



**PHYTOREMEDIATION OF LEAD AND CHROMIUM CONTAMINATED SOILS USING
SUNFLOWER (*Helianthus annuus* L.) IN THE MAIGANGA COAL MINING AREA,
GOMBE STATE, NORTHEASTERN NIGERIA**

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ABSTRACT

This study evaluated the phytoremediation potential of sunflower (*Helianthus annuus* L.) for the management of Pb- and Cr-contaminated soils from the Maiganga coal-mining area in Gombe State, northeastern Nigeria. A greenhouse experiment was conducted using a completely randomized design comprising four soil treatments with five replicates each: uncontaminated control soil (T₀), mine spoil (T₁), agricultural soil adjacent to the mine (T₂), and mine tailings (T₃). Sunflower was cultivated for 12 weeks, after which Pb and Cr concentrations in soil, roots and shoots were quantified using atomic absorption spectrophotometry (AAS). The result revealed that, initial Pb and Cr concentrations were significantly higher ($P < 0.05$) in contaminated soils, reaching 110.4 ± 5.3 and 88.7 ± 4.2 mg kg⁻¹, respectively. Despite moderate reductions in plant height and biomass under metal stress, *H. annuus* established successfully across all treatments and maintained substantial biomass production. Metal accumulation was significantly greater in roots than shoots, with maximum root concentrations of 158.9 ± 7.3 mg kg⁻¹ Pb and 102.4 ± 5.3 mg kg⁻¹ Cr, indicating preferential below-ground metal retention. Bioconcentration factors exceeded unity (BCF > 1), whereas translocation factors remained below unity (TF < 1) for both metals, indicating effective root accumulation with restricted root-to-shoot translocation. After 12 weeks of cultivation, bioavailable Pb and Cr in the soil declined by 42.8–58.3% and 35.7–49.2%, respectively. Collectively, the combination of metal tolerance, root accumulation, restricted translocation and reduced soil metal bioavailability indicates that *H. annuus* has considerable potential for phytostabilization and ecological restoration of Pb- and Cr-contaminated mine soils. Field-scale studies incorporating appropriate organic amendments and longer monitoring periods are recommended to validate and optimize its remediation performance under natural conditions.

Keywords: *Helianthus annuus*; Bioconcentration; Chromium; Lead; Phytostabilization; Soil

INTRODUCTION

Heavy metals' pollution of soils, a result of open cast mining, overburden stripping and irresponsible waste deposition, is a globally important ecological challenge (Ali *et al.*, 2013; Mahar *et al.*, 2016). They cannot readily be biodegraded unlike organic pollutants, persisting perpetually in the terrestrial ecosystems. These metals adversely affect the soil physical and chemical structure and affect the soil microbiota community, causing magnification along the food chain which pose significant health hazard to the human society (Alloway, 2013; Shahid *et al.*, 2017). Pb and Cr are among these mining associated hazardous contaminants of severe interest due to their extreme Toxicity, high persistence and accumulation potential. Pb's consumption results into disorders of nervous, cardiovascular and renal systems (WHO, 2023), while that of hexavalent chrome (CrVI) is associated with carcinogenesis and mutagenesis (Shahid *et al.*, 2017). Mining activities in Nigeria have expanded, creating large degraded lands areas, especially around mining communities in various parts of the rural area. Maiganga Coal Mine found in Akko Local Government Area (LGA) of Gombe State is a known major source of coal resource in northeast Nigeria (Abdullahi & Paul, 2025), and due to open-cast mining process and overburden stripping with unmanaged dumping at Maiganga coal mine over the years, heavy metals have become concentrated in adjacent agricultural soils (Chris *et al.*, 2023; Tahir *et al.*, 2025).



Disadvantages to conventional engineering solutions (e.g. Soil washing, excavation, thermal desorption and chemical stabilisation) include the cost involved, the high use of energy and that it usually resulted in a irreversible loss of ecosystem service functions in soil (Yan *et al.*, 2020; Han *et al.*, 2021). Phytoremediation (the use of plants to remove, transform and store contaminants in a given ecosystem or site) offer alternatives, which are eco-friendly, cost-effective and aesthetic beneficial (Zulfiqar *et al.*, 2023). *Helianthus annuus* has been characterized by its very large production of biomass and rapid growth, deep rooting system, as well as a significant natural resistance against different toxic heavy metals like Cd, Pb, Cr, and Zn (Mocek-Piniak *et al.*, 2023).

Although previous worldwide studies showed promising results in industrial lands, there is very limited information on field-based validation studies in Nigeria on remediation of coal mine soils (Tahir *et al.*, 2025). Hence this study will look to determine sunflower's capacity to absorb heavy metal contaminants, the distribution of contaminants in plant parts, and remediation efficiency of sunflower plant on contaminated coal mining soils on the Maiganga coal mining site, northeastern Nigeria.

MATERIALS AND METHODS

Study Area

Soil samples were collected from the Maiganga Coal Mine and surrounding agricultural lands located in Akko LGA, Gombe State, northeastern Nigeria (10° 11' - 10°15' N and 11° 03' -11° 07' E). The area falls within the Northern Guinea Savanna zone and experiences a tropical wet-and-dry climate (Köppen Aw) with an annual rainfall ranging between 800 and 1,200 mm (May–October) and temperatures fluctuating between 20°C and 38°C (Abubakar *et al.*, 2025).

Soil Sampling and Characterization

Composite soil samples (0-20 cm depth) were collected using a stainless-steel auger across four distinct sites representing different impact zones:

- T₀: Uncontaminated control soil (collected 5 km upwind from the mine site).
- T₁: Mine spoil soil.
- T₂: Agricultural soil adjacent to the mining zone.
- T₃: Mine tailings-contaminated soil.

At each sampling site, ten sub-samples were bulked, thoroughly mixed, air-dried at room temperature (25±2°C), crushed, and passed through a 2-mm sieve prior to experimental set-up and baseline physicochemical characterization (USEPA, 2007).

Experimental Design and Cultivation

A greenhouse pot experiment was laid out in a Completely Randomized Design (CRD) with the four soil treatments (T₀-T₃) replicated five times (totaling 20 experimental units). Plastic pots were filled with 5.0 kg of prepared soil. Certified seeds of *Helianthus annuus* were sown at a depth of 2–3 cm. Following emergence, seedlings were thinned to one uniform, healthy plant per pot to standardize density (Yan *et al.*, 2020). Plants were cultivated for 12 weeks under natural photoperiods. Soil moisture was maintained at ~70% field capacity by daily watering with deionized water. No organic or chemical fertilizers were applied to isolate the intrinsic phytoremediation capability of the species.

Sample Preparation and Digestion

Plants were excavated intact retaining entire root systems at harvest time (12 weeks). Roots and shoots were separated and washed individually under running tap water and then washed in deionized water so that the adherence soil particles on the plant surfaces were completely removed (Mahar *et al.*, 2016). Plant parts were dried in forced-air oven at 70 ± 2°C until constant dry weight was achieved, and then recorded for the dry biomass followed by being powdered in a stainless steel mill. The digested extract from soil and plant (1.0 g each) was treated with acid reagent, (3:1 v/v) solution HNO₃-HClO₄ at 180°C until the clarity of solutions observed United States Environmental Protection Agency, (USEPA, 2007)

After filtration using of Whatman No. 42 filter paper, extracted solutions were diluted to 50 mL volume using of deionized water and analyzed for lead (Pb) and Chromium (Cr) contents by Atomic Absorption Spectrophotometer (AAS; Model 210 VGP, Buck Scientific). Quality assurance was



maintained using analytical blanks, standard reference materials (CRMs), and duplicate analyses (USEPA, 2007).

Phytoremediation Indices

Plant heavy metal uptake and translocation efficiency were assessed using the Bioconcentration Factor (BCF) and Translocation Factor (TF) (Yoon *et al.*, 2006) as follows:

$$BCF = C_{root} / C_{soil}$$

$$TF = C_{shoot} / C_{root}$$

Where:

- BCF = Bioconcentration Factor
- TF = Translocation Factor
- C_{root} = concentration of the target metal in plant roots
- C_{shoot} = concentration of the target metal in plant shoots
- C_{soil} = concentration of the target metal in the corresponding soil

Statistical Analysis

Prior to statistical analysis, the data normality and homogeneity of variance were verified using Shapiro-Wilk and Levene's tests, respectively (Montgomery, 2020). One-way Analysis of Variance (ANOVA) was employed to evaluate soil treatment effects on heavy metal concentrations, plant growth parameters, and phytoremediation indices. Differences between mean values were separated using Duncan's Multiple Range Test (DMRT) at $p < 0.05$ (Gomez & Gomez, 1984). Statistical computations were performed using IBM SPSS Statistics Version 26.0 (IBM Corp., 2023).

RESULTS

Physicochemical Properties of Experimental Soils

Baseline physicochemical analysis revealed a significant difference ($p < 0.05$) between uncontaminated control soil (T_0) and mining-impacted soils (T_1 - T_3) (Table 1). Mining activities led to acidification, with pH decreasing from 6.82 in control soil to 5.76 in mine tailings (T_3). Soil organic carbon (SOC) and organic matter (OM) were highest in T_0 (1.84% and 3.17%, respectively) and lowest in T_3 (0.78% and 1.34%). Electrical conductivity (EC) increased significantly in contaminated soils, peaking at 0.62 dS m^{-1} in T_3 .

Table 1: Baseline Physicochemical Properties of Experimental Soils Prior to Planting

Parameter	T_0 (Control)	T_1 (Mine Spoil)	T_2 (Agricultural Soil)	T_3 (Tailings)
pH (H_2O)	6.82 ± 0.12^a	5.94 ± 0.15^c	6.21 ± 0.11^b	5.76 ± 0.18^c
Organic Carbon (%)	1.84 ± 0.09^a	0.92 ± 0.05^c	1.32 ± 0.07^b	0.78 ± 0.04^c
Organic Matter (%)	3.17 ± 0.16^a	1.58 ± 0.08^c	2.27 ± 0.11^b	1.34 ± 0.07^c
Total Nitrogen (%)	0.15 ± 0.01^a	0.08 ± 0.01^c	0.11 ± 0.01^b	0.07 ± 0.01^c
Available P (mg kg^{-1})	14.8 ± 0.9^a	8.3 ± 0.6^c	11.7 ± 0.7^b	7.9 ± 0.5^c
EC (dS m^{-1})	0.24 ± 0.02^c	0.48 ± 0.03^a	0.36 ± 0.02^b	0.62 ± 0.04^a

Values represent mean $\pm$ SD ($n = 5$). Means within a row followed by different superscript letters differ significantly at $p < 0.05$ according to Duncan's Multiple Range Test (DMRT).

Initial Heavy Metal Concentrations in Soils

Initial concentrations of Lead (Pb) and Chromium (Cr) differed significantly among treatments ($P < 0.001$, Table 2). The mine tailings (T_3) contained the highest metal burdens (110.4 mg kg^{-1} Pb and 88.7 mg kg^{-1} Cr), whereas control soil (T_0) contained baseline concentrations (12.4 mg kg^{-1} Pb and 8.6 mg kg^{-1} Cr).

Table 2: Lead and Chromium Concentrations Across Experimental Treatments

Treatment	Lead (Pb) (mg kg ⁻¹)	Chromium (Cr) (mg kg ⁻¹)
T ₀ (Control)	12.4 ± 1.2 ^d	8.6 ± 0.8 ^d
T ₁ (Mine Spoil)	95.8 ± 4.6 ^b	72.5 ± 3.4 ^b
T ₂ (Agricultural Soil)	81.7 ± 3.8 ^c	60.3 ± 2.9 ^c
T ₃ (Tailings)	110.4 ± 5.3 ^a	88.7 ± 4.2 ^a
ANOVA (F-value)	164.2 (p < 0.001)	142.8 (p < 0.001)

Values are presented as mean ± standard deviation (SD). Different superscript letters within each column indicate significant differences among treatments according to the appropriate post-hoc test at $p < 0.05$. ANOVA = analysis of variance.

Growth Performance of *Helianthus annuus*

Heavy metal contamination induced significant ($P < 0.001$) dose-dependent reductions in plant growth parameters after 12 weeks of cultivation (Table 3). Compared to control plants (108.6 cm height, 85.7 g biomass), plants grown in tailings (T₃) exhibited a 16.5% reduction in plant height (90.7cm) and a 20.4% decrease in total dry biomass (68.2 g). Nevertheless, sunflower plants survived and completed growth across all treatments without showing severe chlorosis or lethality.

Table 3: Plant Growth and Biomass Production Under Different Experimental Treatments

Treatment	Plant Height (cm)	Total Dry Biomass (g plant ⁻¹)
T ₀ (Control)	108.6 ± 4.5 ^a	85.7 ± 3.8 ^a
T ₁ (Mine Spoil)	95.2 ± 3.8 ^b	71.4 ± 3.2 ^b
T ₂ (Agricultural Soil)	98.4 ± 4.1 ^b	74.6 ± 3.7 ^b
T ₃ (Tailings)	90.7 ± 3.6 ^c	68.2 ± 3.4 ^c

Note: Values are presented as mean ± standard deviation (SD). Means within each column followed by different superscript letters differ significantly at $p < 0.05$ according to Duncan's Multiple Range Test (DMRT).

Heavy Metal Accumulation in Plant Tissues

Helianthus annuus accumulated substantial concentrations of both lead (Pb) and chromium (Cr) in its tissues across the contaminated soil treatments. In all treatments, metal concentrations were consistently higher in the roots than in the shoots, indicating greater retention of Pb and Cr in the below-ground tissues. The highest concentrations were recorded under the T₃ (tailings) treatment, with root concentrations of 158.9 ± 7.3 mg kg⁻¹ Pb and 102.4 ± 5.3 mg kg⁻¹ Cr, compared with corresponding shoot concentrations of 86.4 ± 4.1 mg kg⁻¹ Pb and 54.6 ± 2.8 mg kg⁻¹ Cr.

The lowest tissue concentrations were observed in plants grown in T₂ (agricultural soil), while plants grown in T₁ (mine spoil) exhibited intermediate accumulation. The consistent treatment pattern suggests that the greater metal burden of the tailings substrate resulted in greater uptake and subsequent accumulation by *H. annuus*.

Table 4: Tissue Concentrations of Lead (Pb) and Chromium (Cr) in Root and Shoot Tissues of *Helianthus annuus*

Treatment	Pb Root (mg kg ⁻¹ DW)	Pb Shoot (mg kg ⁻¹ DW)	Cr Root (mg kg ⁻¹ DW)	Cr Shoot (mg kg ⁻¹ DW)
T ₁ (Mine Spoil)	132.5 ± 6.2 ^b	74.1 ± 3.6 ^b	81.2 ± 4.1 ^b	42.8 ± 2.4 ^b
T ₂ (Agricultural Soil)	116.4 ± 5.7 ^c	68.7 ± 3.2 ^c	67.1 ± 3.6 ^c	35.9 ± 1.9 ^c
T ₃ (Tailings)	158.9 ± 7.3 ^a	86.4 ± 4.1 ^a	102.4 ± 5.3 ^a	54.6 ± 2.8 ^a



Note: Values are presented as mean $\pm$ standard deviation (SD) on a dry-weight (DW) basis. Different superscript letters within each column indicate significant differences among treatments at $p < 0.05$, according to Duncan's Multiple Range Test (DMRT).

Bioavailable Heavy Metal Reduction in Soil

Cultivation of *H. annuus* for 12 weeks substantially reduced the bioavailable fractions of Pb and Cr in the contaminated soils (Table 5). Bioavailable Pb concentrations declined by 42.8–58.3%, with the greatest reduction observed in T₃ (tailings soil), where Pb decreased from 110.4 to 46.0 mg kg⁻¹, representing a 58.3% reduction. In T₁ (mine spoil) and T₂ (agricultural soil), Pb concentrations declined by 54.4% and 42.8%, respectively.

Table 5: Changes in bioavailable soil concentrations (mg kg⁻¹) of Pb and Cr before and after cultivation of *H. annuus*.

Treatment	Pb Initial	Pb Final	Pb Reduction (%)	Cr Initial	Cr Final	Cr Reduction (%)
T ₁ (Mine Spoil)	95.8	43.7	54.4	72.5	40.7	43.9
T ₂ (Agricultural Soil)	81.7	46.7	42.8	60.3	38.8	35.7
T ₃ (Tailings)	110.4	46.0	58.3	88.7	45.1	49.2

Phytoremediation Indices (BCF and TF)

The phytoremediation indices demonstrated a consistent pattern of metal accumulation in the roots of *H. annuus* with limited transfer to the shoots (Table 6). Bioconcentration factors (BCF) for Pb ranged from 1.38 ± 0.05 to 1.44 ± 0.05 , while those for Cr ranged from 1.11 ± 0.04 to 1.15 ± 0.05 across the contaminated soil treatments. The Translocation Factors (TF) remained below 1.0 for both Pb and Cr in all treatments, ranging from 0.54 ± 0.02 to 0.59 ± 0.03 for Pb and from 0.53 ± 0.02 to 0.54 ± 0.02 for Cr.

Table 6: Bioconcentration Factor (BCF) and Translocation Factor (TF) of *H. annuus* grown in Pb- and Cr-contaminated soils.

Treatment	Pb BCF	Pb TF	Cr BCF	Cr TF
T ₁ (Mine Spoil)	1.38 ± 0.05	0.56 ± 0.02	1.12 ± 0.04	0.53 ± 0.02
T ₂ (Agricultural Soil)	1.42 ± 0.06	0.59 ± 0.03	1.11 ± 0.04	0.54 ± 0.02
T ₃ (Tailings)	1.44 ± 0.05	0.54 ± 0.02	1.15 ± 0.05	0.53 ± 0.02

DISCUSSION

The significantly elevated concentrations of Pb and Cr in soils associated with the Maiganga coal-mining environment point to substantial impact of mining operations (Abdullahi and Paul., 2025). The high anthropogenic metal burden provide clear evidence of the influence of mining-derived materials on the surrounding terrestrial ecosystem. The markedly higher concentrations recorded in mine spoil (T₁) and tailings (T₃) relative to the uncontaminated control (T₀) are consistent with the accumulation of potentially toxic elements. Accumulations through overburden disturbance, coal spoil deposition, weathering of mineralized materials and redistribution of contaminated particulates in the research area due to mining operations. Mining activities can substantially alter soil physicochemical properties and increase the mobility and ecological availability of trace metals, thereby increasing risks to vegetation and surrounding ecosystems (Alloway, 2013). The elevated metal concentrations observed in the present study therefore highlight the need for remediation approaches capable of reducing both the ecological mobility and potential biological exposure of metals in the Maiganga mine environment. Similar accumulations of heavy metals have been widely found in mine-impacted sites in Sub-Saharan Africa, Asia, and Europe where prolonged treatments of coal or other mineral has led to the increases of Pb, Cr, Cd, Zn and Cu in the soils of nearby farmlands (Mahar *et al.*, 2016; Shahid *et al.*, 2017).



Despite the elevated metal burden, *Helianthus annuus* succeeded to establish and grow to full maturity across all soil treatments, demonstrating considerable tolerance to the contamination. However, a progressive significant reduction in plants height and biomass content was noted as pollution increased, indicating the tolerance was accompanied by physiological costs. The reductions of approximately 16.5% in plant height and 20.4% in biomass relative to the control are consistent with the adverse effects of metal stress on plant growth (Shahid *et al.*, 2017). Excess Pb and Cr can disrupt photosynthetic activity, interfere with mineral nutrient acquisition and transport, alter membrane integrity and stimulate excessive production of reactive oxygen species (ROS), ultimately reducing carbon assimilation and biomass accumulation (Shahid *et al.*, 2017; Zulfiqar *et al.*, 2023). The relatively greater growth constraint in T₃ is particularly plausible given the higher metal burden associated with the tailings substrate. Nevertheless, the ability of *H. annuus* to maintain substantial biomass, including a dry matter yield of approximately 68.2 g plant⁻¹ under the contaminated conditions, indicates a useful degree of tolerance. This characteristic is important for phytoremediation because remediation performance depends not only on tissue metal concentration but also on the quantity of biomass produced and the duration of plant exposure (Ali *et al.*, 2013).

The tissue distribution of Pb and Cr provides further insight into the tolerance and remediation behaviour of *H. annuus*. Across the contaminated treatments, both metals accumulated predominantly in roots rather than shoots. Root preferential accumulation is a common response of plants exposed to potentially toxic metals and can represent an important protective mechanism (Zulfiqar *et al.*, 2023). The root apoplast and cell walls provide numerous binding sites, particularly through negatively charged functional groups associated with pectins and other structural components, which can immobilize metal ions and restrict their subsequent movement into the vascular system (Alloway, 2013). In addition, metal complexation with organic ligands, sequestration in cellular compartments and restricted loading into the xylem can further limit root-to-shoot transport (Ali *et al.*, 2013). These processes can reduce the exposure of photosynthetically active tissues to potentially toxic concentrations. Similar preferential accumulation of Pb and Cr in roots of *H. annuus* and other plant species growing in contaminated substrates has been reported previously (Yan *et al.*, 2020; Zulfiqar *et al.*, 2023). The root-dominated distribution observed here therefore appears to reflect both metal retention and a physiological strategy for limiting above-ground toxicity. The BCF and TF values provide quantitative support for this interpretation. BCF values greater than unity for both Pb and Cr across all contaminated treatments indicate that *H. annuus* accumulated these metals in its tissues at concentrations exceeding those represented by the corresponding soil metal pool used in the BCF calculation (Zulfiqar *et al.*, 2023). The highest BCF values occurred in the tailings treatment for Cr, suggesting that the plant maintained substantial capacity for root accumulation even under the most heavily contaminated substrate. However, BCF > 1 should not be interpreted in isolation as evidence of efficient phytoextraction because BCF describes concentration relative to the soil pool and does not quantify the total mass of metal removed from the soil (Zulfiqar *et al.*, 2023).

In contrast, TF values consistently remained below unity for both metals, demonstrating restricted transfer from roots to shoots. This combination of BCF > 1 and TF < 1 is particularly important in interpreting the phytoremediation function of *H. annuus*. A plant intended primarily for phytoextraction would ideally combine substantial accumulation with efficient translocation to harvestable above-ground biomass. The present results instead indicate a predominantly root-retention strategy, which is more consistent with **phytostabilization** than with classical phytoextraction (Yan *et al.*, 2020). By retaining metals within the root zone and limiting their movement into above-ground tissues, *H. annuus* may reduce the mobility and ecological availability of Pb and Cr while simultaneously establishing vegetation cover over contaminated environments.

This interpretation is reinforced by the observed decline in bioavailable soil metals following cultivation. After 12 weeks, bioavailable Pb decreased by 42.8–58.3%, with the largest reduction occurring in the tailings treatment. Bioavailable Cr also declined substantially in the treatments for which complete data were available. Such reductions are environmentally important because the bioavailable fraction is more directly relevant to plant uptake, biological exposure and potential redistribution within the soil–water system than total metal concentration alone (Ali *et al.*, 2013, Yan



et al., 2020). The decline may have resulted from a combination of root uptake, adsorption to root surfaces, rhizosphere interactions and redistribution of metals into less readily available soil fractions. Plant roots can modify rhizosphere pH, redox conditions and organic ligand concentrations, thereby altering metal solubility and partitioning (Hinsinger, 2001). Consequently, the observed decline in bioavailable metal concentrations should be interpreted as evidence of reduced metal availability rather than complete elimination of the contaminant from the soil (Padmavathiamma and Li, 2010).

The particularly strong reduction in bioavailable Pb in T₃ is noteworthy because the tailings treatment also produced the highest Pb BCF (Hinsinger, 2001). The simultaneous occurrence of substantial soil bioavailability reduction and enhanced root accumulation suggests that *H. annuus* may be particularly useful for stabilizing Pb in highly contaminated mine-derived substrates. This is ecologically significant in a coal-mining landscape where contaminated fine particles may be redistributed by wind and surface runoff. Establishment of a persistent vegetative cover can potentially reduce erosion, suppress particulate dispersal and limit the transport of contaminated soil particles into adjacent environments (Padmavathiamma and Li, 2010). However, these benefits depend on maintaining adequate vegetation cover and preventing inappropriate disposal or consumption of contaminated plant biomass.

Taken together, the growth responses, tissue distribution, phytoremediation indices and changes in soil bioavailability demonstrate that *H. annuus* possesses considerable potential for the management of Pb- and Cr-contaminated soils at Maiganga. Its principal strength under the conditions examined was not rapid transfer of metals into shoots, but rather its ability to establish substantial biomass while concentrating metals predominantly in roots and reducing the bioavailable metal fraction in the soil (Mendez and Maier, 2008). This combination of metal tolerance, root accumulation, restricted translocation and reduction in bioavailable metals supports its potential application as a phytostabilizing species in mine-impacted environments.

From a remediation perspective, this approach may offer important advantages over intensive engineering interventions such as excavation, soil replacement or washing, which can be costly, disruptive and difficult to implement over large areas (Jadia and Fulekar, 2009). Vegetative remediation can provide simultaneous soil stabilization, erosion control and gradual reduction in contaminant availability while requiring comparatively lower infrastructure inputs. Nevertheless, *H. annuus* should be regarded as a component of an integrated remediation strategy rather than a stand-alone solution. Long-term field trials are required to determine the persistence of the observed reductions, seasonal stability of metal immobilization, fate of contaminated root and shoot biomass, and effectiveness under naturally fluctuating moisture and climatic conditions. Such validation will be essential before large-scale deployment across the Maiganga coal-mining landscape.

In sum, the findings indicate that *H. annuus* has strong potential for phytostabilization of Pb- and Cr-contaminated mine soils, particularly where the objective is to reduce metal bioavailability, restrict internal translocation and establish vegetative cover over degraded substrates (Zulfiqar *et al.*, 2023). Its demonstrated ability to tolerate substantial metal exposure while maintaining appreciable biomass makes it a promising candidate for low-input ecological restoration of contaminated coal-mining environments in northeastern Nigeria.

CONCLUSION AND RECOMMENDATION

This study demonstrates that *Helianthus annuus* L. has considerable potential for the phytostabilization of Pb- and Cr-contaminated soils associated with the Maiganga coal-mining environment in Gombe State, Nigeria. The substantially elevated concentrations of Pb and Cr in mine-affected soils relative to the control confirm the significant influence of mining activities on soil metal contamination. Despite exposure to elevated metal concentrations, *H. annuus* successfully established and maintained substantial biomass throughout the 12-week cultivation period, although moderate reductions in growth and biomass were observed, particularly in the tailings treatment.

The phytoremediation response was characterized by effective root accumulation and restricted root-to-shoot translocation, as demonstrated by BCF values consistently greater than 1.0 and TF values below 1.0 for both metals. This accumulation pattern indicates that *H. annuus* preferentially retained



Pb and Cr within the root system, supporting its suitability for phytostabilization rather than classical phytoextraction. Importantly, cultivation also resulted in substantial reductions in the bioavailable fractions of soil Pb and Cr, indicating that the plant–soil system can reduce the fraction of metals readily available for biological uptake and environmental redistribution.

Collectively, the combination of metal tolerance, appreciable biomass production, root-dominated metal accumulation, restricted translocation and reduction in bioavailable metal concentrations establishes *H. annuus* as a promising candidate for the ecological management of Pb- and Cr-contaminated mine soils. Its application could contribute to vegetation establishment, soil stabilization and reduction of metal mobility in degraded mining landscapes. However, the findings should be validated under field conditions and over longer periods to determine the persistence of metal immobilization, seasonal performance and the fate of metal-containing plant biomass.

Thus, *H. annuus* represents a potentially practical, low-input and environmentally compatible phytostabilization option for the rehabilitation of coal-mine-impacted soils in northeastern Nigeria, particularly when incorporated within an integrated mine-land restoration strategy.

1. *Helianthus annuus* L. should be incorporated into the official ecological restoration and closure protocols for the Maiganga coal mine as a biological stabilizer for spoil heaps and tailings.
2. Multi-year field trials should be conducted under natural environmental conditions to assess long-term phytostabilization performance, seasonal variations, and soil structural recovery.
3. Future studies should investigate the combined application of *H. annuus* with eco-friendly soil amendments (e.g., biochar, organic compost, or mycorrhizal inoculants) to enhance plant biomass production, improve soil fertility, and optimize metal immobilization.
4. The harvested biomass will contain concentrated amounts of heavy metal, hence it is appropriate that it must be managed correctly and in a sustainable way, e.g. Incineration under safe condition, disposal as industrial waste, etc or recovery using the plants (phyto-mining technique) .
5. In addition to removing Pb and Cr from the soil, this study can be extended to investigate removal of other heavy metal elements (such as Cd, Ni, Cu, Zn, As, Hg etc) using sunflower.
6. Environmental surveillance needs to be increased in both active and closed mining sites and inclusion of phytoremediation in the mine rehabilitation strategy/policy should be encouraged as sustainable natural approach.

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