilizers on plant height (cm) of *Leucaena leucocephala* planted

on heavy metal-polluted soil.

Treatment	HMPH W2	HMPH W4	HMPH W6	HMPH W8
B1	6.00a	7.33a	8.00de	11.00ab
B2	8.00a	9.67a	10.33abcde	12.67ab
B3	7.33a	9.00a	10.00abcde	12.00ab
C1	6.67a	8.67a	11.00abcd	12.67ab
C2	8.00a	9.00a	10.00abcde	10.67bc
C3	6.67a	7.67a	8.33cde	7.67d
C1B1	6.67a	8.67a	8.67bcde	8.33cd
C1B2	5.67a	7.00a	7.33e	8.33cd
C1B3	7.33a	9.33a	10.00abcde	11.33ab
C2B1	7.00a	9.33a	10.67abcd	12.67ab
C2B2	7.33a	9.00a	10.33abcde	11.33ab
C2B3	6.00a	9.33a	11.33abc	13.33ab
C3B1	6.67a	9.00a	12.00a	14.33a
C3B2	6.33a	8.67a	11.00abcd	13.00ab
C3B3	7.33a	8.67a	10.67abcd	13.00ab
CONTROL	6.33a	9.00a	11.67ab	13.00ab

Means followed by the same letters are not significantly different ( $P \leq 0.05$ ). HMPHW = Heavy Metal Plant Height Week; C = Compost; B = Biochar.

### Osmolites Accumulation

Plants growing in heavy metal-polluted soil accumulated substantially higher concentrations of proline and phenolic compounds compared to those in unpolluted soil. Proline accumulation was more in contaminated soil treatments compared to control. It was highest in plants treated with C1B3 and grown in both heavy metal and crude oil-polluted soils (Table 7) while the control plants treated with C2B1 had highest proline compared to other organic treatments. Total phenolic compounds were also more in contaminated soil treatments compared to control. Heavy metal-polluted soil treated with C2B1 gave the highest phenolic concentration in plants and this was followed closely by C1B2 and C2B2 treatments (Table 7). These patterns confirm that plants develop enhanced secondary metabolite production as a defence

mechanism against heavy metal and hydrocarbon stress.

**Table 7** Proline content ( $\mu\text{mol/g}$  fresh weight) in *Leucaena leucocephala* leaves grown on heavy metal-polluted, crude oil-polluted, and normal soils with different organic amendments.

Treatment	Heavy Metal Soil	Crude Oil Soil	Normal Soil
B1	2.15	4.25	3.50
B2	2.89	3.80	2.95
B3	3.42	2.65	4.20
C1	2.05	2.15	3.10
C2	2.98	1.95	2.80
C3	1.52	3.55	4.65
C1B1	2.75	3.45	2.90
C1B2	2.35	2.85	3.40
C1B3	4.85	4.95	3.65
C2B1	3.05	3.15	5.20
C2B2	2.45	1.80	3.75
C2B3	3.80	4.55	3.25
C3B1	2.15	2.35	2.55
C3B2	2.30	3.05	3.85
C3B3	1.95	2.45	2.70
CONTROL	3.65	3.75	1.85

**Table 8** Total phenolic content (mg gallic acid equivalent/g fresh weight) in *Leucaena leucocephala* leaves grown on heavy metal-polluted, crude oil-polluted, and normal soils with different organic amendments.

Treatment	Heavy Metal Soil (mg/g)	Crude Oil Soil (mg/g)	Normal Soil (mg/g)
B1	3.85	5.20	2.15
B2	2.95	3.45	2.80
B3	2.45	2.90	3.10
C1	1.85	2.35	2.50
C2	4.15	4.85	2.25
C3	2.75	3.65	5.40
C1B1	3.25	3.15	2.90
C1B2	4.55	5.75	3.20
C1B3	3.40	4.20	3.50
C2B1	5.85	3.85	3.15
C2B2	4.45	3.55	2.95
C2B3	3.95	4.35	4.65
C3B1	3.15	2.65	4.85
C3B2	2.85	3.25	3.75
C3B3	2.55	2.15	2.45
CONTROL	2.35	2.45	1.65

### Biomass Accumulation

Root and shoot dry matter accumulation was substantially influenced by soil treatment and amendment type. In crude oil-polluted soil (Table 9), the C1B1 combination produced the highest root dry matter, while shoot dry matter was achieved with C2B1 treatment. Heavy metal-polluted soil showed optimal root development with C2B3 amendment, while shoot biomass peaked with B1 and C3B2 treatments (Table 10). Unpolluted control soil without amendments gave reduced biomass accumulation compared to amended soils. Conversely, contaminated soil amended with compost and biochar probably due to stimulation of compensatory growth supported plant development better than uncontaminated soils thereby suggesting that modest contamination may enhance growth, while organic amendments support this response.

**Table 9** Root and shoot dry matter accumulation (g/plant) of *Leucaena leucocephala* grown on crude oil-polluted soil with different organic amendments at 8 weeks post-sowing.

Treatment	Root Dry Matter (g)	Shoot Dry Matter (g)
B1	2.15	5.45
B2	1.85	4.95
B3	1.55	4.35
C1	1.95	6.15
C2	2.35	5.85
C3	1.45	3.95
C1B1	3.85	5.75
C1B2	2.95	5.25
C1B3	2.45	4.85
C2B1	2.85	7.35
C2B2	2.15	5.45
C2B3	2.55	6.25
C3B1	1.95	4.55
C3B2	2.25	5.15
C3B3	1.65	3.85
CONTROL	1.35	3.45

**Table 10** Root and shoot dry matter accumulation (g/plant) of *Leucaena leucocephala* grown on heavy metal-polluted soil with different organic amendments at 8 weeks post-sowing.

Treatment	Root Dry Matter (g)	Shoot Dry Matter (g)
B1	3.45	8.65
B2	2.85	7.95
B3	2.55	7.25
C1	2.95	8.35

C2	2.45	6.85
C3	1.85	5.45
C1B1	2.35	6.75
C1B2	2.15	6.35
C1B3	2.75	7.85
C2B1	2.65	7.55
C2B2	2.45	7.15
C2B3	4.25	9.45
C3B1	3.85	8.95
C3B2	3.55	9.35
C3B3	2.95	7.65
CONTROL	2.15	5.85

### Lead Bioaccumulation and Translocation

Post-harvest soil analysis revealed substantial variation in lead concentration across treatments. Pre-planting contaminated soil lead concentration was 12,095 mg/kg. Control soil (untreated heavy metal-polluted soil) showed reduction in lead concentration from 12,095 to 9,850 mg/kg, demonstrating the plant's capacity for lead removal (Table 11). Treatments with organic amendments generally exhibited increased post-harvest soil lead concentrations, with C2 showing the highest concentration of 18,364.0 mg/kg. Lead concentration in plant tissues demonstrated distinct partitioning patterns. Shoot lead concentration ranged from 0.38 mg/kg (C1 treatment) to 123.4 mg/kg (C1B3 treatment), while root concentrations ranged from 4.56 mg/kg (control) to 172.0 mg/kg (B1 treatment) (Table 12). BAF is calculated as the ratio of total metal concentration in plant tissue to soil concentration ( $C_{\text{plant}}/C_{\text{soil}}$ ). The Biological Absorption Factor (BAF) was relatively low, ranging from 0.0021 to 0.0155, indicating limited overall metal uptake relative to soil concentration (Table 13). TF indicates the efficiency of metal movement from roots to shoots ( $TF = C_{\text{shoot}}/C_{\text{root}}$ ). Values  $> 1.0$  indicate efficient mobilization of lead to shoot tissues. However, the Translocation Factor exceeded unity ( $TF > 1.0$ ) in most treatments (Table 14), with maximum values of 20.36 in C1B3 treatment, confirming the plant's capacity to mobilize lead from roots to shoots—a prerequisite for effective phytoextraction.

**Table 11** Pb level in soil samples before and after planting with different variations of organic amendments.

Treatment	Pb Level (mg/kg)
Before Planting	12,095
C1	10,618.50
C2	18,364.0



C3	11,432.50
B1	12,902.50
B2	10,289.00
B3	13,560.00
C1B1	15,146.50
C1B2	14,862.50
C1B3	15,761.50
C2B1	13,760.00
C2B2	14,427.50
C2B3	16,962.50
C3B1	14,129.00
C3B2	17,272.50
C3B3	15,005.0
CONTROL	9,850

**Table 12** Pb concentration in shoot and root tissues of *Leucaena leucocephala* plants grown in lead-polluted soil with different variations of organic amendments.

Treatment	Shoot Pb Level (mg/kg)	Root Pb Level (mg/kg)
C1	0.38	21.9
C2	67	11.34
C3	107.8	11.70
B1	30.9	172.0
B2	32.78	9.34
B3	70	7.06
C1B1	44.5	8.06
C1B2	41.18	7.28
C1B3	123.4	6.06
C2B1	33.96	7.20
C2B2	82.8	10.80
C2B3	123.0	8.90
C3B1	26.94	7.94
C3B2	26.82	7.72
C3B3	25.68	8.16
CONTROL	20.12	4.56

**Table 13** Biological Absorption Factor (BAF) of *Leucaena leucocephala* plants grown on lead-polluted soil with different variations of organic amendments.

Treatment	Pb Concentration in Soil (mg/kg)	Pb Concentration in Shoot (mg/kg)	Pb Concentration in Root (mg/kg)	Total Pb Concentration in Plant (mg/kg)	Biological Absorption Factor (BAF)
C1	10,618.50	0.38	21.9	22.28	0.002098

C2	18,364.0	67	11.34	78.34	0.004266
C3	11,432.50	107.8	11.70	119.5	0.010453
B1	12,902.50	30.9	172.0	202.9	0.015726
B2	10,289.00	32.78	9.34	42.12	0.004094
B3	13,560.00	70	7.06	77.06	0.005683
C1B1	15,146.50	44.5	8.06	52.56	0.003470
C1B2	14,862.50	41.18	7.28	48.46	0.003261
C1B3	15,761.50	123.4	6.06	129.46	0.008214
C2B1	13,760.00	33.96	7.20	41.16	0.002991
C2B2	14,427.50	82.8	10.80	93.6	0.006488
C2B3	16,962.50	123.0	8.90	131.9	0.007776
C3B1	14,129.00	26.94	7.94	34.88	0.002469
C3B2	17,272.50	26.82	7.72	34.54	0.002000
C3B3	15,005.0	25.68	8.16	33.84	0.002255
CONTROL	9,850	20.12	4.56	24.68	0.002506

**Table 14** Translocation Factor (TF) of *Leucaena leucocephala* plants grown in lead-polluted soil with different variations of organic amendments.

Treatment	Shoot Pb Level (mg/kg)	Root Pb Level (mg/kg)	Translocation Factor (TF = Cshoot/Croot)
C1	0.38	21.9	0.017352
C2	67	11.34	5.908289
C3	107.8	11.70	9.213675
B1	30.9	172.0	0.179651
B2	32.78	9.34	3.509636
B3	70	7.06	9.915014
C1B1	44.5	8.06	5.521092
C1B2	41.18	7.28	5.656593
C1B3	123.4	6.06	20.363036
C2B1	33.96	7.20	4.716667
C2B2	82.8	10.80	7.666667
C2B3	123.0	8.90	13.820225
C3B1	26.94	7.94	3.392947
C3B2	26.82	7.72	3.474093
C3B3	25.68	8.16	3.147059
CONTROL	20.12	4.56	4.412281

## Discussion

The superior growth of *Leucaena leucocephala* in heavy metal-polluted soil compared to crude oil polluted soil reflects the differential phytotoxic mechanisms of these contaminants. It has been previously reported that crude oil contamination might be more toxic for plant growth compared to heavy metals (Agbogodi et al., 2003). This was because aromatic hydrocarbon reduces soil porosity and interfere with water availability, all of which restrict root development. Heavy metal contamination on its own competes with many divalent metals in the soil and might out compete essential elements in the soil during nutrient absorption by plant. This also poses danger to the plant through the increase in reactive oxygen species and oxidative stress. The presence of these contaminants in the agricultural soils therefore a global threat to food security.

Addition of organic amendments could however help in reducing the detrimental effects of soil contamination on agriculture by breaking the PAHs in the oil polluted soil and immobilizing heavy metals in metal contaminated soil. Above all, it would also make essential nutrients available for plant growth in contaminated soil. This was what happened in this study. There was a remarkable increase in the plants grown on contaminated soils amended with biochar and compost as reflected in all the growth parameters. The effect was more pronounced when compost and biochar were combined. The increase in soil fertility supported the plant growth in contaminated soils. Combination of compost and biochar (C3B1 and C2B3) provides the optimal nutrient balance that made it to perform better than sole application.

Proline and phenolics have been reported to be part of the osmolytes used by plants for stress tolerance (Kisa et al., 2016). This was confirmed in this study where elevated levels of proline and phenolics were recorded in the plants grown on contaminated soils without amendments. Production of proline is induced under stress due to the degradation of protein, and it helps in increasing the stress tolerance in plant. It functions as osmo protectant and reactive oxygen species scavenger, all of which help in protecting the cellular macromolecules. Phenolic production in metal and crude oil polluted soil also confirmed the participation of secondary metabolites in stress amelioration and tolerance (Raina et al., 2019). However, the increase in the phenolic content of the control plant grown on the control soil amended with compost and biochar

suggests that phenolic compound production can also be enhanced in the presence of soil nutrients. The organic amendments do not only reduce metal bioavailability, it also provides essential nutrients for plant growth and enhances biomass accumulation in plant. Higher biomass accumulation that was found in the plants grown on amended contaminated soils especially in C2B3 treatment compared to unamended control reflects that this specific combination can balance between nutrient provision and contaminant immobilization.

In this study, *Leucaena leucocephala* accumulated Pb in higher concentration in the above plant tissue and this was confirmed by the Translocation Factor that was greater than 1. This is a good attribute of an hyperaccumulator. The high TF also shows the ability of the organic amendments to mobilize Pb in the soil, a mechanism that is essential for phytoextraction. The plant grown on C1B3 treatment had TF of 20.36, indicating highly efficient shoot translocation. The low BAF values (0.002–0.015) indicates that the Pb in the soil was abnormally higher than the tolerable level. The increased soil lead concentrations in amended treatments require further investigation but likely reflect stabilization of previously soluble lead fractions by amendment-induced pH increases and precipitation reactions.

The reduction in lead concentration in untreated control soil (9,850 mg/kg post-harvest versus 12,095 mg/kg pre-planting) occurred in the absence of organic amendment, demonstrating that *Leucaena leucocephala* alone mediates substantial Pb removal. The study duration (eight weeks) likely constrained metal uptake rates. Extended cultivation periods would likely demonstrate cumulative metal removal sufficient for phytostabilization and potential phytoextraction over multiple cropping cycles, particularly given the plant's rapid growth and high biomass production capacity.

## Conclusions

These findings demonstrate that *Leucaena leucocephala* cultivated in soils amended with combined biochar-compost treatments provides a viable strategy for sustainable remediation of lead contaminated agricultural lands. The combination of metal Phyto stabilization through organic amendments with active plant-mediated lead removal offers a cost-effective and environmentally sound alternative to conventional remediation technologies. The leguminous nature of



*Leucaena leucocephala* provides additional environmental benefits through nitrogen fixation, simultaneously restoring soil fertility while addressing contamination. This research establishes that *Leucaena leucocephala* possesses phytoremediation potential for lead-contaminated soils, demonstrating consistent lead translocation to shoot tissues across treatments. Organic soil amendments, particularly combined biochar-compost treatments, substantially enhance plant growth and biomass accumulation in both polluted and unpolluted soils. While the absolute metal uptake quantified in this eight-week study was modest, the consistent accumulation of lead in plant tissues combined with elevated secondary metabolite production provides evidence of active stress response and contaminant processing. Future research should evaluate extended cultivation periods to assess cumulative metal removal, investigate the efficacy of multiple crop cycles, determine optimal amendment ratios for specific soil types, and characterize the long-term sustainability of this approach in field conditions. The integration of *Leucaena leucocephala* cultivation with biochar and compost amendments represents a promising strategy for addressing environmental contamination while simultaneously improving soil health and productivity in developing regions facing both environmental degradation and agricultural productivity challenges.

### Data Availability Statement

Raw data supporting this study are available from the corresponding author upon request.

### Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Author Contributions

S.A.A. designed the experiment and O.S.O. conducted the experiment, collected and analyzed data, and drafted the manuscript. S.A.A. provided supervision, guidance, and manuscript revision.

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