



Research Article

Phytoremediation Potentials of Selected Plant Species at Nigerian Defence Academy (NDA) Shooting Range, Kaduna State, Nigeria

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ABSTRACT

Environmental contamination by heavy metals from industrial and military activities poses serious ecological and human health risks, particularly in shooting ranges where ammunition residues accumulate. This study assessed the phytoremediation potential and molecular characteristics of selected plant species at the Nigerian Defence Academy (NDA) shooting range. Soil and plant samples were collected from polluted and control sites, analyzed for heavy metals (Cd, Cr, Cu, Pb, Ni, Zn, Mn), and translocation factors (TF) were calculated. Results indicated significant increases in Cu (67.65 ± 0.05 vs 26.55 ± 0.07 mg/kg), Cr (40.65 ± 2.05 vs 3.05 ± 2.05 mg/kg), Mg (111.50 ± 0.60 vs 54.60 ± 0.60 mg/kg), Ni (42.05 ± 0.85 vs 26.75 ± 0.85 mg/kg), Pd (21.700 ± 11.100 vs 33.400 ± 27.000) and Zn (46.55 ± 1.05 vs 21.45 ± 1.15 mg/kg) at polluted soils compared to controls, while Cd showed no significant difference. Among these plants, *Chamaecrista rotundifolia* exhibited high Cd and Zn accumulation with root-to-shoot TF > 1, indicating strong phytoextraction potential. *Waltheria indica* also exhibited high Cd and Zn accumulation with root-to-shoot TF > 1, indicating moderate phytoextraction potential. Furthermore, *Aeschynomene uniflora* demonstrated selective Pb, Cd, Zn, Mn, and Ni translocation, while *Eriosema psoraleoides* and *Isoberlinia doka* primarily exhibited phytostabilization traits. The findings highlight species-specific strategies in metal uptake, translocation, and stabilization. Future studies should include genomic analyses to identify metal tolerance genes in these promising species.

Keywords: Heavy metals; Metal accumulation; Phytoextraction; Phytoremediation; Phytostabilization; Soil contamination; Translocation factor

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INTRODUCTION

Environmental contamination has emerged as a major global concern due to the continuous release of pollutants from industrial, agricultural, mining, and military activities. The accumulation of toxic substances in soil and water ecosystems threatens biodiversity, disrupts ecological processes, reduces soil productivity, and poses significant risks to human health through bioaccumulation and food-chain transfer (FAO and UNEP, 2021; Khan *et al.*, 2021;

Persson *et al.*, 2021). Among environmental pollutants, heavy metals are particularly problematic because of their persistence, toxicity, and non-biodegradable nature. Metals such as cadmium (Cd), lead (Pb), chromium (Cr), copper (Cu), nickel (Ni), Manganese (Mn), and zinc (Zn) can accumulate in soils and adversely affect microbial communities, plant growth, ecosystem stability, and public health (Elnabi *et al.*, 2023; Nnaji *et al.*, 2023).

Military training grounds and shooting ranges are recognized as important sources of heavy metal contamination due to the prolonged deposition of ammunition residues, metallic fragments, and explosive-related compounds. These activities often result in elevated concentrations of Pb, Cu, Cr, Mn, and Ni in soils, creating long-term environmental challenges that require effective remediation strategies (Zhu *et al.*, 2024). Conventional remediation methods, including soil excavation, chemical treatment, and soil washing, are often expensive, energy-intensive, and environmentally disruptive, limiting their applicability for large contaminated areas (Khalid *et al.*, 2021; Wu *et al.*, 2022).

Phytoremediation has gained increasing attention as a sustainable and environmentally friendly alternative for the remediation of contaminated environments. This technology utilizes plants and their associated rhizosphere microorganisms to absorb, accumulate, stabilize, or detoxify pollutants from soil and water systems (Yadav *et al.*, 2020; Sharma *et al.*, 2023). The effectiveness of phytoremediation depends largely on the ability of plants to tolerate and accumulate contaminants, as well as their capacity to translocate metals from roots to shoots. Processes such as phytoextraction, phytostabilization, and rhizofiltration are commonly employed to reduce contaminant mobility and environmental risk. The suitability of plants for phytoremediation is often evaluated using indices such as the Bioconcentration Factor (BCF), Translocation Factor (TF), and Enrichment Factor (EF), which provide insight into metal uptake and distribution within plant tissues (Wu *et al.*, 2022; Sharma *et al.*, 2023).

Despite growing interest in phytoremediation, information on the remediation potential of indigenous plant species in military-contaminated environments in Nigeria remains limited. Most studies have focused on exotic hyperaccumulator species, with relatively little attention given to native plants that may possess superior adaptation and resilience under local ecological conditions (Raza *et al.*, 2021; Wu *et al.*, 2022). Therefore, this study investigated the phytoremediation potential of selected indigenous plant species growing within the Nigerian Defence Academy (NDA) shooting range, Kaduna State. Specifically, the study evaluated soil physicochemical properties, heavy metal

concentrations, and the accumulation and translocation capacities of selected plant species. We hypothesized that native plants at the NDA shooting range would exhibit species-specific differences in metal uptake and translocation, with some showing $TF > 1$ indicative of phytoextraction potential. The findings are expected to contribute to the identification of suitable indigenous phytoremediators for the sustainable restoration and management of heavy metal-contaminated military environments.

MATERIALS AND METHODS

Study Area

The study site, the NDA permanent site, is located in Afaka, Kaduna, Kaduna State. The area lies between latitude 10.607°N and 10.633°N, and longitude 7.363°E and 7.392°E (Figure 1). The region is semi-arid with sparse vegetation during the dry season and portrays a typical savannah biome. A green vegetative strip is visible along the riverine area northwest of the study site. The red rectangular box outlines the study area (shooting range), indicating the precise location within the NDA landscape targeted for analysis. Geologically, the study area is situated within the Basement Complex of northern Nigeria, which is predominantly composed of igneous and metamorphic rocks such as granites, migmatites, gneisses, and schists (Rahaman, 1988; Obaje, 2009).

Sample Collection and Preparation

The research was conducted at the Nigerian Defence Academy (NDA), Afaka, Kaduna State. Soil and Plant samples were collected from the shooting range and a control site, 20km away from the shooting range site (Botanical Garden), to ensure minimal or no influence of contamination from the NDA shooting range through atmospheric dispersion, runoff transport, and dust deposition of heavy metals or explosive residues from the shooting range

Soil sample collection, preparation, and analysis

Soil sample collection

Soil samples were randomly collected from four points at each study site using a soil auger at a depth of 0-15 cm, corresponding to the active root zone where metal accumulation is most pronounced. The subsamples were homogenized to form composite samples, which were then transported to the Kaduna State Ministry of Agriculture for laboratory preparation and analysis.

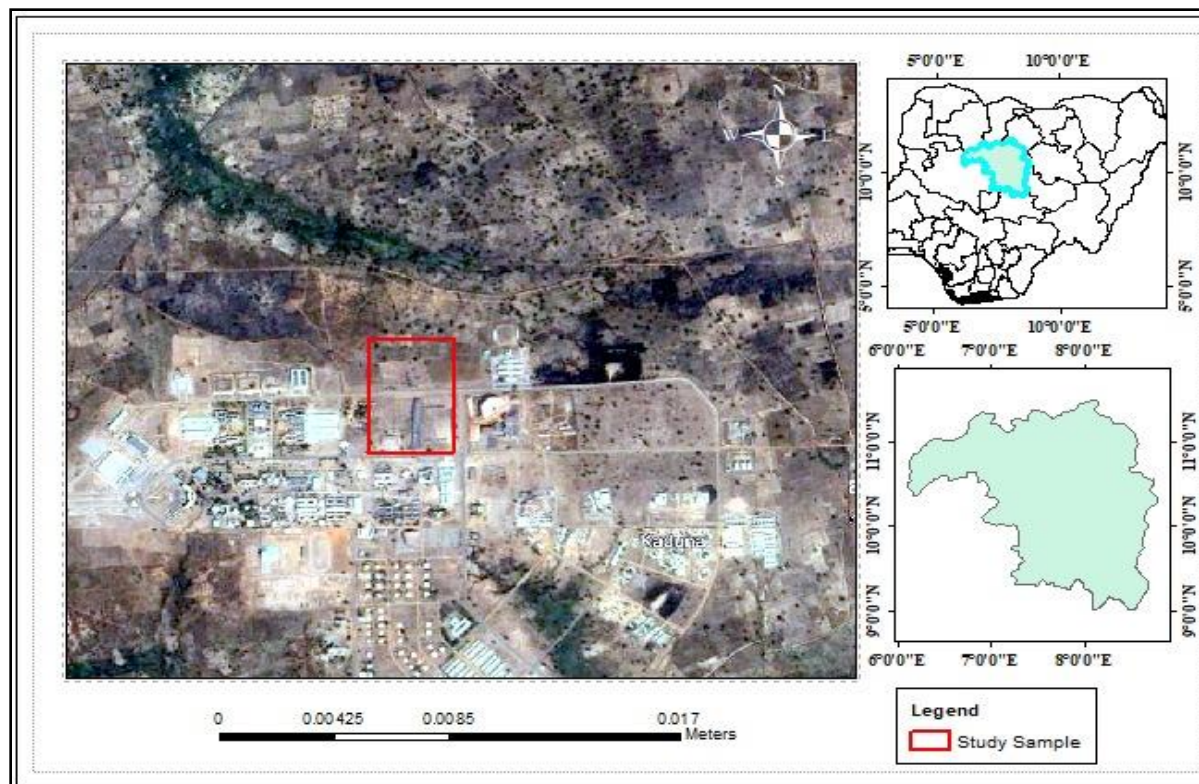


Figure 1: Map of NDA permanent site Afaka, Kaduna State, showing study sites

Source: Geography Department, Kaduna State University, Kaduna

Soil preparation and digestion

Sample preparation followed Jaiswal (2011). Approximately 10 g of each soil sample was oven-dried at 100°C for 1 hour, pulverized using a porcelain mortar and pestle, and sieved through a 250 µm mesh to ensure uniformity.

For metal extraction, 10 g of prepared soil was digested using a tri-acid mixture of H₂SO₄, HClO₄, and HNO₃ in a 5:1:1 ratio. Twenty millilitres of the acid mixture were added, and digestion was carried out on a hot plate at ~80°C in a fume chamber until near dryness. The digests were filtered into 100 cm³ volumetric flasks and made up to volume with deionized water before storage for analysis (Alloway *et al.*, 1990).

Determination of Heavy Metals and Physicochemical Properties

Heavy metals (Pb, Cu, Zn, Ni, Cr, Mn, and Cd) were quantified using Atomic Absorption Spectrophotometry (AAS) as described by Nouri *et al.* (2009), due to its sensitivity for trace metal detection. Soil pH was determined using a 2.5:1 water-soil suspension (20 g soil + 50 mL deionized water) after equilibration, using a calibrated pH meter. Electrical

conductivity (EC) was measured from the same suspension supernatant using a conductivity meter following settling (Rhoades, 1982).

Plant Sampling and Analysis

Plant sample collection and preparation

Representative plant species (trees, shrubs, herbs, and grasses) were collected using simple random sampling. Shoots and roots of trees and shrubs were harvested using a cutlass, while herbs and grasses were uprooted intact. Samples were washed with tap water followed by deionized water, identified and authenticated at the herbarium, then oven-dried at 70°C to constant weight (Larry and Morgan, 1986). Dried materials were ground into fine powder for analysis.

Digestion and heavy metal determination in plants

Approximately 10 g of plant powder was digested using the same tri-acid mixture and procedure described for soil samples. The digests were filtered into 100 cm³ volumetric flasks and diluted to volume with deionized water. Concentrations of Pb, Cu, Zn, Ni, Cr, Mn, and Cd were determined using AAS (Nouri *et al.*, 2009), with separate analysis for roots and

shoots to assess accumulation and distribution patterns.

Translocation Factor

Metal mobility within plants was assessed using the translocation factor (TF) (Nouri, 2009; Fayiga and Ma, 2006), calculated as:

$$TF = C.Shoot / C.Root$$

Where:

C = concentration of the metal in the shoot tissue

C = concentration of the metal in the root tissue

A TF value greater than one ($TF > 1$) indicates efficient translocation of metals from roots to shoots and suggests phytoextraction potential, whereas a TF value less than one ($TF < 1$) indicates greater retention of metals in the roots, reflecting phytostabilization capability.

Data Analysis

All experiments were performed in triplicate, and the data obtained from the study were subjected to Analysis of Variance (ANOVA) to determine the significant differences, and the values obtained are presented in \pm SEM (Standard Error of the Mean) computed with SPSS (Statistical Package for Social Sciences; version 23.0). The least significant difference (LSD) test was used to compare the treatments, where $P < 0.05$ levels were considered significant.

RESULTS

Heavy Metal Concentration in Soil Samples

The concentration of various heavy metals in soil samples of the controlled site and the polluted site is presented in Table 1. Heavy metal analysis showed consistently higher concentrations in the polluted site compared to the control for most elements. Cd showed no significant difference between the control (10.650 ± 1.750) and the polluted site (12.450 ± 1.750). Marked increases were observed in Cu (26.550 ± 0.070 vs 67.650 ± 0.050), Cr (3.050 ± 2.050 vs 40.650 ± 2.050), Mn (54.600 ± 0.600 vs 111.500 ± 0.600), and Ni (26.750 ± 0.850 vs 42.050 ± 0.850), all significantly elevated at the polluted site. Similarly, Pb (21.700 ± 11.100 vs 33.400 ± 27.000) and Zn (21.450 ± 1.150 vs 46.550 ± 1.050) were significantly higher in polluted soils, indicating clear anthropogenic enrichment across most metals assessed.

Physicochemical Parameters

The pH and electrical conductivity (EC) results are presented in Figures 2 and 3. The results show slight differences in both pH and electrical conductivity (EC) between the control and polluted soil samples. The pH values of the soils are 6.80 for the control and 6.90 for the polluted sample, indicating that both soils are

slightly acidic to near neutral. In contrast, a more noticeable difference is observed in the electrical conductivity values due to little or no soluble salt buildup. The polluted soil has a higher EC (0.0359 dS/m) compared to the control soil (0.0234 dS/m). Electrical conductivity reflects the concentration of soluble salts and ions in the soil.

Concentration of the Heavy Metals in Plant Samples **Cadmium (Cd) Concentrations in Selected Plant Samples**

Table 2 shows cadmium (Cd) concentrations in shoots and roots of different plant species under controlled and polluted conditions, revealing species-dependent uptake patterns. Cd accumulation showed clear species-specific responses across control and polluted sites. *Aeschynomene uniflora* and *Eriosema psoraleoides* exhibited relatively stable Cd levels across both conditions, with no marked variation between shoots and roots. Under polluted conditions, *Chamaecrista rotundifolia* and *Waltheria indica* showed increased shoot Cd accumulation (21.200 ± 1.600 and 22.600 ± 1.600 , respectively), while root responses were variable, including a slight reduction in *W. indica* (15.700 ± 1.700). In contrast, *Isobertinia doka* recorded reduced Cd concentrations in both shoots and roots under pollution stress, indicating lower uptake under contaminated conditions. A statistically significant difference was observed between the concentration in the shoot of the plant of the controlled site and the root of the plants of the polluted site.

Copper (Cu) Concentration in Selected Plant Samples

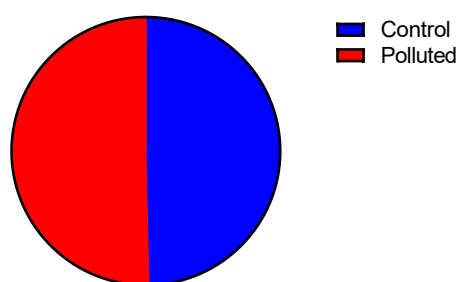
Table 3 shows clear species-specific differences in copper (Cu) distribution between shoots and roots under controlled and polluted conditions. Cu distribution showed strong species-dependent patterns, with roots generally exhibiting higher concentrations than shoots under control conditions, particularly in *Chamaecrista rotundifolia* (26.850 ± 2.050) and *Waltheria indica* (56.300 ± 2.100), while *Eriosema psoraleoides* recorded the lowest levels overall (25.100 ± 2.000). Under polluted conditions, Cu accumulation increased markedly in *C. rotundifolia* (56.700 ± 3.000) and *W. indica* (72.650 ± 2.850), with pronounced enrichment in roots, indicating strong belowground sequestration. *Eriosema psoraleoides* showed increased shoot Cu but reduced root levels 20.800 ppm, suggesting enhanced translocation. *Aeschynomene uniflora* exhibited a slight increase in shoot Cu with reduced root concentration, indicating internal redistribution, whereas *Isobertinia doka* showed reduced shoot Cu (23.250 ± 1.950) and only

marginal root increase, reflecting limited uptake and translocation under pollution stress.

Table 1: Concentration of some heavy metals in the soil samples of the polluted and controlled sites

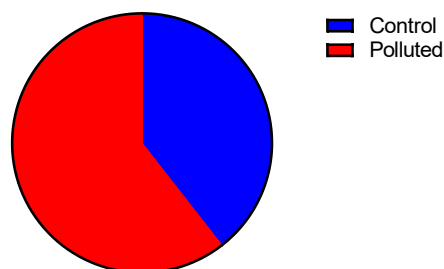
| Heavy Metal | Controlled Site | Polluted Site |
|----------------|------------------------------|------------------------------|
| Cadmium (Cd) | 10.650 ± 1.750 ^a | 12.450 ± 1.750 ^a |
| Copper (Cu) | 26.550 ± 0.070 ^b | 67.650 ± 0.050 ^a |
| Chromium (Cr) | 3.050 ± 2.050 ^a | 40.650 ± 2.050 ^a |
| Manganese (Mn) | 54.600 ± 0.600 ^a | 111.500 ± 0.600 ^a |
| Nickel (Ni) | 26.750 ± 0.850 ^a | 42.050 ± 0.850 ^a |
| Lead (Pb) | 21.700 ± 11.100 ^a | 33.400 ± 27.000 ^b |
| Zinc (Zn) | 21.450 ± 1.150 ^b | 46.550 ± 1.050 ^a |

Values are expressed as mean ± SEM. Statistical significance of the mean difference was considered at p<0.05, and the LSD comparison test was used for post hoc analysis. Values bearing different superscripts across the same row are significantly different.



Total=13.7

Figure 2: pH of the Soil samples



Total=0.0593

Figure 3: Electrical conductivity of the Soil samples

Table 2: Cadmium (Cd) concentration (ppm) in some selected plant samples at the polluted and controlled site

| Plants | Controlled Site | | Polluted Site | |
|------------------------|-----------------------------|------------------------------|-----------------------------|------------------------------|
| | Shoot | Root | Shoot | Root |
| <i>C. rotundifolia</i> | 17.850 ± 1.650 ^a | 17.350 ± 1.650 ^a | 21.200 ± 1.600 ^b | 21.000 ± 1.600 ^b |
| <i>W. indica</i> | 9.850 ± 1.750 ^a | 16.950 ± 1.650 ^b | 22.600 ± 1.600 ^c | 15.700 ± 1.700 ^c |
| <i>A. uniflora</i> | 17.400 ± 1.700 ^a | 18.450 ± 1.650 ^{ab} | 20.650 ± 1.650 ^c | 18.250 ± 1.650 ^{ab} |
| <i>E. psoraleoides</i> | 19.900 ± 1.600 ^a | 16.850 ± 1.650 ^b | 21.000 ± 1.600 ^c | 21.050 ± 1.650 ^c |
| <i>I. doka</i> | 10.050 ± 1.75 ^a | 11.800 ± 1.700 ^a | 15.000 ± 1.700 ^b | 13.400 ± 1.700 ^c |

Values are expressed as mean ± SEM. Statistical significance of the mean difference was considered at p<0.05, and the LSD comparison test was used for post hoc analysis. Values bearing the same superscripts are significantly different from each other across the rows.

Chamaecrista rotundifolia = *C. rotundifolia*; *Waltheria indica* = *W. indica*; *Aeschynomene uniflora* = *A. uniflora*; *Eriosema psoraleoides* = *E. psoraleoides*; *Isobерlinia doka* = *I. doka*.

Table 3: Copper (Cu) concentration (ppm) in some selected plant samples at the polluted and controlled site

| Plants | Controlled Site | | Polluted Site | |
|------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| | Shoot | Root | Shoot | Root |
| <i>C. rotundifolia</i> | 14.100 ± 2.100 ^a | 26.850 ± 2.050 ^b | 79.800 ± 3.000 ^c | 56.700 ± 3.000 ^e |
| <i>W. indica</i> | 40.500 ± 2.100 ^a | 56.300 ± 2.100 ^b | 68.050 ± 2.950 ^c | 72.650 ± 2.850 ^d |
| <i>A. uniflora</i> | 48.650 ± 2.050 ^a | 25.600 ± 2.000 ^b | 53.350 ± 2.950 ^c | 44.550 ± 1.950 ^a |
| <i>E. psoraleoides</i> | 17.650 ± 2.050 ^a | 25.100 ± 2.000 ^b | 56.450 ± 1.950 ^c | 20.800 ± 1.900 ^d |
| <i>I. Doka</i> | 30.600 ± 2.000 ^a | 45.700 ± 2.000 ^b | 23.250 ± 1.950 ^c | 29.750 ± 1.950 ^a |

Values are expressed as mean ± SEM. Statistical significance of the mean difference was considered at $p < 0.05$, and the LSD comparison test was used for post hoc analysis. Values bearing the same superscripts are significantly different from each other across the rows.

Chamaecrista rotundifolia = *C. rotundifolia*; *Waltheria indica* = *W. indica*; *Aeschynomene uniflora* = *A. uniflora*; *Eriosema psoraleoides* = *E. psoraleoides*; *Isobерlinia doka* = *I. doka*

Chromium (Cr) Concentration in Selected Plant Samples

Table 4 shows marked variation in chromium (Cr) accumulation among plant species at both controlled and polluted sites. At the control site, *Aeschynomene uniflora* shows the highest shoot Cr (76.450 ± 7.550), while *Waltheria indica* and *A. uniflora* exhibit the highest root accumulation; *Isobерlinia doka* records the lowest values (8.050 ± 2.550) overall. Under polluted conditions, Cr concentrations decline in both shoots and roots across most species, most notably in *Chamaecrista rotundifolia* and *A. uniflora*. *W. indica* retains comparatively higher shoot and root levels but still shows a marked reduction from control values.

Manganese (Mn) in Selected Plant Samples

Table 5 presents the Manganese concentration in the shoots at the controlled site, which shows variation across species. At the control site, shoot Mn is highest in *Chamaecrista rotundifolia* (986.100 ± 0.500), followed by *Waltheria indica* and *Aeschynomene uniflora*, while *Eriosema psoraleoides* records the lowest levels (744.050 ± 0.350). Root Mn shows a similar trend, with *C. rotundifolia* highest and *E. psoraleoides* consistently lowest across tissues. Under polluted conditions, shoot Mn generally decreases in most species (*C. rotundifolia*, *A. uniflora*, *E. psoraleoides*, and *I. doka*), while *W. indica* shows a marked increase, becoming the dominant shoot accumulator. Root Mn shifts toward higher retention in *Isobерlinia doka*, followed by *W. indica* and *A. uniflora*, with *E. psoraleoides* remaining lowest.

Nickel (Ni) Concentration in Selected Plant Samples

Nickel (Ni) concentrations in various plant species at both controlled and polluted sites are presented in Table 6. At the control site, *Chamaecrista rotundifolia*

and *Eriosema psoraleoides* show the highest shoot Ni, while *Aeschynomene uniflora* records the lowest (9.400 ± 3.100). Root concentrations are generally higher than shoots, with *A. uniflora* showing the greatest root accumulation and *Waltheria indica* the lowest. Under polluted conditions, Ni accumulation increases markedly in *E. psoraleoides* (highest in both shoots and roots), followed by *A. uniflora*. *C. rotundifolia* shows reduced shoot Ni but elevated root retention, while *W. indica* exhibits moderate increases in both tissues. *Isobерlinia doka* consistently records the lowest shoot Ni levels (32.150 ± 6.950).

Lead (Pb) Concentration in Selected Plant Samples

The data in Table 7 indicate clear species-specific differences in lead (Pb) uptake and translocation between controlled and polluted sites, with distinct patterns observed in both shoots and roots. At the control site, *Aeschynomene uniflora* records the highest shoot Pb (72.550 ± 5.050), while *Eriosema psoraleoides* shows the highest root accumulation; *Chamaecrista rotundifolia* has the lowest root Pb (11.800 ± 5.100) overall. Under polluted conditions, shoot Pb remains highest in *A. uniflora* (85.800 ± 4.200), with an overall increase, while *C. rotundifolia* and *Isobерlinia doka* show reduced shoot levels. Root Pb increases markedly in *C. rotundifolia* and *E. psoraleoides*, indicating strong root sequestration, whereas *Waltheria indica* records the lowest root accumulation (9.700 ± 0.200).

Zinc (Zn) Concentration in Selected Plant Species

Zinc (Zn) concentrations in various plant species at both controlled and polluted sites are presented in Table 8. At the control site, *Chamaecrista rotundifolia* shows the highest shoot Zn (64.800 ± 2.100), while *Aeschynomene uniflora* records the lowest; roots are highest in *Eriosema psoraleoides* and lowest in *C.*

rotundifolia and *A. uniflora*. Under polluted conditions, shoot Zn increases markedly in *Waltheria indica*, *C. rotundifolia*, and *A. uniflora*, while *E. psoraleoides* and *Isobertinia doka* show reduced

shoot levels. Root Zn is highest in *I. doka*, followed by *W. indica* and *C. rotundifolia*, whereas *A. uniflora* shows a notable decline and *E. psoraleoides* a slight reduction (46.150 ± 0.050).

Table 4 Chromium (Cr) concentration (ppm) in some selected plant samples at the polluted and controlled site

| Plants | Controlled Site | | Polluted Site | |
|------------------------|-----------------------------|------------------------------|------------------------------|------------------------------|
| | Shoot | Root | Shoot | Root |
| <i>C. rotundifolia</i> | 60.250 ± 7.550 ^a | 42.950 ± 7.550 ^{ab} | 10.300 ± 2.800 ^{ac} | 32.600 ± 2.800 ^{ad} |
| <i>W. indica</i> | 8.750 ± 7.550 ^a | 65.950 ± 7.550 ^b | 48.600 ± 2.800 ^c | 13.850 ± 2.750 ^d |
| <i>A. uniflora</i> | 76.450 ± 7.550 ^a | 53.950 ± 2.550 | 8.300 ± 2.800 | 8.750 ± 1.350 ^d |
| <i>E. psoraleoides</i> | 30.050 ± 2.550 ^a | 20.250 ± 2.550 ^b | 19.100 ± 1.400 | 20.050 ± 1.350 ^d |
| <i>I. doka</i> | 8.050 ± 2.550 ^a | 4.350 ± 2.550 ^b | 18.050 ± 1.350 | 10.050 ± 1.350 ^d |

Values are expressed as mean ± SEM. Statistical significance of the mean difference was considered at $p < 0.05$, and the LSD comparison test was used for post hoc analysis. Values bearing the same superscripts are significantly different from each other across the rows.

Chamaecrista rotundifolia = *C. rotundifolia*; *Waltheria indica* = *W. indica*; *Aeschynomene uniflora* = *A. uniflora*; *Eriosema psoraleoides* = *E. psoraleoides*; *Isobertinia doka* = *I. doka*.

Table 5: Manganese (Mn) concentration (ppm) in some selected plant samples at the polluted and controlled site

| Plants | Controlled Site | | Polluted Site | |
|------------------------|------------------------------|------------------------------|-------------------------------|------------------------------|
| | Shoot | Root | Shoot | Root |
| <i>C. rotundifolia</i> | 986.100 ± 0.500 ^a | 810.550 ± 0.550 ^b | 830.900 ± 0.400 ^c | 745.550 ± 0.350 ^d |
| <i>W. indica</i> | 952.350 ± 0.550 ^a | 738.800 ± 0.500 ^b | 1029.250 ± 0.350 ^c | 838.450 ± 0.350 ^d |
| <i>A. uniflora</i> | 852.850 ± 0.550 ^a | 714.800 ± 0.400 ^b | 957.650 ± 0.350 ^c | 818.200 ± 0.800 ^d |
| <i>E. psoraleoides</i> | 744.050 ± 0.350 ^a | 624.100 ± 0.400 ^b | 747.100 ± 0.800 ^a | 614.300 ± 0.800 ^c |
| <i>I. doka</i> | 805.900 ± 0.400 ^a | 889.850 ± 0.350 ^b | 867.300 ± 0.800 ^c | 899.400 ± 0.800 ^d |

Values are expressed as mean ± SEM. Statistical significance of the mean difference was considered at $p < 0.05$, and the LSD comparison test was used for post hoc analysis. Values bearing the same superscripts are significantly different from each other across the rows.

Chamaecrista rotundifolia = *C. rotundifolia*; *Waltheria indica* = *W. indica*; *Aeschynomene uniflora* = *A. uniflora*; *Eriosema psoraleoides* = *E. psoraleoides*; *Isobertinia doka* = *I. doka*.

Table 6: Nickel (Ni) concentration (ppm) in some selected plant samples at the polluted and controlled sites

| Plants | Controlled Site | | Polluted Site | |
|------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| | Shoot | Root | Shoot | Root |
| <i>C. rotundifolia</i> | 44.200 ± 3.100 ^a | 35.050 ± 3.150 ^b | 33.200 ± 0.000 ^b | 51.000 ± 0.000 ^c |
| <i>W. indica</i> | 30.500 ± 0.000 ^a | 6.600 ± 0.000 ^b | 39.900 ± 0.000 ^c | 35.900 ± 0.000 ^c |
| <i>A. uniflora</i> | 9.400 ± 3.100 ^a | 42.050 ± 2.550 ^b | 50.300 ± 0.000 ^c | 41.600 ± 6.900 ^b |
| <i>E. psoraleoides</i> | 45.700 ± 2.600 ^a | 32.100 ± 2.600 ^b | 54.950 ± 6.950 ^c | 56.350 ± 6.950 ^c |
| <i>I. doka</i> | 20.400 ± 2.600 ^a | 41.450 ± 2.050 ^b | 30.300 ± 6.900 ^c | 32.150 ± 6.950 ^c |

Values are expressed as mean ± SEM. Statistical significance of the mean difference was considered at $p < 0.05$, and the LSD comparison test was used for post hoc analysis. Values bearing the same superscripts are significantly different from each other across the rows.

Chamaecrista rotundifolia = *C. rotundifolia*; *Waltheria indica* = *W. indica*; *Aeschynomene uniflora* = *A. uniflora*; *Eriosema psoraleoides* = *E. psoraleoides*; *Isobertinia doka* = *I. doka*.

Table 7: Lead (Pb) concentration (ppm) in some selected plant samples at the polluted and controlled sites

| Plants | Controlled Site | | Polluted Site | |
|------------------------|-----------------------------|-----------------------------|------------------------------|------------------------------|
| | Shoot | Root | Shoot | Root |
| <i>C. rotundifolia</i> | 48.750 ± 5.050 ^a | 11.800 ± 5.100 ^b | 31.900 ± 4.200 ^c | 67.700 ± 4.200 ^d |
| <i>W. indica</i> | 48.450 ± 5.050 ^a | 43.200 ± 5.100 ^a | 22.250 ± 4.150 ^b | 9.700 ± 0.200 ^c |
| <i>A. uniflora</i> | 72.550 ± 5.050 ^a | 39.600 ± 2.100 ^b | 85.800 ± 4.200 ^c | 52.650 ± 31.350 ^d |
| <i>E. psoraleoides</i> | 47.000 ± 2.100 ^a | 91.200 ± 2.100 ^b | 64.500 ± 27.700 ^c | 70.500 ± 6.800 ^d |
| <i>I. doka</i> | 50.600 ± 2.100 ^a | 36.300 ± 2.100 ^b | 20.850 ± 19.850 ^c | 24.900 ± 13.200 ^c |

Values are expressed as mean ± SEM. Statistical significance of the mean difference was considered at p<0.05, and the LSD comparison test was used for post hoc analysis. Values bearing the same superscripts are significantly different from each other across the rows.

Chamaecrista rotundifolia = *C. rotundifolia*; *Waltheria indica* = *W. indica*; *Aeschynomene uniflora* = *A. uniflora*; *Eriosema psoraleoides* = *E. psoraleoides*; *Isobertinia doka* = *I. doka*.

Table 8: Zinc (Zn) concentration (ppm) in some selected plant samples at the polluted and controlled sites

| Plants | Controlled Site | | Polluted Site | |
|------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| | Shoot | Root | Shoot | Root |
| <i>C. rotundifolia</i> | 64.800 ± 2.100 ^a | 37.050 ± 2.050 ^b | 74.500 ± 1.000 ^c | 54.400 ± 0.000 ^d |
| <i>W. indica</i> | 44.400 ± 2.100 ^a | 43.900 ± 2.100 ^a | 75.000 ± 1.000 ^b | 60.400 ± 1.000 ^d |
| <i>A. uniflora</i> | 38.200 ± 2.100 ^a | 32.050 ± 0.050 ^a | 63.800 ± 1.000 ^b | 29.350 ± 0.050 ^c |
| <i>E. psoraleoides</i> | 43.750 ± 0.050 ^a | 54.400 ± 0.100 ^b | 47.900 ± 0.000 ^a | 46.150 ± 0.050 ^a |
| <i>I. doka</i> | 39.600 ± 0.100 ^a | 49.750 ± 0.150 ^b | 35.950 ± 0.050 ^a | 54.350 ± 0.050 ^c |

Values are expressed as mean ± SEM. Statistical significance of the mean difference was considered at p<0.05, and the LSD comparison test was used for post hoc analysis. Values bearing the same superscripts are significantly different from each other across the rows.

Chamaecrista rotundifolia = *C. rotundifolia*; *Waltheria indica* = *W. indica*; *Aeschynomene uniflora* = *A. uniflora*; *Eriosema psoraleoides* = *E. psoraleoides*; *Isobertinia doka* = *I. doka*

Translocation Factor (Tf) of Different Metals from Soil Root, Root to Shoot of *Chamaecrista rotundifolia* in Uncontaminated and Contaminated Sites.

Table 4a provides the Translocation Factors (TFs) for various metals in *Chamaecrista rotundifolia* at both uncontaminated and contaminated sites. TF analysis revealed metal-specific shifts between uncontaminated and contaminated sites. Cd showed increased root uptake under contamination, with relatively stable shoot translocation, indicating restricted shoot mobility. Cu remained low in uptake but showed increased shoot redistribution under contamination.

Cr exhibited high uptake and translocation under uncontaminated conditions but declined sharply under contamination, suggesting transport inhibition. Mn showed reduced uptake and translocation under stress, though shoot movement remained comparatively stable. Ni displayed moderate uptake and efficient translocation in uncontaminated soil, both of which decreased under contamination. Pb showed low uptake but high translocation in uncontaminated soil, shifting to higher uptake but reduced shoot movement under contamination, indicating root sequestration. Zn maintained efficient

uptake and translocation in uncontaminated conditions, with only slight uptake reduction under contamination while retaining relatively effective shoot transport.

Translocation Factor (Tf) of Different Metals from Soil Root, Root to Shoot of *Waltheria indica* in Uncontaminated and Contaminated Sites

Translocation Factors (TFs) for various metals in *Waltheria indica* at both uncontaminated and contaminated sites are presented in Table 4b. Across both sites, TF responses in *W. indica* were highly metal-dependent, reflecting shifts in uptake and internal partitioning under contamination stress. Cd showed a consistent uptake pattern but a clear shift toward enhanced shoot translocation under contamination, indicating increased aerial redistribution. Cu declined in uptake under polluted conditions, while shoot movement remained comparatively steady. Cr demonstrated strong uptake but limited shoot transfer in uncontaminated soil; contamination reversed this pattern by suppressing uptake while promoting translocation to shoots. Mn declined in both uptake and translocation under stress, reflecting reduced mobility. Ni displayed a stress-responsive increase in both uptake and shoot

translocation under contamination, indicating enhanced internal mobility. Pb shifted from moderate uptake and efficient translocation in uncontaminated soil to reduced uptake but increased shoot movement under contamination. Zn showed reduced uptake under contamination with a slight elevation in shoot translocation efficiency.

Translocation Factor (Tf) of Different Metals from Soil Root, Root to Shoot of *Aeschynomene uniflora* in Uncontaminated and Contaminated Sites

TF responses showed distinct adjustments in uptake and shoot allocation between uncontaminated and contaminated conditions in Table 4c. Cd maintained moderate uptake across sites but showed enhanced root-to-shoot movement under contamination, indicating increased aerial detoxification. Cu exhibited low uptake but comparatively efficient shoot translocation, particularly under contamination. Cr and Mn were highly accumulated under uncontaminated conditions but declined sharply under contamination, with only moderate shoot transfer retained. Ni showed low translocation under control conditions but increased shoot mobility under contamination, reflecting stress-driven redistribution. Pb increased in both uptake and shoot translocation under contamination, suggesting aerial accumulation as a tolerance strategy. Zn followed a similar trend of reduced uptake but improved shoot translocation under contaminated conditions.

Translocation Factor (Tf) of Different Metals from Soil Root, Root to Shoot of *Eriosema psoraleoides* in Uncontaminated and Contaminated Sites

TF behavior in *E. psoraleoides* reflected a shift from broad uptake capacity under uncontaminated conditions to more regulated metal handling under contamination stress in Table 4d. Cd uptake increased under contamination, but shoot transfer remained relatively constrained, indicating controlled internal

allocation. Cu showed a contrasting response, with reduced uptake but enhanced movement toward shoots, suggesting redistribution-based detoxification. Cr and Mn were strongly accumulated in uncontaminated soil but declined markedly under contamination, though a baseline level of shoot translocation was still maintained. Ni exhibited reduced shoot mobility under contamination, consistent with restricted translocation. Pb persisted as a high-uptake element across both conditions but remained only moderately mobile to shoots, implying preferential retention away from aerial tissues. Zn followed a stress-associated pattern of reduced uptake but marginally improved shoot translocation efficiency.

Translocation Factor (Tf) of Different Metals from Soil Root, Root to Shoot of *Isoberlinia doka* in Uncontaminated and Contaminated Sites

In Table 4e, the TF responses in *I. doka* showed a transition from strong baseline uptake capacity to more selectively regulated metal movement under contamination. Cd increased in both uptake and shoot translocation under contamination, indicating enhanced accumulation tolerance. Cu declined in uptake under stress, with only slight enhancement in shoot transfer. Cr maintained efficient uptake and relatively strong shoot translocation across both sites, despite reduced absorption under contamination. Mn consistently showed high soil-to-root transfer with stable shoot distribution in both environments. Ni decreased in uptake under contamination but showed a slight rise in shoot translocation, suggesting stress-driven redistribution.

Pb increased in uptake under contamination but showed reduced shoot movement, indicating root-level restriction. Zn declined in both uptake and translocation under contamination stress.

Table 4a: Translocation Factor (TF) of different metals from soil root, root to shoot of *Chamaecrista rotundifolia* in uncontaminated and contaminated sites

| Metals | Location | Uncontaminated | | | | Contaminated | | | |
|--------|----------|-------------------|-------------------------------------|---|---|-------------------|-------------------------------------|---|---|
| | | Metal Conc. (ppm) | Bioconcentration (BCF) Soil to Root | Factor Translocation (TF) Root to Shoot | Factor Translocation (TF) Root to Shoot | Metal Conc. (ppm) | Bioconcentration (BCF) Soil to Root | Factor Translocation (TF) Root to Shoot | Factor Translocation (TF) Root to Shoot |
| | | | | | | | | | |
| Cd | Shoot | 17.85±1.65 | 1.39 | 1.03 | 21.20±1.60 | 1.97 | | 1.01 | |
| | Root | 17.35±1.65 | | | 21.00±1.60 | | | | |
| | Soil | 12.45±1.75 | | | 10.65±1.75 | | | | |
| Cu | Shoot | 14.10±2.10 | 1.01 | 0.53 | 79.80±3.00 | 0.84 | 1.41 | | |
| | Root | 26.85±2.05 | | | 56.70±3.00 | | | | |
| | Soil | 26.55±0.07 | | | 67.65±0.05 | | | | |
| Cr | Shoot | 60.25±7.55 | 14.08 | 1.40 | 10.30±2.80 | 0.80 | 0.34 | | |
| | Root | 42.95±7.55 | | | 32.60±2.80 | | | | |
| | Soil | 3.05±2.05 | | | 40.65±2.05 | | | | |
| Mn | Shoot | 986.10±0.50 | 14.84 | 1.22 | 830.90±0.40 | 6.69 | 1.11 | | |
| | Root | 810.55±0.55 | | | 745.55±0.35 | | | | |
| | Soil | 54.60±0.60 | | | 111.50±0.60 | | | | |
| Ni | Shoot | 44.20±3.10 | 1.31 | 1.26 | 33.20±0.00 | 1.21 | 0.65 | | |
| | Root | 35.05±3.15 | | | 51.00±0.00 | | | | |
| | Soil | 26.75±0.85 | | | 42.05±0.85 | | | | |
| Pb | Shoot | 48.75±5.05 | 0.35 | 4.13 | 31.90±4.20 | 3.11 | 0.47 | | |
| | Root | 11.80±5.10 | | | 67.70±4.20 | | | | |
| | Soil | 33.40±27.00 | | | 21.70±11.10 | | | | |
| Zn | Shoot | 64.80±2.10 | 1.72 | 1.75 | 74.50±1.00 | 1.17 | 1.37 | | |
| | Root | 37.05±2.05 | | | 54.40±0.00 | | | | |
| | Soil | 21.45±1.15 | | | 46.55±1.05 | | | | |

Table 4b: Translocation Factor (TF) of different metals from soil root, root to shoot of *Waltheria indica* in uncontaminated and contaminated sites

| Metals | Location | Uncontaminated | | | Contaminated | | |
|--------|----------|-------------------|----------------------------------|------------------------------|-------------------|----------------------------------|------------------------------|
| | | Metal Conc. (ppm) | Bioconcentration Factor (BCF) | Translocation Factor (TF) | Metal Conc. (ppm) | Bioconcentration Factor (BCF) | Translocation Factor (TF) |
| | | | Soil to Root | Root to Shoot | | Soil to Root | Root to Shoot |
| Cd | Shoot | 9.85±1.75 | 1.36 | 0.58 | 22.60±1.60 | 1.47 | 1.44 |
| | Root | 16.95±1.65 | | | 15.70±1.70 | | |
| | Soil | 12.45±1.75 | | | 10.65±1.75 | | |
| Cu | Shoot | 40.50±2.10 | 2.12 | 0.72 | 68.05±2.95 | 1.07 | 0.94 |
| | Root | 56.30±2.10 | | | 72.65±2.85 | | |
| | Soil | 26.55±0.07 | | | 67.65±0.05 | | |
| Cr | Shoot | 8.75±7.55 | 21.62 | 0.13 | 48.60±2.80 | 0.34 | 3.51 |
| | Root | 65.95±7.55 | | | 13.85±2.75 | | |
| | Soil | 3.05±2.05 | | | 40.65±2.05 | | |
| Mn | Shoot | 952.35±0.55 | 13.53 | 1.29 | 1029.25±0.35 | 7.52 | 1.23 |
| | Root | 738.80±0.50 | | | 838.45±0.35 | | |
| | Soil | 54.60±0.60 | | | 111.50±0.60 | | |
| Ni | Shoot | 30.50±0.00 | 0.25 | 4.62 | 39.90±0.00 | 0.85 | 1.11 |
| | Root | 6.60±0.00 | | | 35.90±0.00 | | |
| | Soil | 26.75±0.85 | | | 42.05±0.85 | | |
| Pb | Shoot | 48.45±5.05 | 1.29 | 1.12 | 22.25±4.15 | 0.45 | 2.30 |
| | Root | 43.20±5.10 | | | 9.70±0.20 | | |
| | Soil | 33.40±27.00 | | | 21.70±11.10 | | |
| Zn | Shoot | 44.40±2.10 | 2.05 | 1.01 | 75.00±1.00 | 1.30 | 1.24 |
| | Root | 43.90±2.10 | | | 60.40±1.00 | | |
| | Soil | 21.45±1.15 | | | 46.55±1.05 | | |

Table 4c: Translocation Factor (TF) of different metals from soil root, root to shoot of *Aeschynomene uniflora* in uncontaminated and contaminated sites

| Metals | Location | Uncontaminated | | | Contaminated | | | |
|--------|----------|------------------|---------------------------|---------------|------------------|------------------------------------|---------------------------|---------|
| | | Metal Conc (ppm) | Translocation Factor (TF) | | Metal Conc (ppm) | Bioconcentration Factor (BCF) Root | Translocation Factor (TF) | |
| | | | Soil to Root | Root to Shoot | | | Soil to Shoot | Root to |
| Cd | Shoot | 17.40±1.70 | 1.48 | 0.94 | 20.65±1.65 | 1.71 | 1.13 | |
| | Root | 18.45±1.65 | | | 18.25±1.65 | | | |
| | Soil | 12.45±1.75 | | | 10.65±1.75 | | | |
| Cu | Shoot | 48.65±2.05 | 0.96 | 1.90 | 53.35±2.95 | 0.66 | 1.20 | |
| | Root | 25.60±2.00 | | | 44.55±1.95 | | | |
| | Soil | 26.55±0.07 | | | 67.65±0.05 | | | |
| Cr | Shoot | 76.45±7.55 | 17.69 | 1.42 | 8.30±2.80 | 0.22 | 0.95 | |
| | Root | 53.95±2.55 | | | 8.75±1.35 | | | |
| | Soil | 3.05±2.05 | | | 40.65±2.05 | | | |
| Mn | Shoot | 852.85±0.55 | 13.09 | 1.19 | 957.65±0.35 | 7.34 | 1.17 | |
| | Root | 714.80±0.40 | | | 818.20±0.80 | | | |
| | Soil | 54.60±0.60 | | | 111.50±0.60 | | | |
| Ni | Shoot | 9.40±3.10 | 1.57 | 0.22 | 50.30±0.00 | 0.99 | 1.21 | |
| | Root | 42.05±2.55 | | | 41.60±6.90 | | | |
| | Soil | 26.75±0.85 | | | 42.05±0.85 | | | |
| Pb | Shoot | 72.55±5.05 | 1.19 | 1.83 | 85.80±4.20 | 2.43 | 1.63 | |
| | Root | 39.60±2.10 | | | 52.65±31.35 | | | |
| | Soil | 33.40±27.00 | | | 21.70±11.10 | | | |
| Zn | Shoot | 38.20±2.10 | 1.49 | 1.19 | 63.80±1.00 | 0.63 | 2.17 | |
| | Root | 32.05±0.05 | | | 29.35±0.05 | | | |
| | Soil | 21.45±1.15 | | | 46.55±1.05 | | | |

Table 4d: Translocation Factor (TF) of different metals from soil root, root to shoot of *Eriosema psoraleoides* in uncontaminated and contaminated sites

| Metals | Location | Uncontaminated | | | Contaminated | | |
|--------|----------|------------------|---------------------------|---------------|------------------|---------------------------|---------------|
| | | Metal Conc (ppm) | Translocation Factor (TF) | | Metal Conc (ppm) | Translocation Factor (TF) | |
| | | | Soil to Root | Root to Shoot | | Soil to Root | Root to Shoot |
| Cd | Shoot | 19.90±1.60 | 1.35 | 1.18 | 21.00±1.60 | 1.98 | 1.00 |
| | Root | 16.80±1.65 | | | 21.05±1.65 | | |
| | Soil | 12.45±1.75 | | | 10.65±1.75 | | |
| Cu | Shoot | 17.65±2.05 | 0.95 | 0.70 | 56.45±1.95 | 0.30 | 2.71 |
| | Root | 25.10±2.00 | | | 20.80±1.90 | | |
| | Soil | 26.55±0.07 | | | 67.65±0.05 | | |
| Cr | Shoot | 30.05±2.55 | 6.64 | 1.48 | 19.10±1.40 | 0.49 | 0.95 |
| | Root | 20.25±2.55 | | | 20.05±1.35 | | |
| | Soil | 3.05±2.05 | | | 40.65±2.05 | | |
| Mn | Shoot | 744.05±0.35 | 11.43 | 1.19 | 747.10±0.80 | 5.51 | 1.22 |
| | Root | 624.10±0.40 | | | 614.30±0.80 | | |
| | Soil | 54.60±0.60 | | | 111.50±0.60 | | |
| Ni | Shoot | 45.70±2.60 | 1.20 | 1.42 | 54.95±6.95 | 1.34 | 0.98 |
| | Root | 32.10±2.60 | | | 56.35±6.95 | | |
| | Soil | 26.75±0.85 | | | 42.05±0.85 | | |
| Pb | Shoot | 47.00±2.10 | 2.73 | 0.52 | 64.50±27.70 | 3.25 | 0.91 |
| | Root | 91.20±2.10 | | | 70.50±6.80 | | |
| | Soil | 33.40±27.00 | | | 21.70±11.10 | | |
| Zn | Shoot | 43.75±0.05 | 2.54 | 0.80 | 47.90±0.00 | 0.99 | 1.03 |
| | Root | 54.40±0.10 | | | 46.15±0.05 | | |
| | Soil | 21.45±1.15 | | | 46.55±1.05 | | |

Table 4e: Translocation Factor (TF) of different metals from soil root, root to shoot of *Isoberlinia doka* in uncontaminated and contaminated sites

| Metals | Location | Uncontaminated | | | Contaminated | | |
|--------|----------|------------------|-------------------------------|---------------------------|------------------|-------------------------------|---------------------------|
| | | Metal Conc (ppm) | Bioconcentration Factor (BCF) | Translocation Factor (TF) | Metal Conc (ppm) | Bioconcentration Factor (BCF) | Translocation Factor (TF) |
| | | | | | | | |
| Cd | Shoot | 10.05±1.75 | 0.95 | 0.85 | 15.00±1.70 | 1.26 | 1.12 |
| | Root | 11.80±1.70 | | | 13.40±1.70 | | |
| | Soil | 12.45±1.75 | | | 10.65±1.75 | | |
| Cu | Shoot | 30.60±2.00 | 1.72 | 0.67 | 23.25±1.95 | 0.44 | 0.78 |
| | Root | 45.70±2.00 | | | 29.75±1.95 | | |
| | Soil | 26.55±0.07 | | | 67.65±0.05 | | |
| Cr | Shoot | 8.05±2.55 | 1.43 | 1.85 | 18.05±1.35 | 0.25 | 1.80 |
| | Root | 4.35±2.55 | | | 10.05±1.35 | | |
| | Soil | 3.05±2.05 | | | 40.65±2.05 | | |
| Mn | Shoot | 805.90±0.40 | 16.30 | 0.91 | 867.30±0.80 | 8.07 | 0.96 |
| | Root | 889.85±0.35 | | | 899.40±0.80 | | |
| | Soil | 54.600±0.600 | | | 111.50±0.60 | | |
| Ni | Shoot | 20.400±2.600 | 1.55 | 0.49 | 30.30±6.90 | 0.76 | 0.94 |
| | Root | 41.45±2.05 | | | 32.15±6.95 | | |
| | Soil | 26.75±0.85 | | | 42.05±0.85 | | |
| Pb | Shoot | 50.60±2.10 | 1.09 | 1.39 | 20.85±19.85 | 1.89 | 0.84 |
| | Root | 36.30±2.10 | | | 24.90±13.20 | | |
| | Soil | 33.40±27.00 | | | 21.70±11.10 | | |
| Zn | Shoot | 39.60±0.10 | 2.32 | 0.80 | 35.95±0.05 | 1.17 | 0.66 |
| | Root | 49.75±0.15 | | | 54.35±0.05 | | |
| | Soil | 21.45±1.15 | | | 46.55±1.05 | | |

DISCUSSION

This study provides insight into the phytoremediation potential of selected indigenous plant species growing within the Nigerian Defence Academy (NDA) shooting range, an area impacted by long-term military activity and associated heavy metal deposition. The results confirm that anthropogenic inputs from ammunition discharge and metallic residues have significantly altered soil chemistry, leading to elevated concentrations of Cu, Cr, Mn, Ni, and Zn in the polluted site. Key increases were observed for Cu (0.91 ± 0.00 to 2.95 ± 0.00 ppm) and Cr (0.33 ± 0.00 to 4.73 ± 0.00 ppm), while Zn and Ni also showed notable enrichment, consistent with reports on shooting range contamination (Rai *et al.*, 2019; Okoro *et al.*, 2021; Wuana and Okieimen, 2011). Although Cd and Pb increased, their relatively lower detected levels may reflect partial precipitation during digestion (e.g., PbSO_4 formation), potentially underestimating total soil Pb content.

Chamaecrista rotundifolia showed strong phytoextraction potential, particularly for Cd and Zn, with shoot Cd increasing from 15.550 ± 2.050 to 21.200 ± 1.600 ppm and Zn from 64.800 ± 2.100 to 74.500 ± 1.000 ppm under pollution. These trends indicate efficient uptake and internal mobility, although values remain below hyperaccumulator thresholds, classifying the species as a moderate accumulator with phytoextraction potential (Baker and Brooks, 1989).

Similarly, *Waltheria indica* demonstrated strong stress-responsive metal handling. Cd translocation increased significantly (TF: 0.58 to 1.44), while shoot Zn also rose markedly (44.400 ± 2.100 to 75.000 ± 1.000 ppm). These findings suggest activation of inducible detoxification mechanisms involving chelation and transporter-mediated redistribution (Shanker *et al.*, 2005). The species also exhibited dual functionality, combining phytoextraction for Cd and Zn with partial root retention of Cu and Pb.

Aeschynomene uniflora emerged as a key multi-metal accumulator, consistently recording the highest Pb concentrations in shoots (72.550 ± 5.050 to 85.800 ± 4.200 ppm). Its Zn translocation factor also increased from 1.19 to 2.17 under contamination, indicating strong internal mobility. These results highlight its broad phytoextraction potential, although still below hyperaccumulation criteria (Hall, 2002; Krämer, 2010).

Chromium behavior varied significantly across species. While *Chamaecrista rotundifolia* and *Aeschynomene uniflora* showed reduced Cr uptake

and translocation under contamination—suggesting transport inhibition and root stress—*Waltheria indica* exhibited a marked increase in Cr translocation (TF: 0.13 to 3.51), indicating adaptive aerial sequestration as a detoxification strategy (Zayed and Terry, 2003). Manganese uptake generally declined under contamination, except in *Waltheria indica*, which maintained relatively higher shoot Mn levels, likely reflecting protective responses against oxidative stress (Rengel and Zhang, 2003). *Isobertlinia doka* retained higher Mn in roots, indicating strong nutrient homeostasis. Nickel accumulation peaked in *Eriosema psoraleoides*, particularly under polluted conditions, suggesting strong tolerance mechanisms such as vacuolar sequestration and ligand binding (Krämer, 2010), while *Waltheria indica* and *Isobertlinia doka* showed lower accumulation, indicating exclusion strategies.

Lead distribution further emphasized species-specific strategies. *Aeschynomene uniflora* consistently accumulated high shoot Pb across both sites, confirming strong phytoextraction ability. In contrast, *Chamaecrista rotundifolia* and *Eriosema psoraleoides* preferentially retained Pb in roots under contamination, indicating phytostabilization behavior that limits aerial transfer and toxicity risk (Pourrut *et al.*, 2011).

Importantly, none of the species reached hyperaccumulator thresholds. Cd levels across all plants remained far below the >100 ppm benchmark required for hyperaccumulator classification (Baker and Brooks, 1989; van der Ent *et al.*, 2021). Thus, the studied species are better described as moderate accumulators with phytoremediation relevance, particularly for low-to-moderately contaminated soils where biomass production and ecological resilience are critical.

Translocation factor analysis further clarified functional roles. *Waltheria indica* and *Aeschynomene uniflora* exhibited the strongest inducible translocation systems under contamination, especially for Cd, Zn, and Pb. In contrast, *Eriosema psoraleoides* consistently displayed root-bound accumulation, confirming its role as a phytostabilizer. *Isobertlinia doka* showed a mixed strategy, selectively translocating Zn and Cr while restricting Pb and Cu movement, reflecting a regulated compartmentalization system typical of woody species (Clemens *et al.*, 2022).

From an applied perspective, these findings highlight that phytoremediation effectiveness depends on functional diversity rather than single-species dominance. However, practical deployment must

consider ecological constraints such as biomass disposal, food web transfer risks, and vegetation structure alteration during repeated harvesting (Naidu *et al.*, 2025). As such, the studied species are better suited for integrated phytomanagement rather than intensive extraction-only remediation systems.

CONCLUSION

This study demonstrates that NDA shooting range soils are enriched with Cu, Cr, Mn, Ni, and Zn due to anthropogenic military activities. The investigated plant species exhibited clear, species-specific differences in metal uptake and translocation under contaminated conditions. *Chamaecrista rotundifolia*, *Waltheria indica*, and *Aeschynomene uniflora* showed moderate phytoextraction potential, particularly for Cd, Zn, and Pb. *Eriosema psoraleoides* was more effective for phytostabilization, while *Isoberlinia doka* displayed selective dual uptake and restriction patterns. Overall, the species demonstrate complementary phytoremediation roles suitable for integrated restoration of metal-contaminated soils. However, the use of non-standard acid digestion and the absence of molecular characterization constrain the generalizability of these findings. Future studies should address these methodological issues.

The identified species should be validated through long-term, field-scale phytoremediation studies under natural environmental conditions. Soil amendments such as biochar, organic matter, lime, and chelators should be explored to enhance phytoextraction or phytostabilization efficiency. Safe biomass management strategies, including phytomining and controlled disposal, are required to prevent secondary pollution. Molecular and ecological studies should be conducted to clarify metal tolerance mechanisms and plant-microbe interactions. These approaches should be integrated into policy frameworks for restoring contaminated military and industrial sites.

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