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Phytoremediation of Cd, Pb, and Ni-co-contaminated soil of the Niger Delta by using Local Maize (*Zea mays*) plant

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ABSTRACT

Phytoremediation is an innovative, cost-effective technology that uses plants to extract metals from polluted soils. Experiments were conducted using *Zea mays* plants grown in soils contaminated with varying levels of Cd, Pb, and Ni. The results indicated that rising soil heavy metal concentrations decreased plant height, weight, and chlorophyll content. Plants grown in soil with the highest levels of Cd, Pb, and Ni (20, 120, and 60 mg/kg) showed the highest amounts of Cd (11.71 mg/kg Dwt in roots and 2.55 mg/kg Dwt in shoots), Pb (29.60 mg/kg Dwt in roots and 9.10 mg/kg Dwt in shoots), and Ni (38.70 mg/kg Dwt in roots and 10.90 mg/kg Dwt in shoots). As the soil's metal levels rose, the bioconcentration factor (BCF) and translocation factor (TF) values declined. In 80% of cases, Ni had BCF values over 1, while Cd exceeded 1 in only 20%, and Pb had none. All metals had TF values below 1. Our findings indicate that *Z. mays* primarily employs phytostabilization to remediate these elements, supported by high BCF values, particularly for Ni, and low TF values across all examined treatments, suggesting minimal metal translocation from roots to shoots.

Keywords: Bioconcentration factor, Translocation factor, phytostabilization, metals, physicochemical properties

Introduction

The rapid growth of the global population, urbanization, and industrialization have led to the contamination of millions of hectares of land with heavy metals, affecting over 50% of contaminated sites worldwide (Behnisch et al., 2022; Elehinafe et al., 2022; Gill et al., 2023). These metals can be from natural sources or anthropogenic activities like emissions from waste incinerators, residues from mining and military activities, the smelting industry, use of chemical fertilizers and pesticides, burning fossil fuels, and municipal trash (Andresen & Küpper, 2013; Zulfiqar et al., 2022). Heavy metals in soils at high concentrations negatively affect crop health and productivity, disrupt cellular structures, and cause oxidative stress (Rashid et al., 2023). They may also make their way into the food chain, putting people at risk of developing cancer (Gill et al., 2023). According to national and international organisations, certain metal concentrations in soil and plants have surpassed allowable limits, endangering both human health and the environment (Alengebawy et al., 2021; Behnisch et al., 2022). Several heavy metal pollutants are frequently found in soil, including Cd, Pb, and Ni. These metals, like others, are difficult to break down into innocuous byproducts like carbon dioxide, therefore they must usually be removed from contaminated soils (Wuana & Okieimen, 2011).

There are multiple approaches to addressing soils contaminated with heavy metals. Although there are traditional methods like excavation, burning, and chemical washing, they can be quite costly, require a lot of manual labour, and may release harmful secondary pollutants that can negatively impact biological processes and the environment (Ding et al., 2023). Due to the current circumstances, there is a growing need for a solution that is both affordable and eco-friendly. Phytoremediation is an effective and eco-friendly strategy that utilises plants to reduce metal toxicity. It involves the transportation of ions to shoots and their elimination from roots, resulting in a cost-effective solution. Phytoremediation involves the utilisation of plants to absorb, sequester, and detoxify contaminants, with a specific focus on heavy metals (Ashraf et al., 2019). Several mechanisms are involved in phytoremediation: phytoextraction, phytostimulation, phytovolatilization, rhizofiltration, and phytostabilization. Whereas phytostimulation seeks to improve plant growth for greater metal absorption, phytoextraction uses plants to gather metals from the soil. Rhizofiltration is the process by which roots remove metals from water; phytovolatilization is the process by which plants release metals into the atmosphere. Finally, phytostabilization aims to immobilise metals in soil or plant roots, thereby limiting their mobility (Ashraf et al., 2019; Kanwar et al., 2020; Zhu et al., 2024). The useful implementation of phytoremediation methods depends on the choice of plant species with suitable characteristics for certain soil contaminants. Sunflower, Indian mustard, water hyacinth, willow, and Indian pennywort are among the more than 400 plant species that have been identified as heavy metal hyperaccumulators; nevertheless, because of the way that heavy metals affect plant cellular processes, most growing plants are not hyperaccumulators for heavy metals (Shrivastava et al., 2019). Since plant capacities to collect heavy metals vary, the choice of plant species for phytoextraction of heavy metals is mostly determined by the biomass and tolerance capacity of the chosen plant (Peng et al., 2021; Zulfiqar et al., 2022).

Maize (*Zea mays*) an indigenous annual plant belonging to the Poaceae grass family, plays a vital role in Nigerian agriculture and culinary practices. Originally from the Americas, Maize thrives in the Niger Delta region, where it can grow to heights exceeding 10 feet under optimal soil conditions. This crop is known for its rapid growth and high biomass production, offering promise in soil remediation by reducing heavy metal concentrations. The plant's photosynthetic efficiency and nutrient profile significantly influence its growth rate and biomass output (Atta et al., 2023). Previous research has indicated Maize's notable resilience to heavy metal exposure (Irfan et al., 2021; Ni et al., 2022; Tariq, 2022). But, while Maize (*Zea mays*) thrives in a variety of soil types, not all soils in the Niger Delta are equally conducive to its growth (Anoliefo et al., 2006; Egobueze et al., 2019). This study is therefore carried out to: (i) evaluate an indigenous Maize variety to see if it is naturally adapted to sandy soil conditions and capable of metal uptake. (ii) determine the ability of local Maize to accumulate Cd, Pb, and Ni without external amendments like fertilizer and (iii) investigate the impact of phytoremediation on some selected soil properties and the effect of Cd, Pb and Ni-co-contaminated soil on the total biomass of Maize.

MATERIALS AND METHODS

Location of Study

The research was conducted at Delta State University (DELSU), located in Abraka, Nigeria, between March and May in the year 2023. Located at latitude 6° 30' 59.99" N and longitude 3° 23' 5.99" W, the campus is roughly 29 metres above sea level. Abraka is located around 49 miles northeast of Warri and experiences a tropical wet and dry climate.

Preparation of Soil and Conducting Experiments in Pots

A soil sample was obtained from DELSU (Campus 3) at a depth of 0-20 cm beside a coal-tarred road adjacent to an agricultural region. The soil was air-dried by exposure to air and subsequently filtered through a stainless-steel screen with a 2 mm mesh size. A pot experiment was conducted in a rain-protected net-house where *Zea mays* plants were cultivated for sixty days, being subjected to natural sunlight. Cadmium acetate, lead sulphate, and nickel sulphate served as the corresponding sources of Cd, Pb, and Ni. Varying quantities of these compounds were mixed in containers along with soil (2kg) and distilled water. Five treatment levels (n = 3) of Cd, Pb, and Ni (P treatments) and control groups (CT) were part of the trial. The P-group included Cd, Pb, Ni, and plants; the control group had unspiked soil with plants. Table 1 offers specifications of the metal addition levels to the soil.

Table 1: Cd, Pb, and Ni concentration per treatment pot (mg/kg)

Metals	CT	P1	P2	P3	P4
Cd	0	5	10	15	20
Pb	0	30	60	90	120
Ni	0	15	30	45	60

The pots were put in a dark room for 14 days, with tap water added to maintain them at 75% field capacity. Three *Zea mays* seedlings were transplanted to each container after ten days of growth in fertilizer-free, unspiked soil. Two or three times a week, the pots were watered and inspected. The experiment ended with an examination of soil parameters including pH, EC, TOC, TN, Av. P., and texture.

Analysis

Physicochemical Properties and Heavy Metals of Soil

The soil sample was tested chemically using approved procedures. Phosphorus and total nitrogen concentrations were assessed using the Bray 1 and Kjeldahl methods, respectively (Bray & Kurtz, 1945; Bremner & Bremner, 1996). The total organic carbon (TOC) concentration of the soil was assessed by the Walkley-Black method (Nelson & Sommers, 1996). The texture of the soil was measured by the hydrometer method (Bouyoucos, 1962). A 1:1 weight-to-volume soil-to-water extract had its pH measured with a pH meter. The metal content of 0.5 g of air-dried, sieved soil sample was determined by utilising the method given by Paunović et al. (2019) using microwave-digested aqua regia (HCl, 36% and HNO_3, 65%). The resulting solution was filtered and diluted before the levels of Cd, Pb, and Ni were determined using atomic absorption spectrophotometry (Perkin Elmer 700, Boston, MA, USA). The test soil has a sandy texture, an average total organic carbon concentration of 0.19 %, and physicochemical parameters of 6.75 pH and 1.40 EC micro/Sm. Besides, the soil contained 6.95, 35.55, and 20.80 mg/kg on average for total Cd, Pb, and Ni. Similar baseline values for metals in soils have been reported in other studies around the Niger Delta (Tubotu & Agbaire, 2022).

Harvesting, Preparing, and Analyzing Plants

The plants were methodically pulled out of the experiment, cleaned, and rinsed with deionized water, and then their roots and shoots were separated. Following note of the plant heights and fresh biomass, the roots and shoots were dried in an oven at 70 °C for 24 hours to calculate the dry biomass. After that, the metal contents in the plant tissues were analysed. For the analysis of metals (Cd, Pb, and Ni) in plant root and shoot, a solution of hydrochloric acid and hydrogen nitrate in a 3:1 volume ratio (HCl/HNO_3, 3:1 v/v) was used to digest 0.5 g of the sifted plant material after it had been powdered. The Cd, Pb, and Ni concentrations in the resulting digests were determined using atomic absorption spectroscopy (AAS) (Alaboudi et al., 2018). The study examined the chlorophyll levels in *Zea mays* by extracting it with acetone and measuring it using spectrophotometry. The quantities of chlorophyll a, chlorophyll b, and total chlorophyll were measured using equations provided by Kumar et al. (2018): total chlorophyll: $20.2(A_{645}) + 8.02(A_{663})$, chlorophyll a: $12.7(A_{663})$ $2.69(A_{645})$ and chlorophyll b: $22.9(A_{645})$ $4.68(A_{663})$.

Factors of Bioconcentration and Translocation

By use of bioconcentration and translocation factors, as described by Takarina and Pin (2017) and Usman et al. (2019), the study examined *Zea mays*' capacity to absorb and disseminate cadmium (Cd), lead (Pb), and nickel (Ni) from the soil using the following equations:

$$\mathrm{BCF} = \frac{C_r}{C_s} \quad \text{(eqn. 1)} \tag{1}$$

$$\mathrm{TF} = \frac{C_{sh}}{C_r} \quad \text{(eqn. 2)} \tag{2}$$

$$\mathrm{BCF} = \frac{C_{sh}}{C_s} \quad \text{(eqn. 3)} \tag{3}$$

where C_s, C_r, and C_{sh} are the metal concentrations (mg/kg) in the soil, root, and shoot, respectively.

Should the bioconcentration factor be less than one (BCF <1), soil heavy metal concentrations exceed plant absorption. Larger absorption by plants or crops is indicated by BCF values larger than one (BCF >1). Trace metals are detected predominantly in the biomass of the roots of plants with a translocation factor (TF) less than 1 but in the shoot biomass of plants with a TF >1.

Statistical Analysis

This paper used Excel 2016 and IBM SPSS Statistics 27 for statistical analysis. The data provided are the mean ± standard deviation of three independent replicates (n = 3). One-way analysis of variance (ANOVA) was used to analyze the data, and Tukey's HSD post-hoc test found significant mean differences. Statistical significance was determined at $p<0.05$. Additionally, the Pearson correlation coefficient (r) was used to assess the relationships between plant characteristics, metal concentrations in roots and shoots, and soil physicochemical factors.

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Table 2: Selected soil physicochemical properties at the end of the experiment

Treatment	pH	EC	TN	SOC	Av. P	Cd	Pb	Ni
CT	6.25 ± 0.04^a	1.41 ± 0.3^e	0.71 ± 0.01^a	0.91 ± 0.01^a	29.74 ± 0.10^a	2.69 ± 0.04^e	18.11 ± 0.00^e	3.60 ± 0.00^e
P1	5.80 ± 0.02^b	2.60 ± 0.11^d	0.58 ± 0.01^b	0.81 ± 0.01^b	26.92 ± 0.39^b	4.00 ± 0.27^d	29.70 ± 1.68^d	8.90 ± 0.09^d
P2	5.00 ± 0.30^c	3.94 ± 0.04^c	0.51 ± 0.01^c	0.48 ± 0.00^c	26.31 ± 0.10^c	7.81 ± 0.10^c	43.57 ± 0.52^c	19.40 ± 0.30^c
P3	4.00 ± 0.09^d	5.16 ± 0.18^b	0.50 ± 0.02^c	0.42 ± 0.01^d	13.63 ± 0.20^d	9.89 ± 0.22^b	58.53 ± 1.02^b	29.88 ± 0.16^b
P4	3.01 ± 0.04^e	6.40 ± 0.12^a	0.46 ± 0.02^d	0.42 ± 0.01^d	12.11 ± 0.10^e	14.88 ± 0.59^b	82.91 ± 1.03^a	39.81 ± 0.83^a

Mean $\pm$ standard deviation; n = 3; statistically significant difference at a level of $P < 0.05$ is evidenced by the mean values that do not share a common letter.

RESULTS

Physicochemical Properties of the Soil Following Corn Harvest

Following the maize harvest, *Table 2* displays the soil's physicochemical parameters. Significant variability in pH was observed across all treatments (p <0.05). The control soil exhibited the highest pH at 6.25, while the soil treated with 20 mg/kg Cd, 120 mg/kg Pb, and 60 mg/kg Ni (P4 soil) showed the lowest pH at 3.01. Control soil had the highest total organic carbon, nitrogen, and phosphorus levels. Higher metal concentrations in treatment soils decreased pH, organic carbon, total nitrogen, and available phosphorus, but enhanced electrical conductivity post-harvest. Among the treatments, P4 soil had the highest electrical conductivity. The control soil had the lowest concentrations of bioavailable Cd, Pb, and Ni.

Concentration of heavy metals in the soil after Maize harvest

Table 2 displays the average concentrations of soil Cd, Pb, and Ni in both the control and P pots after 60 days of planting. Compared to the initial soil samples, the results indicate a decrease in the three metals in the control, P1, P2, P3, and P4. P4 exhibited significantly higher metal concentrations (14.88, 82.91, and 39.81 mg/kg Cd, Pb, and Ni, respectively) compared to the control group, with a p-value of less than 0.05. The soil's metal concentrations increased in proportion to the spike concentrations.

Plant Development and Biomass

As the soil's Cd, Pb, and Ni levels climbed, maize shoot length and total biomass diverged significantly from the control (*Figure 1* and *Figure 2*). In P1, plant height dropped by 8.59%; in P2, by 14.30%; and in P3 and P4, by 25.71%. Regarding biomass, the fresh and dry weights of plants in the Cd, Pb, and Ni co-contaminated growth media (P1 to P4) were substantially lower than the control by 26.32 to 57.71% and 22.48 to 72.14% in the root, respectively, and by 17.10 to 39.74% and 40.90 to 68.27% in the shoot. Growing in the growth media tainted with the largest quantities of Cd, Pb, and Ni (P4), the weights of the plants reduced most dramatically (p <0.001). The results confirm the unfavourable association between higher levels of Cd, Pb, and Ni and plant development markers.

Contents of chlorophyll

The soil's contamination with Cd, Pb, and Ni lowered the quantities of Chl-a and Chl-b; control plants had higher values. Concerning the total chlorophyll (t-Chl) levels of the plants, significant decreases were also observed (*Figure 3*). Plants treated with 20 mg/kg Cd, 120 mg/kg Pb, and 60 mg/kg Ni had the lowest levels of Chl-a, Chl-b, and t-Chl. All the plants proved, on average, to have more Chl b than Chl a. As the chlorophyll a/b value was less than 1.00, Cd, Pb, and Ni stress impaired the plant's photosynthetic resilience. As the amount of metal in the soil grew, all chlorophyll contents fell in a dose-dependent way.

Distribution of Cd, Pb, and Ni in Tissues of Plants

As the metal concentrations in the treated soils increased in relation to the control, so did the metal concentrations in *Zea mays* roots and shoots (*Figure 4*). Plants grown on soil treated with co-contamination of 20 mg/kg Cd, 120 mg/kg Pb, and 60 mg/kg Ni (or P4 treatment) increased their Cd (11.71 and 2.55 mg/kg Dwt), Pb (29.60 and 9.10 mg/kg Dwt), and Ni (38.70 and 10.90 mg/kg Dwt) contents in their roots and shoots, respectively, to the highest significant (p <0.001) levels. The control group of plants exhibited the lowest levels of Cd, Pb, and Ni

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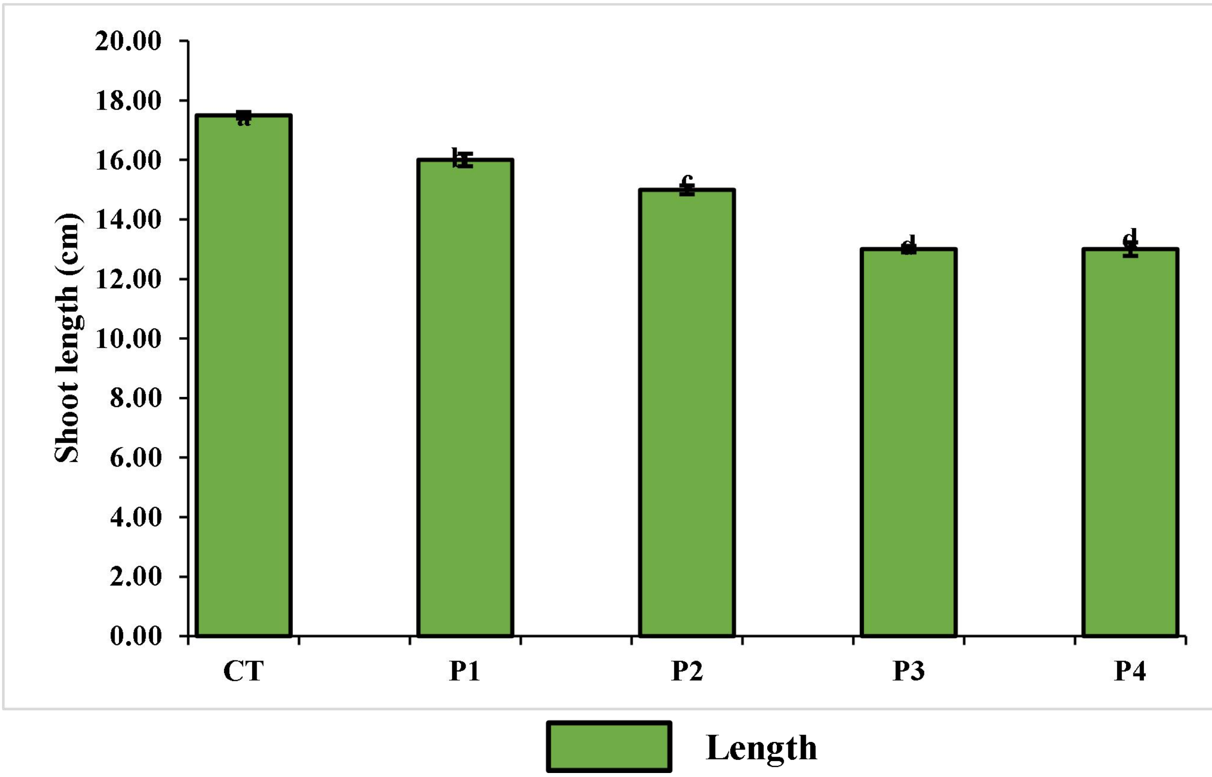

Figure 1. *Zea mays* shoot development in soil as impacted by metals (Cd, Pb, and Ni). Mean ± standard deviation; n = 3; statistically significant difference at a level of $P < 0.05$ is evidenced by the mean values that do not share a common letter.

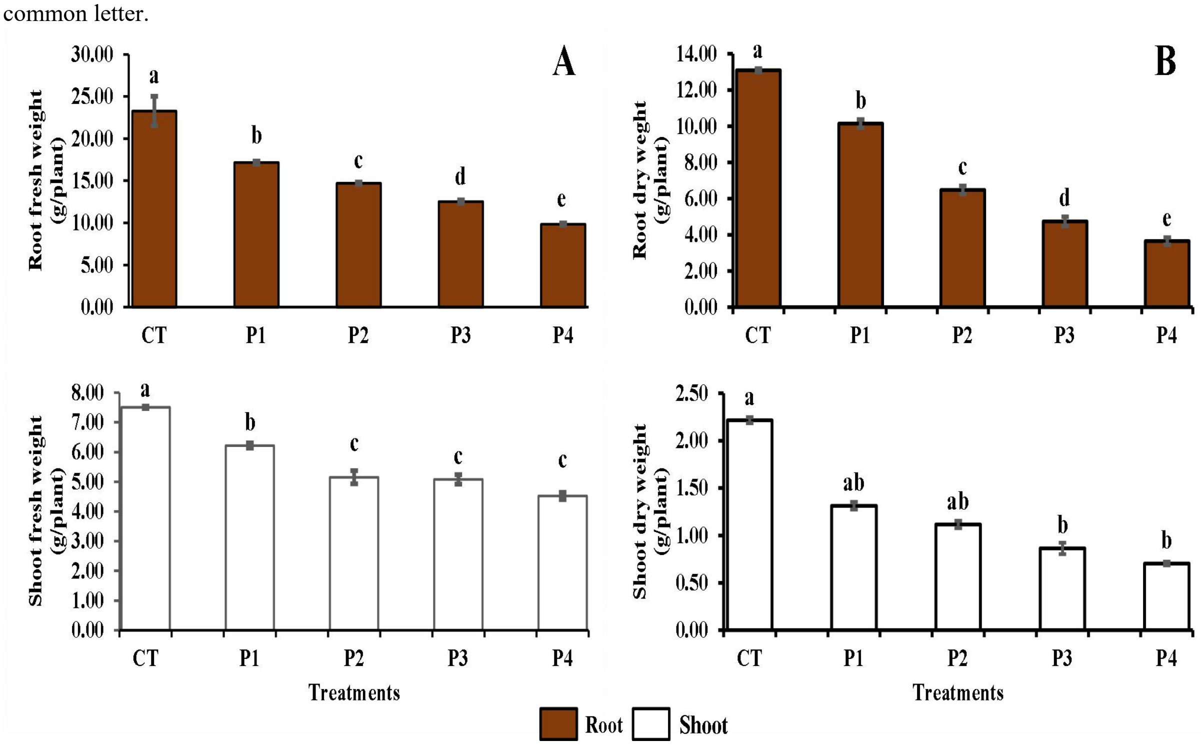

Figure 2. Effects of metals (Cd, Pb, and Ni) on soil-grown *Zea mays* biomass. Mean ± standard deviation; n = 3; statistically significant difference at a level of $P < 0.05$ is evidenced by the mean values that do not share a common letter.

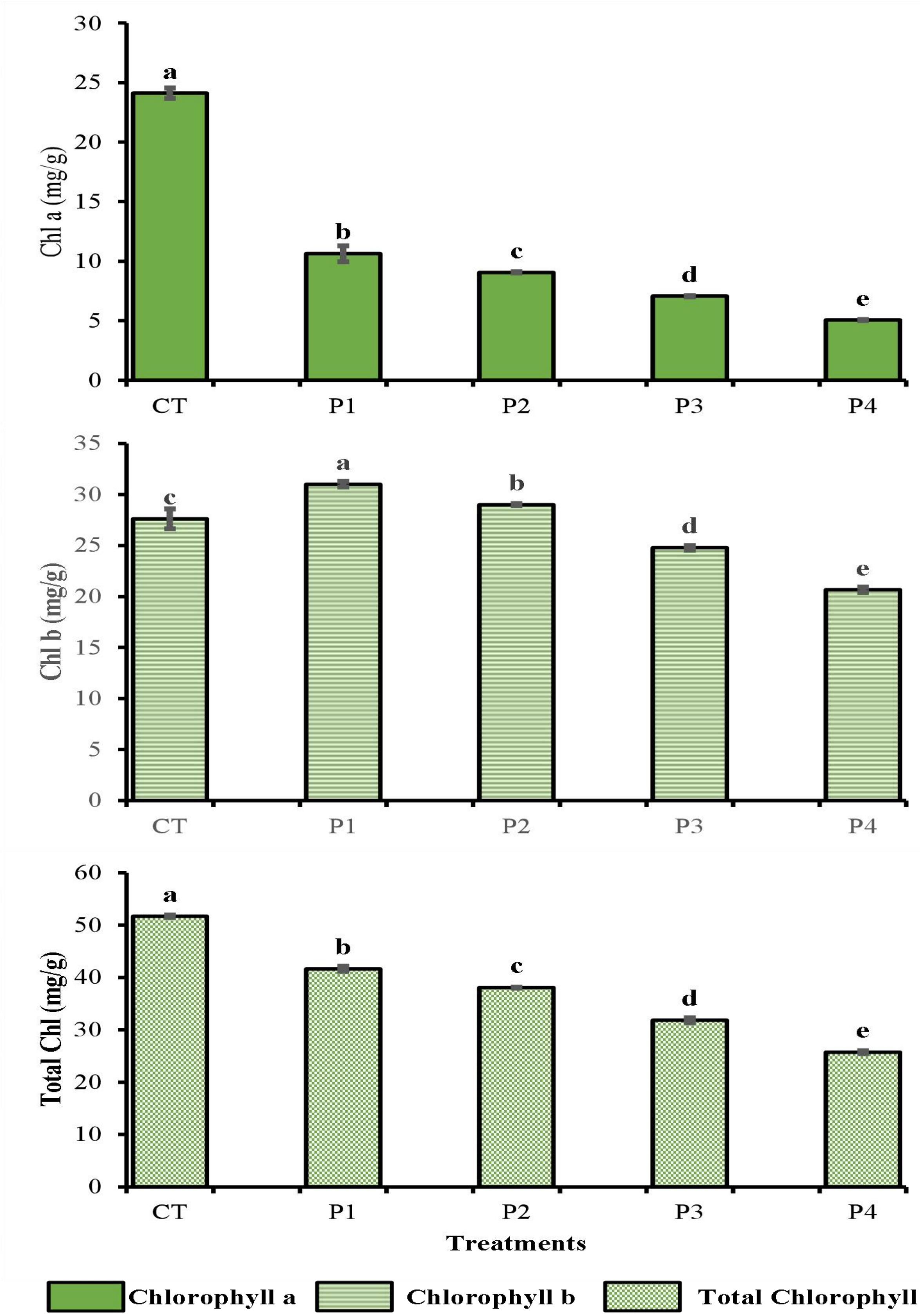

Figure 3: Effects of metals (Ni, Pb, and Cd) on soil-grown *Zea mays* chlorophyll concentration. Mean ± standard deviation; n = 3; statistically significant difference at a level of $P < 0.05$ is evidenced by the mean values that do not share a common letter.

in both their roots and shoots. Notably, a statistically significant difference (p <0.05) was observed in the concentrations of these elements between the roots and shoots of plants grown in spiked pots compared to those in the control group. The roots were identified as the primary site for the accumulation of Cd, Pb, and Ni in plants across various treatment soils, as indicated by the distribution of concentrations of these elements in plant tissues.

Translocation Factor (TF) and Bioconcentration Factor (BCF) of Cd, Pb, and Ni

As soil metal levels increased, the bioconcentration factor (BCF) for each of Cd, Pb, and Ni decreased. *Zea mays* BCF followed the pattern $\mathrm{Ni} > \mathrm{Cd} > \mathrm{Pb}$. From 1.20 (at 5 mg/kg Cd, 30 mg/kg Pb, and 15 mg/kg Ni co-contamination level) to 0.79 (20 mg/kg Cd, 120 mg/kg Pb, and 60 mg/kg Ni co-contamination level), the Cd root BCF values steadily fell. The other metals followed similar patterns ($\mathrm{Pb} = 0.51$ to 0.36; $\mathrm{Ni} = 2.00$ to 0.97). Cd had one larger-than-1 root-BCF value in $\mathrm{P1}$ ($\mathrm{BCF} > 1$). Except for $\mathrm{P4}$, Ni root BCF values were more than 1 ($\mathrm{BCF} > 1$) in every treated soil and the control. All shoot BCF values for the metals were less than 1 except for Ni in the control (1.14).

Maximum TF values were found in the control. Generally, when soil metal concentrations increased, the TF values of the metals decreased (P >P2 >P3 >P4): Cd TF decreased from 0.33 to 0.22; Pb from 0.49 to 0.31; and Ni from 0.34 to 0.28. The recorded data make it clear that roots had higher BCF than shoots and that, in all treatments, there was very little metal translocated from root to shoot (TF <1). Tables 5, along with supplementary tables 1 and 2, provide insight into the Pearson correlations among plant features, metal concentrations in plant tissues (roots and shoots), and soil physicochemical parameters. Parameters such as shoot fresh weight (SFW), root fresh weight (RFW), shoot dry weight (SDW), root dry weight (RDW), shoot length (SL), chlorophyll a (Chl-a), chlorophyll b (Chl-b), total chlorophyll content (t-Chl), and metal-related traits (e.g., Cd, Pb, Ni concentrations in plant tissues and soil) displayed significant correlations. Notably, Maize plant metal characteristics and soil properties exhibited both positive and negative associations. While all metals (Cd, Pb, Ni) demonstrated negative relationships with plant growth characteristics, strong positive connections were observed between soil physicochemical properties and plant growth traits, except for electrical conductivity and soil metal concentrations as indicated in supplementary tables 1 and 2.

Discussion

Soil properties can impact heavy metal availability and plant uptake. The test soil of this study is sandy, has low organic carbon and nutrient levels typical of tropical areas like the Niger Delta and its fertility level can be described as low. The presence of heavy metals in the soil altered the physicochemical properties of the soil, leading to higher EC values and a reduction in pH. This reduction in soil pH, which in turn increases the solubility and plant uptake of metals, indicates that the test soil has a high potential for the transport of metals from the soil solution to the plant.

The results of the current study reveal that Maize growth parameters, including shoot lengths and root and shoot weights, are significantly reduced when exposed to various levels of cadmium, lead, and nickel co-contamination in the growth media (Figures 1 and 2). The deleterious impact is dose-dependent due to increased hazardous heavy metals (HMs) absorption as metal concentration in the soil increases. The study also found that the application of cadmium, lead, and nickel co-contamination significantly lowered harvestable biomass, indicating Maize vulnerability to toxicity. In the current study, the longest Maize shoot length was observed in control soil with an average value of 17.5 cm, while the shortest shoot length (13.0 cm) was recorded under P3 and P4 treatments (Fig. 1). Similar findings have been observed in other similar investigations. In a study conducted by Liu et al. (2018), the impact of arbuscular mycorrhizal (AM) inoculation and biochar amendment on Maize growth, cadmium (Cd) uptake, and soil Cd speciation in Cd-contaminated soil was investigated. The researchers found that the introduction of 6 mg/kg Cd resulted in a 20.96% reduction in Maize shoot length compared to the control group (Liu et al., 2018). In another study by Coulibaly et al. (2021), where *P. maximum* was subjected to 2 ppm of Cd, 50 ppm of Ni, and 100 ppm of Pb contaminated soil and uncontaminated soil, for 120 days in a greenhouse, it was observed that the stem height of *Panicum maximum* was reduced by around 5.11%, 23.30%,

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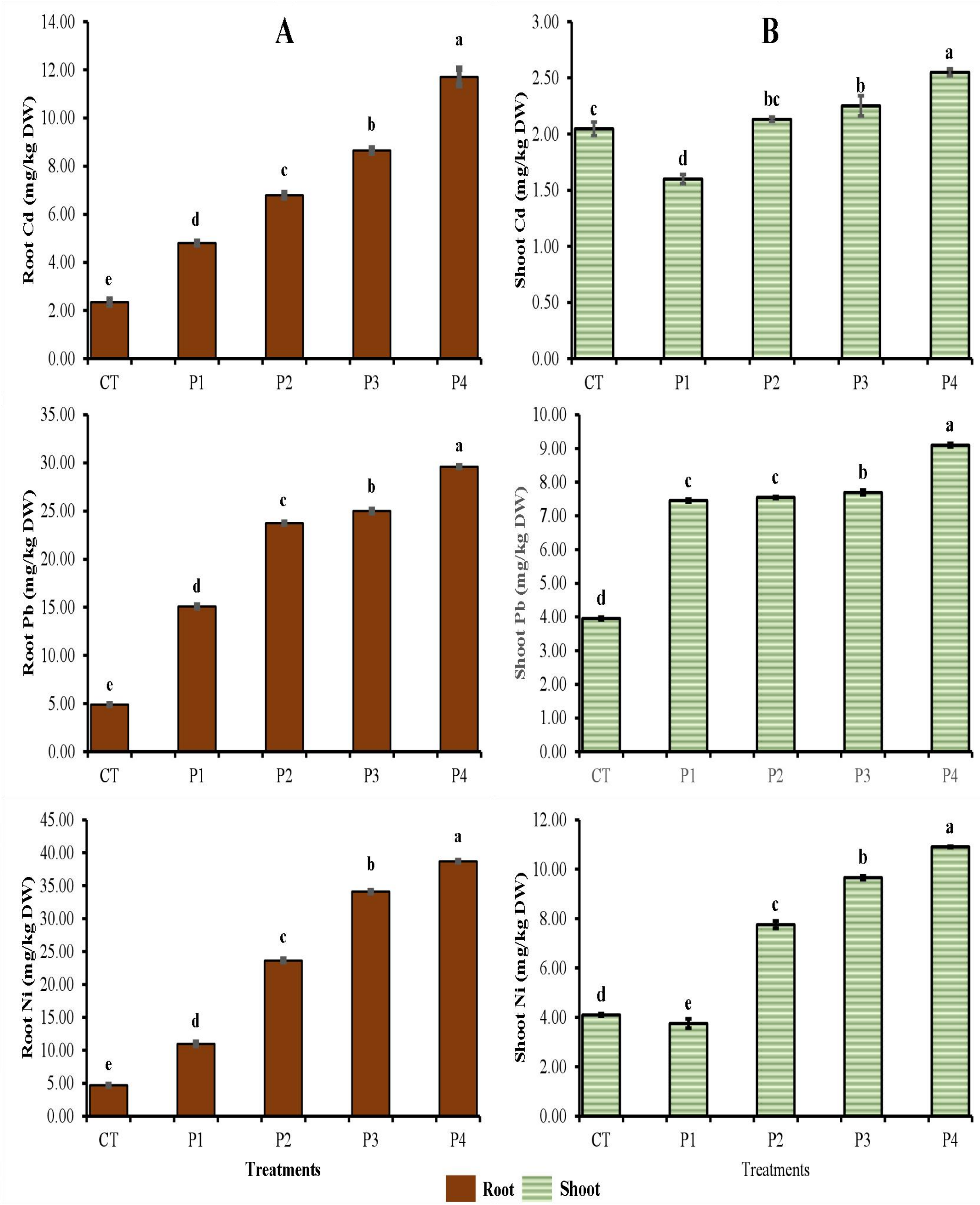

Figure 4. The concentrations of metals (Cd, Pb, and Ni) in *Zea mays* roots and shoots grown on soil supplemented with a mix of nickel, lead, and cadmium. Mean ± standard deviation; n = 3; statistically significant difference at a level of $P < 0.05$ is evidenced by the mean values that do not share a common letter.

Table 3: Cd, Pb and Ni bioconcentration factors in Maize tissues

	BCF-Root			BCF-Shoot		
	Cd	Pb	Ni	Cd	Pb	Ni
CT	0.88 ± 0.05b	0.27 ± 0.11c	1.31 ± 0.00c	0.76 ± 0.03a	0.22 ± 0.02a	1.14 ± 0.02a
P1	1.20 ± 0.04a	0.51 ± 0.01a	2.00 ± 0.13a	0.40 ± 0.01b	0.25 ± 0.03a	0.38 ± 0.01c
P2	0.86 ± 0.01bc	0.55 ± 0.04a	1.36 ± 0.05b	0.27 ± 0.02c	0.16 ± 0.02b	0.45 ± 0.01b
P3	0.87 ± 0.02bc	0.43 ± 0.01ab	1.14 ± 0.03b	0.23 ± 0.01c	0.14 ± 0.020b	0.32 ± 0.01d
P4	0.79 ± 0.01c	0.36 ± 0.02bc	0.97 ± 0.02c	0.17 ± 0.02d	0.11 ± 0.01b	0.27 ± 0.01e

Mean ± standard deviation; n = 3; statistically significant difference at a level of P < 0.05 is evidenced by the mean values that do not share a common letter.

Table 4: Translocation factors of Cd, Pb and Ni in Maize tissues

	Cd	Pb	Ni
CT	0.87 ± 0.02a	0.81 ± 0.01a	0.87 ± 0.02a
P1	0.33 ± 0.01b	0.49 ± 0.01b	0.34 ± 0.01b
P2	0.31 ± 0.01b	0.32 ± 0.04c	0.33 ± 0.01b
P3	0.26 ± 0.01c	0.31 ± 0.03c	0.28 ± 0.02c
P4	0.22 ± 0.01d	0.31 ± 0.03c	0.28 ± 0.01c

Mean ± standard deviation; n = 3; statistically significant difference at a level of P < 0.05 is evidenced by the mean values that do not share a common letter.

Table 5: Pearson correlations for plant different traits and for metals in plant tissues (roots and shoots)

	R-Cd	*R-Pb*	*R-Ni*	*ST-Cd*	*ST-Pb*	*ST-Ni*	*Chl-a*	*Chl-b*	*t-Chl*	*SL*	*RFB*	*STFB*	*RDB*	*SDB*
R-Cd	1.000													
R-Pb	.952*	1.000												
R-Ni	.974**	.953*	1.000											
ST-Cd	0.749	0.623	0.782	1.000										
ST-Pb	.885*	.934*	0.827	0.373	1.000									
ST-Ni	.940*	.901*	.980**	.882*	0.718	1.000								
Chl-a	-0.872	-.951*	-0.852	-0.366	-.984**	-0.744	1.000							
Chl-b	-0.796	-0.597	-0.782	-.923*	-0.441	-0.838	0.407	1.000						
t-Chl	-.989**	-.968**	-.968**	-0.655	-.930*	-.908*	.928*	0.718	1.000					
SL	-.953*	-.944*	-.984**	-0.675	-0.853	-.935*	.891*	0.716	.970**	1.000				
RFB	-.971**	-.988**	-.955*	-0.599	-.956*	-.887*	.962**	0.634	.992**	.962**	1.000			
STFB	-.943*	-.999**	-.943*	-0.605	-.938*	-.890*	.954*	0.573	.961**	.935*	.985**	1.000		
RDB	-.964**	-.988**	-.986**	-0.700	-.884*	-.950*	.913*	0.677	.972**	.977**	.979**	.983**	1.000	
SDB	-.921*	-.974**	-.910*	-0.472	-.973**	-0.819	.992**	0.513	.965**	.940*	.987**	.974**	.954*	1.000

Cd concentration in shoot (ST-Cd) and roots (R-Cd), Pb concentration in shoot (ST-Pb) and roots (R-Pb), Ni concentration in shoot (ST-Ni) and roots (R-Ni); shoot length (SL), chlorophyll a (Chl-a), chlorophyll b (Chl-b), total chlorophyll (t-Chl); shoot fresh weight (SFW), root fresh weight (RFW), shoot dry weight (SDW), and root dry weight (RDW).

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

and 52.84% in Pb, Cd and Ni contaminated soils respectively. Heavy metals can generate oxidative stress, damage cell structures, and disrupt metabolic pathways, resulting in stunted development and lower stem height (Rashid et al., 2023; Zulfiqar et al., 2022).

In our study, low biomass production was reported in all the treatments (P1 to P4) compared with control (Figure 2). This reduction implies a deleterious influence of heavy metals on Maize growth. The reduction in biomass compared with the control might potentially be attributable to higher Cd, Pb and Ni uptake as the level of concentrations of the metals in soil increased. In the present study, the fresh and dry weights of plants significantly decreased in the root by 26.32 to 57.71% and 22.48 to 72.14% and in the shoot by 17.10 to 39.74% and 40.90 to 68.27% in the Cd, Pb and Ni co-contaminated growth conditions (P1 to P4) compared with control (Table 2). The results of our investigation are in agreement with similar studies by other researchers. For instance, the addition of 6 mg/kg Cd to soil has been observed to lower the fresh weight of Maize by 21.50% when compared with control (Liu et al., 2018). It may be deduced that exposure to excessive Cd, Pb and Ni may adversely influence plant development and biomass production and these detrimental effects might be further amplified by an increase in the metal concentrations in the growth medium.

Cd, Pb, and Ni co-contamination significantly lowered plant growth and development, potentially due to a decrease in the photosynthetic rate (Asare et al., 2023). The chl-a, chl-b and total chlorophyll content in Maize plants cultivated in the Cd, Pb, and Ni co-contaminated soil compared with the control decreased significantly, with an increase in metal concentrations in the growth medium. This destruction of chlorophyll structure may be due to the substitution of the central Mg^{2+} ion by Cd, Pb, and Ni ions, which may damage the chlorophyll molecule (Bechaieb et al., 2018). As metal concentrations increase in soil, it may accelerate metal uptake, further affecting the detrimental effect of toxicity on chlorophyll content (Chtouki et al., 2021; Ewais, 1997).

Our investigation demonstrates a negative association between plant growth indices, chlorophyll content, and increasing concentrations of heavy metals (Cd, Pb, and Ni) in soil. The higher rate of metal concentrations in soil decreased these metrics compared to the control. Heavy metal stress impacts plant metabolic activity, hinders photosynthesis, and lowers the uptake of critical nutrients from the soil, leading to decreased plant biomass establishment (Ghori et al., 2019).

Based on the obtained results, *Z. mays* seems to be a tolerant and rapidly growing plant, suitable for phytoremediation due to its fast growth, large root development potential, impressive biomass establishment, and high storage capacity for heavy metals (Daryabeigi Zand & Mühling, 2022).

Metal speciation in soil is crucial in limiting metal uptake by plants. In our investigation, Cd, Pb, and Ni levels in Maize root and shoot systems increased as metal concentrations in soil increased (Figs. 1 and 2). Plants grown in P4 soil had the highest Cd (11.71 and 2.55 mg/kg Dwt), Pb (29.60 and 9.10 mg/kg Dwt), and Ni (38.70 and 10.90 mg/kg Dwt) contents in their roots and shoots, respectively. The study found that *Z. mays* roots are the preferred organ for cadmium, lead and nickel storage, which is consistent with previous research on zinc, copper, and lead (Sagbara et al., 2020). Heavy metals in soil may compete with mineral nutrients for absorption by plant roots. This occurrence may lead to a lack of vital elements such as iron, for plant viability. Furthermore, higher amounts of heavy metals can alter water balance and nutrient digestion, potentially resulting in plant death (Siyar et al., 2020).

Phytoextraction Efficiency of Metals (Cd, Pb, and Ni)

Our findings indicate that *Z. mays* accumulates more Cd, Pb, and Ni in its roots than in its shoots, with roots absorbing more Ni than Cd or Pb. At low Ni concentrations, root BCF values are $>$ 1, but when Ni concentrations exceed 45 mg/kg, root BCF values drop. Our findings suggest that phytostabilization is the primary mechanism by which *Z. mays* remediates these elements, as the BCF values (particularly for Ni) in most treatments were higher than 1, while the TF values of all metals (Cd, Pb, and Ni) in all examined treatments were less than 1. The results of our study also suggest that *Zea mays*' capacity to translocate heavy metals from roots to shoots diminishes with an increase in soil concentration of these metals. Heavy metals in the soil can impede a plant's capacity to absorb vital nutrients and water by blocking the root apex. This root-level interference may lessen the plant's capacity to move heavy metals from its roots to its aerial portions, which may affect the plant's general growth and health (Thomas, 2021). There have also been reports of other plants, like *Tetraena qataranse*, being tolerant to Cd, Cr, Cu, and Ni (Usman et al., 2019).

Conclusion

This study sought to determine the ability of native *Z. mays* in Abraka, Delta State, Nigeria, to remove Cd, Pb, and Ni from contaminated soil. The acquired data demonstrated that *Z. mays* can collect Cd, Pb, and Ni in its tissues (shoots and roots). However, Ni buildup in plant roots was preferable to Cd and Pb. Ni treatments below 60 mg/kg had a greater BCF value than 1, indicating metal ion absorption. Furthermore, the BCF of Cd showed a similar result at 5 mg/kg, whereas that of Pb for all treatments did not reach 1. Phytostabilization is the primary process by which *Z. mays* remediates soil contaminated with Cd, Pb, and Ni (TF < 1). Additional research is required to explore the phytoremediation performance of *Z. mays* for heavy metals when combined with plant growth boosters in order to maximise the plant's heavy metal removal effectiveness in sandy soils.

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