Assessment of phytoremediation potentials of native economically-valuable tree species in a lead-zinc abandoned mining site in Enyigba, Nigeria

John Yakubu Magaji
University of Abuja
Sani Abubakar Mashi
abubakar.sani@uniabuja.edu.ng
University of Abuja
Gunkolade Oludare Okikiola
University of Abuja
Hadiza Abubakar Ahmad
University of Abuja
Elizabeth Dorsuu Jenkwe
University of Abuja

Research Article

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Posted Date: August 25th, 2025

DOI: https://doi.org/10.21203/rs.3.rs-6641746/v1

Additional Declarations: No competing interests reported.

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John Yakubu Magaji, Sani Abubakar Mashi*, Gunkolade Oludare Okikiola, Hadiza Abubakar Ahmad, Elizabeth Dorsuu Jenkwe

Department of Geography, Faculty of Geography and Atmospheric Sciences, University of Abuja, PMB 117, Abuja, Nigeria.

*Correspondence (abubakar.sani@uniabuja.edu.ng; +234-80-36066564; https://orcid.org/0000-0001-6472-5463)

Authors' email Addresses:

John Yakubu Magaji:	john.magaji@uniabuja.edu.ng
Sani Abubakar Mashi:	abubakar.sani@uniabuja.edu.ng
Gunkolade Oludare Okikiola:	gunkolade.okikiola@uniabuja.edu.ng
Hadiza Abubakar Ahmad:	hadiza.ahmad@uniabuja.edu.ng
Elizabeth Dorsuu Jenkwe:	elizabeth.jenkwe@uniabuja.edu.ng

Abstract

This study investigated heavy metal contamination in soils from an abandoned minefield and assessed the phytoremediation potential of *Spondias mombin, Cola gigantea,* and *Ceiba pentandra* tree species. Soils from the minefield exhibited significantly higher concentrations of heavy metals, including Pb (1411 ± 164.1 mg/kg), Ni (194.9 ± 20.5 mg/kg), Cd (22.9 ± 4.4 mg/kg), and Fe (50.3 ± 10.8 mg/kg), compared to the control site. These elevated levels indicate persistent pollution from past mining activities. In plants, heavy metals were mainly concentrated in root tissues. Spondias mombin accumulated the highest levels of As (12.1 mg/kg), Ni (127 mg/kg), and Fe (28.2 mg/kg), while Ceiba pentandra showed maximum Hg (6.9 mg/kg) and Pb (1417 mg/kg) uptake. Bioaccumulation factors (BAFs) for all species were below 1, indicating none are hyperaccumulators. However, *Spondias mombin* recorded relatively high BAFs (e.g., Pb = 0.97, Hg = 0.97), making it the most effective for phytostabilization. Translocation factors (TFs) were also below 1, signifying metal retention in roots. Ceiba pentandra had the lowest BAF and TF values, limiting its remediation potential. These results underscore *Spondias mombin* and *Cola gigantea* as suitable species for phytostabilization of mine-contaminated sites. The study highlights the need for species-specific phytoremediation strategies, including biomass management and soil amendments. Soil analysis showed higher concentrations of Hg, As, Ni, Pb, Cr, Cd, Fe, Cu, and Zn in the minefield, with Pb, Cd, and Fe posing the greatest risks. Plant tissue analysis revealed metal accumulation in roots, with Spondias mombin showing the highest bioaccumulation potential for Hg, As, Pb, and Zn, making it ideal for phytostabilization. Cola gigantea exhibited moderate uptake, while Ceiba pentandra had the lowest bioaccumulation. The study suggests alternative methods like soil amendments and microbial-assisted techniques for better metal stabilization and risk reduction.

Keywords: mining, heavy metals, contamination, phytoremediation, abandoned sites, tree species

Introduction

Mineral resource extraction has long been a key driver of economic growth worldwide. However, extensive research has shown that it significantly contributes to soil, surface water, and groundwater contamination, posing serious environmental and public health risks especially through accumulation of toxic heavy metals like cadmium (Cd), arsenic (As), lead (Pb), Mercury (Hg) and nickel (Ni) in different parts of the world (Okereafor et al., 2020; Sengupta, 2021; Worlanyo and Jiangfeng, 2021; Leyton-Flor and Sangha, 2024; Podgórska and Jóźwiak, 2024; Hoxha et al., 2025). Addressing this issue requires a sustainable mining approach that balances economic growth, social equity, and environmental protection, aligning with the Sustainable Development Goals (SDGs) (Hofmann and Juergensen, 2017a; 2017b; Padhiary and Kumar, 2024; Hirlekar et al., 2025). Bioremediation using metal-accumulating plants, known as phytoremediation, offers a sustainable and cost-effective alternative to traditional remediation methods. This approach not only reduces heavy metal bioavailability but also improves soil quality, prevents erosion, and restores biodiversity. Phytoremediation is an eco-friendly, cost-effective method for mitigating soil and water contamination using plants, but its effectiveness depends on site conditions, plant species, and contamination type (Bhat et al., 2022; Sabreena et al., 2022; Nenman et al., 2023).

Research evidences have shown that there are six main phytoremediation mechanisms that are suited to different contaminants. Phytoextraction involves plants absorbing heavy metals and storing them in biomass. *Brassica juncea* (Indian mustard) and *Helianthus annuus* (sunflower) absorb lead (Pb) and cadmium (Cd) (Tan et al., 2023; Zhang et al., 2024), but the process is slow (Kafle et al., 2022; Lavanya et al., 2024). Phytostabilization immobilizes contaminants, preventing leaching. Chrysopogon zizanioides (vetiver grass) and Populus spp. (poplars) stabilize arsenic (As) and lead (Pb) (Shen et al., 2022; Kucher et al., 2023). Phytovolatilization absorbs mercury (Hg) and selenium (Se) and releases them in less toxic forms. *Brassica juncea* and *Nicotiana tabacum* (tobacco) volatilize selenium (Terry and Zayed, 1998), though air pollution risks remain (Madhav et al., 2024). Rhizofiltration filters heavy metals from water. *Helianthus annuus* and *Eichhornia crassipes* (water hyacinth) remove Pb and uranium (U) (Putra et al., 2025). Phytodegradation breaks down organic pollutants. *Salix spp.* (willows) and *Populus spp.* degrade polycyclic aromatic hydrocarbons (Chamba-Eras et al., 2022; Oladoye et al., 2022). Rhizodegradation enhances microbial activity for organic pollutant breakdown. *Medicago sativa* (alfalfa) and *Lolium perenne* (ryegrass) aid oil spill degradation (Wei et al., 2021; Al-sayaydeh et al., 2022).

The literature on phytoremediation for rehabilitating mining-affected landscapes is extensive, underscoring the potential of various plant species for ecological restoration across diverse regions. A key emerging direction in this field involves the identification and deployment of underutilized or genetically enhanced plant species with superior capacities for heavy metal uptake, tolerance, and stabilization—particularly relevant for highly contaminated or degraded sites (Ali et al., 2013; Mahar et al., 2016). Recent research also highlights the critical role of plant-microbe interactions, especially with rhizobacteria and mycorrhizal fungi, which can facilitate metal solubilization, enhance nutrient acquisition, and bolster plant resilience under toxic conditions (Liu et al., 2023; Priya et al., 2023; Gamalero and Glick, 2024). Another innovative approach targets complex contamination scenarios by addressing multi-contaminant systems involving both heavy metals and organic pollutants (Tangahu et al., 2024). Integrating phytoremediation with complementary strategies—such as biochar amendments, nanotechnology, and electrokinetic treatments—has also shown promise in accelerating and enhancing remediation outcomes (Mao et al., 2016; Khan et al., 2021; Beesley et al., 2022). Additionally, advancements in omics technologies are providing deeper insights into the molecular basis of metal accumulation and stress tolerance, enabling the selection or bioengineering of more efficient plant genotypes (Singh et al., 2016; Yadav et al., 2022; Sharma et al., 2023). Research into climate-resilient species adapted to arid, saline, or nutrient-deficient soils is expanding the applicability of phytoremediation under shifting environmental conditions (Ashraf et al., 2023). Finally, integrating ecological and socioeconomic assessments—such as ecosystem service valuation, land-use potential, and livelihood benefits—can guide the sustainable and scalable implementation of phytoremediation interventions (Pulford and Watson, 2003; Yadav et al., 2021). This study contributes towards addressing these existing knowledge gaps by evaluating the phytoremediation potential of three previously understudied, economically valuable native tree species - *Cola gigantea* (Giant Cola), *Spondias mombin* (Yellow Mombin), and *Ceiba pentandra* (Silk Cotton) - that have naturally re-established in a lead and zinc-abandoned mine site in Enyigba, Abakaliki LGA, Ebonyi State, Nigeria. These species hold significant local economic value and may contribute to ecological recovery in the area. The study investigates their capacity to remediate heavy metal contamination linked to historic mining activities, as documented by Uriah et al. (2013), Adesuyi et al. (2018), and Uchendu et al. (2020). The specific objectives are to:

1. Quantify and compare the concentrations of selected heavy metals (Cd, As, Pb, Hg, Ni, etc.) in soils and plant tissues from the abandoned mining site and an uncontaminated control site.
2. Assess the metal accumulation and translocation capacities of the three tree species to determine their suitability for different phytoremediation mechanisms
3. Identify the most effective species for stabilizing or removing heavy metals based on calculated bioaccumulation and translocation factors.
4. Examine the potential of these species to support ecological restoration and sustainable land use in post-mining landscapes.
5. Contribute to the growing body of phytoremediation research by demonstrating the relevance of locally adapted, multipurpose tree species in environmentally and socioeconomically integrated mine reclamation strategies.

The findings of this will serve as a guide for remediating heavy metal-contaminated soils in mining areas and similar environments. Existing research largely centers on herbaceous hyperaccumulators and largely based on studies conducted within strictly controlled setting (greenhouse experiments, mainly), which often lack broader ecological or socioeconomic value. This study addresses that gap by investigating three underutilized native tree species - *Cola gigantea, Spondias mombin,* and *Ceiba pentandra* - that have naturally recolonized a contaminated lead-zinc mine in Enyigba, Abakaliki, Nigeria. Their persistence in polluted soils suggests potential for metal tolerance and accumulation, making them suitable candidates for phytoremediation. In addition, this study also responds to the regional imbalance in phytoremediation research, which is heavily skewed toward temperate, non-African contexts. It offers site-specific insights into a historically polluted tropical environment, where low-cost, sustainable remediation strategies are urgently needed. In addition to ecological recovery, the selected species provide local economic value through timber, fruit, and cultural use, aligning with global calls for nature-based solutions that deliver both environmental and community benefits. By assessing the metal uptake and restoration potential of these species, the study expands the phytoremediation plant portfolio and supports climate-resilient land rehabilitation strategies. The findings can inform environmental policy and guide sustainable reclamation efforts in Nigeria and similar mining-impacted areas across sub-Saharan Africa.

Materials and methods

Site description

Enyigba community (Figure 1) is located in Abakaliki Local Government Area (LGA) (Figure 1) of Ebonyi State, Nigeria. The community is 14 km southeast of Abakaliki and lies between latitudes 6°07′N and 6°12′N and longitudes 8°05′E and 8°10′E (Abraham et al., 2018). Enyigba is approximately 54.56km^2 and the entire area is located vein ridges and low-lying mineralization terrains of lead-zinc (Abraham,*et al.,* 2018). This has attracted series of lead-zinc ore mining company with foot print of unclaimed abandoned mines (Okolo, *et al.,* 2018). The area of interest within the mining field is that operated by Royal Salt limited, covering 2.01km^2 parcel of land and located on latitude 6°10'44.52" and longitude 8° 8'19.88"E. The site is characterized by mine spoils, ponds and mine pits.

The study area, has a humid tropical climate with distinct wet and dry seasons. The wet season lasts for eight months (April–July, September–November), interrupted by the "August break." Annual rainfall ranges from 1,700 to 2,000 mm, often torrential. Temperatures range from 27°C to 31°C, with 60–80% relative humidity. Geologically, Enyigba lies within the Abakaliki anticlinorium, underlain by Abakaliki shales of the Asu River Group (Albian-Cretaceous sediments). The terrain consists of black calcareous shales with siltstone intercalations, extensively fractured due to past tectonic activities. The soil belongs to the Ultisol order. Originally a tropical rainforest, human activities have transformed the vegetation into parkland with grasses and shrubs. The area has rich diversity of plant species, but those with very high economic value include *Crotolaria retusa* (Devil Bean), *Pennisetum polystachion* (Mission Grass), and *Paspalum scrobiculatum* (Kodo Millet). Major crops include rice (*Oryza glaberrima*), yam (*Dioscorea rotundata*), cassava (*Manihot esculenta*), and vegetables like fluted pumpkin (*Telfairia occidentalis*) and bitter leaf (*Vernonia amygdalina*). The Ebonyi River and its tributaries drain the area, often overflowing during peak rainfall. The landscape is undulating, with hilly rocks rising up to 200m. Enyigba, an ancient mining community since 1925, has seen increased artisanal and large-scale mining, leading to land degradation and environmental challenges. The population of Enyigba is about 8,000, forming 3.6% of Abakaliki LGA's estimated 223,000 residents.

The area presents a uniquely suitable and scientifically significant setting for phytoremediation research due to its history of extensive lead and zinc mining, which has left the landscape heavily contaminated with toxic metals. Despite the cessation of formal mining activities, elevated levels of heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg) persist in the soil, water, and vegetation, posing ongoing threats to environmental and public health. Studies by Uriah et al. (2013), Adesuyi et al. (2018), and Uchendu et al. (2020) confirm that metal concentrations in this area often exceed permissible safety thresholds, with documented impacts on agriculture, water quality, and local communities. Enyigba is also ecologically and socioeconomically important, with a rural population that relies on the land for subsistence farming and natural resource use. Yet, in the absence of government-led cleanup programs, low-cost, nature-based solutions like phytoremediation are both timely and necessary. The spontaneous regeneration of native, economically valuable tree species - such as *Cola gigantea, Spondias mombin,* and *Ceiba pentandra* - within the contaminated site provides a rare opportunity to assess the phytoremediation potential of naturally adapted species in situ. Furthermore, the tropical climate, variable soil conditions, and post-mining land-use pressures of Enyigba reflect broader environmental challenges facing many post-extractive landscapes in sub-Saharan Africa. Conducting this study in Enyigba not only addresses a pressing local environmental issue but also contributes valuable context-specific knowledge to the global phytoremediation discourse. The findings can directly inform ecological restoration and land management strategies in Ebonyi State while offering scalable lessons for similar degraded areas across the region.

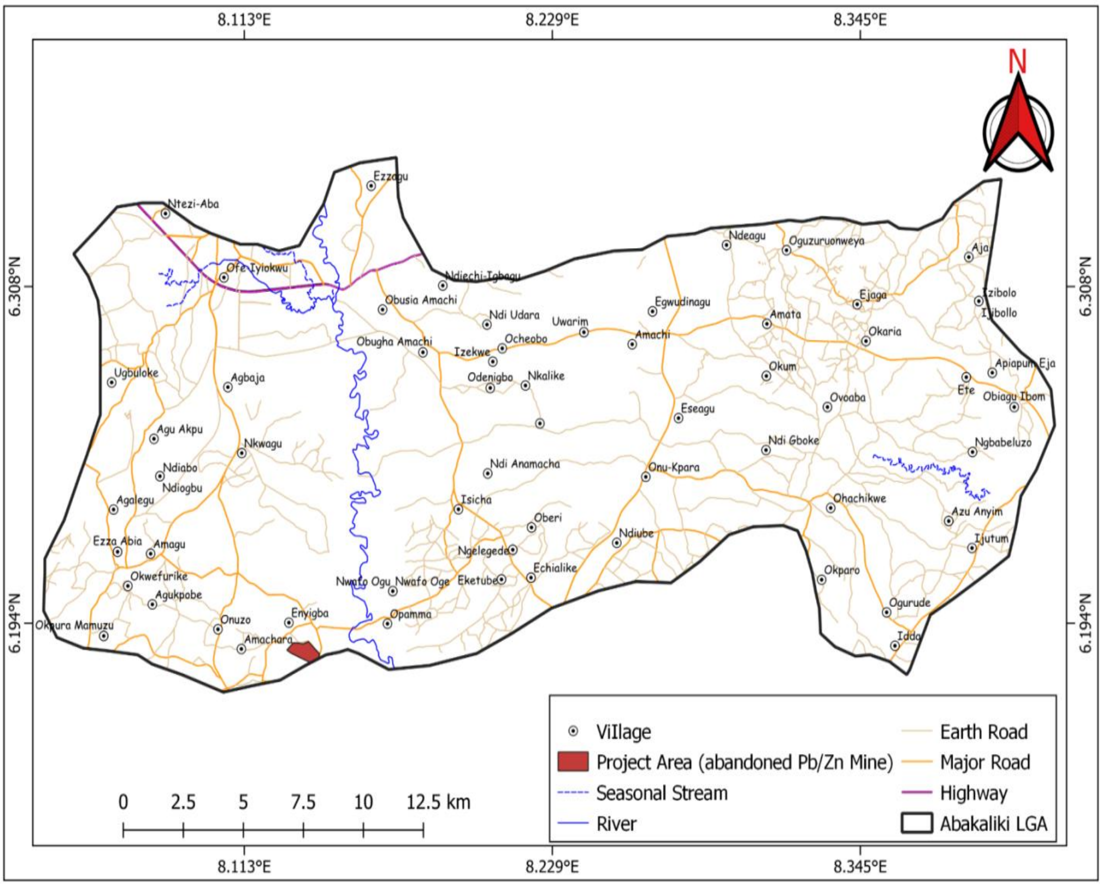

Figure 1: Location of Enyigba lead and zinc mining area in Abakaliki LGA, Nigeria

Research design

The study employed a mixed-methods approach, combining quantitative and qualitative techniques to enable a comprehensive evaluation of hyperaccumulator tree species for bioremediation purposes. This methodological integration is increasingly recognized for its ability to strengthen environmental research by capturing both measurable outcomes and contextual insights (Creswell and Plano, 2023). Field sampling and laboratory analyses generated precise quantitative data on heavy metal concentrations and the efficiency of contaminant uptake by selected hyperaccumulator trees. Such precision is essential for assessing the feasibility of phytoremediation as a land reclamation strategy, especially in regions affected by mining-related degradation (Alloway, 2013; Ali et al., 2013). The inclusion of qualitative analysis, through literature review and contextual evaluation of field sites, further enriched the study by identifying ecological impacts, management challenges, and best practices from comparable remediation projects. This dual lens aligns with best practice in bioremediation research, which emphasizes both technical effectiveness and socio-ecological sustainability (Tangahu et al., 2024).

To ensure that findings were generalizable and practically applicable, the study deliberately selected abandoned lead and zinc mining sites with diverse contamination profiles and ecological settings - including some areas currently under cultivation. This sampling strategy recognizes the heterogeneity of mining-impacted landscapes and supports the development of site-specific remediation recommendations (Mulligan, 2021). Moreover, the inclusion of cultivated plots highlights the relevance of bioremediation to ongoing land-use transitions, particularly in communities seeking to restore degraded land for agricultural purposes.

Reconnaissance survey

Field surveys were a critical component of this study, serving to identify tree species and guide sample collection within the targeted mining landscape. Conducted between June 7–11, 2023, these surveys incorporated site verification techniques to locate abandoned lead and zinc mining sites and assess their suitability for bioremediation research. Field verification is an essential step in environmental fieldwork as it ensures spatial accuracy and helps confirm the current status of land use, especially in degraded or informally repurposed areas (Marcum, 2005; Jensen, 2007). Three potential sites were identified during the reconnaissance phase: one actively used for small-scale artisanal mining and two that had been fully abandoned by a former industrial operator. This distinction is crucial because artisanal and abandoned mining sites often exhibit different levels of contamination, land degradation, and ecological recovery potential (Hilson and Potter, 2003; UNEP, 2011). The largest abandoned site was selected for detailed investigation due to its extent and representative contamination features, making it ideal for assessing the effectiveness of hyperaccumulator tree species in bioremediation. Moreover, the reconnaissance survey played an instrumental role in sampling design, enabling the strategic selection of sampling points for both soil and plant material collection. Properly planned sampling is essential in contaminated landscapes to capture spatial variability and ensure that the data generated accurately reflect site conditions (USEPA, 2002). This preparatory phase enhances the reliability of subsequent laboratory analyses and supports sound ecological interpretation of remediation potential.

Sampling sites and procedure

To evaluate the bioremediation potential of naturally occurring hyperaccumulator tree species, experimental plots were established in both contaminated (mined) and relatively undisturbed (control) sites. This comparative design aligns with best practices in ecological restoration research, where reference (control) sites provide a baseline for assessing the degree of contamination and the effectiveness of remediation (Harries et al., 2024; Huslina et al., 2025). The experimental area was demarcated into a 60 m × 50 m quadrant, which was further subdivided into 30 uniform 10 m × 10 m cells, a sampling structure that enables spatially stratified analysis of soil and vegetation attributes (Carter and Gregorich, 2007).

A Table of Random Numbers was used to select six cells for sampling, ensuring unbiased spatial representation across the site (Thompson, 2012). In each selected cell, composite soil samples were generated by collecting soil from the four corners and the diagonal intersection point. Composite sampling is widely recommended in environmental assessments to account for small-scale heterogeneity and improve the representativeness of chemical analyses (USEPA, 2002). In addition to these six plots, two sampling points were designated in the control site, bringing the total to eight soil sampling points. This design facilitates robust comparisons between mined and unmined areas, enhancing the reliability of conclusions drawn about the impacts of contamination and the remediation potential of vegetation (Alloway, 2013).

Three dominant hyperaccumulator tree species were identified at the site, and for each species, three sampling locations were selected, resulting in nine plant sampling points. Collecting multiple samples per species ensures replication, which is essential for detecting differences in metal uptake and physiological responses (Ali et al., 2013). This design not only supports statistical rigor but also enables species-specific assessment of phytoremediation potential in variable field conditions.

Collections of soil and plant samples

Soil and plant sampling were carefully designed to ensure the integrity and representativeness of materials used in the heavy metal analysis. Soil samples were collected from a depth of 0–30 cm using a soil auger, a standard practice in environmental soil studies, as this layer represents the most biologically active zone and is most affected by surface contamination (Kabata-Pendias and Pendias, 2011; Carter and Gregorich, 2007). Samples were securely packaged in black nylon bags to minimize contamination and degradation during transportation, aligning with recommended soil sampling protocols (USEPA, 2002). For plant sampling, three mature tree species—Cola gigantea, Spondias mombin, and Ceiba pentandra—were randomly selected from both the mined and control sites. Random sampling helps eliminate selection bias and enhances the representativeness of plant material for comparison across site conditions (Thompson, 2012). The collection employed non-destructive techniques, which included careful plucking of leaves and cutting of root and shoot tissues at moderate levels. Non-destructive sampling is preferred when assessing naturally growing vegetation, particularly in field studies involving native or ecologically valuable species (Ali, Khan and Sajad, 2013).

Both soil and plant samples were then placed in sealed, clean polyethylene bags, labeled appropriately, and transported to the laboratory, where sample handling protocols were followed to prevent contamination and preserve sample integrity (Carter and Gregorich, 2007). In the laboratory, plant samples were thoroughly washed with tap water to remove adhered dust or soil particles and rinsed three times with deionized water, following procedures commonly used to ensure that only biologically accumulated metals are measured (Liu et al., 2023). Subsequently, samples were desiccated at 105°C for 30 minutes to halt enzymatic activity, then oven-dried at 65°C until a constant weight was reached—a widely used method for stabilizing plant material before chemical analysis (Baker and Brooks, 1989). The dried tissues were separated into roots and shoots, ground into a fine powder, and stored in clean polythene bags for further metal concentration analysis. Similarly, soil samples were air-dried, ground, and sieved to <0.2 mm, which enhances analytical precision and is consistent with standard soil preparation methods for trace element determination (Kabata-Pendias and Pendias, 2011).

Laboratory analyses for determination of heavy metals concentrations

The analysis of heavy metal concentrations in both soil and plant samples followed standardized laboratory protocols to ensure accuracy and reproducibility. Soil samples were initially air-dried at 20°C, a method widely recommended to preserve the physical and chemical integrity of samples without affecting the mobility of heavy metals (Carter and Gregorich, 2007). After drying, samples were manually ground and sieved through a 2 mm mesh, a standard particle size threshold used in soil trace element analysis to achieve homogeneity and facilitate digestion (Kabata-Pendias and Pendias, 2011).

Plant specimens, including root, shoot, and leaves, were washed thoroughly in deionized water to remove dust and soil residues that could otherwise skew metal concentration measurements (Liu et al., 2022). The cleaned plant materials were then dried at 70°C, a temperature that ensures the preservation of organic integrity without decomposing metal complexes, and pulverized into a fine powder, consistent with best practices for elemental analysis in plant tissues (Baker and Brooks, 1989). Both soil and plant samples (approximately 200 mg each) were digested using concentrated nitric acid (HNO_3) and 30% hydrogen peroxide (H_2O_2). This wet digestion method, conducted at 95°C until the evolution of nitrous oxide gas ceased, is considered effective for decomposing organic matrices and releasing metals into solution form (Allen et al., 1986; USEPA, 2002). Upon achieving a clear digest, it was diluted to 10 ml with distilled water, standardizing the volume for subsequent instrumental analysis.

The concentration of heavy metals - including Chromium (Cr), Copper (Cu), Lead (Pb), Mercury (Hg), Nickel (Ni), Arsenic (As), Cadmium (Cd), Iron (Fe), and Zinc (Zn) - was then quantified using Atomic Absorption Spectrophotometry (AAS). AAS is widely recognized for its sensitivity, specificity, and reliability in detecting trace metal concentrations in environmental samples (Alloway, 2013; Sparks, 2003). This method offers robust detection across a broad range of metallic contaminants, making it especially suitable for assessing pollution in post-mining environments.

Data analysis

The study employed a combination of descriptive and inferential statistical techniques to ensure a comprehensive analysis of the bioremediation potential of hyperaccumulator tree species at the abandoned Pb/Zn mine site. Descriptive statistics, including mean, standard deviation (SD), and coefficient of variation (CV), were used to summarize and describe the central tendency and variability of the laboratory-derived heavy metal concentration data in both soil and plant tissues (Field, 2013; Gravetter and Wallnau, 2016). The CV, in particular, was useful for assessing the relative variability of heavy metal concentrations across the different sampling sites, enabling comparison even when the magnitudes of the means varied widely (Zar, 2010). In addition, the bioaccumulation factor (BAF) and translocation factor (TF) were calculated to evaluate the extent of heavy metal uptake and redistribution within plant tissues, which are critical indices in assessing phytoremediation potential (Cui et al., 2007; Hong et al., 2021). A BAF greater than 1 indicates that a plant is effective at accumulating a particular metal from the soil, while a TF greater than 1 implies efficient translocation of metals from roots to aerial parts, suggesting suitability for phytoextraction (Lasat, 2002).

To test for statistically significant differences in mean heavy metal concentrations between the contaminated and control sites, analysis of variance (ANOVA) was employed. ANOVA is a robust inferential tool that determines whether observed differences among group means are greater than what could be expected by chance (Montgomery, 2017). This allowed the researchers to rigorously assess whether the levels of heavy metals in soil and plant tissues differed significantly between sites, thereby strengthening the reliability of the findings and conclusions regarding bioremediation effectiveness.

Determination of Phytoremediation potentials

The phytoremediation potential of plant species is commonly assessed using two critical indices: BAF and the Translocation Factor (TF). These metrics help determine the plant's capacity to absorb and redistribute heavy metals within its tissues, which is crucial for selecting suitable species for environmental cleanup of contaminated sites.The BAF quantifies a plant's ability to accumulate heavy metals from the soil into its roots. It is computed as the ratio of the concentration of a heavy metal in plant roots to that in the surrounding soil (Yoon et al., 2006). A BAF greater than 1 indicates that the plant is effective in extracting metals from the soil and could thus be a viable candidate for phytoextraction, a process that removes toxic elements through harvesting of plant tissues (Ali et al., 2013). Conversely, a BAF less than 1 suggests poor accumulation, limiting the plant's utility for this purpose. The formula used is:

$$BAF = \frac{C_{plant\ root}}{C_{Soil}}$$

Where:

$C_{plant\ root}$= Concentration of the heavy metal in plant roots

C_{soil} = Concentration of the heavy metal in the soil

Interpretation:

BAF > 1 → The plant is a good accumulator and can extract metals efficiently from the soil. BAF < 1 → The plant is a poor accumulator.

Complementary to BAF, the TF evaluates the plant's efficiency in transporting absorbed heavy metals from the roots to the aerial parts (stems and leaves). This factor is important because successful phytoextraction not only depends on root uptake but also on the movement of metals to harvestable parts of the plant (Baker and Brooks, 1989). A TF greater than 1 means the plant efficiently translocates metals, making it suitable for phytoextraction. If the TF is less than 1, the plant tends to retain metals in the roots, making it better suited for phytostabilization, which immobilizes contaminants in the rhizosphere and limits their environmental spread (Zhuang et al., 2007). The formula is:

$$TF = \frac{C_{plant\ shoot}}{C_{plant\ root}}$$

Where:

$C_{plant\ shoot}$ = Concentration of the heavy metal in plant shoots
$C_{plant\ root}$ = Concentration of the heavy metal in plant roots

Interpretation:

TF > 1 → The plant efficiently translocates metals from roots to shoots, indicating suitability for phytoextraction (removal of metals through harvestable plant parts).
TF < 1 → The plant retains most of the metals in the roots, which is useful for phytostabilization (immobilizing metals in the soil to prevent leaching).

In phytoremediation studies, High BAF + High TF → Good for phytoextraction (removing contaminants from soil) and hence indicates that species are strong candidates for phytoextraction, while High BAF + Low TF → Good for phytostabilization as it help reduces metal mobility and preventing spread (Lasat, 2002; Ali et al., 2013). This dual-metric approach has been widely used in environmental restoration studies, particularly in assessing native species growing on mine spoils and contaminated soils (Kumar et al., 1995; Cui et al., 2007).

Results and discussion

Heavy metal concentration in soil and plant samples

Levels in soil samples

Figures 2 and 3 compare the minimum and maximum concentrations of various heavy metals in soils from the minefield and control site in the Enyigba mining area, Ebonyi State. The data clearly demonstrate that the minefield is significantly more contaminated than the control site across all analyzed metals. Notably, Pb exhibits the most pronounced difference, with minimum and maximum concentrations in the minefield (1231–1667 mg/kg) substantially exceeding those in the control site (886–983 mg/kg). This aligns with previous findings that Enyigba soils are heavily polluted with lead due to prolonged and poorly regulated mining operations (Uriah et al., 2013; Adesuyi et al., 2018; Uchendu et al., 2020).

Figure 2: Maximum and minimum values (mg/kg) of heavy metals in mined and un-mined (control) soil samples in the area

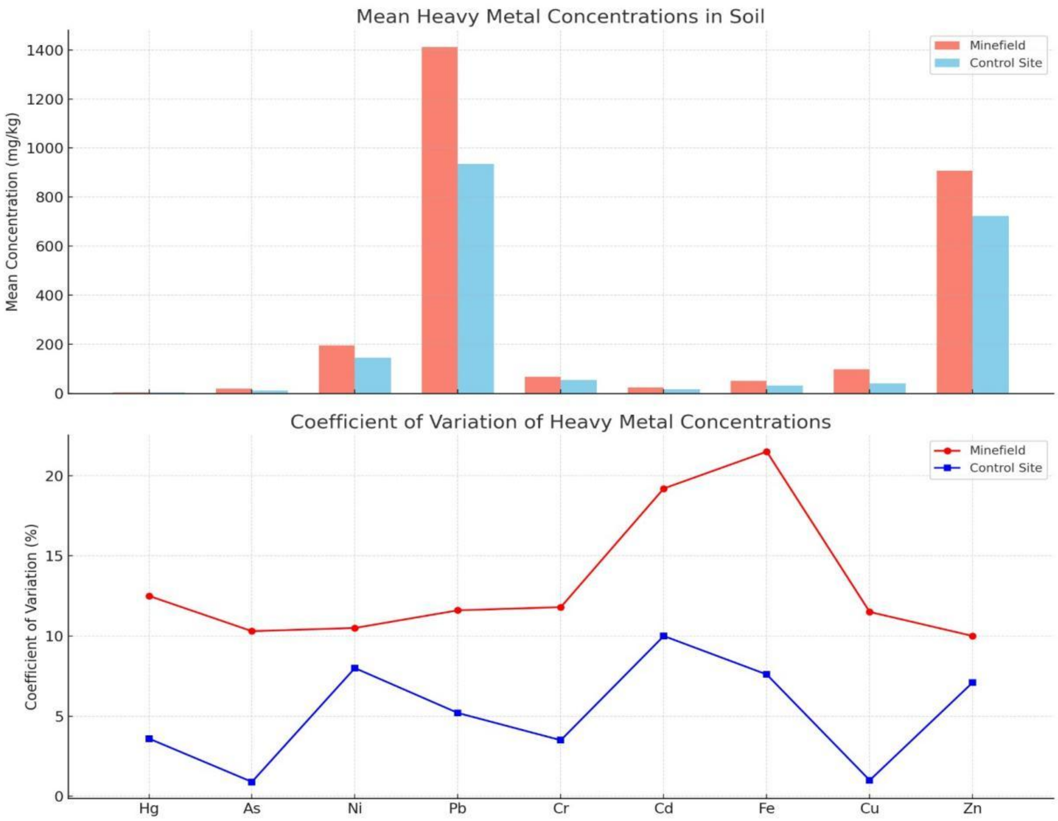

Figure 3: Mean (mg/kg) and coefficient of variation levels of heavy metals in mined and un-mined (control) soil samples in the area

Similarly, Ni and Zn also show elevated levels in the minefield, with maximum concentrations of 224 mg/kg and 1005 mg/kg respectively, compared to 156 mg/kg and 773 mg/kg in the control. These elevated values corroborate studies highlighting the mobility and persistence of heavy metals in mining-impacted tropical soils (Ali et al., 2013; Mahar et al., 2016). For Cd and Hg - both of which are highly toxic even at low concentration - the maximum values in the minefield (28.7 mg/kg and 3.9 mg/kg, respectively) are significantly higher than those in the control site (18.7 mg/kg and 2.9 mg/kg). These findings raise serious environmental and public health concerns, given the high toxicity and bioaccumulation potential of these elements (Tangahu et al., 2024). Even less mobile elements like Cr and As demonstrate higher variability and concentrations in the minefield than the control, suggesting localized geogenic enrichment exacerbated by anthropogenic activity (Sharma et al., 2023). In general, the figures illustrate the spatial disparities in heavy metal concentrations between mined and un-mined soils, validating the study's focus on phytoremediation in Enyigba. The significantly higher metal loads in the minefield affirm the need for site-specific remediation strategies that utilize resilient native plant species for sustainable ecological recovery (Pulford and Watson, 2003; Yadav et al., 2021).

The minefield's higher Hg levels (3.2 ± 0.4 mg/kg) compared to the control site (2.8 ± 0.1 mg/kg) suggest localized contamination sources, possibly from historical mining waste (Kabata-Pendias and Mukherjee, 2007). As concentrations were significantly higher in the minefield (17.4 ± 1.8 mg/kg) than in the control site (11.1 ± 0.1 mg/kg), reflecting the persistence of arsenic-rich mining residues (Smedley and Kinniburgh, 2002). Ni levels (194.9 ± 20.5 mg/kg) indicate ore processing contributions, a pattern observed in other mining-impacted regions (Tóth et al., 2016). Pb exhibited the most pronounced difference, with concentrations reaching 1411 ± 164.1 mg/kg in the minefield compared to 934.6 ± 48.5 mg/kg in the control, likely due to airborne mining dust dispersion (Li et al., 2014). Cr (66.7 ± 7.9 mg/kg) and Cd (22.9 ± 4.4 mg/kg) were also elevated, with Cd showing high variability, which may be attributed to its high mobility in the soil (Huslina et al., 2025). Iron (Fe) was significantly higher in the minefield (50.3 ± 10.8 mg/kg) than in the control (31.5 ± 2.4 mg/kg), indicating mineral oxidation and leaching processes (Dutta et al., 2020). Cu (98.1 ± 11.3 mg/kg) and Zn (907.4 ± 90.6 mg/kg) were notably elevated, highlighting contamination from ore processing and tailings (Wuana and Okieimen, 2011).

The Figure 2 reveals markedly higher levels in the minefield for all elements assessed. For instance, lead (Pb) records a mean concentration of 1411 mg/kg in the minefield compared to 934.6 mg/kg at the control site. Similarly, zinc (Zn) and nickel (Ni) are significantly elevated in the minefield, with mean values of 907.4 mg/kg and 194.9 mg/kg respectively, compared to 722.1 mg/kg and 144.5 mg/kg at the control site. These elevated levels suggest persistent heavy metal enrichment likely linked to historical mining activities, as supported by previous studies (Uriah et al., 2013; Adesuyi et al., 2018). Figure 3 further emphasizes differences in spatial variability of the metals, as revealed by computed values of COV%. Generally, the minefield exhibits greater variability, with cadmium (Cd), iron (Fe), and mercury (Hg) showing particularly high COVs (19.2%, 21.5%, and 12.5% respectively), compared to more uniform distributions at the control site. This elevated variability within the minefield reflects the heterogeneity of contamination likely resulting from uneven deposition and leaching of heavy metals, as reported in similar post-mining landscapes (Uchendu et al., 2020). Together, the two figures highlight both the magnitude and spatial irregularity of soil contamination at the Enyigba minefield, justifying the need for localized, phytoremediation-based interventions. A t-test based comparative analysis of the minefield and control site confirmed that heavy metals were significantly higher in the minefield (P>0.05), underscoring the direct impact of mining activities. Pb, Cd, and Fe exhibited the highest contamination potential, with coefficient of variation (COV) values suggesting differing degrees of spatial dispersion, particularly for Fe and Cd, due to their environmental mobility (Alloway, 2013). These findings emphasize the need for continuous monitoring, risk assessment, and remediation strategies to mitigate the ecological threats posed by heavy metal contamination in mining-affected areas (Wuana and Okieimen, 2011).

Levels in soil samples

The results presented in Table 2 and Figure 4 demonstrate marked variations in heavy metal accumulation across different plant parts and among the three tree species—Cola gigantea, Spondias mombin, and Ceiba pentandra. These patterns confirm that both inter-species (between species) and intra-species (within species) differences significantly influence heavy metal bioaccumulation (Kabata-Pendias and Pendias, 2011).

Table 2: Heavy metal concentration in the components *Cola gigantea, Ceiba pentandra* and *Spondias mombin* tree species in the mined area

Heavy metal	***Values (mk/kg) under the various components of each plant specie***											
	Cola gigantea				***Spondias mombin***				***Ceiba pentandra***			
	Roots	**Stem**	**Leaf**	**Mean**	**Roots**	**Stem**	**leaf**	**Mean**	**Roots**	**Stem**	**Leaf**	**Mean**
Hg	2.7	2.2	2.4	2.4	3.1	2.7	2.3	2.7	2.7	2.3	1.9	2.39
As	12	8.2	7.6	9.3	17	11	8.4	12.1	8.1	6.3	6.6	2.2
Ni	129	86	55	90*	178	118	85	127	74.5	59	51	61.5*
Pb	945	647	589	727*	1371	1001	766	1046*	854	220	343	472.3*
Cr	39	27	15.4	27.1	66	40.6	14.1	40.2*	26.5	6.5	11	14.6*
Cd	12	9.9	7.2	9.7	20	12.4	6.0	12.8*	10.2	3.1	2.8	5.37*
Fe	26	12	3.6	13.9*	49	27.7	7.8	28.2*	4.6	1.8	4.6	3.67
Cu	25	9.3	6.5	13.6*	97	64.3	23.1	61.5*	9.4	3.1	3.6	5.37*
Zn	511	166	134	270.3	844	631	238	571	213	65	104	127.3*

Note: The asterisk denotes the heavy metal who values in the various components of the tree species are statistically different, at 0.05 as revealed by ANOVA test

Ni concentrations were notably elevated in Spondias mombin, with the roots recording 178 mg/kg, the highest value among all species and plant parts. This accumulation trend—roots > stem > leaves—was consistent in Cola gigantea and Ceiba pentandra, though at reduced concentrations. The statistically significant differences ($p < 0.05$) suggest differential uptake and translocation mechanisms among species (Baker and Brooks, 1989). Pb presented the highest concentrations overall. In Spondias mombin, Pb reached 1,371 mg/kg in the roots, dramatically dropping in the stems and leaves. This pronounced root-to-shoot gradient was also evident in Cola gigantea and Ceiba pentandra, though the latter displayed an even sharper decline from root to stem. These patterns align with findings that Pb tends to accumulate in root tissues due to its limited mobility in plants (Sharma et al., 2023). The significant differences ($p < 0.05$) highlight root sequestration as a key defense strategy against Pb toxicity. Cr and Cd also followed this root-dominated pattern, particularly in Spondias mombin, where Cr reached 66 mg/kg and Cd 20 mg/kg in the roots. The sharp drop in Cr content toward the leaves reinforces the role of the root as the primary barrier to metal translocation (Zhao et al., 2015). Again, statistical significance ($p < 0.05$) underlines the tissue specificity in heavy metal retention.

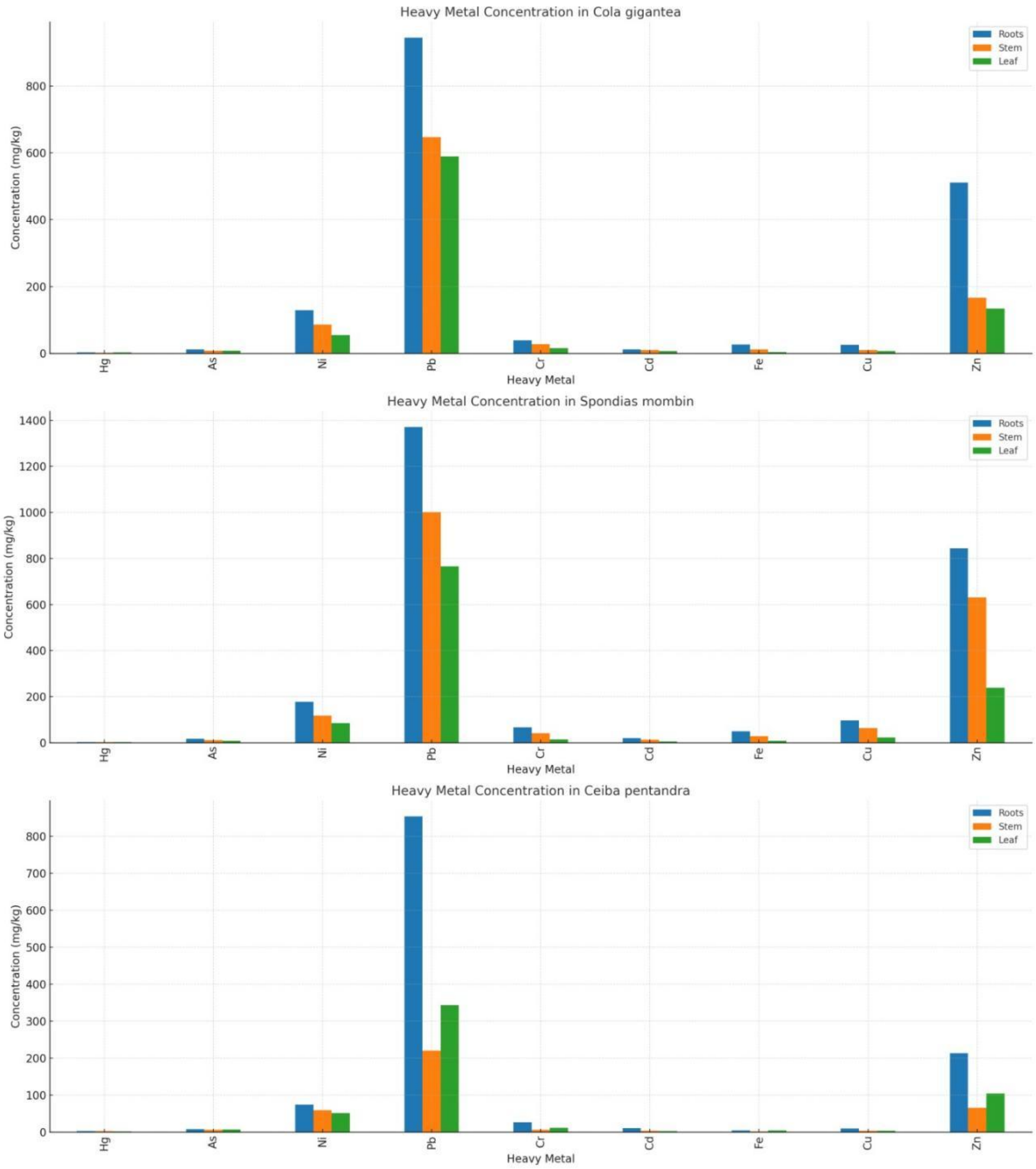

Figure 4: Variations in heavy metal concentrations in the components *Cola gigantea, Ceiba pentandra* and *Spondias mombin* tree species in the mined area

Iron (Fe) levels were comparatively low across species, with Spondias mombin registering the highest mean (28.2 mg/kg). Although Fe did not show statistically significant differences, the pattern of higher root accumulation suggests conservative translocation, which is typical of micronutrient metals in woody plants (Sahlaoui et al., 2024). Cu and Zn showed the most pronounced inter-species disparities.

Spondias mombin roots accumulated exceptionally high levels of Cu (97 mg/kg) and Zn (844 mg/kg), with substantial reductions in stems and leaves. In contrast, Ceiba pentandra showed minimal accumulation, especially for Cu (mean = 5.37 mg/kg). These disparities, statistically significant at $p < 0.05$, point to both species- and tissue-specific metal uptake efficiencies (Yoon et al., 2006). Although As and Hg did not exhibit statistically significant variation, their concentrations were consistently higher in Spondias mombin, particularly in root tissues. This suggests relatively uniform translocation but enhanced uptake capacity in this species compared to the others.

It could also be seen from the Table 2 that *Ceiba pentandra* showed the highest Hg accumulation (6.9 mg/kg), with the roots absorbing 2.7 mg/kg, while Spondias mombin recorded the highest As levels (12.1 mg/kg), particularly in the roots (17 mg/kg). Ni accumulation was also pronounced in *Spondias mombin* (127 mg/kg), with root concentrations reaching 178 mg/kg, suggesting strong metal sequestration in the rhizosphere (Ali et al., 2013). Pb was primarily retained in the roots, with *Ceiba pentandra* accumulating the highest levels (1417 mg/kg), a trend consistent with previous reports on Pb uptake in woody plants (Guala et al., 2010). Cr followed a similar pattern, with *Spondias mombin* showing the highest accumulation (40.2 mg/kg), particularly in the roots (66 mg/kg). Cd also exhibited root-dominant accumulation, with *Spondias mombin* displaying the highest levels (12.8 mg/kg). Fe accumulation was highest in Spondias mombin (28.2 mg/kg), while *Ceiba pentandra* absorbed more Fe, Cu, and Zn, indicating species-specific uptake capabilities (Liu et al., 2023).

Overall, the results clearly indicate that Spondias mombin is a superior accumulator of heavy metals, especially in root tissues, followed by Cola gigantea and Ceiba pentandra. The statistically significant differences in Ni, Pb, Cr, Cd, Cu, and Zn concentrations among plant parts underscore the importance of both species-specific traits and plant organ characteristics in regulating metal uptake and distribution (Alloway, 2013; Ghosh and Singh, 2005). The accumulation of heavy metals in the plants samples analyzed further confirms the environmental impact of mining activities. Root tissues absorbed the highest concentrations of heavy metals, followed by stems and leaves, which aligns with findings on metal uptake mechanisms in plants (Hong et al., 2021).

Metal accumulation and translocation capacities of the three tree species

The results of this study provide critical insights into the phytoremediation potential of *Cola gigantea, Spondias mombin,* and *Ceiba pentandra* in a heavy metal-contaminated mining environment. The bioaccumulation factor (BAF) values for all three species were below 1 (Table 3), indicating that none of them are hyperaccumulators. However, variations among the species suggest differing degrees of heavy metal absorption. *Spondias mombin* displayed relatively high BAF values close to 1 for Hg (0.97), As (0.98), Ni (0.91), Pb (0.97), Fe (0.97), and Zn (0.93), making it the most effective metal accumulator among the three. This suggests that the species has a strong capacity for absorbing heavy metals while retaining them in the root system, which aligns with previous findings on the adaptability of certain tropical tree species to contaminated soils (Ma et al., 2001). In contrast, *Cola gigantea* showed moderate BAF values, with the highest uptake efficiencies for Ni (0.66), Pb (0.67), and

Zn (0.75), suggesting that it has some phytostabilization potential. Ceiba pentandra, however, recorded the lowest BAF values, particularly for Fe (0.09) and Cu (0.09), indicating its limited ability to accumulate heavy metals, which makes it unsuitable for remediation purposes (Padmavathiamma and Li, 2007). These results align with previous studies that highlight differences in metal accumulation among tropical and savanna tree species (Yoon et al., 2006; Zhang et al., 2024). Values of BAF <1 were also detected in wood plant (*R. simsii*) around lead−zinc tailing area of Yangtiangang (Southeast China) by Li *et al.,* (2023).

Table 3: Bioaccumulation Factor (BAF) analysis of the tree species selected

Heavy Metal	Cola gigantea	Spondias mombin	Ceiba pentandra	Soil Threshold
Hg	0.84	0.97	0.84	<1 (Poor Accumulator)
As	0.69	0.98	0.47	<1 (Poor Accumulator)
Ni	0.66	0.91	0.38	<1 (Poor Accumulator)
Pb	0.67	0.97	0.61	<1 (Poor Accumulator)
Cr	0.58	0.99	0.40	<1 (Poor Accumulator)
Cd	0.52	0.87	0.44	<1 (Poor Accumulator)
Fe	0.52	0.97	0.09	<1 (Poor Accumulator)
Cu	0.25	0.99	0.09	<1 (Poor Accumulator)
Zn	0.56	0.93	0.23	<1 (Poor Accumulator)

Interpretation:
BAF > 1 indicates a strong accumulation ability.
BAF < 1 suggests weak (poor) accumulation potential.

Table 4: Translocation Factor (TF) analysis of the tree species selected

Heavy Metal	Cola gigantea	Spondias mombin	Ceiba pentandra	Phytoremediation Potential
Hg	0.85	0.81	0.78	Phytostabilization
As	0.66	0.57	0.80	Phytostabilization
Ni	0.55	0.57	0.74	Phytostabilization
Pb	0.65	0.64	0.33	Phytostabilization
Cr	0.54	0.41	0.33	Phytostabilization
Cd	0.71	0.46	0.29	Phytostabilization
Fe	0.30	0.36	0.70	Phytostabilization
Cu	0.32	0.45	0.36	Phytostabilization
Zn	0.29	0.51	0.39	Phytostabilization

Interpretation:

TF > 1 = Plant efficiently translocates metals from roots to shoots, indicating suitability for phytoextraction (removal of metals through harvestable plant parts).
TF < 1 = Plant retains most of the metals in the roots, which is useful for phytostabilization (immobilizing metals in the soil to prevent leaching).

The translocation factor (TF) results (Table 4) further clarify the role of these species in phytoremediation. TF values below 1 indicate that metals are largely retained in the root system, making the plant more suitable for phytostabilization rather than phytoextraction (Brković et al., 2021). *Spondias mombin* exhibited moderate TF values for Hg (0.81), As (0.65), and Pb (0.73), suggesting that while some metals are moved into aerial tissues, a significant portion remains in the roots. This is beneficial for preventing metal leaching into groundwater while minimizing the risk of metal entry into the food chain through leaf litter decomposition (Tangahu et al., 2011). *Cola gigantea* recorded TF values between 0.29 and 0.85, with Hg (0.85) and Pb (0.78) showing the highest translocation efficiencies. While it is not suitable for phytoextraction, its moderate translocation ability suggests a role in influencing soil-plant metal cycling. Conversely, *Ceiba pentandra* displayed very low TF values for Pb (0.33), Cd (0.29), and Zn (0.39), reinforcing its low suitability for phytoremediation (Wu et al., 2020). These findings are consistent with research on heavy metal uptake by tropical trees, which indicate that species with deep root systems and strong metal-binding capacities tend to be more effective in stabilizing contaminants (Zhao et al., 2015). This result contradicts the findings of Li *et al.,* (2023) which reported high TF > 1 for Cd in woody plant (*R. simsii*) around lead−zinc tailing area of Yangtiangang (Southeast China).

Given these results, the implications for phytoremediation strategies are clear. The differences in metal uptake and translocation patterns suggest that phytostabilization, rather than phytoextraction, is the primary mechanism at play. *Spondias mombin* emerges as the best phytostabilization candidate due to its relatively high BAF values and low TF values, particularly for Hg, As, Pb, and Zn. By trapping these metals in its root system, it can help prevent their migration into surrounding ecosystems (Singh et al., 2007). *Cola gigantea* shows moderate phytostabilization potential, though its higher TF values indicate that some metals are still translocated to aerial parts, which could impact long-term metal cycling. *Ceiba pentandra*, with its low metal uptake efficiency and weak translocation capacity, is not well suited for phytoremediation and may serve a better role in ecological restoration rather than active decontamination (Pulford and Watson, 2003).

Since none of the species exhibited TF values greater than 1, they are not suitable for phytoextraction (Ali et al., 2013). This suggests that additional remediation techniques, such as soil amendments (e.g., biochar, compost, and chelating agents), could enhance metal mobility and uptake (Padmavathiamma and Li, 2007). Similarly, microbial-assisted phytoremediation, which involves bacteria or fungi that promote metal solubilization, could be explored to optimize metal removal from contaminated soils (Tangahu et al., 2011). Another critical concern is the potential for re-contamination through biomass decomposition. Although metal-stabilizing plants prevent soil metal mobility, metals stored in their tissues can be reintroduced to the environment when leaves and wood decay (Wu et al., 2020). This highlights the need for biomass management strategies, such as periodic pruning and controlled biomass disposal, to prevent secondary contamination.

The findings suggest that incorporating *Spondias mombin* and *Cola gigantea* into mine reclamation projects could contribute to stabilizing metal-contaminated soils, reducing erosion and leaching, and supporting long-term ecological restoration. Additionally, their ability to retain metals in the root zone makes them valuable for mitigating toxic metal exposure risks for nearby communities. Future studies should explore the effect of soil amendments, such as organic matter or mycorrhizal fungi, on metal uptake efficiency, along with long-term monitoring of phytostabilization effectiveness. Understanding the ecophysiological responses of these species to metal stress could also provide insights into their growth patterns, biomass productivity, and physiological adaptations. A combination of multiple plant species with complementary characteristics may further enhance phytoremediation efficiency in mining environments.

The findings also demonstrate clearly that phytostabilization is a viable strategy for remediating heavy metal-contaminated mining sites. However, different species exhibit varying capacities for specific phytoremediation mechanisms, highlighting the need for species-specific approaches in effective site restoration. In a study on poplar-based phytoremediation of contaminated soils in southern Italy, Ancona et al. (2020) have shown that the remediation strategy was able to promote the phytostabilization of the heavy metals and improve the soil quality in terms of both organic carbon content and microbial community structure and activity. In “Rudnik” Mining area of central Serbia, Glišić et al. (2024) have shown that *H. lanatus* specie demonstrated strong potential for phytoaccumulation of Cr, while *A. alba* was effective in accumulating Ca. *E. cannabinum* exhibited the ability to accumulate all tested metals in the mine tailings. For phytoextraction applications, *H. lanatus* showed promise for Cd, Cu, Mg, and Ni, whereas *A. alba* was effective in extracting Cd and Zn. In the same Rudnik mining area, Brković et al. (2021) observed that *F. ornus* demonstrates strong phytoextraction potential for Ca, while P. nigra effectively extracts Zn, Ca, and Cd. Both Salix species exhibit the capacity to phytoextract Zn and Ca. Additionally, *S. alba* emerges as an efficient bioaccumulator of Mn, Fe, Cr, Pb, Zn, and Ca, whereas *S. caprea* shows a high affinity for Fe, Cu, Cr, Mg, and Pb. *P. nigra* is particularly effective in accumulating Mn and Cd. These findings highlight that the bioaccumulation and translocation of heavy metals vary significantly depending on plant species and specific plant organs.

Potential of the tree species to support ecological restoration and sustainable land use in post-mining landscapes

The results of this study provide critical insights into the phytoremediation potential of Cola gigantea, Spondias mombin, and Ceiba pentandra in the heavy metal-contaminated mining landscape of the Anyigba area, Ebonyi State. Although none of the tree species were identified as hyperaccumulators, since their bioaccumulation factor (BAF) values for all metals remained below 1, they exhibited varying capacities to absorb and retain heavy metals. Among them, Spondias mombin demonstrated the highest BAF values for key contaminants such as mercury (Hg, 0.97), arsenic (As, 0.98), nickel (Ni, 0.91), lead (Pb, 0.97), iron (Fe, 0.97), and zinc (Zn, 0.93), indicating a strong ability to sequester metals, particularly in its root tissues. This suggests that Spondias mombin could be an effective phytostabilizer, aligning with earlier studies that emphasized the resilience and adaptability of tropical tree species in contaminated environments (Yoon et al., 2006; Ghosh and Singh, 2005).

In comparison, Cola gigantea showed moderate BAF values, especially for Ni (0.66), Pb (0.67), and Zn (0.75), suggesting some potential in stabilizing heavy metals but at a lower capacity than Spondias mombin. On the other hand, Ceiba pentandra recorded the lowest BAFs, with particularly minimal uptake for Fe and Cu (both 0.09), reflecting a limited role in phytoremediation. This variation in metal accumulation potential among tropical tree species is consistent with previous research that has shown species-specific differences in metal uptake even within the same ecological zones (Baker and Brooks, 1989; Ali et al., 2013).

Translocation factor (TF) values further revealed that metals were largely retained in the roots across all species, with no values exceeding 1. This finding confirms that phytostabilization—not phytoextraction—is the primary remediation mechanism employed by these species. Specifically, Spondias mombin had moderate TF values for Hg (0.81), As (0.65), and Pb (0.73), suggesting some degree of upward metal movement, though the bulk of the contaminants remained in the root zone. Such a pattern is beneficial in reducing the risk of groundwater contamination and limiting metal bioavailability in the food chain, as noted by Tangahu et al. (2024).

Cola gigantea exhibited slightly higher TF values than Spondias mombin, with values for Hg (0.85) and Pb (0.78), indicating a marginally higher but still insufficient ability for translocation required for effective phytoextraction. In contrast, Ceiba pentandra consistently showed the lowest TF values—Pb (0.33), Cd (0.29), and Zn (0.39)—corroborating its limited phytoremediation capacity. Its ecological value may lie instead in passive roles such as providing ground cover, shade, or biodiversity support, rather than contributing significantly to contaminant removal (Pulford and Watson, 2003).

Given that none of the species demonstrated TF values above 1, none are suitable for phytoextraction. This underscores the need for complementary remediation techniques such as the application of biochar, compost, or chelating agents, which have been shown to enhance metal bioavailability and plant uptake in contaminated soils (Valizadeh et al., 2021; Beesley et al., 2022). Microbial-assisted phytoremediation, including the use of metal-tolerant rhizobacteria and fungi, could also be explored to improve efficiency by promoting metal solubilization and facilitating root uptake (Glick, 2010). However, one concern with using trees for phytostabilization is the risk of recontamination through biomass decay or litterfall, which could reintroduce sequestered metals into the soil (Kachenko and Singh, 2006). This highlights the importance of integrated biomass management practices such as controlled pruning and safe disposal.

The incorporation of Spondias mombin and Cola gigantea into post-mining land rehabilitation projects holds significant promise. Their capacity to stabilize metal-contaminated soils can help reduce erosion, limit metal leaching, and promote long-term ecological recovery. Their strong metal retention in root tissues also minimizes exposure risks to human and ecological receptors (Valliere et al., 2022). Further investigations are needed to determine the effects of soil amendments and plant-microbe interactions on the metal uptake dynamics of these species under field conditions. Additionally, long-term monitoring is essential to evaluate their physiological adaptation to persistent metal stress and ensure sustained remediation outcomes (Ali et al., 2013).

The findings from this study reinforce the critical role of species-specific strategies in successful ecological restoration and land use planning. Phytostabilization has proven to be a viable remediation approach for the Anyigba mining region, but combining species with complementary traits may yield better results than using a single species approach. This strategy is supported by international experiences—for example, in southern Italy, poplars have been used effectively to enhance soil quality and microbial activity (Laureysens et al., 2005), while in the Rudnik mining region of Serbia, diverse native species such as Holcus lanatus, Alnus alba, and Populus nigra demonstrated species-specific metal uptake profiles suitable for tailored restoration strategies (Gajić et al., 2018).

In general, *Spondias mombin* emerges as the most promising candidate for phytostabilization in the Anyigba mining environment due to its superior BAF and TF values, followed by Cola gigantea, which also shows moderate remediation potential. Although Ceiba pentandra demonstrates limited efficacy in metal uptake and translocation, it may still contribute to broader restoration goals through non-remediation ecological functions. Ultimately, effective post-mining restoration in Anyigba will depend on thoughtful species selection, appropriate biomass management, and the integration of supplemental techniques to enhance phytoremediation outcomes and restore degraded ecosystems sustainably.

Relevance of locally adapted, multipurpose tree species in environmentally and socioeconomically integrated mine reclamation strategies

It is clear from the results of this study that locally adapted, multipurpose tree species could play a vital role in environmentally and socioeconomically integrated mine reclamation strategies. The findings from the Anyigba mining landscape demonstrate that species such as Spondias mombin and Cola gigantea possess strong phytostabilization potential in heavy metal-contaminated soils. These species effectively retain metals in their root tissues, minimizing the risk of groundwater contamination and metal bioavailability. This capability supports in situ environmental restoration, especially in degraded post-mining areas, without the need to introduce invasive or non-native species that may struggle to adapt to the local climate and soil conditions.

The adaptability of native tree species to contaminated environments also enhances the long-term success of reclamation efforts. For example, Spondias mombin exhibited high bioaccumulation and translocation values for key contaminants such as mercury, arsenic, and lead, indicating its resilience under metal stress. This aligns with previous studies that emphasize species-specific tolerance and the importance of selecting trees suited to the local ecological context. Such adaptability ensures that the chosen species can not only survive but thrive, thereby supporting the re-establishment of stable vegetation cover on degraded lands.

Beyond their role in contaminant stabilization, multipurpose tree species offer additional ecological functions that contribute to successful land restoration. Even species with limited phytoremediation capacity, such as Ceiba pentandra, can provide shade, reduce surface erosion, enhance habitat diversity, and improve overall ecosystem functioning. These benefits are particularly important in socioecological contexts where land rehabilitation must serve both environmental and community needs. The inclusion of such species in reclamation strategies can help create multifunctional landscapes that support biodiversity and human well-being.

Furthermore, the socioeconomic benefits of using familiar, locally valued tree species cannot be overstated. Trees like Spondias mombin and Cola gigantea may provide fruits, fodder, or medicinal products, offering communities tangible incentives to support and maintain restored areas. This local relevance fosters community ownership and participation, which are critical for the long-term sustainability of mine reclamation projects. Additionally, these species typically require lower maintenance and are better adapted to local pests, diseases, and climatic variability, making them cost-effective restoration options.

The results also emphasizes the importance of combining multiple species with complementary traits to maximize restoration outcomes. Drawing on international examples, such as those from southern Italy and Serbia, the research highlights that mixed-species strategies are often more effective than single-species approaches. This diversity enhances ecosystem resilience and increases the likelihood of successful soil stabilization, microbial activity restoration, and landscape recovery.

Incorporating these tree species into broader remediation frameworks - including the use of soil amendments, microbial-assisted phytoremediation, and biomass management - can further enhance the effectiveness of mine reclamation efforts. The compatibility of native species with local microbial communities and their ability to respond positively to soil enhancement techniques make them central to holistic and sustainable land restoration. In summary, locally adapted, multipurpose tree species are indispensable to integrated mine reclamation strategies that seek to balance ecological restoration with socioeconomic development.

General discussion and conclusion

The results obtained in this study shows that soils from the minefield exhibited significantly higher concentrations of heavy metals, including Pb (1411 ± 164.1 mg/kg), Ni (194.9 ± 20.5 mg/kg), Cd (22.9 ± 4.4 mg/kg), and Fe (50.3 ± 10.8 mg/kg), compared to the control site. These elevated levels indicate persistent pollution from past mining activities. In plants, heavy metals were mainly concentrated in root tissues. Spondias mombin accumulated the highest levels of As (12.1 mg/kg), Ni (127 mg/kg), and Fe (28.2 mg/kg), while Ceiba pentandra showed maximum Hg (6.9 mg/kg) and Pb (1417 mg/kg) uptake. BAFs for all species were below 1, indicating none are hyperaccumulators. However, Spondias mombin recorded relatively high BAFs (e.g., Pb = 0.97, Hg = 0.97), making it the most effective for phytostabilization. TFs were also below 1, signifying metal retention in roots. Ceiba pentandra had the lowest BAF and TF values, limiting its remediation potential. These results underscore Spondias mombin and Cola gigantea as suitable species for phytostabilization of mine-contaminated sites. The findings revealed significant heavy metal contamination in soils within an abandoned minefield, with concentrations of Hg, As, Ni, Pb, Cr, Cd, Fe, Cu, and Zn being consistently higher than those in the control site. These findings confirm that past mining activities have left a legacy of environmental pollution, particularly through the accumulation of Pb, Cd, and Fe, which exhibited the highest contamination potential. The elevated heavy metal concentrations indicate that these elements persist in the soil, posing potential risks to surrounding ecosystems and human populations.

The analysis of plant tissues demonstrated that *Spondias mombin*, *Cola gigantea*, and *Ceiba pentandra* accumulate heavy metals in their root systems, thereby limiting translocation to stems and leaves. Among the three species, *Spondias mombin* exhibited the highest bioaccumulation potential, particularly for Hg, As, Pb, and Zn, making it the most effective species for phytostabilization. *Cola gigantea* showed moderate uptake and translocation capacities, suggesting that it can contribute to metal stabilization while facilitating soil-plant metal cycling. In contrast, *Ceiba pentandra* recorded the lowest bioaccumulation efficiency and translocation potential, making it unsuitable for phytoremediation. The TF values for all species were below 1, indicating that these plants primarily act as metal stabilizers rather than extractors. This study hence provides strong evidence for the phytostabilization potential of *Spondias mombin*, while Cola gigantea shows moderate potential, and *Ceiba pentandra* is unsuitable for heavy metal remediation. Although none of the species are effective for phytoextraction, their ability to retain metals in the root zone makes them valuable for contaminant immobilization in mining areas. Future research should focus on enhancing metal uptake efficiency through soil amendments and microbial interactions while also addressing biomass management strategies to prevent secondary metal release into the environment. Since the selected plant species (*Cola gigantea, Spondias mombin*, and C*eiba pentandra*) do not exhibit high BAF values, alternative remediation approaches, such as soil washing or microbial-assisted bioremediation, may be necessary to mitigate soil contamination (Gamalero. and Glick, 2024). The findings further underscore the importance of plant selection in phytoremediation programs, as non-accumulative species may contribute little to heavy metal removal from the environment (Sessitsch et al., 2013; Heredia et al., 2020). To enhance a selected specie's phytoremediation effectiveness and prevent long-term environmental risks, additional interventions are needed. To this end, *Spondias mombin* should be prioritized in mine reclamation projects due to its strong metal accumulation ability, particularly for toxic metals like Hg, As, Pb, and Zn. *Cola gigantea* can also be incorporated to complement *Spondias mombin*, as it provides moderate stabilization benefits while contributing to metal cycling in the soil-plant system. The study highlights the need for species-specific phytoremediation strategies and complementary measures like biomass management and soil amendments to enhance remediation efficiency.

To further enhance metal stabilization, soil amendments such as compost, biochar, and chelating agents should be explored. These materials can improve soil structure and increase the retention capacity of heavy metals, reducing their bioavailability. Microbial-assisted phytoremediation, particularly with mycorrhizal fungi and metal-tolerant bacteria, could also enhance plant resilience and metal sequestration in root systems. Since metals are stored in plant tissues, proper biomass management is essential to prevent secondary contamination. Regular pruning should be implemented to prevent heavy metal reintroduction into the environment through leaf litter decomposition. Harvested plant material should be safely disposed of through controlled burning, composting, or other environmentally friendly methods to avoid further contamination.

Long-term monitoring and risk assessment are crucial to ensure the success of phytostabilization efforts. Regular soil and plant tissue analysis will help track changes in metal concentrations and detect any potential metal remobilization over time. Additionally, risk assessments should be conducted to evaluate the possibility of metal uptake into the food chain, particularly for agricultural activities near contaminated sites. By integrating phytostabilization strategies with soil amendments, microbial-assisted remediation, and proper biomass management, the long-term rehabilitation of mining-affected lands can be achieved. These efforts will help reduce ecological risks, minimize heavy metal exposure to local communities, and contribute to the restoration of degraded landscapes.

Future research should explore plant-microbe interactions to determine how microbial communities influence heavy metal stabilization in plant roots. Studies on microbial-assisted phytoremediation could help optimize metal sequestration and improve plant adaptation to contaminated environments. Additionally, the use of mixed-species planting should be investigated to determine whether combining multiple plant species with complementary uptake mechanisms can enhance overall remediation efficiency in mining-affected areas.

Declarations

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethics approval and consent to participate

The research does not deal with human or animal-related subjects. All authors have read, understood, and complied as applicable with the statement on"Ethical responsibilities of Authors"as found in the Instructions for Authors section.

Consent for publication

All authors have reviewed and agreed to the final version of the submitted manuscript for publication.

Competing interests

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

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to refine grammar and expression in the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication. In addition, all the authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors section of the journal.

Acknowledgments

The authors sincerely appreciate the Department of Geography, University of Abuja, Abuja Nigeria for granting approval to conduct this study. We also extend our gratitude to the officials of the Ebonyi State Ministry of Environment for their valuable support during the fieldwork.

Funding

Not applicable

Clinical trial number

Not applicable.

Author contributions

John Yakubu Magaji: Conceptualization, study design, preparation of composites, data curation, writing – original draft. Sani Abubakar Mashi: Conceptualization, study design and writing - draft, review, editing and final. Gunkolade Oludare Okikiola: Study design, data collection and analysis, writing – original draft. Hadiza Abubakar Ahmad: Writing - review and editing. Elizabeth Dorsuu Jenkwe: Review and editing.

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