Journal of Materials and Environmental Science
ISSN : 2028-2508
e-ISSN : 2737-890X
CODEN : JMESCN

J. Mater. Environ. Sci., 2025, Volume 16, Issue 1, Page 68-91

http://www.jmaterenvironsci.com

Phytoremediation Potential of *Jatropha gossypiifolia* for Toxic metals in Waste-Impacted Soils Amended with Citric and Ethylenediaaminetetraacetic Acids

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Received *03 Jan 2025,*
Revised *14 Jan 2025,*
Accepted *15 Jan 2025*

Keywords:
- ✓ *Jatropha gossypiifolia*
- ✓ *Phytoremediation;*
- ✓ *Chelant;*
- ✓ *Toxic Metals;*
- ✓ *Phytoextraction*

Citation: *Ejeh, A. M., Ebong, G. A. and Moses, E. A. (2025) Phytoremediation Potential of Jatropha gossypiifolia for Toxic metals in Waste-Impacted Soils Amended with Citric and Ethylenediaaminetetraacetic* Acids, *J. Mater. Environ. Sci., 16(1), 68-91*

Abstract: Phytoremediation is a recent technique that used plant for the extraction of toxic substances from impacted environment. The phytoextraction of Cd, Cr, Ni, and Pb from waste dumpsite soil (WDS), automobile waste-impacted soil (AIS), electronic waste-impacted soil (EWS), and paint waste-impacted soil (PIS) by the leaves and roots of *Jatropha gossypiifolia* was assessed in this study. The seeds of *J. gossypiifolia* were cultivated in forty-eight (48) bags in a set of twelve for each impacted soil amended with 5.0. 10.0, 15.0, and 20.0 mLday^{-1} of citric acid (CA), ethylenediaaminetetraacetic acid (EDTA) and mixed CA+EDTA chelants and four (4) soils without amendment (one for each set of impacted soil) were used as the Controls. The cultivated seeds in polyethylene bags were watered daily for twelve (12) weeks. *J. gossypiifolia* cultivated in the amended soils and those without amendment were harvested after 12 weeks, treated and analysed. The background impacted soils were treated and analysed for the concentrations of these toxic metals. The results revealed that the concentrations (mgkg^{-1}) of Cd, Cr, Ni, and Pb in the background soils varied as follows: 2.02-3.86, 5.09-7.71, 8.59-13.44, and 34.18-39.36, respectively. The mean concentrations of all the metals except Cd were within their acceptable limits. The concentrations of metals extracted by the roots of *J. gossypiifolia* harvested from the studied and control soils were higher than the leaves. The concentrations of the metals in the amended soils varied with the concentrations in the background soils. Higher concentrations of toxic metals were extracted in the amended soils than the control. The potentials of the chelants in extracting the metals was in the order CA+EDTA >EDTA>CA. The rate of metal extraction by *J. gossypiifolia* from the impacted soils was directly proportional to the concentration of the chelants. CA and mixed CA+EDTA improved the growth of *J. gossypiifolia*, while EDTA in inhibited the growth. The bioaccumulation factors (BCFs) of all the metals in the amended soils were higher than one, but less than one in the control soils. The translocation factors (TFs) of all the metals in the amended soils were higher than in the control pots. This study indicated that, *J. gossypiifolia* has very high potential to extract toxic metals from impacted soils amended with chelants.

1. Introduction

Phytoremediation is a technique used for the reduction or elimination of toxic substances from impacted environments such as air, water, and land with suitable plants. This method is simple, economical, nature-based, eco-friendly, and improves the quality of soil (Asante-Badu *et al*., 2020). Nevertheless, phytoremediation may be ineffective for contaminants such aspolychlorinated biphenyls (PCBs). It can also cause contamination of the soil and underground water (Liu *et al*., 2020). The process of phytoremediation is slow compared to the traditional excavation method of contaminated soils (Yan *et al*., 2020).The various approaches involved in phytoremediation are (i) Phytoextraction: This involves the removal of contaminants in water or soil, and transferring them to the aboveground parts of the plants (Jacob *et al*., 2018; Suman *et al*., 2018), (ii)Phytostabilization: This is a process whereby contaminants mostly metals are immobilized and accumulated by some metal-tolerant plants thereby reducing their availability within the environment (Lan *et al*., 2020; Yan *et al*., 2020), (iii) Phytovolatilization: This involves the use of plants to extract toxic metals from contaminated site, convert them into less toxic volatile form, and later release them into the atmosphere (Yan *et al*., 2020; Kafle *et al*., 2022), (iv) Phytofiltration: This is a process whereby plant roots (rhizofiltration), seedlings (blastofiltration), or shoots (caulofiltration) extract contaminants from impacted water or aqueous waste (Nedjimi, 2021), (v) Phytodegradation: This involves a practice whereby the roots of plant degrade organic contaminants in water or soil by the release of enzymes (Kafle *et al*., 2022), and (vi) Rhizodegradation: This is the breaking down of organic contaminants in soil by microorganisms within the plant root zone or rhizosphere (Jha and Songachan, 2022; Chojnacka *et al*., 2023). However, this study dealt exclusively on the phytoextraction and phytostabilization of toxic metals from impacted soils using *Jatropha gossypiifolia* plant. *Jatropha gossypiifolia* is plant that grows optimally in the tropics mostly in Nigeria within dumpsite soils (Awokunmi *et al*., 2012; Mokhtari *et al*., 2017; Awotedu *et al*., 2018).

Toxic metals have adverse negative effects on human, animal, and plant lives hence; they should be eliminated from the environment by any possible but eco-friendly method (Rai *et al*., 2019; Okon *et al*., 2023; Etuk *et al*., 2023). Some plants naturally have the potentials to extract high levels of contaminants from the impacted environment, while most plants have low potential for the extraction of contaminants. Consequently, chelating agents are introduced into the impacted area to accelerate the process of phytoremediation by these plants (Aghelan *et al*., 2021; Kafle *et al*., 2022). Chelating agents are both organic and synthetic; citric acid (CA) is an example of organic chelator, while ethylenediaaminetetraacetic acid (EDTA) belongs to the synthetic class. The organic chelating agents are biodegradable hence; they are suitable for use in large quantities (Diarra *et al*., 2021). However, due to the efficient nature of EDTA, it is the widely used chelating agent (Mousavi *et al*., 2021). Consequently, EDTA persists in soil thus; it can contaminate the soil, plant, surface and underground water, and plants (Guo *et al*., 2015).

Studies have shown that numerous plants have been employed for the different techniques of phytoremediation (Lone *et al*., 2008; Antoniadis *et al*., 2021; Bortoloti and Baron, 2022). Nevertheless, the perfect plant for phytoremediation should be able to accumulate and tolerate high levels of toxic contaminants, easy to cultivate, and high biomass (Shabani and Sayadi, 2012). Although, *Jatropha gossypiifolia* has these properties it has not been intensively applied in the area of phytoremediation mostly within the study area. Thus, this study was undertaken to explore the potentials of *Jatropha gossypiifolia* for the remediation of toxic metals from different impacted soils. The various impacted soils examined were amended with citric and ethylenediaaminetetraacetic acids. The study also aimed at assessing relatively the potentials of CA and EDTA as chelating agents. The subsequent impacts of these chelating agents on the growth of *Jatropha gossypiifolia*will be examined. The rate of accumulation of toxic metals from the different impacted soils by the roots and leaves of the plant will be evaluated.

2. Methodology

2.1. Experimental design

Plastic bags of 20 cm and 10 cm in diameter and height respectively were filled with 1.50 kg of the air-dried impacted soils. The seeds of *Jatropha gossypiifolia* obtained from Makurdi in Benue State, Nigeria, were planted in all the bags and allowed to germinate. A total of 52 bags were used for this experiment and the bags were separated into four groups of twelve (12) bags each. A set of 12 bags each for soil from municipal waste dumpsite (WDS), automobile waste-impacted soil (AIS), electronic waste-impacted soil (EWS), and paint waste-impacted soil (PIS) all obtained in Akwa Ibom State, Nigeria. Each group of 12 bags was subdivided into four sets and for each set, 5.0, 10.0, 15.0, and 20.0 $mLday^{-1}$of citric acid (CA), ethylenediaminetetraacetatic acid (EDTA) and mixed CA + EDTA chelants were added separately. For each of the groups of 12 pots of impacted soils, one bag was without chelants and was used as the control bag. The entire bags were watered daily with 500 mL of distilled water except the day prior to harvest. The growth of the plant in each bag was monitored daily by measuring the height of stems and width of the leaves for twelve (12) weeks. At the end of 12 weeks, the plants were harvested from all the pots and treated for further experiments (Waziri *et al.*, 2016; Njoku *et al*., 2020; Waseem *et al*., 2024).

2.2. Sample collection, treatment, and digestion

At the end of twelve (12) weeks, *Jatropha gossypiifolia* were harvested with hand trowel to avoid loss of plant part (Figure 1). The plants were washed with distilled water to remove dirt, and separated into leaves and roots. The leaves and roots of plant separated were air dried for three weeks, then ground and sieved as reported by Ebong *et al*. (2023). The impacted soil samples were sun dried for 72 hours, ground and sieved. One gram (1 g) each of the plant tissue and soils were digested with 10 mL of 1:1 (w/v) HNO_3: H_2O in a beaker. The mixture was homogenized, the beaker covered with a watch glass and heated to 95 °C, then refluxed for 15 minutes. The mixture was allowed to cooled, and then 5 mL concentrated HNO_3 added and refluxed again for 30 minutes. The beaker was covered with a ribbed beaker and allowed to evaporate to 5 mL.When this step was completed, the mixture was cooled and 2 mL of distilled water and 3 mL of 30 % H_2O_2 were added.

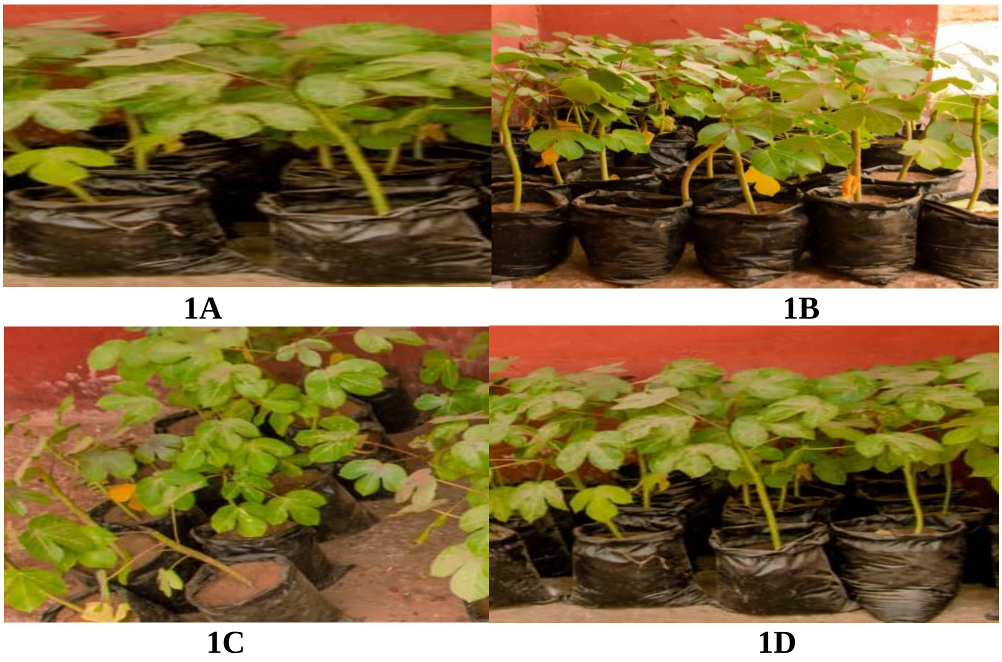

Figure 1.1A= *J. gossypiifolia* in control plot, 1B = *J. gossypiifolia* in WDS + 20 $mLday^{-1}$ CA
1C = *J. gossypiifolia* in WDS + 20 $mLday^{-1}$ EDTA, 1D = *J. gossypiifolia* in WDS + 20 $mLday^{-1}$ CA+EDTA

The mixture was heated until effervescence from the peroxide reaction stopped. The mixture was cooled again and 1 mL of H_2O_2 added until effervescence was minimal. The mixture was cooled, 2 mL of concentrated HNO_3 and 10 mL distilled water added then the mixture was refluxed for 15 minutes again. The mixture was centrifuged at 4000 rpm for 30 minutes to separate the filtrate from the residue (Saa-Aondo *et al.,* 2024). The concentrations (mgkg^{-1}) of Cd, Cr, Ni, and Pb in the filtrates were determined using Inductively Coupled Plasma Optical Emission spectroscopy (ICP-OES) (Shahbazi and Beheshti, 2019; Njoku and Nwani, 2022).

2.3. Determination of Bioaccumulation factor (BCF)

The bioaccumulation factor (BCF) of toxic metals in *Jatropha gossypiifolia* was determined using Eqn. 1

$$\mathrm{BCF} = \frac{\mathrm{Cmroot}}{\mathrm{Cmsoil}} \qquad \textbf{Eqn. I}$$

where BCF is the bioaccumulation factor, Cmroot is the concentration of toxic metal in root, and Cmsoil is the concentration of toxic metal in soil.

2.4. Determination of translocation factor (TF)

The translocation factor (TF) of toxic metals in *Jatropha gossypiifolia*was calculated using Eqn. 2 below:

$$\mathrm{TF} = \frac{\mathrm{Cmleaf}}{\mathrm{Cmroot}} \qquad \textbf{Eqn. 2}$$

where TF is the transfer factor, Cmleaf represents the concentration of toxic metal in the leaf, Cmroot is concentration of toxic metal in the root.

2.5. Data Treatment

Data obtained in this study were subjected to statistical analysis using IBM SPSS Statistic version 29.0.2.0 (20) Software. The mean, maximum, minimum, and standard deviation (SD) were obtained directly from the Software. Multivariate analyses were performed by Varimax Factor analysis and Dendrograms using average linkage.

3. Results and Discussion

3.1. Concentrations of Toxic Metals in the Background Impacted Soils

The results of toxic metals in the studied impacted soils are shown in **Table 1**above,cadmiun (Cd) ranged from 2.02 to 3.86 mgkg^{-1}. The highest concentration of Cd was obtained in EWS, while the lowest was recorded for PIS. The reported high level of Cd in electronic waste-impacted soil is similar to the findings by Manikandan *et al.* (2023). The average value of Cd obtained (3.00±0.82 mgkg^{-1}) is above the recommended limit for unpolluted soil by FAO/WHO (1999). Consequently, cultivation of edible crops may result in severe negative impacts on the consumers' health (Bouida *et al.,* 2022; Karim *et al.,* 2016). The concentrations of Cd at the different impacted soils examined followed the order EWS > WDS > ARS > PIS. This indicates that, the lowest concentration of Cd was recorded in the paint waste-impacted soil. Chromium (Cr) in the studied impacted soils ranged from 5.09 to 7.71 mgkg^{-1}between AIS and PIS, respectively. These results correspond with the one obtained by Woldeamanuale and Hassen, (2017). Thus, paint-related wastes have the potential of contaminating the environment with high level of Cr. However, the mean value of Cr obtained (6.44±1.09 mgkg^{-1}) is within the safe limit of 100.0 mgkg^{-1} by FAO/WHO (1999). Nevertheless, as metals have the capacity to bio-accumulate and persist in an environment, it can still be a serious problem over time (Ali *et al.,* 2019; Ullah *et al.,* 2023). On the other hand, the levels of Cr obtained in this study could support plant growth (Christou *et al*., 2021; Gao *et al*., 2022). The concentrations of Cr recorded in the different studied soils revealed the following trend PIS > WDS > EWS > ARS. Thus, automobile wastes showed lowest potential of contaminated the soil with Cr in the study.

Table 1: Concentration (mgkg-1) of Toxic Metals in the Background Impacted soils

SAMPLE	Cd	Cr	Ni	Pb
WDS	3.45	6.73	11.23	39.36
AIS	2.67	5.09	13.44	35.14
EWS	3.86	6.23	12.31	35.70
PIS	2.02	7.71	8.59	34.18
MIN	2.02	5.09	8.59	34.18
MAX	3.86	7.71	13.44	39.36
MEAN	3.00	6.44	11.39	36.10
SD	0.82	1.09	2.08	2.27
ASL	0.80	100.0	35.0	85.0

***WDS = Waste dumpsite soil, AIS = Automobile waste-impacted soil, EWS = Electronic waste-impacted soil, PIS = Paint waste-impacted soil, MIN = Minimum, MAX = Maximum, SD = Standard deviation, ASL = Acceptable safe limit**

The concentrations of nickel (Ni) in the soils examined varied from 8.59 mgkg^{-1} at PIS to 13.44 mgkg^{-1} in AIS. The reported high concentration of Ni in automobile waste-impacted soil is consistent with the results obtained by Liu *et al.* (2024). The average value of Ni recorded (11.39±2.08 mgkg^{-1}) is within the acceptable limit of 35.0 mgkg^{-1}for an unpolluted soil by FAO/WHO (1999). Hence, the levels of Ni at all the studied soils could be considered as contaminant rather than pollutant. According to Shahzad *et al.* (2018), the level of Ni in the impacted soil assessed can promote plant growth and enzymatic activities. The concentrations of Ni in the studied soils followed the sequence ARS > EWS > WDS > PIS. Thus, wastes from paint industry had the lowest potential of impacting the soil with Ni.

The concentrations of lead (Pb) recorded varied from 34.18 to 39.36 mgkg^{-1} (**Table 1**). The highest level was reported in the sample from WDS, while the lowest was obtained in PIS. The high concentration of Pb obtained in waste dumpsite soil is in agreement with the report by Agbeshie *et al.* (2020). The mean value of Pb obtained is within the acceptable limit of 85.0mgkg^{-1} recommended by FAO/WHO (1999). Thus, the level of Pb at each location examined may not have adverse negative effect on environment and human health. Nevertheless, Pb is a highly poisonous metal without any beneficial impact thus; the level in the studied soils should be closely monitored to avoid toxicity and the related risks (Collin *et al*., 2022). The concentrations of Pb at the different studied impacted soils followed the order WDS > EWS > ARS > PIS. The results revealed that, paint-related wastes showed the lowest degree of soil contamination by Pb.

3.2. Multivariate Analyses of Toxic Metals in the Impacted Soils

3.2.1. Principal Component Analysis of Toxic Metals

Principal component analysis (PCA) is a means of establishing the source(s) of contaminants in a studied ecosystem (Liu *et al*., 2023). The outcome of PCA of toxic metals in the studied impacted soils indicated two key sources with Eigen value over one (1) and a cumulative variance of 91.7% (**Table 2**). Factor one (F1) with Eigen value 2.39 donated 59.7% to the total variance. F1 had significant positive loadings on Cd and Ni, moderate positive loading on Pb, and strong negative loading on Cr.

This may be the impact of electronic and automobile-related wastes (Manikandan *et al*., 2023; Liu *et al*., 2024). The second factor (F2) with Eigen value of 1.28, contributed 32.0% of the total variance. The factor (F2) had moderate positive loading on Cr and a significant positive loading on Pb (**Table 2**). This could be the negative influence of paint-related wastes and wastes at the municipal dumpsite (Woldeamanuale and Hassen, 2017; Agbeshie *et al*., 2020).

Table 2: Results of Principal component analysis of Toxic metals in the Background Impacted Soils

	F1	F2
Cd	0.762	0.493
Cr	-0.838	0.524
Ni	0.945	-0.327
Pb	0.459	0.810
Eigen value	2.39	1.28
% Variance	59.7	32.0
% Cumulative	59.7	91.7

3.2.2. Hierarchical Cluster Analysis of Toxic Metals in the Impacted Soils

This work employed Hierarchical cluster analysis (HCA) for the identification of toxic metals with similar source as reported by Ebong *et al*. (2019) and Ebong *et al*. (2022). The HCA in **Figure 2**shows three outstanding clusters namely: (a) The first Cluster links automobile waste-impacted soil (AIS) with electronic waste-impacted soil (EWS), (b) The second Cluster connects waste dumpsite soil (WDS) alone, and (c) The third Cluster links paint waste-impacted soil (PIS) only. This indicates that automobile and electronic wastes may have contributed common kind of metal contaminants to the soil environment, whereas metal contaminants contributed by wastes at municipal dumpsite and paint industry might have been peculiar to the source (Vesselinov *et al*., 2018; Khaled-Khodja *et al*., 2023).

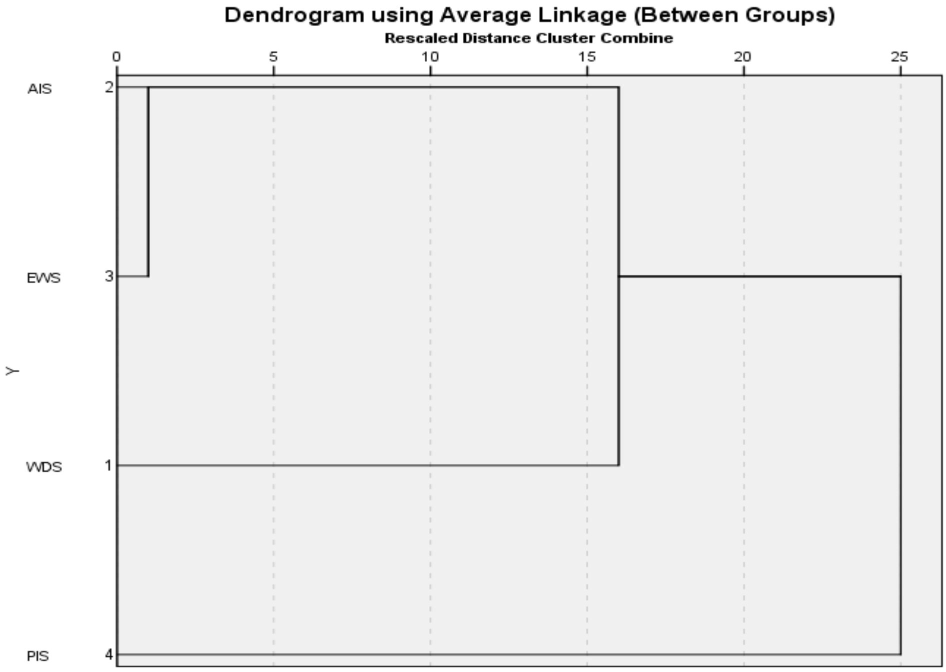

Figure 2: Hierarchical Clusters of Toxic Metals in the Impacted Soils

3.3. Concentrations of Toxic Metals Extracted by the Leaves and Roots of J. gossypiifolia from the different Impacted Soils Amended with Chelants

The results of toxic metals extracted by the leaves of *J. gossypiifolia* harvested from waste dumpsite soil (WDS) treated with different chelating agents are shown in **Table 3**. The concentrations (mgkg^{-1}) of toxic metals translocated to the leaves of *J. gossypiifolia* harvested from WDS enhanced with various concentrations of citric acid (CA) as the chelating agent varied as follows: 0.07 – 0.11, 0.22 – 0.25, 0.38 – 0.42, and 1.55 – 1.59 for Cd, Cr, Ni, and Pb, respectively. Concentrations (mgkg^{-1}) of toxic metals translocated from WDS to the leaves of *J. gossypiifolia* enhanced by different concentrations of EDTA were 0.08 – 0.12, 0.23 – 0.26, 0.39 – 0.43, and 1.56 – 1.60 for Cd, Cr, Ni, and Pb, respectively. Various concentrations of mixed CA+EDTA accelerated the translocation of 0.07 – 0.10, 0.18 – 0.21, 0.48 – 0.53, and 1.37 – 1.43 mgkg^{-1} of Cd, Cr, Ni, and Pb, respectively.

Table 3: Concentrations of Toxic Metals in the Leaves and Roots of *J. gossypiifolia* from WDS Treatedwith Different Chelants

	Cd	Cr	Ni	Pb	Cd	Cr	Ni	Pb
Conc. (mLday^{-1})	**LEAVES**				**ROOTS**			
CA								
5.0	0.07	0.22	0.38	1.55	0.08	0.24	0.41	1.57
10.0	0.09	0.23	0.40	1.57	0.10	0.25	0.42	1.58
15.0	0.10	0.24	0.41	1.58	0.11	0.26	0.42	1.59
20.0	0.11	0.25	0.42	1.59	0.12	0.29	0.43	1.61
EDTA								
5.0	0.08	0.23	0.39	1.56	0.09	0.25	0.42	1.58
10.0	0.10	0.24	0.41	1.58	0.11	0.26	0.43	1.59
15.0	0.11	0.25	0.42	1.59	0.12	0.27	0.44	1.60
20.0	0.12	0.26	0.43	1.60	0.13	0.30	0.45	1.62
CA + EDTA								
5.0	0.09	0.25	0.41	1.57	0.10	0.27	0.44	1.60
10.0	0.11	0.26	0.42	1.59	0.12	0.29	0.45	1.61
15.0	0.12	0.27	0.43	1.60	0.13	0.30	0.46	1.62
20.0	0.13	0.28	0.44	1.62	0.14	0.32	0.47	1.63

*** WDS = WASTE DUMPSITE SOIL, CA = CITRIC ACID, EDTA = ETHYLENEDIAMINETETRAACETIC ACID**

Table 3 shows the concentrations of toxic metals extracted from WDS by the roots of *J. gossypiifolia* with various concentrations of CA chelant. The results varied for Cd, Cr, Ni, and Pb as follows: 0.08 – 0.12, 0.24 – 0.29, 0.41 – 0.43, and 1.57 – 1.61 mgkg^{-1}, respectively. The Concentrations of Cd, Cr, Ni, and Pb extracted by the roots of *J. gossypiifolia* with EDTA as the chelating agent ranged as follows: 0.09 – 0.13, 0.25 – 0.30, 0.42 – 0.45, and 1.58 – 1.62 mgkg^{-1}, respectively. The concentrations (mgkg^{-1}) of toxic metals extracted by the roots of *J. gossypiifolia* with mixed CA+EDTA at different concentrations as chelating agent varied respectively as 0.10 – 0.14, 0.27 – 0.32, 0.44 – 0.47, and 1.60 – 1.63mgkg^{-1} for Cd, Cr, Ni, and Pb, respectively. The concentrations of all the toxic metals extracted by the roots of the studied plant from WDS were higher than the concentrations translocated to the leaves as reported by Shehata *et al*. (2019).

The results in **Table 3** indicate that, the leaves of *J. gossypiifolia* harvested from waste dumpsite-impacted soil (WDS) extracted the following percentage of toxic metals 35.6, 44.4, 44.1, and

48.3 for Cd, Cr, Ni, and Pb, respectively. The proportions of Cd, Cr, Ni, and Pb extracted by the roots were 39.1, 49.1, 46.7, and 48.7%, respectively. The results reported confirmed that higher proportions of the metals were extracted by the roots than the leaves. This is consistent with the reports published by Riza and Hoque (2021) and Hemani *et al*. (2024) from similar studies. Generally, the leaves and roots of *J. gossypiifolia* extracted a total of 74.7%, 93.5%, 90.8%, and 97.0% of Cd, Cr, Ni, and Pb from the contaminated soil (**Table 7**).

Table 4: Concentrations of Trace Metals in the Leaves and Roots of *J. gossypiifolia* from AIS Treated with Different Chelants

	Cd	Cr	Ni	Pb	Cd	Cr	Ni	Pb
Conc. (mLday^{-1})	**LEAVES**				**ROOTS**			
CA								
5.0	0.05	0.16	0.46	1.35	0.06	0.15	0.49	1.38
10.0	0.06	0.17	0.49	1.37	0.07	0.15	0.51	1.39
15.0	0.07	0.18	0.50	1.39	0.08	0.16	0.52	1.40
20.0	0.08	0.19	0.51	1.41	0.09	0.17	0.53	1.42
EDTA								
5.0	0.06	0.17	0.47	1.36	0.07	0.15	0.49	1.38
10.0	0.07	0.18	0.50	1.38	0.08	0.16	0.52	1.40
15.0	0.08	0.19	0.51	1.40	0.09	0.17	0.53	1.42
20.0	0.09	0.20	0.52	1.42	0.10	0.18	0.54	1.43
CA + EDTA								
5.0	0.07	0.18	0.48	1.37	0.08	0.16	0.51	1.42
10.0	0.08	0.19	0.50	1.40	0.09	0.17	0.54	1.43
15.0	0.09	0.20	0.52	1.41	0.10	0.18	0.55	1.44
20.0	0.10	0.21	0.53	1.43	0.11	0.20	0.56	1.46

*** AIS = AUTOMOBILE WASTE-IMPACTED SOIL, CA = CITRIC ACID, EDTA = ETHYLENEDIAMINETETRA ACETIC ACID**

The ranges of Cd, Cr, Ni, and Pb extracted from AIS by the leaves of *J. gossypiifolia* with various concentrations of citric acid (CA) as the chelant were 0.05 – 0.08, 0.16 – 0.19, 0.46 – 0.51, and 1.35 – 1.41 mgkg^{-1}, respectively (**Table 4**). The applications of various concentrations of EDTA as chelating agent to AIS improved the concentrations of Cd, Cr, Ni, and Pb extracted by the leaves of *J. gossypiifolia* as indicated by the following ranges: 0.06 – 0.09, 0.17 – 0.20, 0.47 – 0.52, and 1.36 – 1.42 mgkg^{-1}, respectively (**Table 4**). The mixed CA+EDTA at various concentrations resulted in the extraction of 0.07 – 0.10 mgkg^{-1} Cd, 0.18 – 0.21 mgkg^{-1} Cr, 0.48 – 0.53 mgkg^{-1} Ni, and 1.37 – 1.43 mgkg^{-1}Pb by the leaves of *J. gossypiifolia* from AIS.

The concentrations (mgkg^{-1}) of Cd, Cr, Ni, and Pb extracted by the roots of *J. gossypiifolia* from AIS with different concentrations of CA chelant ranged as follows: 0.06 – 0.09, 0.15 – 0.17, 0.49 – 0.53 and 1.38 – 1.42 mgkg^{-1}, respectively (**Table 4**). The addition of EDTA at various concentrations enhanced the extraction of higher ranges (mgkg^{-1}) of Cd, Cr, Ni, and Pb by the roots of *J. gossypiifolia* from AIS as follows: 0.07 – 0.10, 0.15 – 0.18, 0.49 – 0.54 and 1.38 – 1.43mgkg^{-1}, respectively (**Table 4**). **Table 4** indicates the ranges of Cd, Cr, Ni, and Pb extracted by the roots of *J. gossypiifolia* from AIS after the addition of various concentrations of mixed CA+EDTA chelant as 0.08 – 0.11, 0.16 – 0.20, 0.51 – 0.56 and 1.42 – 1.46 mgkg^{-1}, respectively. Consequently, the concentrations of metals extracted by both the leaves and roots of *J. gossypiifolia* from AIS followed the order Pb > Ni > Cr > Cd as also reported for WDS. The results obtained from AIS revealed that, the concentrations of Cr translocated to the leaves of *J. gossypiifolia* were higher than those extracted by the roots. This is similar to the results obtained by Mng'ong'o *et al*. (2021) from a related study. However, the concentrations of Cd, Ni, and Pb extracted by the roots were higher those obtained in the leaves. As shown in **Table 7**, the leaves of *J. gossypiifolia* extracted 33.6, 43.6, 44.6, and 47.5% of Cd, Cr, Ni, and Pb, respectively from AIS. The roots extracted 38.1, 39.4, 46.9, and 48.3% of Cd, Cr, Ni, and Pb. Hence, a total of 71.7, 83.0, 91.5, and 95.8% of Cd, Cr, Ni, and Pb, respectively were extracted by both the leaves and roots of *J. gossypiifolia* from AIS.

Table 5: Concentrations of Toxic Metals in the Leavesand Roots of *J. gossypiifolia* from EWS Treated with Different Chelants

	Cd	Cr	Ni	Pb	Cd	Cr	Ni	Pb
Conc. (mLday^{-1})	**LEAVES**				**ROOTS**			
CA								
5.0	0.09	0.18	0.42	1.42	0.10	0.20	0.44	1.38
10.0	0.10	0.20	0.44	1.44	0.11	0.21	0.45	1.39
15.0	0.12	0.21	0.45	1.45	0.12	0.22	0.47	1.41
20.0	0.13	0.22	0.46	1.47	0.14	0.24	0.49	1.43
EDTA								
5.0	0.11	0.19	0.43	1.43	0.12	0.22	0.46	1.40
10.0	0.11	0.21	0.45	1.45	0.13	0.23	0.47	1.41
15.0	0.12	0.22	0.46	1.46	0.14	0.24	0.49	1.42
20.0	0.14	0.23	0.48	1.48	0.15	0.25	0.50	1.44
CA + EDTA								
5.0	0.12	0.21	0.45	1.45	0.13	0.23	0.48	1.42
10.0	0.13	0.22	0.46	1.47	0.14	0.24	0.49	1.44
15.0	0.13	0.23	0.47	1.48	0.15	0.25	0.50	1.45
20.0	0.15	0.24	0.49	1.50	0.16	0.26	0.51	1.46

*** EWS = AUTOMOBILE WASTE-IMPACTED SOIL, CA = CITRIC ACID, EDTA = ETHYLENEDIAMINETETRAACETICACID**

Table 5 above shows the ranges of Cd, Cr, Ni, and Pb translocated to the leaves of *J. gossypiifolia* from electronic waste-impacted soil (EWS) enhanced by CA chelant as 0.09 – 0.13, 0.18 – 0.22, 0.42 – 0.46, and 1.42 – 1.47 mgkg^{-1}, respectively between concentrations of 5.0 and 20.0 mLday^{-1}. The addition of EDTA chelant improved the ranges of Cd, Cr, Ni, and Pb translocated to the leaves of *J. gossypiifolia* from EWS as 0.11 – 0.14, 0.19 – 0.23, 0.43 – 0.48, and 1.43 – 1.48 mgkg^{-1}, respectively between the concentrations of 5.0 and 20.0 mLday^{-1}. The ranges (mgkg^{-1}) of Cd, Cr, Ni, and Pb translocated to the leaves of *J. gossypiifolia* with mixed CA+ EDTA were 0.12 – 0.15, 0.21 – 0.24, 0.45 – 0.49, and 1.45 – 1.50mgkg^{-1} between 5.0 and 20.0 mLday^{-1} CA+EDTA chelant.

The concentrations (mgkg^{-1}) of Cd, Cr, Ni, and Pb extracted by the roots of *J. gossypiifolia* from EWS were 0.10 – 0.14, 0.20 – 0.24, 0.44 – 0.49, and 1.38 – 1.43mgkg^{-1} between 5.0 and 20.0 mLday^{-1}concentrationsof CA chelant. Ranges of 0.12 – 0.15, 0.22 – 0.25, 0.46 – 0.50, and 1.40 – 1.44 mgkg^{-1} of Cd, Cr, Ni, and Pb were extracted by the roots of *J. gossypiifolia*from EWS between the 5.0 and 20.0 mLday^{-1}concentrations of EDTA. The ranges of Cd, Cr, Ni, and Pb extracted by the leaves of the studied plant were 0.13 – 0.16, 0.23 – 0.26, 0.48 – 0.51, and 1.42 – 1.46 mgkg^{-1} between the mixed CA+EDTA chelant concentrations of 5.0 and 20.0mLday^{-1}. **Table 5** also indicates that higher concentrations of Pb were extracted by the leaves of *J. gossypiifolia* than the roots, whereas the concentrations of Cd, Cr, and Ni were higher in the roots than leaves. This is consistent with the report published by Abdulkadir *et al.* (2019) from a phytoremediation study. The proportions of Cd, Cr, Ni, and Pb extracted by the leaves of *J. gossypiifolia* from EWS were 37.5, 41.1, 44.4, and 49.0%, respectively (**Table 7**). The roots of the studied plant extracted 41.2, 44.8, 46.7, and 47.8% of Cd, Cr, Ni, and Pb, respectively. Thus, a total of 78.7, 85.9, 91.1, and 96.8% of Cd, Cr, Ni, and Pb were extracted from EWS by the leaves and roots of *J. gossypiifolia* (**Table 7**).

Table 6: Concentrations of Toxic Metals in the Leavesand Roots of *J. gossypiifolia* from PIS Treated with Different Chelants

	Cd	Cr	Ni	Pb	Cd	Cr	Ni	Pb
Conc.(mLday^{-1})	**LEAVES**				**ROOTS**			
					CA			
5.0	0.04	0.22	0.27	1.34	0.04	0.25	0.25	1.31
10.0	0.05	0.23	0.28	1.35	0.05	0.26	0.26	1.33
15.0	0.06	0.25	0.29	1.37	0.05	0.27	0.27	1.35
20.0	0.07	0.26	0.30	1.39	0.06	0.28	0.29	1.36
					EDTA			
5.0	0.05	0.24	0.28	1.36	0.05	0.26	0.26	1.33
10.0	0.07	0.25	0.29	1.37	0.06	0.27	0.27	1.35
15.0	0.08	0.26	0.30	1.39	0.06	0.28	0.28	1.37
20.0	0.09	0.27	0.32	1.40	0.07	0.29	0.30	1.38
					CA + EDTA			
5.0	0.06	0.25	0.30	1.38	0.06	0.27	0.27	1.34
10.0	0.07	0.26	0.32	1.39	0.07	0.28	0.29	1.36
15.0	0.09	0.27	0.33	1.40	0.07	0.29	0.29	1.38
20.0	0.10	0.28	0.35	1.42	0.08	0.31	0.31	1.39

*** PIS = PAINT WASTE-IMPACTED SOIL, CA = CITRIC ACID, EDTA = ETHYLENEDIAMINETETRAACETIC ACID**

The concentrations of toxic metals extracted by the leaves and roots of *J. gossypiifolia* from paint waste-impacted soil (PIS) are indicated in **Table 6**. The concentrations of Cd, Cr, Ni, and Pb extracted by the leaves of *J. gossypiifolia* from PIS amended with CA chelant varied as follows: 0.04 – 0.07, 0.22 – 0.26, 0.27 – 0.30, and 1.34 – 1.39 mgkg^{-1}, respectively between 5.0 and 20.0mLday^{-1} concentrations. Concentrations of the metals extracted by the leaves of *J. gossypiifolia* from PIS amended with various concentrations of EDTA chelant between 5.0 and 20.0mLday^{-1} ranged as follows: 0.05 – 0.09, 0.24 – 0.27, 0.28 – 0.32, and 1.36 – 1.40 mgkg^{-1} for Cd, Cr, Ni, and Pb, respectively. The use of different concentrations of mixed CA+EDTA for the amendment of PIS resulted in the extraction of 0.06 – 0.10, 0.25 – 0.28, 0.30 – 0.35, and 1.38 – 1.42 mgkg^{-1} of Cd, Cr, Ni, and Pb, respectively.

Table 6 also indicates the ranges of Cd, Cr, Ni, and Pb extracted by the roots of *J. gossypiifolia* from PIS with CA chelant as 0.04 – 0.06, 0.25 – 0.28, 0.25 – 0.29, and 1.31 – 1.36 mgkg^{-1}, respectively between the concentrations of 5.0 and 20.0mLday^{-1}. The ranges of 0.05 – 0.07, 0.26 – 0.29, 0.26 – 0.30, and 1.33 – 1.38 mgkg^{-1} of Cd, Cr, Ni, and Pb, respectively were extracted from PIS amended with different concentrations of EDTA by the roots of the studied plant. Concentrations (mgkg^{-1}) of Cd, Cr, Ni, and Pb extracted by the roots of *J. gossypiifolia* from PIS amended with mixed CA+EDTA ranged as follows: 0.06 – 0.08, 0.27 – 0.31, 0.27 – 0.31, and 1.34 – 1.39mgkg^{-1} between 5.0 and 20.0 mLday^{-1} concentrations of the chelant. The results obtained at PIS revealed that, higher concentrations of Cd, Ni, and Pb were extracted by the leaves of *J. gossypiifolia* than the roots nevertheless; higher concentrations of Cr were extracted by the roots than the leaves. This is in agreement with the results published in literature (Sêkara *et al*., 2005; Abdulkadir *et al*., 2019; Coulibaly *et al*., 2021). The quantities of Cd, Cr, Ni, and Pb extracted by the leaves of *J. gossypiifolia* from EWS were 41.11, 39.5, 42.3, and 48.6%, respectively. The roots of the studied plant extracted 35.7, 43.0, 38.9, and 47.6% of Cd, Cr, Ni, and Pb, respectively. Thus, a total of 76.8, 82.5, 81.2, and 96.2% of Cd, Cr, Ni, and Pb were extracted from EWS by the leaves and roots of *J. gossypiifolia* (**Table 7**).

3.4. Proportions of Toxic Metals in the Leaves and Roots of J. gossypiifolia harvested from the control soils

The results in **Table 7**indicate that, the highest proportion of Cd was obtained in electronic waste-impacted soil (EWS), while the lowest was recorded for the automobile waste-impacted soil (AIS). This confirms the findings by Chakraborty *et al*. (2022) and Ishchenko (2019) that, Cd is mainly released to the soil environment by e-wastes. The high concentration of Cd extracted from EWS could be attributed to the presence of Ni-Cd batteries as reported by Khan *et al*. (2017) and Kubier *et al.* (2019). The highest proportion of Cr was extracted from the municipal waste dumpsite soil (WDS), while the lowest was extracted in paint waste-impacted soil (PIS). This result corroborates the reports by previous authors that, municipal waste dumpsite soils have elevated levels of Cr (Afolagboye *et al*., 2020; Agbeshie *et al*., 2020; Sanga and Pius, 2024). This could be due to the presence of agricultural, electroplated metallic, timber, and leather-related wastes at the dumpsite (Xia *et al*., 2020). The highest quantity of Ni was extracted from the automobile waste-impacted soil (AIS), whereas the lowest Ni fraction was extracted from PIS. This is in agreement with the findings by the previous authors that, activities at the automobile mechanic workshops increase the concentrations of Ni in the host and adjourning soil environments (Vincent *et al*., 2022; Iwegbue *et al*., 2024).

Table 7: Total percentage of Toxic Metals extracted by the Leavesand Roots of *J. Gossypiifolia* harvested from the various impacted soils investigated

SAMPLE		Cd	Cr	Ni	Pb
WDS	LEAVES	35.6	44.4	44.1	48.3
	ROOTS	39.1	49.1	46.7	48.7
	TOTAL	74.7	93.5	90.8	97.0
ARS	LEAVES	33.6	43.6	44.6	47.5
	ROOTS	38.1	39.4	46.9	48.3
	TOTAL	71.7	83.0	91.5	95.8
EWS	LEAVES	37.5	41.1	44.4	49.0
	ROOTS	41.2	44.8	46.7	47.8
	TOTAL	78.7	85.9	91.1	96.8
PIS	LEAVES	41.1	39.5	42.3	48.6
	ROOTS	35.7	43.0	38.9	47.6
	TOTAL	76.8	82.5	81.2	96.2

The high proportion of Ni extracted from AIS could be attributed mostly to the combustion of petrol and diesel at these workshops (Shahzad *et al*., 2018; Bartzas *et al*., 2021). The highest quantity of Pb was extracted from WDS, while the lowest proportion was extracted from AIS. The high proportion of Pb extracted from WDS is consistent with the previous studies documented in literature (Akanchise *et al*., 2020; Ibrahim *et al*., 2020; Onwukeme and Eze, 2021).The high quantity of Pb extracted from WDS could be attributed to the presence of domestic, metallic, plastic, and agricultural wastes and batteries at the studied dumpsite (Twumasi *et al*., 2016; Zhou *et al*., 2022). The variations in the quantity of toxic metals extracted from one impacted soil to the other could be influenced mainly by the difference in soil properties (Farrag *et al*., 2011; Cui *et al*., 2021; Wieczorek *et al*., 2023). The following observations were deduced generally from the results obtained:

(i) The proportions of the metals extracted were directly proportional to the concentrations of the metals in the impacted soils before the amendment with chelantsas reported by Orr *et al*. (2020) and Alawsy *et al*. (2024).

(ii) The potential of chelating agent used generally followed the trend CA+EDTA > EDTA > CA hence; the highest concentrations in all the studied impacted soils were extracted by mixed chelants, while CA extracted the lowest concentrations of the metals. This is in agreement with the findings by Guo *et al*. (2018) and Yang *et al*. (2022). The reported trend also revealed that, EDTA chelant was more effective in the phytoremediation study than CA (Shinta *et al*., (2021); Nawaza *et al*., 2022).

(iii) The extraction of metals based on their concentrations followed the increasing order 5.0 > 10.0 > 15.0 > 20.0mLday^{-1}. Accordingly, the concentrations of metals extracted varied directly with the concentration of the chelants as reported by Olusegun and Oluwafemi, (2012); Boulouiz*et al*., (2020); Khare *et al*. (2024); Tayiem *et al*. (2025).

(iv) The concentrations of the toxic metals extracted from all the impacted soils examined followed the trend Pb > Ni > Cr > Cd. Hence, the highest metal extracted by *J. gossypiifolia* was Pb, while Cd was the lowest. The high concentrations of Pb extracted by*J. gossypiifolia*reported is similar to the results reportedin literature (Gzar *et al*., 2014; Li and Gao, 2019; Tatu *et al*., 2020). Njoku and Nwani (2022) also documented from their phytoremediation study that, the lowest metal extracted from impacted soils was recorded for Cd.

3.5.Results of Toxic Metals extracted by the Leaves and Roots of J. gossypiifolia harvested from the Control Soils

Results for the concentrations of toxic metals extracted by the leaves and roots of *J. gossypiifolia* harvested from the control pots are shown in **Table 8**. The concentrations (mgkg^{-1}) of toxic metals translocated from the municipal waste dumpsite soil (WDS) without amendment (Control) to the leaves of *J. gossypiifolia* were 0.56, 0.78, 0.83, and 3.15mgkg^{-1} for Cd, Cr, Ni, and Pb, respectively. The concentrations of Cd, Cr, Ni, and Pb extracted by the roots of *J. gossypiifolia* from the control pot of WDS were 0.73, 0.96, 1.10, and 4.32 mgkg^{-1}, respectively.The proportions of the metals translocated from the control pot of WDS to the leaves of *J. gossypiifolia* were 16.2, 11.6, 7.4, and 8.0% for Cd, Cr, Ni, and Pb, respectively. The roots extracted 21.2, 14.3, 9.8, and 11.0% of Cd, Cr, Ni, and Pb, respectively from the control pot of WDS.The trend for the concentrations of toxic metals extracted from the control pot of WDS by the leaves and roots of *J. gossypiifolia* was Pb > Ni > Cr > Cd. Thus, the trend for both the leaves and roots were similar.

Table 8 shows that the concentrations of Cd, Cr, Ni, and Pb, translocated from the control pot of AIS to the leaves of *J. gossypiifolia* were 0.40, 0.61, 0.53, and 2.19mgkg^{-1}, respectively. The roots of the studied plant extracted 0.74, 0.83, 0.90, and 3.47 mgkg^{-1} of Cd, Cr, Ni, and Pb, respectively from the control pot of AIS. The concentrations of metals extracted from the control soil of AIS followed the orders Pb > Cr > Ni > Cd and Pb > Ni > Cr > Cd, respectively for the leaves and roots of *J. gossypiifolia*.

The proportion of Cd, Cr, Ni, and Pb extracted by the leaves of *J. gossypiifolia* from AIS not amended by chelants were 15.0, 12.0, 3.9, and 6.2%, respectively. The proportions of Cd, Cr, Ni, and Pb extracted by the roots of *J. gossypiifolia* from AIS not treated with chelants were 27.7, 16.3, 6.7, and 9.9%, respectively.The concentrations (mgkg^{-1}) of Cd, Cr, Ni, and Pb translocated from the roots to the leaves of *J. gossypiifolia* control pot of EWS were 0.58, 0.47, 0.49, and 1.73mgkg^{-1}, respectively.

This follows the sequence Pb > Cd > Ni > Cr. **Table 8** indicates that, the roots of *J. gossypiifolia* extracted 0.97, 0.64, 0.62, and 2.68 mgkg^{-1} of Cd, Cr, Ni, and Pb, respectively from the control pot of EWS. Thus, the concentrations of the toxic metals extracted by the roots followed the order Pb > Cd > Cr > Ni.

Table 8: Total concentrations of metals in leaves and roots of *J. gossypiifolia* harvested from the different control soils

	Cd	Cr	Ni	Pb	Cd	Cr	Ni	Pb
	LEAVES				**ROOTS**			
WDS	0.56	0.78	0.83	3.15	0.73	0.96	1.10	4.32
AIS	0.40	0.61	0.53	2.19	0.74	0.83	0.90	3.47
EWS	0.58	0.47	0.49	1.73	0.97	0.64	0.62	2.68
PIS	0.35	0.55	0.43	2.40	0.46	0.72	0.64	3.11

***WDS = Municipal wastes dumpsite soil, ARS = Automobile waste-impacted soil, EWS = Electronic waste-impacted soil, PIS = Paint waste-impacted soil**

The proportions of Cd, Cr, Ni, and Pb extracted by the leaves of *J. gossypiifolia* from the control pot of EWS were 15.0, 7.5, 4.0, 4.9%, respectively. The fractions of Cd, Cr, Ni, and Pb extracted by the roots of *J. gossypiifolia* from the EWS not amended with chelants were 25.1, 10.3, 5.0, and 7.5%, respectively. The leaves of *J. gossypiifolia* extracted 0.35, 0.55,0.43, and 2.40 mgkg^{-1}of Cd, Cr, Ni, and Pb, respectively from the control pot of PIS (**Table 8**). The concentrations (mgkg^{-1}) of Cd, Cr, Ni, and Pb extracted by the roots of *J. gossypiifolia* from the control pot of AIS were 0.46, 0.72, 0.64, and 3.11mgkg^{-1}, respectively. The results obtained for the concentrations of toxic metals extracted by both the leaves and roots of the studied plants followed the order Pb > Cr > Ni > Cd.

The amounts of Cd, Cr, Ni, and Pb extracted by the leaves of *J. gossypiifolia* from the control pot of PIS were 17.3, 7.1, 5.0, and 7.0%, respectively. The roots of the studied plant extracted 22.8, 9.3, 7.5, and 9.1% of Cd, Cr, Ni, and Pb, respectively from the control pot of PIS.The results for the total proportions of toxic metals extracted by both the leaves and roots of *J. gossypiifolia* from the control pots as illustrated in **Figure 3** were 37.4, 25.9, 17.2, and 19.0% for Cd, Cr, Ni, and Pb in the control pot of WDS. In the control pot of AIS, the leaves and roots of *J. gossypiifolia* collectively extracted 42.7% Cd, 28.3% Cr, 10.6% Ni, and 16.1% Pb (**Figure 3**). The leaves and roots of*J. gossypiifolia* extracted a total of 40.1, 17.8, 9.0, and 12.4% of Cd, Cr, Ni, and Pb, respectively from EWS (**Figure 3**). **Figure 3** shows that 40.1%, 16.4%, 12.5% and 16.1%, respectively of total proportions of Cd, Cr, Ni, and Pb were extracted by the leaves and roots of *J. gossypiifolia* from the control pot of PIS.

The results obtained from the control pots revealed that, the concentrations of all the metals were higher in the roots of *J. gossypiifolia* than the leaves. Consequently, the study has confirmed that, the application of chelants to a contaminated soil can enhance the translocation of metals to the shoots of the plant during phytoremediation (Chen *et al.*, 2010, Lateefat *et al.*, 2023). Generally, the proportions of the toxic metals extracted by both the leaves and roots of *J. gossypiifolia* followed a decreasing order of Cd > Cr > Pb > Ni. Obviously, the proportions of toxic metals extracted from the impacted soils amended with chelants were much higher than in the control pot as reported by Shehata *et al.* (2019) and Helaoui *et al.* (2023). Accordingly, the application of chelants to the impacted soils promoted the extraction of toxic metals by *J. gossypiifolia* (Bian *et al.*, 2018; Dong *et al.*, 2023; Lateefat *et al.*, 2023; Zulkernain *et al.*, 2023).

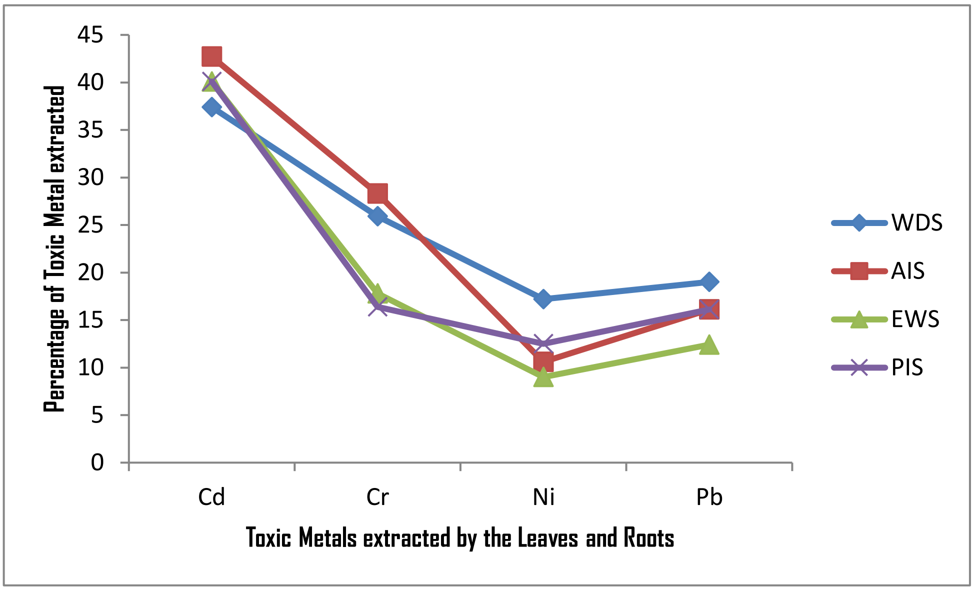

Figure 3: Total Percentage of Toxic Metals phytoextracted from the Control Pots

3.6. Results of Toxic Metals in the amended and controls after phytoextraction by J. gossypiifolia

The results of the fractions of toxic metals in the control and amended soils after extraction by *J. gossypiifolia* are shown in **Table 9**. The proportions (%) of Cd in the control soils were 62.6, 57.3, 59.9, and 59.9 for WDS, AIS, EWS, and PIS, respectively. The amounts of Cr in the control soils of WDS, AIS, EWS, and PIS were 74.1, 71.7, 82.2, and 83.6%, respectively. The fractions of Ni in the control soils after phytoextraction by *J. gossypiifolia* were 82.8, 89.4, 91.0, and 87.5% in WDS, AIS, EWS, and PIS, respectively. Pb in the control soils after phtoextraction by the studied plant were 81.0, 83.9, 87.6, and 83.9% in WDS, AIS, EWS, and PIS, respectively.

Table 9: The proportions of Toxic metals in control and amended soils after phytoextraction by *J. gossypiifolia*

	Cd	Cr	Ni	Pb	Cd	Cr	Ni	Pb
	CONTROL SOIL				**AMENDED SOIL**			
WDS	62.6	74.1	82.8	81.0	25.3	6.5	9.2	3.0
AIS	57.3	71.7	89.4	83.9	28.3	17.0	8.5	4.2
EWS	59.9	82.2	91.0	87.6	21.3	14.1	8.9	3.2
PIS	59.9	83.6	87.5	83.9	23.2	17.5	18.8	3.8

***WDS = Municipal wastes dumpsite soil, ARS = Automobile waste-impacted soil, EWS = Electronic waste-impacted soil, PIS = Paint waste-impacted soil**

The fractions of Cd in the soils amended with chelants after phytoextraction by *J. gossypiifolia* were 25.3, 28.3, 21.3, and 23.2% in the WDS, AIS, EWS, and PIS, respectively (**Table 9**). The amounts of Cr in the amended WDS, AIS, EWS, and PIS after extraction by the studied plant were 6.5, 17.0, 14.1, and 17.5%, respectively (**Table 9**). The results in Table xx indicate that the fractions of Ni in the amended WDS, AIS, EWS, and PIS after phytoextraction were 9.2, 8.5, 8.9, and 18.8%, respectively. The proportions of Pb in the soils amended with chelants varied as follows: 3.0, 4.2, 3.2, and 3.8% respectively for WDS, AIS, EWS, and PIS. Accordingly, the proportions of toxic metals extracted from the soils amended with chelants were much higher than that of the control soils (Adjia *et al*., 2008; Yang *et al*., 2021). This corroborates the observations that, chelants increase the rate of metals uptake by plants (Aghelan *et al*., 2021; Hosseinniaee *et al*., 2023).

3.7. Results of Bioaccumulation factor (BCF) of Toxic Metals *J. gossypiifolia*

The results of the bioaccumulation factor (BCF) of toxic metals in soils without amendment (Control) and the amended soils are shown in **Table 10**. The mean BCF of toxic metals in the control soils were as follows: Cd (0.64), Cr (0.35), Ni (0.20), and Pb (0.25). The BCF of all the toxic metals in the entire control soils were less than one (1). This agrees with the report by Olayinka-Olagunju *et al.* (2021) from a similar study. Consequently, *J. gossypiifolia*could be effectively employed as excluder of these metals in the control soils (Usman *et al.*, 2019; Zakari and Audu, 2021). The reported BCF values of the toxic metals in the control soils followed a descending order of Cd > Cr > Pb > Ni.

Table 10: Bioaccumulation Factor (BCF) of toxic metals from the Soil to *J. gossypiifolia*

	Cd	Cr	Ni	Pb	Cd	Cr	Ni	Pb
	CONTROL SOIL				**AMENDED SOIL**			
WDS	0.58	0.40	0.27	0.30	1.14	1.42	1.38	1.46
AIS	0.71	0.44	0.18	0.26	1.10	1.22	1.38	1.44
EWS	0.65	0.28	0.14	0.20	1.20	1.31	1.38	1.45
PIS	0.63	0.26	0.21	0.25	1.13	1.25	1.20	1.44
Mean	0.64	0.35	0.20	0.25	1.14	1.30	1.34	1.45

***WDS = Municipal wastes dumpsite soil, ARS = Automobile waste-impacted soil, EWS = Electronicwaste-impacted soil, PIS = Paint waste-impacted soil**

In the impacted soils amended with chelants, the mean BCF obtained for Cd, Cr, Ni, and Pb were 1.14, 1.30, 1.34, and 1.45, respectively. The BCF of all the metals in all the amended soils were higher than one. Hence, *J. gossypiifolia* could regarded as hyperaccumulator in the amended soils and could effectively be used for the remediation of soil impacted with these metals (Usman *et al.*, 2019). The mean BCF values of toxic metals in the studied soils followed the descending order of Pb > Ni > Cr > Cd. Accordingly, the high BCF recorded for Pb is similar to the results reported by Anani and Olomukoro (2020) and Ombugadu *et al.* (2023). It was also deduced from the results that, higher BCF were reported in the amended soils than the control soils (Padmavathiamma and Li, 2010; Sulaiman and Hamzah, 2018; Embrandiri *et al.*, 2017). Hence, soil amendment by the application of chelants can increase the rate of metal accumulation by plants from a contaminated site (Lateefat *et al.*, 2023; Zulkernain *et al.*, 2023).

3.8. Results of Translocation factor (TF) of Toxic Metals *J. gossypiifolia*

The results of the translocation factor (TF) of toxic metals from the roots of *J. gossypiifolia* to the leaves in both the amended soils and soils without amendment (Control) are shown in **Table 11**. TF is the ratio of a particular metal in the leaves of a plant to that of the roots (Sanjosé *et al.*, 2022). The TF of Cd in the control's soils ranged between 0.54 in AIS and 0.77 in WDS. TF of Cr in control soils varied from 0.73 in EWS and 0.81 in WDS. In the control pots, the TF of Ni ranged from 0.59 in AIS to 0.79 in EWS. The TF of Pb in the control soils ranged between 0.63 in AIS and 0.77 in PIS. The TF of all the toxic metals in soils without amendment were less than one. As a result of this, *J. gossypiifolia* could be effectively employed for the phytostabilization of these metals in the control soils (Madanan *et al.*, 2021; Mocek-Płóciniak *et al.*, 2023). The TF of toxic metals in the amended soils ranged from 0.88 to 1.15 between AIS and PIS for Cd. The TF of Cr in the amended soils varied between 0.90 in WDS and 1.11 in AIS. A range of 0.95 – 1.09 was recorded for Ni between WDS and PIS. The TF of Pb in the amended soils varied from 0.98 in AIS to 1.03 in EWS. The TF of all the toxic metals in WDS were less than one (**Table 11**).

Table 11: Translocation factor of toxic metals from the roots to the leaves of *J. gossypiifolia* in the control and amended soils

	Cd	Cr	Ni	Pb	Cd	Cr	Ni	Pb
	CONTROL SOIL				**AMENDED SOIL**			
WDS	0.77	0.81	0.75	0.73	0.91	0.90	0.95	0.99
AIS	0.54	0.74	0.59	0.63	0.88	1.11	0.95	0.98
EWS	0.60	0.73	0.79	0.65	0.91	0.92	0.96	1.03
PIS	0.76	0.76	0.67	0.77	1.15	0.92	1.09	1.02
Mean	0.67	0.76	0.70	0.70	0.96	0.96	0.99	1.01

***WDS = Municipal wastes dumpsite soil, ARS = Automobile waste-impacted soil, EWS = Electronic waste-impacted soil, PIS = Paint waste-impacted soil**

In AIS, the TF of Cr was higher than one but less than one for other metals. The TF of all the metals except Pb were less than one, while the TF of Cd and Ni, and Pb were higher than one but were less than one for Cr. Thus, *J. gossypiifolia* could be effectively utilized for the phytoextraction of Cd, Cr, Ni, and Pb in paint, automobile, and electronic waste-impacted soils (Sajad *et al*., 2020). The results also revealed that Cd, Cr, Ni, and Pb were highly mobile in the paint, automobile, and electronic waste-impacted soils (Nahar and Hossen, 2020). However, in the locations where the TF were less than one, *J. gossypiifolia* could used for phytostabilizationof the metals in those locations (Eribo *et al*., 2021; Naz *et al*., 2024; Aziz *et al*., 2023). The translocation factors of toxic metals were higher in the amended soils than the soils without amendment (Control). This agrees with the results obtained from previous phytoremediation studies by Embrandiri *et al*. (2017) and Kulsoom *et al*. (2024). Hence, the application of chelants can improve the translocation of metals from contaminated soils to the plant (Saifullah *et al*., 2009; Zulkernain *et al*., 2023).

3.9. Impacts of soil amendment with chelants on the growth of J. gossypiifolia

The application of citric acid (CA) to the impacted soils enhanced the growth of *J. gossypiifolia* (**Figure 1B**). The use of CA for the amendment of the studied soils improved the height of the plant and enlarged the leaves (Shareef *et al*., 2022; Ali *et al*., 2024). The results obtained indicated that, the growth of *J. gossypiifolia* was directly proportional to the concentration of CA chelant (Farid *et al*., 2017; Kaur *et al*., 2017; Kalousek *et al*., 2024). The results also indicated improved plant growth for the soils amended with CA thanplant in the control soil as reported by Twaij *et al*. (2019).

As shown in **Figure 1C**, the application of EDTA reduced the growth of *J. gossypiifolia* significantly, and the growth was inversely proportional to the concentration of EDTA (Wirosoedarmo *et al*., 2018; Huang *et al*., 2021; Hosseinniaee *et al*., 2023). It was deduced that, while the application of CA promoted the growth of *J. gossypiifolia*, EDTA inhibited the growth of the plants. This conforms tothe results documented from previous studies (Han *et al*., 2018; Hosseini *et al*., 2021; Shinta *et al*., 2021). **Figure 1D** indicates that, the addition of mixed CA+EDTA chelant promoted the growth of *J. gossypiifolia* as previously reported by Saleem *et al*. (2020) and Nawaza *et al*. (2022). However, the rate of growth did not show a direct relationship with the concentration of mixed CA+EDTA.

Jatropha gossypiifolia exhibited a steady growth in all the control pots with the number of weeks. However, the tallest height of the stem and largest width of the leaves were recorded for the plant cultivated in the control pot of WDS (**Figure 1A**). The *J. gossypiifolia* cultivated in electronic waste-impacted soil (EWS) was the shortest. The luxuriant growth exhibited by *J. gossypiifolia* in the control soil of WDS could be attributed to the high plant nutrients available at dumpsite soil (Obianefo *et al*., 2017; Ogbuehi *et al*., 2021). The growth of *J. gossypiifolia* in the control soils without amendment followed a decreasing order of :

WDS > PIS > AIS > EWS.

Conclusion

Based on the results, it could be concluded that, *J. gossypiifolia* could be applied for pytoremediation of soils impacted with toxic metals. Higher concentration of toxic substances could be extracted by plants from highly impacted soils. The study also revealed that EDTA is a more effective chelant than citric acid however; a mixture of the two has a higher potential as chelant. Higher concentrations of metals were extracted when higher concentrations of the chelsnts were applied. The application of EDTA can impact negatively on the growth of plants used for phytoremediation while; citric acid improves their growth. Hence, the use of EDTA as a chelant for soil amendment during phytoremediation study should be minimized. The application of chelants could also improve the uptake of toxic substances by plants.

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