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Impact of Spatial Contamination Levels of Heavy Metals on Cowpea and Soybean Growth, Yield and Nodulation

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Abstract

Agricultural soil contamination poses a global threat to crop productivity and food safety. Agricultural expansion led farmers to cultivate cowpea (*Vigna unguiculata*) and soybean (*Glycine max*) on land near a wet battery waste disposal site. This study evaluates the effect of battery waste deposits at varying distances on biomass, grain yields, and nodulation of these crops, as well as the impact on microbial populations. Twenty (20) soil sampling points were randomly selected across four sites: a non-contaminated control site, the main battery dumpsite (MDS), and areas located 20 meters and 40 meters away from the MDS, with five sampling points per site. Using a 2 × 4 factorial Complete Randomized Design, the crops were grown with recommended best practices and inoculated with effective USDA 110 *Bradyrhizobium* strains. Results from analyses indicated that contamination significantly reduced plant height, leaf number, pod number, dry root and shoot weights, grain yield, and microbial population. Soil analysis revealed high concentrations of Lead (Pb), Chromium (Cr), Arsenic (As), and Cobalt (Co) at the contamination sites. Specifically, Pb levels were 1772.4, 563.1, and 157.6 times higher in the MDS, 20 MDS, and 40 MDS sites, respectively, compared to the control soil, which had a concentration of 20.10 mg kg^{-1}. The bacterial population decreased by approximately 83% in the MDS area relative to the control. Findings from this study indicate that wet battery waste deposition significantly increases soil contamination with heavy metals, adversely affecting legume yield, growth, and microbial populations, rendering the area unsuitable for cultivation.

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Introduction

Industrial waste disposal over the past decades has exacerbated soil pollution, with heavy metals posing significant environmental hazards. These contaminants disrupt soil productivity and adversely affect crop performance (Alengebawy *et al.*, 2021). Industrial discharge and improper application of agrochemicals are major contributors to soil pollution, resulting in heavy metal persistence due to their resistance to bio-thermal degradation (Hananingtyas *et al.*, 2022). In agricultural soils, heavy metals impair crop growth, photosynthesis, nutrient uptake, and nitrogen fixation, culminating in stunted growth, chlorosis, and reduced yields (Haddad *et al.*, 2015). Notably, these effects are prevalent in staple crops like soybean and cowpea, which are essential for food security and soil nitrogen enrichment (Huynh *et al*., 2016).

Soybean (*Glycine max*) and cowpea (*Vigna unguiculata* L.) are among the most valuable leguminous crops, providing high-quality food and feed for significant portions of human and animal populations worldwide (Valliyodan *et al.*, 2017). USDA (2022) put the global production of soybeans at 355.60 million tons and projected a 10% increase in 2023. In Africa, Nigeria is only 2nd to South Africa in terms of production (USDA, 2023). According to FAO STAT (2016) cowpea's global annual production was 6.5 million. tons, covering 14.5 million. ha, leading to 6,991,174 tons of dry grain yield. Nigeria is the largest cowpea producer in Africa, recording about 2.8 million. Tons per year (Rugare *et al.,* 2013). Both crops supplement nitrogen to the soil and serve as a green cover against erosion and water depletion (Acharya, 2019).

Several strategies have been explored to mitigate heavy metal toxicity in agricultural soils. Crop tolerance mechanisms, though often at the expense of productivity, have been observed (Kaur *et al.*, 2013). Advances in agronomic practices and bioremediation, such as the use of metal-resistant microbial inoculants, offer potential for minimizing metal toxicity (Shahid *et al*., 2017). However, most studies focus on artificially contaminated soils, leaving gaps in understanding the field-level impacts of industrial waste contamination, particularly in tropical agricultural systems (Haddad *et al.*, 2015).

This study investigates the effects of heavy metals from battery waste disposal on cowpea and soybean cultivated on reclaimed agricultural lands by analyzing contamination at varying distances from the dumpsite. It evaluates impacts on crop growth, nodulation, and microbial populations.

Materials and Methods

Soil Sampling Location and Experimental procedure

The experiment was executed in the Screenhouse of the Department of Agriculture and Industrial Technology, Babcock University in Ilisan-Remo, Ogun State, located in the rainforest agroecology of Nigeria, during the early rainy season (March to May) of 2023. Soil samples were collected at a depth of 0-15 cm from four locations: a non-contaminated control site, the main contaminated dumpsite, and sites located 20 meters and 40 meters away from the dumpsite of the defunct battery manufacturing company with screw auger. The sampling points were respectively located at the following coordinates: 7.7644° N, 4.1256° E; 7.7703° N, 4.1114° E; 7.7697° N, 4.1103° E; and 7.7692° N, 4.1094° E. Each experimental unit was replicated three times, resulting in a total of 24 experimental plots.

Heavy metals, such as Lead (Pb), Arsenic (As), Chromium (Cr) and Cobalt (Co), were analyzed on both contaminated and non-contaminated soils prior to the establishment of the experiment. Urea (20 kg ha^{-1}), single super phosphate (40 kg ha^{-1}) and muriate of potash (30 kg ha^{-1}) were applied. Five (5) kg of soil samples were filled into 7-liter capacity (25 × 20 × 14 cm) plastic pots perforated at their base for easy drainage. Initial water application was done a week before planting, and the b*radyrhizobium* strain of USDA 110 (that is characteristically infective and effective as well as compatible with cowpea and soybean) obtained from the International Institute of Tropical Agriculture was introduced into the soil using peat as its carrier a week after planting and spread around the rhizosphere of the seedlings (da Silva Júnior *et al.*, 2018). Both the cowpea and soybean seeds were obtained from the Institute of Agricultural Research and Training and sown at 3.0cm soil depth. After germination (4-5 days), waterings were adequately carried out until the field capacity moisture status.

Laboratory Analyses

To estimate the quantity of the heavy metals, the prepared samples of the soil were further ground with the aid of stainless steel, and 1 g was weighed into a digestion flask and digested using HF: $HClO_4$:HNO_3 chemical and heated on the hotplate for 180 minutes at 150–200°C as recommended by Nwajei and Gagophien (2000). Then, the digested mixture was filtered and distilled water was added to make it up to 100ml. Finally, the flame atomic absorption spectrophotometry AA240FS model was used to read the concentration accordingly. Soil particle sizes were determined using the hydrometer method (Agbenin, 1995), organic carbon by the potassium dichromate method (Walkley and Black, 1934), pH in $CaCl_2$ solution of 1:2.5 by the use of pH meter, available phosphorus using Bray 1 extraction solution (Bray and Kurtz, 1945), exchangeable bases and exchangeable acidity as described by Okalebo *et al.* (2002), and microbial population by plate count method (Holt *et al.,* 1994).

Data Collection and Statistical Analysis

Data collected from the experiment included plant height by using a measuring tape and the number of leaves by manual counting from 2 to 12 weeks after planting. Also, the number of pods and the number of nodules were manually counted at weeks 10 and 12. Microbial population count was measured at 12 weeks after planting. Data obtained were processed using analysis of variance and post-hoc tests was conducted where applicable using the Duncan Multiple Range Test (DMRT) at 95% confidence level by the RStudio package 4.3.2, 2023 version.

Results and Discussion

Soil Physical and Chemical Properties of Experimental Sites

Table 1 illustrates the physical and chemical properties of the four treatment soils, highlighting significant variations in heavy metal concentrations and nutrient levels. The Main Dump Site (MDS) exhibited the highest lead (Pb) concentration at 1772.4 times the control value of 20.10 mg kg^1. Similarly, soils sampled 20 m (20 MDS) and 40 m (40 MDS) away contained Pb concentrations 521 and 146 times higher than the control, respectively, reflecting an exponential decline with distance from the MDS. Chromium (Cr) concentrations displayed a decreasing trend, with levels in the MDS soil being 185.7%, 48.1%, and 39.8% higher than the control, 20 MDS, and 40 MDS, respectively. Arsenic (As) and cobalt (Co) followed similar patterns, indicating the spatial impact of contamination. However, copper (Cu) was 3.3% higher in the control compared to 20 MDS, deviating from the general trend. Among nutrients, sodium (Na) was significantly elevated in the MDS, 97.9% higher than the control, but dropped sharply in 20 MDS, reducing by 90.98%. Magnesium (Mg) remained moderately rated across all sites. Interestingly, nitrogen (N) levels were 89.7% lower in the MDS compared to the control, suggesting a negative impact on organic matter turnover. These findings emphasize the severe environmental effects of proximity to the MDS on soil health and agricultural productivity. The pH of the soils was predominantly moderately acidic, except for the MDS, which approached neutrality. This finding suggests the influence of specific environmental and anthropogenic factors on soil properties, contrasting with the results of Adegoke (2009) and Rahman *et al.* (2012), who observed significant shifts in soil pH under similar conditions. These differences may be due to the unique characteristics of the study site or varying industrial activities, highlighting soil pH as a sensitive indicator of ecological disruptions. Consistent with Jolly *et al.* (2012), untreated or partially treated industrial discharges were found to elevate heavy metal concentrations, exacerbating soil pollution and impairing soil functionality. Similarly, Fagbenro *et al.* (2021) documented moderate to high contamination loads in

Nigerian gold mining sites, reinforcing the persistent threat of industrial and mining activities on soil chemical properties, including pH. The neutral pH trend of MDS soils could be linked to inherent buffering capacity or ameliorative influences such as organic inputs or vegetation. Investigating these soils' mineralogical and microbial properties is vital for understanding resilience mechanisms and promoting sustainable soil management practices.

Table 1. Physical and Chemical Properties of the Soil Across the Contamination Treatment

Parameters	Control	20 m MDS	40 m MDS	MDS	SE
pH (H_2O)	5.34 c	6.00 b	5.99 b	6.58 a	0.326
Organic carbon %	1.155 b	2.112 a	2.310 a	0.660 c	0.289
Total nitrogen %	0.127 b	0.232 a	0.254 a	0.013 c	0.082
Av. P. (mg kg^{-1})	12.8 a	10.6 b	10.1 b	11.0 b	1.26
Exch. A. (Cmol kg^{-1})	0.41 a	0.30 b	0.30 b	0.35 ab	0.036
Ca (Cmol kg^{-1})	3.14 c	6.99 a	6.43 a	4.46 b	1.211
Mg (Cmol kg^{-1})	0.99 a	0.91 a	0.96 a	0.76 b	0.072
K (Cmol kg^{-1})	0.08 c	0.21 b	0.18 b	0.65 a	0.048
Na (Cmol kg^{-1})	0.43 b	1.84 b	0.76 b	20.41 a	0.388
Mn (mg/kg)	85.0 c	89.0 c	101.0 b	123.0 a	5.221
Fe (mg kg^{-1})	121.0 c	141.0 a	156.0 a	148.0 a	7.345
Cu (mg kg^{-1})	1.23 b	1.19 b	1.31 b	6.0 a	0.999
Zn (mg kg^{-1})	1.56 b	1.74 b	1.80 b	3.25 a	0.766
Sand %	81.0 a	82.0 a	79.0 a	3.55 b	2.000
Silt %	12.0 b	13.0 b	14.0 b	22.00 a	3.552
Clay %	7.0 b	5.0 b	7.0 b	31.00 a	2.844
Pb (mg kg^{-1})	20.10	11315.5	3167.95	35645.75	12.33
Cr (mg kg^{-1})	10.85 c	16.10 b	18.65 b	31.00 a	2.56
Co (mg kg^{-1})	3.70 c	16.45 a	11.20 b	5.25 bc	1.466
As (mg kg^{-1})	1.25 c	2.80 bc	5.10 ab	8.75 a	1.18

Means with same letter (s) in a column are not significantly different at 5 % level of probability by Duncan Multiple Range Test (DMRT), ns; not significant, 20 MDS = 20 meters away from the dump site, 40 MDS = 40 meters away from the dump site. S.E= Standard Error.

Effects of Soil Contamination and Legume Type on Plant Height and Number of Leaves

Table 2 presents a significant reduction in plant height over time, particularly in the MDS and 20 MDS treatments. In the MDS treatment, the plant height declined progressively by 39.4%, 60.7%, 62.4%, 56.5%, 47.9%, and 53.4% at weeks 2, 4, 6, 8, 10, and 12, respectively, when compared to the control. This substantial decrease in height reflects the detrimental impact of the battery residue contamination, likely due to the heavy metal accumulation and its toxic effects on plant growth. Conversely, the test crops in the 40 MDS treatment exhibited a 2.4% increase in plant height compared to the control, indicating a potential buffering effect or some resilience in plant growth despite the presence of contamination. Table 3 demonstrates that the 20 MDS (management disturbance sites) significantly hindered the leaf development of the test crops compared to both the 40 MDS and the control treatments. Specifically, at 4, 6, and 10 weeks after planting, the crops in the 20 MDS exhibited reduced leaf numbers, highlighting the detrimental effect of this particular disturbance on plant growth. At week 4, the number of leaves in the 20 MDS treatment was noticeably lower than in both the 40 MDS and control groups, with similar trends observed at weeks 6 and 10. The contrast between the MDS and 40 MDS treatments in this study, highlights the spatial variation in contamination effects on leguminous crops. The reduction in growth observed in the 20 MDS and MDS treatments aligns with previous studies on heavy metal toxicity, which have shown that high concentrations of contaminants can impair plant development by disrupting nutrient uptake, photosynthetic processes, and cellular structures (Ashraf *et al*., 2019). Heavy metal accumulation in soil systems significantly impacted plant growth and physiological processes, which led to diminished agricultural productivity. As reported by Vineeth *et al*. (2014) and Arif *et al.* (2016), the presence of toxic heavy metals such as Pb and Cd impeded critical plant development stages, including leaf budding and vertical growth. These disruptions result in stunted growth and reduced vigor, as further corroborated by Mehboob *et al*. (2018).

The number of leaves in the 20 MDS treatment which was noticeably lower compared to both the 40 MDS and control groups at week 4 with similar trends observed at weeks 6 and 10 suggests that the 20 MDS may have imposed greater stress on the crops. This could be potentially due to higher levels of soil contamination, which hindered the normal growth processes of the plants. In contrast, the 40 MDS and control treatments exhibited more favorable conditions, supporting better leaf production, likely due to less severe environmental impacts at these sites. These findings underscore the importance of assessing spatial variations in management disturbance to understand their influence on crop performance, particularly in environments exposed to anthropogenic stresses. High concentrations of Pb adversely affect plants by impairing physiological and biochemical pathways, as highlighted by Gomes (2011). This is particularly evident in the reduction of chlorophyll content, which diminishes proportionally with increasing Pb levels, as demonstrated by Ali *et al*. (2014). Chlorophyll depletion directly affects photosynthesis, leading to compromised plant energy production and growth potential. Furthermore, Rasool *et al.* (2020) reveal that plants exposed to elevated Pb and Cd levels exhibit significant reductions in stomatal conductivity, chlorophyll concentration, and photosynthetic activity rates. The accumulation of Cd at 20 mg L^{-1} reduced soluble protein content by 52% and 70% after 24 and 30 days, respectively. These findings emphasize the urgent need for strategies to mitigate heavy metal contamination in soils to preserve crop health and productivity.

Table 2. Effects of Soil Contamination Level and Legume Type on Plant Height

Treatments	2 WAP	4 WAP	6 WAP	8 WAP	10 WAP	12 WAP
Legume Type	**(cm)**					
Cowpea	27.4 a	36.4 b	39.6 b	42.1 b	48.5 b	58.0 b
Soybean	23.5 b	49.5 a	74.1 a	98.0 a	112.4 a	145.7 a
SE	1.55	2.64	3.88	5.22	5.49	3.77
Contamination						
Control	23.6 b	45.5 a	57.5 b	68.2 b	79.4 ab	108.1 a

MDS	14.3 c	17.9 c	21.6 c	29.7 c	41.3 c	50.0 c
20 MDS	22.7 b	35.1 b	440 c	56.7 c	73.7 b	86.7 b
40 MDS	30.0 a	48.4 a	69.0 a	85.3 a	88.2 a	110.7 a
SE	1.83	2.00	4.22	5.86	4.91	9.33
Interaction						
L x **C**	N.S	N.S	*	*	N.S	N.S

Means with different letter (s) in a column for a treatment are significantly different at 95 % confidence level by the Duncan Multiple Range Test (DMRT). N.S = not significant, 20 MDS = 20 meters away from the main dump site, 40 MDS = 40 meter away from the main dump site, L = legume type and CL = contamination, WAP = weeks after planting.

Table 3. Effects of Soil Contamination Level and Legume Type on the Number of Leaves plant^{-1}

Treatments	2 WAP	4 WAP	6 WAP	8 WAP	10 WAP	12 WAP
Legume Type						
Cowpea	5.0 a	8.1b	10.7 b	12.1 b	14.4 b	14.0 b
Soybean	4.0 b	10.8 a	12.9 a	17.4 a	26.4 a	28.8 a
SE	0.22	0.56	0.33	1.35	2.33	2.00
Contamination						
Control	4.5 n.s	10.2 ab	13.0 a	15.2 a	20.8 ab	20.2 a
MSD	3.5 n.s	5.0 c	7.5 c	10.0 c	13.0 c	13.5 b
20 MDS	4.5 n.s	7.7 bc	9.0 ab	13.2 bc	17.0 b	23.2 a
40 MDS	4.5 n.s	10.5 a	13.3 a	16.0 a	23.5 a	24.8 a
SE	0.97	2.12	2.35	1.99	2.0	2.66
Interaction						
L*C	N.S	*	*	N.S	*	N.S

Means with different letter (s) in a column for a treatment are significantly different at 95 % confidence level by Duncan Multiple Range Test (DMRT), N.S: Not significant, 20 MDS = 20 meters away from the dump site, 40 MDS = 40 meters away from the dump site, L = legume type and CL = contamination level, WAP = weeks after planting.

Effects of Soil Contamination and Legume Type on the Numbers of Pods, and Nodules and Dry Shoot and Root Weights

The data presented in Table 4 highlight that the 20 MDS (metallic disposal sites) did not significantly enhance pod growth in either cowpea or soybean, particularly in the case of cowpea at weeks 10 and 12. Additionally, the number of nodules at these time points and the dry root weight at 2 WAP were also not favorably impacted by the 20 MDS treatment. These findings suggest that while both crops were adversely affected, soybean exhibited greater sensitivity to soil contamination across several growth parameters. Notably, there were no significant differences observed in dry root weight between cowpea and soybean at 12 WAP, indicating a comparable response to the contamination at later growth stages. In Table 5, the effects of 20 MDS contamination on cowpea were more pronounced, with significant reductions in plant height at week 6 and pod number at week 10. In contrast, cowpea grown in uncontaminated (control) soil demonstrated significantly higher pod numbers at weeks 10 and 12, as well as increased dry shoot and root weights at week 12, underscoring the detrimental impact of metal contamination on leguminous crop growth. Figure 1 further elucidates the interactive effects between legume type and contamination on final grain yield. Cowpea grown in control soil versus 40 MDS produced the highest grain yield, whereas the lowest yields (0 g/plant) were recorded under MDS contamination. In contrast, soybeans only produced grain under control soil conditions, illustrating their heightened sensitivity to heavy metals.

Figure 2 corroborates this trend, showing that the combined effect of soybean and contamination closely mirrored that of cowpea, where both crops exhibited significantly higher biomass yield when grown in control soil, further supporting the hypothesis that soil contamination severely impairs crop growth and yield. These results collectively emphasize the vulnerability of leguminous crops, particularly soybean, to heavy metal contamination and underscore the need for careful management of contaminated soils to ensure the sustainability of legume-based agriculture. The results observed in this study aligned with Sheirdil *et al.* (2012), who reported that the application of 16 mg kg^{-1} of Cd negatively affected soybean shoot length, root development, and nodulation, which resulted in a 50% maximum decline in % N fixation. Other researchers noted that nodule reduction in legumes could be due to inhibition of nitrogenase activity and photosynthesis by accumulated heavy metals in polluted soil (Manier *et al*., 2009). Other works have also reported a reduction in root and shoot dry weight, as well as pod number from heavy metal contamination in the soil (Basha and Selvaraju, 2015; Kumar *et al.*, 2016). Also, Zhao *et al.* (2021) revealed that the high Cd level facilitated a decrease in the net growth of plants and their aboveground biomass. Progressive declines of about 27.57 % and 28.95% were also observed in root biomass when exposed to 50 mg kg^{-1} and 100 mg kg^{-1} Cd concentrations, respectively. Collin *et al.* (2022) reported a 42% decrease in the growth of plant roots when exposed to high concentrations of Pb. Moreso, according to Abdul-Aziz et al. (2022), toxic concentrations of as in the legumes biomass and grains were noted to be above the 0015 mg kg^{-1} FAO/WHO guideline limit. Heavy metal's deleterious effect on crops' yield and biomass is not limited to legumes since previous investigations have reported a reduction in rice yield catalyzed by Pb Cd and Cr accumulations (Xie *et al*., 2018).

Table 4. Effects of Soil Contamination Level and Legume Type on the Number of Pod Plant^{-1}, Number of Nodules plant^{-1}, Dry Shoot and Root Weight (g)

Treatments	PDN WK 10	PDN WK 12	NN WK 10	NN WK12	DSWT WK 12	DRWT WK 12
Legume Type						
Cowpea	3.4 a	3.8 a	3.6 a	5.6 a	3.4 b	2.5
Soybean	0.0 b	0.0 b	0.0 b	0.0 b	5.6 a	2.8 n.s
SE	0.882	0.459	0.351	0.351	0.399	0.251
Contamination						
Control	2.3 a	3.0 a	1.9 b	4.7 a	6.1 a	5.2 a

MDS	0.00	0.00	0.5 c	0.8 c	1.5 c	0.5 c
20 MDS	0.3 b	0.3 b	1.2 b	2.5 a	6.0 a	1.6 b
40 MDS	2.5 a	0.8 b	2.5 a	2,5 b	4.00	1.5 b
SE	0.0002	0.001	0.002	0.001	0.003	0.001
C*S	*	*	*	*	*	*

Means with different letter (s) in a column for a treatment are significantly different at 95 % confidence level by Duncan Multiple Range Test (DMRT), ns = Not significant; PDN =number of pod, NN = Nodule number, DSWT =Dry shoot weight, DRWT = Dry root weight, MDS = main dumpsite, 20 MDS = 20 meters away from the MDS, 40 MDS = 40 meters away from the MDS.

Table 5. Interaction between Contamination and Legume type on Plant Height (cm), Number of Pods /Plant, Dry Shoot and Root Weight (g plant^{-1})

LT	**CL**	**PLH 6 WAP**	**8 WAP**	**NPD WK 10**	**WK 12**	**DSWT WK 12**	**DRWT WK 12**
Cowpea	Control	41.3 a	44.9 a	4.7 a	6.0 a	460 a	362 a
	20 MDS	33.4 b	36.7 b	1.7 b	2.7 b	371 b	229 b
	40 MDS	44.2 a	44.8 a	5.0 a	5.7 a	360 c	198 b
	MDS	20.5 d	23.9 c	1.1 c	1.6 c	200 d	109 c
Soybean	Control	73.7 b	91.5 b	0.0 n.s	0.0 n.s	463 ab	289 a
	20 MDS	54.7 c	76.7 c	0.0 n.s	0.0 n.s	391 a	197 b
	40 MDS	93.8 a	125.9 a	0.0 n.s	0.0 n.s	388 b	276 a
	MDS	43.4 d	48.3 d	0.0 n.s	0.0 n.s	311 c	108 c

Means with different letter (s) in a column for a treatment are significantly different at 95 % confidence level by Duncan Multiple Range Test (DMRT), ns: Not significant; NPD = number of pods, DSWT =Dry shoot weight, DRWT = Dry root weight, MDS = main dumpsite, 20 MDS = 20 meter away from the MDS, 40 MDS = 40 meter away from the MDS.

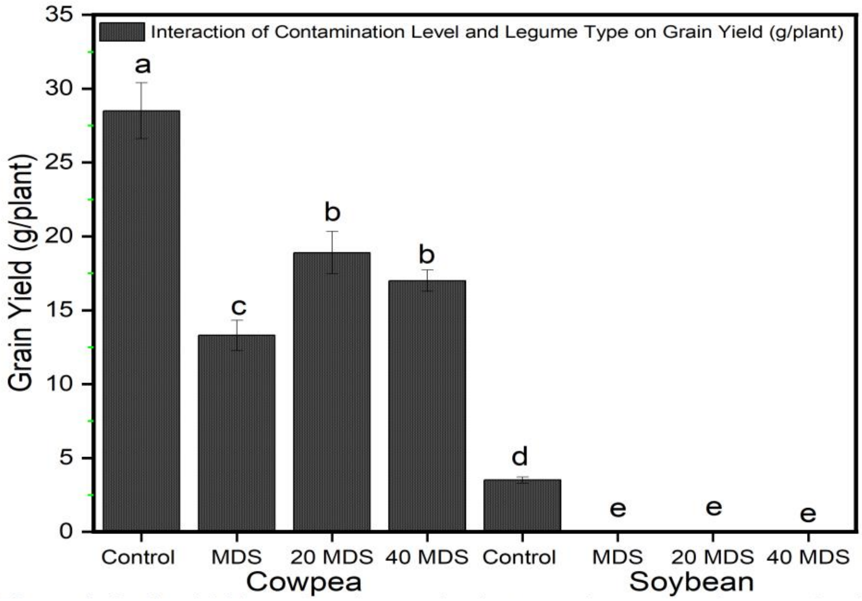

Figure 1. Interaction of Contamination and Legume Type on the Grain Yield (g plant^{-1})

MDS = Main dumpsite, 20 and 40 = 20 and 40 meters away, respectively

Means with different letter (s) across treatment for the crop are significantly different at 95 % confidence level by Duncan Multiple Range Test (DMRT), MDS = main dumpsite, 20 MDS = 20 meters away from the MDS, 40 MDS = 40 meters away from the MDS.

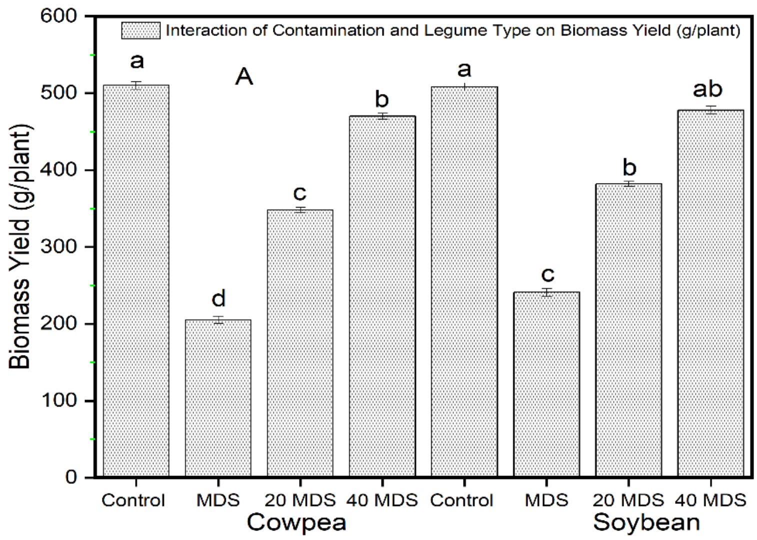

Figure 2. Interaction of Contamination and Legume Type on the Biomass Yield (g plant^{-1})

MDS = Main dumpsite, 20 and 40 = 20 and 40 meters away, respectively

Means with different letter (s) across treatment for test crop are significantly different at 95 % confidence level by Duncan Multiple Range Test (DMRT), MDS = main dumpsite 20 MDS = 20 meters away from the MDS, 40 MDS = 40 meters away from the MDS.

Effects of Soil Contamination and Legume Type on Above-ground Biomass

The grain yield results, presented in Figure 3a, indicate that cowpea achieved the highest yield among the legume types evaluated, however, the spatial contamination analysis, as shown in Figure 3b, revealed a significant decline in grain yield at 20 meters from the MDS, with a reduction of approximately 50% compared to the control. Interestingly, the grain yield at both 20 and 40 meters from the contamination source did not differ statistically, suggesting a plateau effect in the spatial distribution of contamination impact on crop performance.

When examining biomass yield (Figure 4a), soybean demonstrated superior biomass production over cowpea, emphasizing its greater overall growth potential under the given conditions. Further biomass yield analysis based on spatial contamination level in Figure 4b, indicated a widening disparity between the control and MDS, where the above-ground biomass in MDS was notably lower. At the same time, 20 meters from the contamination site outperformed 40 meters by about 22%, highlighting the potential for localized differences in contamination severity. These findings underline the significant impact of spatial contamination on both grain and biomass yields, emphasizing the need for strategic soil management and remediation in areas exposed to industrial waste. Based on the findings of this study, it was observed that there was a significantly higher concentration of Pb and other heavy metals in MDS which might have played a key role in reducing both the grain and the biomass yields. However, Nkansah *et al.* (2021), reported a lower level of Fe and Zn, Cr and Ni in processed cassava due to contamination. Ahmad *et al.* (2012) as well as Keshavarzi and Kumar (2020) discussed that the heavy metals have reached toxicity levels in the soil, thus stagnated growth.

Effect of Contamination Level on Microbial Population

Table 6 shows that the MDS and 20 MDS had 88.9 and 80.7% less bacterial population in dilutions 6, respectively, compared with the control. Also, significantly highest population of fungi was found in 20 MDS, while MDS showed a contrary result. However, the rhizosphere of soybean was observed to have a significantly lower fungi population compared to that of the cowpea in dilutions 6 and 7. Figure 5 contains the interaction, in which cowpea under MDS and 20 MDS exhibited significantly reduced bacterial population. A similar observation was noted for cowpea-MDS interaction regarding fungi population in dilutions 6 and 7. Interaction between soybean and MDS and 20 MDS was significantly low in the fungi population. On the other hand, the result of the Interaction of contamination level and legume type on the microbial population as provided in figure 5 (supplementary material) recorded that the interaction between soybean and MDS significantly reduced the fungi population. The reduction in microbial population found in the rhizosphere of the two test crops when they interacted with the various contaminated sites is in agreement with the findings of Rengel *et al.* (2015), who reported the negative impact of heavy metal toxicity to beneficial soil microbiota, as well as depression of their functions. Abdu *et al.* (2016) also reported that heavy metal causes a decrease in the nutrient status, microbial functionality, and uniformity of the soil. Additionally, Pan Jing and Long (2011). revealed that changes in certain enzymatic functions due to Pb and Cd interference bring about declination and changes in soil microbial communities.

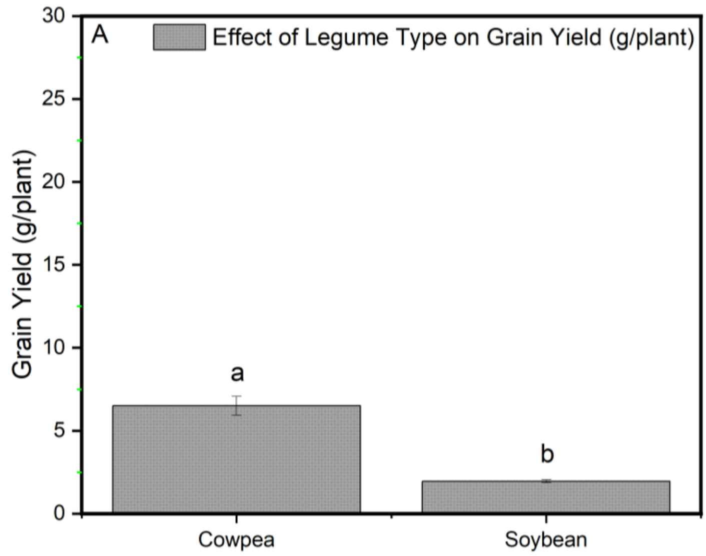

Figure 3a. Grain yield based on legume type

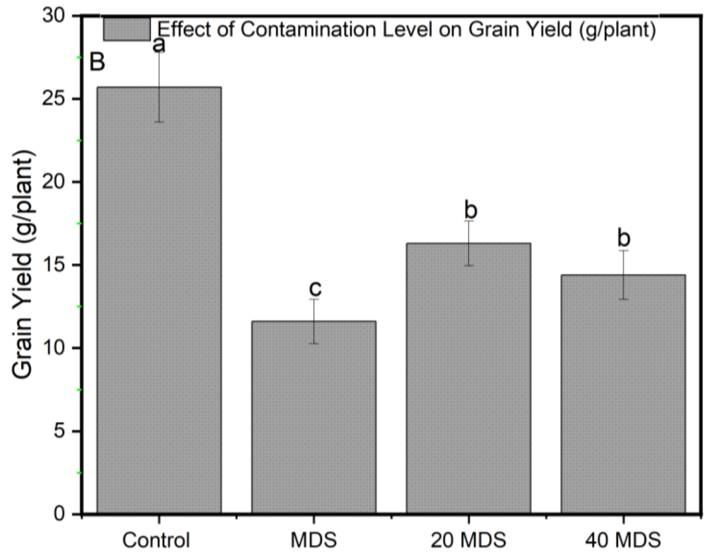

Figure 3b. Grain yield based on Spatial Contamination Level

MDS = Main dumpsite, 20 and 40 = 20 and 40 meters away, respectively

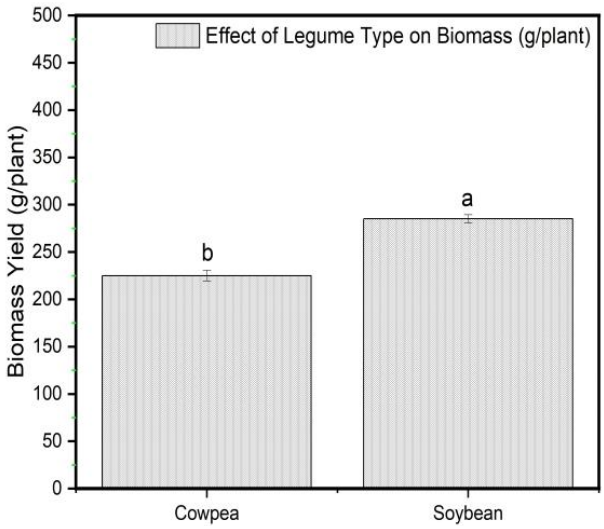

Figure 4a. Biomass yield based on legume type

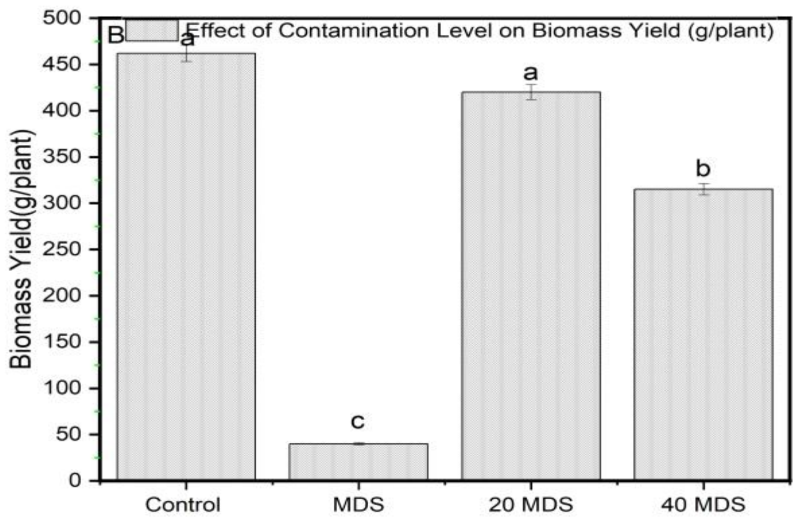

Figure 4b. Biomass yield based on Spatial Contamination level

MDS = Main dumpsite, 20 and 40 = 20 and 40 meters away, respectively

Table 6. Effect of Contamination on Microbial Population in (CFU g^{-1} of soil)

Legume Type	**Bacteria 10^6**	**Bacteria 10^7**	**Fungi 10^6**	**Fungi 10^7**
Cowpea	15.8	7.4	55.5 a	33.3 a
Soybean	16.2 n.s	6.4 n.s	28.4b	27.0 b
SE	2.11	1.98	4.77	2.00
Contamination				
Control	38.0 a	9.7 a	22.5 c	12.0 c
MDS	4.2 c	3.8 b	28.8 c	29.7 b
20 MDS	5.2 c	3.7 b	65.2 a	40.2 a
40 MDS	16.7 b	10.5 a	51.3 b	38.7 a
SE	1.33	1.21	2,33	4.52
C*S	N.S	*	*	*

Means with different letter (s) in a column for a treatment are significantly different at 95 % confidence level by Duncan Multiple Range Test (DMRT), N.S: not significant, 20 MDS = 20 meters away from the dump site, 40 MDS = 40 meters away from dump site.

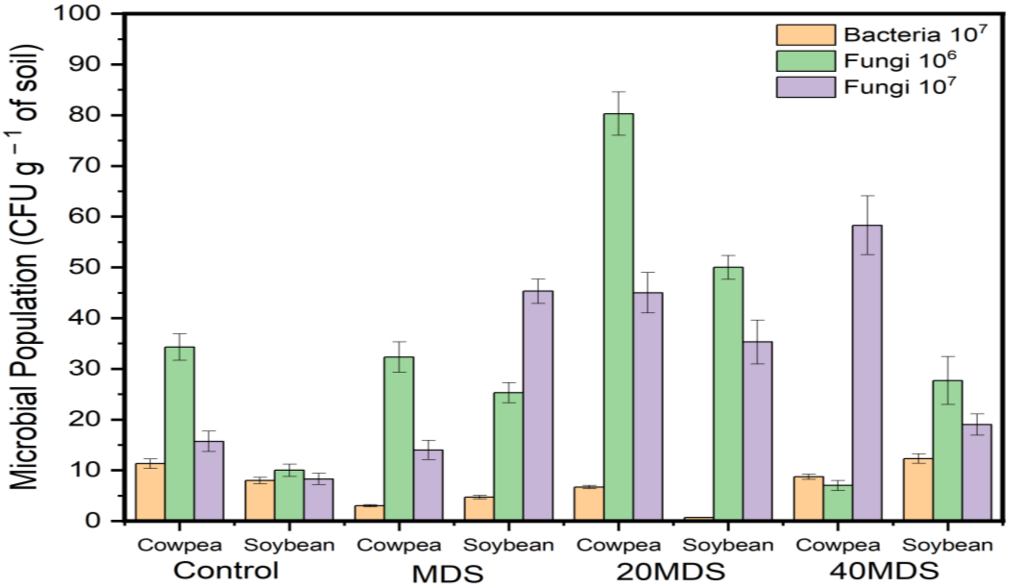

Figure 5. Interaction of Contamination Level and Legume Type on the Microbial Population (CFU g^{-1} of soil)

Conclusions

This study demonstrates that wet battery waste disposal markedly elevates heavy metal concentrations-particularly lead, chromium, arsenic, and cobalt-in agricultural soils, leading to significant reductions in cowpea and soybean growth, nodulation, yield, and microbial populations. Spatial analysis revealed a gradient of contamination impact, with the main dumpsite exhibiting the most severe effects. The findings highlight the unsuitability of such contaminated lands for legume cultivation and emphasize the urgent need for remediation and stricter environmental controls to safeguard food safety and soil health.

Conflict of Interest

Authors declare that there are no conflicts of interest with respect to this manuscript.

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