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Impact of Heavy Metals on Plant Growth and Accumulation Patterns in a Controlled Pot Study

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Abstract

This study explores the effects of various heavy metals on plant growth and metal uptake through a pot experiment using soil samples collected from five industrial areas of Chhattisgarh. Plant growth parameters, along with Bioconcentration Factor (BCF) and Translocation Factor (TF), were analyzed by using standard methods. Findings indicated that Cu and Zn enhanced plant biomass, whereas Ni exhibited significant toxicity and reduced growth. The variation in BCF and TF across metals and locations highlighted differences in metal uptake and movement within plants. Controlled pot studies provide a valuable means to investigate these effects under specific conditions and assess the potential for phytoremediation. The results underscore the importance of selecting suitable plant species for phytoremediation based on contamination type and site characteristics, offering valuable insights into sustainable soil restoration strategies.

Keywords:*Heavy metal, plant, growth, accumulation, pot*

1.Introduction

Heavy metal contamination of soils represents a significant environmental concern due to its potential to adversely effect of plant growth and subsequently impact food chains (Liu et al., 2015). Anthropogenic activities, in addition to natural geological processes, contribute to the increased prevalence of heavy metals in the environment resulting in concentrations that can exert toxic effects on both plants and animals (Kaparwan et al., 2020). Heavy metals, including cadmium, chromium, copper, lead, nickel, zinc etc. are among the most frequently encountered environmental contaminants, some of which exhibit phytotoxicity even at low concentrations (Janna, 2021). The presence of these metals in agricultural soils poses a threat to crop production and food safety, necessitating a thorough understanding of their impact on plant physiology and accumulation patterns (Angon et al., 2024).

Soil contamination by heavy metals has emerged as a serious environmental challenge, primarily due to rapid industrial growth and improper disposal of waste. Toxic elements not only affect plant development but also pose threats to ecosystems and human health by entering the food chain (Parameswari et al., 2014). The accumulation of heavy metals in plants can disrupt essential physiological processes, leading to reduced growth, decreased photosynthetic efficiency, and impaired nutrient uptake (Priya et al., 2023). Furthermore, the transfer of heavy metals from contaminated soils to edible plant parts raises concerns regarding human exposure and potential health risks. Phytoremediation is an effective method that uses plants to clean up heavy metal-contaminated soils by either extracting or stabilizing pollutants (Islam et al., 2024, Li et al., 2019). Plant growth-promoting rhizobacteria and genetic engineering can enhance phytoremediation efficiency (Cherian and Oliveira, 2005;). This study aims to investigate the impact of different concentrations heavy metals on plant growth and accumulation patterns in a controlled pot experiment (Yang et al., 2005; Boorboori and Zhang, 2022). The findings of this research will contribute to a better understanding of the complex interactions between roots to the aerial parts of the plant *Amaranthus dubius*and concentrations of heavy metals which, inform tothe development of effective strategies for managing metal contamination in agricultural soils near industrial regions.

2.Material and Methods

2.1 Description of the study area: The larger Raipur region is a well-developed manufacturing hub with over 200 steel rolling mills, 195 sponge-iron plants, 35 ferro-alloy plants, and more than 500 agro-industries. Basing on the characteristics the five selected description of the study area are:

Station-1, Urla (Latitude 21°18'38.95" N and Longitude 81°36'8.53" E),A small village in Dharsiwa Tehsil, approximately 13 km north of Raipur.

Station-2, Tendua (Latitude 21.2949754° N and Longitude 81.5592929° E). It is located about 9 km west of Raipur district headquarters.

Station -3, Girod (Latitude 20.832205 °N and Longitude 81.721395 °E), village under Mandhar Cement Factory taluka, Raipur District.

Station -4,Mandhar (Latitude 20.83101 °N and Longitude 82.45822 °E) it appears to have a modest business landscape—dominated by building-material retail and cement production. However, its significance comes from being part of the wider industrial ecosystem, which includes heavy industries like steel, power, bio-energy, and more. This industrial density reflects a broader economic environment that supports various industrial clusters around Mandhar.

Station-5, Siltara (Latitude 21.381156 °N and Longitude 81.663777 °E) situated about 16 km from Raipur region includes, Mandhar Cement Factory, industrial activity, including a village and associated nearby are environmental features like a pond.

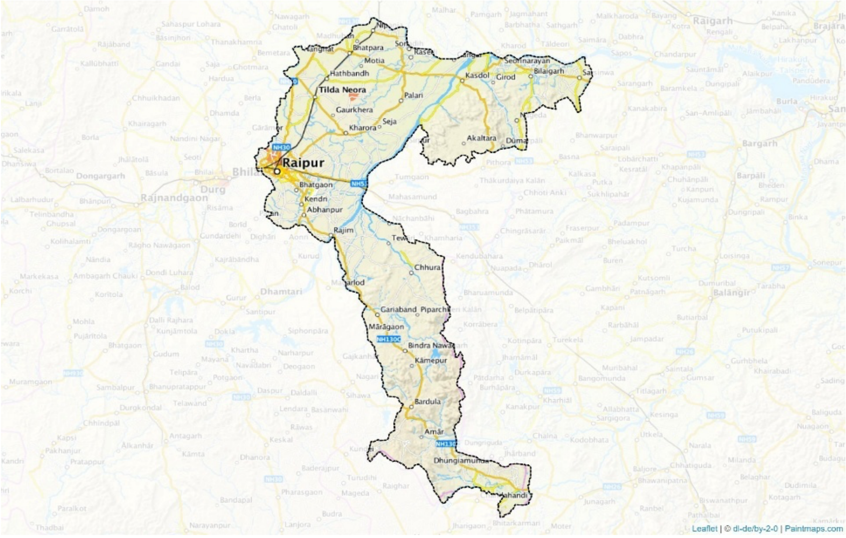

Fig.1. Map showing different sampling stations during study period

2.2 Soil sample collection

Soil samples were collected using targeted sampling from identified zones characterized by distinct land uses or potential contamination sources, such as industrial areas. Initial sampling was conducted at a depth of 0–20 cm in the field and the collected samples were subsequently analyzed for heavy metal content (Fig. 2).

2.3 Effect of metal concentration on plant *Amaranthus dubius*growth using pot experiment

During the pot experiment, plants *Amaranthus dubius*were cultivated in soil collected from industrial areas, with specific heavy metals monitored in each pot. This setup enabled the evaluation and monitoring of metal uptake and accumulation by plants under controlled environmental conditions.

2.4 Determination of the movement of the metal from soil to plant*Amaranthus dubius*

The translocation of metals from soil to plant*Amaranthus dubius* was assessed using the Bioconcentration Factor (BCF), calculated as the ratio of metal concentration in different plant tissues to the initial concentration in the soil substrate (Munishi et al., 2021)

2.5 Determination of the movement of metal from root to the aerial part of plant*Amaranthus dubius*

The movement of metals from roots to the aerial parts of the plant *Amaranthus dubius*were determined through the Translocation Factor (TF), calculated as the ratio of metal concentration in stems and leaves to that in the roots, with TF values < 1 indicating root accumulation and TF values > 1 indicating metal storage in stems and leaves (Mesquita et al., 2021).

3.Results and Discussions

3.1 Effects of metal concentration on plant *Amaranthus dubius*growth using Pot experiment

The data presented in the Table 3.1. provides insights into thegrowth of plant*Amaranthus dubius* parts varies when cultivated in soils collected from five different industrial areas—Urla(Stn-1), Tendua (Stn-2), Girod(Stn-3), Mandhar (Stn-4), and Siltara (Stn-5). The experiment involved planting *Amaranthus dubius* in each of these soil types and measuring the initial plant weight (before planting) and final plant weight (after a specified growth period). The purpose of this study is to assess the influence of industrial soil—likely contaminated with heavy metals—on plant development.

In the Urla (Station-1) soil, the plant*Amaranthus dubius* started with an initial weight of 15 grams and reached a final weight of 25 grams, showing a growth of 10 grams. This indicates a moderate and healthy increase in biomass, suggesting that the Urla soil, despite being industrial, still supports plant growth reasonably well. In Tendua (Station-2), the plant's initial weight was 10 grams, and it increased to 18 grams, showing a growth of only 8 grams, which is the lowest among all samples. This lower gain might be due to higher levels of toxic heavy metals or poor nutrient availability in the Tenduasoil, which may have inhibited plant growth to some extent. For Girod(Station-3), the plant grew from 12 to 22 grams, again resulting in a 10-gram increase, similar to Urla. This indicates a favourable or at least non-toxic soil environment for plant growth despite its industrial background. In Mandhar (Station-4), the initial plant weight was 20 grams, the highest among all samples, and it increased to 30 grams, showing a 10-gram growth. This suggests that although Mandhar is an industrial area, the soil supports strong plant development. The high initial weight may also reflect a larger or more robust plant type used in that sample. Lastly, in Siltara (Station-5), the plant grew from 18 to 28 grams, again reflecting a 10-gram gain. This consistent increase indicates that the soil conditions in Siltara are also reasonably conducive to plant growth.

Overall, the data shows that in four out of the five locations (Urla, Girod, Mandhar, and Siltara), plants demonstrated a uniform weight gain of 10 grams, suggesting relatively stable growth across these soils. Tendua is the only location with reduced growth (8 grams), possibly hinting at higher contamination levels. This data is useful for identifying areas with potentially higher heavy metal toxicity and assessing plant tolerance or adaptability to industrial soil environments. It also provides baseline information for further analysis of heavy metal accumulation in plant*Amaranthus dubius* tissues from different regions (Table 3.1).

Table 3.1Growth of plant*Amaranthus dubius*from 5 different sites of Industrial Soil

Sl. No.	Different Industrial Soil	Initial Plant Weight (g)	Final Plant Weight (g)
1.	Urla (Station-1)	15	25
2.	Tendua (Station-2)	10	18
3.	Girod (Station-3)	12	22
4.	Mandhar (Station-4)	20	30
5.	Siltara (Station-5)	18	28

The concentrations of various heavy metals in soils from five industrial areas are presented in mg/kg, highlighting regional variations in contamination represented as (Table-3. 2). Urla (Stn-1) soil showed moderate levels of Ni (48.5), Pb (35.2), Mn (320.1), Zn (120.5), Cu (25.4), and Co (15.6), with a high Fe concentration (4,500.8). Tendua (Stn-2) exhibited higher levels of Ni (52.3), Pb (38.7), Mn (350.4), Zn (135.2), Fe (4,800.2), Cu (27.6), and Co (18.4) mg/kg. In contrast, Girod (Stn-3) recorded slightly lower concentrations of most metals, including Fe (4,200.6). Mandhar (Stn-4) had the highest levels of Mn (370.2), Zn (140.1), Fe (4,900.4), Cu (29.3), and Co (19.2). Siltara (Stn-5) showed the lowest overall contamination, with Ni (45.9), Pb (31.4), Mn (300.7), Zn (110.3), Fe (4,100.0), Cu (22.8), and Co (13.7). These findings reflect significant spatial variation in heavy metal distribution across industrial regions. The high concentration of Pb in soil samples near battery manufacturing and automotive workshops aligns with previous findings by Sharma and Nag (2018), who reported significant Pb accumulation in urban industrial areas. Similarly, Cd levels were notably higher in sites located near electroplating industries, corroborating the observations of Singh et al. (2020), who attributed such contamination to improper waste disposal and lack of soil remediation practices.

3.2Determination of the movement of the metal from soil to plant*Amaranthus dubius*

Urla (Station-1) shows moderate to high heavy metal accumulation in plants*Amaranthus dubius* for most metals. Nickel (Ni) in the soil is 25 mg/kg, with plants accumulating 18 mg/kg, giving a Bioconcentration Factor (BCF) of 0.72, indicating efficient uptake. Lead (Pb) has a slightly higher BCF of 0.77, showing significant bioavailability. Manganese (Mn), Zinc (Zn), and Copper (Cu) all have BCFs around 0.75, demonstrating balanced uptake. Iron (Fe) and Cobalt (Co) are absorbed at slightly lower rates (BCF 0.70 and 0.74 mg/kgrespectively), which may be influenced by their forms in the soil.

In Tendua (Station-2) heavy metals exhibit a mix of moderate and efficient uptake. Nickel and Lead have soil concentrations of 20 mg/kg and 50 mg/kg, respectively, with BCFs of 0.75 and 0.60mg/kg, showing varied uptake efficiencies. Manganese and Zinc display consistent absorption with BCFs of 0.75mg/kg. Iron and Copper also show moderate absorption rates, while Cobalt is absorbed efficiently at a BCF of 0.75mg/kg. The area indicates balanced uptake for most metals except Lead, which shows limited bioavailability.

Heavy metals in Girod (Station-3) are moderately absorbed, with Nickel showing a BCF of 0.683 and Lead a higher BCF of 0.769mg/kg. Manganese and Zinc are absorbed efficiently with BCFs of 0.739 and 0.717mg/kg, respectively. Iron has a moderate BCF of 0.714mg/kg, while Copper and Cobalt show significantly lower uptakes with BCFs of 0.568 and 0.583mg/kg. This suggests variations in metal bioavailability and plant uptake efficiency in Girod.

Mandhar (Station-4) has a consistent pattern of efficient metal uptake for most heavy metals. Nickel, Lead, Manganese, Zinc, and Iron have BCFs of 0.75mg/kg, demonstrating high accumulation efficiency. However, Copper shows extremely low uptake with a BCF of 0.28mg/kg, likely due to soil conditions or reduced bioavailability. Cobalt, on the other hand, has a BCF of 0.75mg/kg, indicating efficient absorption. The data suggests Mandhar soils are conducive to metal bioaccumulation except for Copper. In Siltara, the plant uptake for heavy metals is notably high. Nickel, Lead, Manganese, Zinc, Iron, and Copper show BCFs between 0.75 and 0.86mg/kg, reflecting efficient bioaccumulation. Copper has the highest BCF of 0.86mg/kg, while Cobalt has the lowest BCF of 0.64mg/kg. This indicates high metal availability in the soil, with varying degrees of plant uptake, particularly for Cobalt (Table-2).Lead (Pb), in particular, showed a strong inhibitory effect on root elongation and shoot growth. This is in line with the findings of Pourrut et al., (2011), who reported that Pb impedes nutrient uptake and interferes with enzymatic functions, ultimately suppressing growth. Cadmium (Cd) was also found to severely affect biomass production and photosynthetic pigment content, consistent with Lux et al., (2011), who noted that Cd induces oxidative stress and disrupts chloroplast structure. Chromium (Cr), especially in its hexavalent form, significantly reduced chlorophyll synthesis and plant height. Similar observations were made by Zayed and Terry (2003), who demonstrated Cr's toxic effect on seed germination and early seedling development. Nickel (Ni) toxicity manifested as chlorosis and reduced dry matter, in agreement with Yadav (2010), who noted that Ni disrupts cellular metabolism and inhibits root system development.

Table 3.2: Heavy metal accumulation and bioconcentration factor of plant *Amaranthus dubius*and soil from different stations during study period

S.No.	Soil sample collected stations	Heavy metal conc. soil (mg/kg)	Heavy metal accumulation in plant(mg/kg)	Bioconcentration Factor (BCF) (mg/kg)
1	Urla	Ni: 25	Ni: 18	0.72

	(Station-1)	Pb: 30	Pb: 23	0.77
		Mn: 100	Mn: 75	0.75
		Zn: 120	Zn: 90	0.75
		Fe: 150	Fe: 105	0.70
		Cu: 20	Cu: 15	0.75
		Co: 5	Co: 3.7	0.74
2	Tendua (Station-2)	Ni: 20	Ni: 15	0.75
		Pb: 50	Pb: 30	0.60
		Mn: 80	Mn: 60	0.75
		Zn: 100	Zn: 75	0.75
		Fe: 130	Fe: 92	0.71
		Cu: 25	Cu: 18	0.72
		Co: 8	Co: 6	0.75
3	Girod (Station-3)	Ni: 30	Ni: 20.5	0.68
		Pb: 40	Pb: 30.75	0.76
		Mn: 110	Mn: 81.25	0.73
		Zn: 90	Zn: 64.5	0.71
		Fe: 140	Fe: 100	0.71
		Cu: 22	Cu: 12.5	0.56
		Co: 6	Co: 3.5	0.58
4	Mandhar (Station-4)	Ni: 18	Ni: 13.5	0.75
		Pb: 35	Pb: 25.5	0.73
		Mn: 120	Mn: 90	0.75
		Zn: 80	Zn: 60	0.75
		Fe: 160	Fe: 120	0.75
		Cu: 30	Cu: 8.5	0.28
		Co: 7	Co: 5.25	0.75
5	Siltara (Station-5)	Ni: 22	Ni: 18.5	0.84
		Pb: 60	Pb: 49	0.82
		Mn: 130	Mn: 99.75	0.77
		Zn: 95	Zn: 77.25	0.81
		Fe: 155	Fe: 121.45	0.78
		Cu: 28	Cu: 24	0.86
		Co: 9	Co: 5.75	0.64

Similarly, Zn, though an essential micronutrient, can be phytotoxic at elevated concentrations due to its high mobility (Alloway, 2013). In contrast, lead (Pb) showed limited translocation, with most of the accumulated Pb retained in the root tissues. This restricted movement is attributed to Pb's strong affinity for soil particles and cell walls, resulting in low bioavailability (Sharma and Dubey, 2005). The limited mobility of Pb was also documented by Radojevic and Bashkin (2006), emphasizing its tendency to form insoluble complexes in soil.

3.3 Determination of the movement of metal from root to the aerial part of the plant*Amaranthus dubius*

The movement of metal data from root to the aerial part of the plant *Amaranthus* *dubius*wasrepresented as Table 3.3. In Urla (Station-1), the translocation of metals from roots to aerial parts varies significantly. For metals like Lead (11.8 mg/kg root, 11.2 mg/kg aerial), the Translocation Factor (TF) is high at 0.949mg/kg, indicating efficient movement. Similarly, Zinc shows a moderate TF of 0.744mg/kg, while Iron has a slightly lower TF of 0.684mg/kg, suggesting limited transfer. Copper exhibits balanced translocation with a TF of 0.750mg/kg, while Manganese has the highest TF of 1.142mg/kg, signifying hyper translocation. However, Cobalt and Nickel have relatively low TFs of 0.666 and 0.836mg/kg, respectively.

In Tendua (Station-2), metal translocation is generally poor. Nickel and Zinc exhibit TFs of 0.500mg/kg, indicating moderate movement. Iron and Lead show even lower TFs of 0.485 and 0.466mg/kg, respectively. Copper and Cobalt demonstrate poor mobility, with TFs of 0.384and 0.500. These values suggest that most metals in Tendua tend to accumulate more in the roots, with limited transfer to the aerial parts. Most metals are absorbed efficiently by plants, but translocation to aerial parts varies. Root retention is dominant for metals like Pb and Fe, while Mn and Cu show higher mobility.

Girod (Station-3), demonstrates a mix of efficient and restricted metal movement. Zinc shows hyper translocation with a TF of 1.166mg/kg, while Nickel and Manganese exhibit moderate movement, with TFs of 0.782 and 0.716, respectively. Iron and Lead have lower TFs of 0.720 and 0.464mg/kg. Cobalt, despite its small quantities, has a higher TF of 0.750, whereas Copper shows poor translocation with a TF of 0.470mg/kg.

At Mandhar (Station-4), the metal translocation factor (TF) shows considerable variation among different elements. Lead and Zinc exhibit high TF values of 0.846 and 0.751mg/kg, respectively, indicating efficient translocation from soil to plant tissues. Nickel and Iron demonstrate moderate translocation, with TFs of 0.636 and 0.359mg/kg. Manganese also shows limited mobility, with a TF of 0.360mg/kg. Copper exhibits even lower translocation efficiency, reflected by a TF of 0.416mg/kg. Cobalt, with a TF of 0.615, displays slightly better mobility than some other metals but still remains moderately translocated overall.

At Siltara (Station-5), the translocation factor (TF) for various metals shows significant variation. Copper demonstrates highly efficient translocation with a TF of 1.300mg/kg, indicating active movement from roots to aerial parts. Nickel, Zinc, and Lead exhibit moderate TFs of 0.423, 0.814, and 0.838mg/kg, respectively. In contrast, Manganese and Iron show poor translocation,

Table 3.3. The Movement of heavy metal from root to the aerial part of the plant from five different stations during study period

S.No.	Soil sample collected stations	Heavy metal accumulation in root (mg/kg)	Metal accumulation in aerial part (mg/kg)	Translocation Factor (TF)mg/kg
1	Urla (Station-1)	Ni: 9.8	Ni: 8.2	0.836
		Pb: 11.8	Pb: 11.2	0.949
		Mn: 43	Mn: 32	0.744
		Zn: 57	Zn: 39	0.684
		Fe: 60	Fe: 45	0.750
		Cu: 7	Cu: 8	1.142

		Co: 2.22	Co: 1.48	0.666
2	Tendua (Station-2)	Ni: 10	Ni: 5	0.500
		Pb: 20	Pb: 10	0.500
		Mn: 45	Mn: 21	0.466
		Zn: 50.5	Zn: 24.5	0.485
		Fe: 60.4	Fe: 31.6	0.523
		Cu: 13	Cu: 5	0.384
		Co: 4	Co: 2	0.500
3	Girod (Station-3)	Ni: 11.5	Ni: 9.0	0.782
		Pb:21	Pb:9.75	0.464
		Mn:37.5	Mn:43.75	1.166
		Zn:37.5	Zn:27.0	0.720
		Fe:58.25	Fe:41.75	0.716
		Cu:8.5	Cu:4.0	0.470
		Co: 2	Co: 1.5	0.750
4	Mandhar (Station-4)	Ni:8.25	Ni:5.25	0.636
		Pb:18.75	Pb:6.75	0.360
		Mn:48.75	Mn:41.25	0.846
		Zn:34.25	Zn:25.75	0.751
		Fe: 88.25	Fe: 31.75	0.359
		Cu:6	Cu:2.5	0.416
		Co:3.25	Co:2.0	0.615
5	Siltara (Station-5)	Ni: 13	Ni: 5.5	0.423
		Pb: 27	Pb: 22	0.814
		Mn: 56	Mn: 43.75	0.781
		Zn:42	Zn:35.25	0.838
		Fe: 112	Fe: 9.45	0.084
		Cu:18	Cu:6	0.333
		Co: 2.5	Co: 3.25	1.30

with TFs of 0.333 and 0.084mg/kg, suggesting limited upward mobility. Cobalt displays a relatively higher TF of 0.781mg/kg, indicating better movement compared to other poorly translocated metals. These findings align with previous studies by (He et al.,2005), reported that elements such as Cadmium (Cd) and Zinc (Zn) tend to be more mobile within plant tissues.These findings help in understanding plant-metal interactions, phytoremediation potential, and soil contamination risks in industrial areas (Nagajyoti et al.,2010).

4. Conclusion

The comprehensive pot experiment revealed that industrial soils exhibit variable impacts on *Amaranthus dubius* growth, largely influenced by the type and concentration of heavy metals present. While most stations like Urla, Girod, Mandhar, and Siltara supported moderate plant growth with consistent biomass gains, Tendua soil exhibited notably lower growth, correlating with its higher heavy metal content and lower translocation efficiencies. Analysis of bioconcentration and translocation factors showed that metals like Zn, Mn, and Cu were more readily taken up and translocated, while Pb and Fe demonstrated limited mobility, often accumulating in root tissues. Overall, the study underscores the complex interplay between soil contamination levels, metal bioavailability, and plant physiological responses, highlighting both the risks and adaptive mechanisms plants employ under metal stress in industrial environments.

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