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Phytoremediation Efficiency of Flax (*Linum usitatissium* L.) of Heavy Metal-Contaminated Soil in the Kwashe Industrial Region Using Soil Amendments

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ABSTRACT
The study was conducted in the contaminated soils surrounding the petroleum refineries and iron scrap recycling factories in the Kwashe Industrial region, Duhok Governorate, Kurdistan Region of Iraq. Soils were taken from the surface at a depth of 0-30 cm. A pot experiment was carried out in a greenhouse to evaluate the effectiveness of using amendments such as humic acid (HA), biochar (BC) at 5 g kg^{-1} soil, and ammonium nitrite (NH_4NO_3) (AN) at 230 mg kg^{-1} soil, as well as a control, on the phytoremediation efficiency of flax (*Linum usitatissium* L.). The results showed a significant increase in Zn, Pb, and Cd in flax shoots and roots when treated with different amendments. The high uptake of metals with the addition of amendments was in the following order: BC > HA > AN, while for roots, the increase was in the following order: HA > BC > AN. Biochar effectively enhanced the uptake of Zn and Pb in flax shoots, while humic acid enhanced the uptake of Cd in flax shoots. The results also revealed that flax successfully accumulates these metals in both its shoots and roots; however, the roots accumulate significantly more than the shoots. Additionally, the bioconcentration factor (BCF > 1) and the translocation factor (TF < 1) indicate that flax roots can be utilized as a phytostabilizer for soil contaminated with Zn, Pb, and Cd.

***Keywords*:** Phytoremediation, amendments, Flax, Zinc, Cadmium, Lead.

INTRODUCTION

Industrialization has contaminated soils with heavy metals such as cadmium (Cd), lead (Pb), and zinc (Zn), which represent major environmental and public health risks due to their toxicity, persistence, and non-biodegradability [1]. These pollutants originate from both human activities and natural processes. Main contributors include smelting, fossil fuel combustion, mining, and industrial effluents. After being discharged, the metals move through the ecosystem and find their way into food chains, where they can come into contact with humans and animals through drink, food, dust, and skin contact [2]. Heavy metal mobility and bioavailability in soil are affected by pH, soil texture and organic matter, making polluted soils difficult to manage [3]. Understanding the origins, behavior, and ecological consequences of heavy-metal pollution is critical for establishing effective remediation and risk-assessment procedures [4].

Human activity that releases heavy metals in biologically available forms can damage or alter both natural and man-made environments [5]. According to [6], soil contaminated with heavy metals has impacted almost 10 million individuals globally. There is a significant risk because heavy metals accumulate in crops through the soil-root interface [7]. Long-term heavy metal exposure via the air, soil, water, and food causes various diseases [8]. Lead can remain in soil for about 150–5,000 years and maintains elevated concentrations for up to 150 years following sludge application [9], while the biological half-life of cadmium is roughly 10–30 years [10].

Flax, a fibrous plant historically cultivated for oilseed and industrial purposes, has shown the ability to absorb significant levels of Cd and Zn from polluted soils, which is due to its deep root zone and modest biomass output [11]. Studies reveal that flax has the ability to partly immobilize and absorb metals, which may eventually lower the bioavailable proportion [12].

Phytoremediation, which uses plants to remove, stabilize, or detoxify pollutants from soil, is a low-cost and ecologically friendly means [13]. Flax (*Linum usitatissimum* L.) has showed promise as a phytoremediator due to its rapid growth, high biomass output, and capacity to accumulate particular heavy metals in its tissues [14]. In a comparative study, it has been shown that flax may be more effective at phytoextraction, which is the accumulation of metals in above-ground biomass [15].

The Kwashe industrial region's soils are polluted with excessive quantities of heavy metals, endangering both the environment and public health. Phytoremediation using flax can help reduce these pollutants, and its effectiveness can be improved with soil amendments. Understanding the combined impacts of flax cultivation and soil amendments is critical for developing successful remediation solutions.

Recent research has shown that the use of soil amendments, such as biochar, organic composts, and mineral additions, can enhance metal bioavailability, soil characteristics, and hence plant metal absorption capability [4][3]. A chelate can release a heavy metal from soil cation exchange sites by creating a complex with it, allowing the chelated metal species to move more freely in soil as a chelate-metal complex [16]. Excessive NH_4NO_3 increased soil Pb, Cd, Ni, and Cu concentrations compared to urea in controlled experiments, resulting in increased plant uptake [17]. Humic acid can enhance Cd absorption in the short term but may lower soil Pb, Zn, and Cd contents when mixed with nitrogen fertilizers over time [18]. Biochar is a carbon-rich material derived from the pyrolysis of organic materials with large surface area and specific functional groups that bind heavy metals [3].

By adsorbing free ions and changing the pH and cation exchange capacity of soil, its use can lower the bioavailability of metals [19]. Heavy metals are extremely difficult to remove from the environment because, like other contaminants, they cannot be broken down chemically or biologically. Numerous mechanisms, including phytoextraction, phytostabilization, rhizodegradation, phytodegradation, phytovolatilization, and phytoaccumulation, are involved in the uptake of heavy metals by phytoremediation technology [20]. The aim of this study is to assess the ability of amendments to improve the phytoremediation efficiency of flax of heavy metals from contaminated soil.

Materials and Methods

Study site

This study was focused on the two sites of the studied industrial area located in Kwashe District, about 20 km west of Duhok Province, Kurdistan Region, Iraq. One of the sites is located in an oil refinery (OR) (latitude 36°59′N; longitude 42°47′E), which is exposed to oil waste spills from the local petroleum company. The other site is located in an iron factory (IF) (latitude 36°59′N; longitude 42°48′E); it is a recycling factory for scraped iron where they dump its waste into the soil. being a free-trade zone with numerous industries (Figure 1).

Soil sampling

A composite contaminated soil sample was collected from ten sub-samples taken at both sites. Soil was taken from the soil surface (0–30 cm depth) using auger equipment. The collected soil samples were spread on a piece of nylon; the soil was air-dried at room temperature; stones or debris were removed by hand; and then the soil samples were crushed and sieved through a 4 mm sieve for pot experiment. The soils were then pass through 2mm sieve and the subjected to chemical and physical characteristics as shown in Table 1.

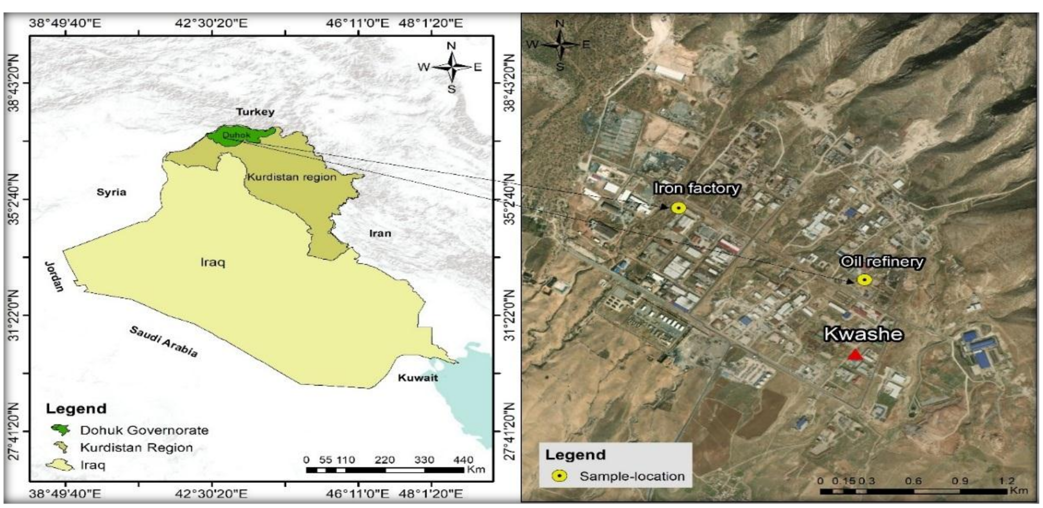

Figure 1. The map shows the locations for taking of soil samples

Pot experiments setup

This experiment was conducted in pots of a capacity of 5 kg (Ø 25cm) under greenhouse conditions at the college of agricultural engineering science, university of Duhok, Kurdistan region, Iraq. A factorial experiment in the form of completely randomized block design (RCBD) was with three block (replicates) was performed to assign the studied treatments. In this experiment, two types of contaminated soil were used for remediation as first factor: Oil refinery (OR) and Iron factory (IF). The second factor was three types of amendments (Humic acid, Biochar, and NH_4NO_3) in addition to control. The amended used in present study was applied at one rate as follow (Table 2): NH_4NO_3 (230 mg/kg), humic acid (5 g/kg) and biochar (5 g/kg) along with control. The whole experimental units for current study were 24 (2 types of soil × 4 types of amendments × 3 replicates).

Table 1: Physicochemical characteristics of studied soils.

Characteristics	Units	Iron factory	Oil Refinery
pH		7.51	8.13
EC	dSm^{-1}	9.40	4.25
Ca^{+2}		43.28	23.80
Mg^{+2}		6.11	6.39
Na^{+}		25.94	8.45
K^{+}		12.31	5.02
Cl^{-}	$mmol_c\ l^{-1}$	59.23	1.12
HCO_3^{-}		2.03	5.41
CO_3^{-2}		0.00	0.00
SO_4^{-2}		26.38	37.13
$CaCO_3$		13.22	16.29
OM	$g\ kg^{-1}$	6.74	15.79
TN		0.378	0.14
CEC	$Cmol_c$ kg	29.05	49.58
Av. P	$mg\ kg^{-1}$	0.15	0.17
THC		12700	63900
Total Cd^{+2}		1.44	0.96
Total Pb^{+2}		228.26	324.80
Total Zn^{+2}	$mg\ kg^{-1}$	200.42	123.26
Av. Cd^{+2}		0.00493	0.00346
Av. Pb^{+2}		2.3082	0.5292
Av. Zn^{+2}		1.2691	0.8670
Clay		311.4	359.4
Silt	$g\ kg^{-1}$	364.2	332.0
Sand		324.4	308.6
Texture		Clay Loam	Clay Loam
Bulk density	$g\ cm^{-3}$	1.55	1.28

Prior experiment conduction, an activating dose of NPK fertilizer was applied to the pot soils before planting and the addition of amendments according to recommended levels for pepper authorized by the Ministry of Agriculture of Iraq/ Directorate of Extension Services [21]. The form of inorganic fertilizers was urea (46 % N), triple super phosphate (46 % P_2O_5), and potassium sulphate (50 % K_2O). The contaminated soils with amendments were incubated for 40 days. This duration may facilitate the degradation or transformation of hydrocarbon pollutants; therefore, the soil conditions more accurately reflect actual farm situations

For the purpose of providing an adequate supply of nitrogen treatment for the pots, 250 mg of NH_4NO_3 was dissolved in 300 mL of distilled water and left for one day; this solution was then applied evenly to the pots after 8 days of sowing [22]. Each pot was sown with 15 seeds of flax

Table 2: Total concentrations of Zn, Pb, and Cd for different amendments (mg kg^{-1})

Chelates	Zn	Pb	Cd
Humic acid	25.76	62.66	0.00002
Biochar	48.37	75.15	0.22499
NH_4NO_3	13.18	37.28	0.000011

(*Linum usitatissium* L.) in the top layer of soil 2 cm deep. Individual pots were placed at a distance of 0.15 meters from each other. After germination the seedlings were then thinned into 10 seedlings. Under carefully monitored conditions, the assay was carried out in a greenhouse. The crop was irrigated with tap water according to crop requirements throughout the experiment.

Analytical procedures

The following characteristics of the soil were measured using standard laboratory procedures (Table 1): Soil pH and electrical conductivity (EC) were measured in a 1:2.5 soil/water solution [23]. Soluble cations (Ca^{++}, Mg^{++}, Na^{+}, and K^{+}) and anions (HCO_3^{-}, CO_3^{-}, Cl^{-}, and $SO_4^{=}$) were determined using standard procedures as described by [24]. Soil organic matter was determined using the method outlined by [25]. The cation exchange capacity (CEC) was measured by using a solution of ammonia acetate (1N) NH_4OAc, following the steps outlined by [26]. Equivalent calcium carbonate ($CaCO_3$) was determined using hydrochloric acid (1N HCl) by the Calcimeter apparatus. The Kjeldahl digestion method, described by [27], was used to measure total nitrogen (TN). Available phosphorus (Av. P) was extracted with 0.5 M $NaHCO_3$ (pH 8.5) and measured by the blue color method using ascorbic acid [28]. Total hydrocarbons (THC) were measured using dichloromethane based on weight gravimetrically [29]. The bulk density was determined using the core method [30], and the particle size distribution was measured using the hydrometer method in accordance with the methods of [31]. Bulk density and particle density were used to calculate porosity mathematically [32].

Preparing plant samples for heavy metal analysis

To eliminate soil particles and dust on the plant tissues, the plants were carefully uprooted and washed with distilled water. The roots were separated, cut with a knife, and left to dry in an oven at 70°C for 3 days. Then the sample was ground into a fine powder. Powder was oven-dried before digestion using the method of [33]. About 0.5 grams of each sample was digested in 5 ml of concentrated HNO_3 and swirled gently, then 2 ml of concentrated $HClO_4$ solution was added. The filters were kept in a 50-ml volumetric, and the volume was completed to 50 ml by adding distilled water. The filters were analyzed for Cd, Pb, and Zn using atomic emission spectroscopy (ICP-OES/iCAP-7000 *PLUS* SERIES) [34].

Measurement of soil available heavy metals

Post experiment, the soil of each treatment was subjected to air drying for seventy-two hours at a regulated temperature of 25±2°C. To guarantee uniform particle size, the dry samples were thoroughly crushed using a porcelain mortar and then sieved through a 2-mm screen before being labeled and stored. The extracting solution was prepared by dissolving high-purity DTPA (1.97 g/L) with NH_4HCO_3 (79.06 g/L), and the solution pH was adjusted to 7.6. For the extraction, 15 grams of prepared soil was mixed with 30 mL of DTPA solution. The mixes were shaken for precisely one hour at a constant temperature of 25°C. The samples were filtered to remove any residual contaminants. The metals in the extracts were measured using atomic emission spectroscopy with the best settings for measuring metals (ICP-OES/iCAP-7000 *PLUS* SERIES) [35]

Evaluation the efficiency of plant uptake

Based on the heavy metal content in the tissues and soils, in order to evaluate phytoremediation efficiency, bioconcentration (BCF) and translocation (TF) factors were calculated. The bioconcentration (BCF) factor shows the ability of the plant to uptake heavy metals from the soil and is calculated (Equation 1) as the ratio of the heavy metal concentration in the plant root (C_{root}) to the heavy metal concentration in the soil (C_{soil}) [36].

$$\mathrm{BCF} = \frac{C_{root}}{C_{soil}} \qquad \textbf{(1)}$$

If BCF > 1, it indicates the plant serves as an accumulator of that metal [37]. TF indicates the ability of the plant to relocate heavy metals from the roots to aboveground tissues (leaves, stems, and seeds) and thus is calculated (Equation 2) as a ratio of the heavy metal concentration in shoots (C_{shoots}) to the concentration of heavy metals in the root (C_{roots}) [36].

$$\mathrm{TF} = \frac{C_{shoot}}{C_{root}} \qquad \textbf{(2)}$$

If TF > 1, it indicates the heavy metals accumulate in aerial parts of plant (shoot) [37].

Statistical Analyses

Data analysis was conducted by analysis of variance (ANOVA) with the GLM (generalized linear model) procedure to examine the significant effect of soil types and different amendments on heavy metal content in the shoot and root of the plant at a level of significance ($P < 0.05$), using the Minitab software package 19. Subsequently, Tukey's test was used to identify the significant differences between treatment means.

Results and Discussions

Heavy meats in shoot

There was a significant main effect of all of the locations and amendments on the concentration of Cd, Pb, and Zn in shoots ($P < 0.001$) (Table 3). It was found that there were significantly higher concentrations of Pb (1.38 mg kg^{-1}) and Zn (6.82 mg kg^{-1}) in the iron factory than in the oil refinery, while the concentration of Cd was opposite. These differences in metal concentration could be due to the fact that most iron scraps contain alloys, solders, or coatings with Pb and Zn metals, and when these scraps are melted, these metals are released into the surrounding soil, and in contrast, Cd in the oil refinery, after the process of combustion of crude oil, eventually spills into nearby soil.

Table 3: Main effects of locations and amendments on studied heavy metals in each shoot, and root with the summary of ANOVAs.

	Shoot			Root		
	Cd	Pb	Zn	Cd	Pb	Zn
Locations (L)						
Iron factory	0.0265b	1.38685a	6.82472a	0.364069a	13.8323b	18.6020b
Oil refinery	0.0524a	1.16886b	6.28266b	0.326454b	20.6292a	45.8294a
Amendments (A)						
Control	0.0084d	0.20643d	2.8477d	0.226924c	5.8804c	11.7673d
Biochar	0.0425b	2.08643a	12.0986a	0.410119a	199.2443b	34.7833c
Humic acid	0.0897a	1.56485b	5.3956c	0.364628b	24.0431a	45.1716a
NH_4NO_3	0.0171c	1.25371c	5.8729b	0.379374ab	19.7552b	37.1406b
Summary of ANOVA tables (p-values)						
Locations (L)	< 0.001	0.005	< 0.001	< 0.001	< 0.001	< 0.001
Amendments (A)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
L X A	< 0.001	0.008	< 0.001	< 0.001	< 0.001	< 0.001

Means in columns for each factor having different litters are significantly different at *P-values* < 0.05.

This finding is consistent with the study of [38], who observed that industrial zones associated with metal works show raised concentrations of Zn and Pb, whereas refinery zones demonstrate increased Cd concentrations due to petroleum combustion.

Regarding the main effect of amendments, it was found to be significantly different among each type of metal (Table 3). The concentration of Pb (2.08 mg kg^{-1}) and Zn (12.09 mg kg^{-1}) was higher under soil amended by biochar than other soils, followed by soil amended by humic acid and NH_4NO_3, and the control had the lower concentrations, while the concentration of Cd (0.089 mg kg^{-1}) was significantly higher in humic acid soil, followed by biochar, NH_4NO_3, and finally the control. The higher concentrations of Pb and Zn in shoots from soil treated by biochar could be due to changes in soil chemistry caused by the biochar, such as pH and cation exchange capacity, which enhances heavy metal mobility and plant uptake, or may be due to the metal release from the biochar itself (Table 2). The concentrations of Zn and Pb in biochar were estimated to be approximately 74.1 and 127.9 mg kg^{-1}, respectively, as shown in Table 3. In the same line, [39] and [6] revealed that biochar under certain conditions can enhance the bioavailability of Pb and Zn, leading to greater shoot contents. However, [27] noticed that the elevated Pb and Zn might be due to the release of these metals from the biochar amendment itself. However, the increase of Cd concentration in soils amended with humic acid could be due primarily to humic acid properties, which act as a natural chelating agent**,** forming soluble Cd-humate complexes that increase Cd bioavailability in the soil solution, facilitating its translocation from roots to shoots. Similar affinity was found by [19], who reported that adding 2 g kg^{-1} pure humic acid to tobacco shoots enhanced Cd absorption by up to 65% in short-term pot experiments. This increment was attributed to Cd's increased soluble capacity and mobility as a result of complexation with humic compounds, enabling faster uptake by plant roots.

Interaction between locations and amendments

A significant interaction effect between location and amendment was also found on heavy metal in shoot ($P < 0.001$) (Table 4). This interaction indicates that, at the iron factory location, the concentration of Cd was significantly higher in soil amended with biochar compared to the other treatments. In contrast, at the oil refinery location, the concentration of Cd was significantly higher in soil amended with ammonium nitrate (NH_4NO_3) compared to the control. The interaction effect for Zn indicates that, at the iron factory location, the concentration of Zn was significantly higher in soil amended with biochar. This was followed by soil amended with NH_4NO_3, then humic acid, and finally the control.

Table 4: Interaction effect between locations and amendments on Cd, Zn, and Pb in shoot.

	Cd		Zn		Pb	
Amendments	IF	OR	IF	OR	IF	OR
Biochar	0.0691b	0.0160cde	20.439a	3.758de	2.671a	1.502b
Control	0.0065e	0.0104de	4.249d	1.446f	0.146d	0.266d
Humic acid	0.0170cd	0.1625cde	6.466c	4.325d	2.358a	0.771c
NH_4NO_3	0.0135cde	0.0207c	8.615b	3.131e	0.764c	1.744b

Means having different litters are significantly different at *P-values* < 0.05.

For Pb concentration, the interaction revealed that under the iron factory site, the concentration of Pb was significantly higher under soil amended by both biochar and humic acid, followed by NH_4NO_3 and then the control, while under the oil refinery location, the concentration of Pb was significantly higher under biochar and NH_4NO_3 (with similar effect) > humic acid > control. Biochar is generally regarded as one of the most effective amendments for mobilizing and absorbing Cd, Pb, and Zn in plants. It is followed by humic acid and NH_4NO_3, particularly in both areas when compared to the control. In the same line, [9] revealed that biochar under certain conditions can enhance the bioavailability of Pb and Zn, leading to greater shoot contents. However, [27], noticed that the elevated Pb and Zn might be due to the release of these metals from the biochar amendment itself (Table 2). However, the increase of Cd concentration in soils amended with humic acid could be due primarily to humic acid properties, which act as a natural chelating agent**,** forming soluble Cd-humate complexes that increase Cd bioavailability in the soil solution, facilitating its translocation from roots to shoots. Similar affinity was found by [19], who reported that adding 2 g kg^{-1} pure humic acid to tobacco shoots enhanced Cd absorption by up to 65% in short-term pot experiments. While Cd's increased soluble capacity and mobility as a result of complexation with humic compounds, enabling faster uptake by plant roots. The potential causes of NH_4NO_3 may involve various physiological and chemical mechanisms. NH_4NO_3 reduces soil pH by nitrifying NH_4^+ ions, releasing H^+ ions, and acidifying the soil. Acidic soils raised the solubility and bioavailability of Zn, Cd, and Pb, making them easier for plants to uptake. Moreover, nitrate (NO_3^-) is a plant nutrient that increases the growth of roots and promotes the release of metal transporters, resulting in enhanced metal uptake. A similar trend was observed by [40], who found that NH_4NO_3 significantly increased Zn, Cd, and Pb absorption by oats in polluted soil by reducing pH and increasing available metals.

Heavy meats in root

The results indicated in Table 3 revealed that locations and amendments had a significant main effect on Cd, Pb, and Zn concentrations in the plant roots ($P < 0.001$). In the oil refinery site, Zn and Pb concentrations increased significantly to 45.82 mg kg^{-1} and 20.62 mg kg^{-1}, respectively; these levels were higher than those found in the iron factory site. Conversely, Cd concentration was highly significant in the iron factory site, in which the concentration was 0.36 mg kg^{-1}; compared to the other site, Cd concentration was opposite. These differences in metals values might be due to the variances of chemical characteristics of the soil and particularly pH, CEC and hydrocarbons (Table 1).
The most successful amendment for immobilizing Zn and Pb roots was humic acid, which reached 45.17 and 24.04 mg kg^{-1}, respectively, higher than the control. The biochar amendment was the most effective at immobilizing Cd, reaching 0.41 mg·kg^{-1}. In contrast, NH_4NO_3 was the least effective treatment for root stabilization of all the heavy metals. Hence, its values were still higher than the control. The reason for Zn and Pb root immobilization efficiently

by humic acid might be due to the humic acid that contains functional groups, such as carboxylic groups, which are responsible for immobilizing Zn and Pb in plant roots. By binding to metals, these groups help to stabilize the Zn and Pb, lowering their transportation and bioavailability and, as a result, lowering plant uptake. Similarly, [41] found that carboxylic and phenolic groups of humic acid are responsible for binding heavy metals in the rhizosphere zone. Also, according to [42], humic acid can immobilize heavy metals by forming a stable organic fraction or by adsorption. Even so, it might reduce the metals' mobility through the soil. On the other hand, biochar had effectively immobilized cadmium (Cd) in the roots. Applying biochar to the soil improves its cation exchange capacity, which enables it to retain positively charged ions such as Cd. Because of this binding, Cd's mobility and bioavailability in the root zone are decreased. Similar findings were reported by [43], who came to the conclusion that adding biochar increased maize growth and enhanced the roots' ability to immobilize cadmium (Cd), which prevented Cd from accumulating in the grains.

Interaction between locations and amendments

It was found that there was a significant increase in the root immobilizing of Cd, Zn, and Pb when the sites were amended with the different amendments ($P < 0.001$) (Table 5). It has been found that the biochar, which has been amended under the iron factory site, had a higher Cd root concentration (0.49 mg kg^{-1}) more than other amendments. According to the [44], biochar primarily lowers metal bioavailability through sorption/precipitation processes and at high pH. Biochar can also be efficient in decreasing metal concentration and mobility [9]. Humic acid was attributed to increasing concentrations of Zn at the oil refinery site and Pb at the iron factory site, which reached 58.48 and 37.92 mg/kg^{-1}, respectively. The reason could be due to humic acid having a difference in functional groups (phenolic, hydroxyl, carboxyl, and quinonoid) capable of binding metals (e.g., Zn, Cd, and Pb). Metal-HA complexes can change metal speciation, lower free ionic activity and stabilizing in the root zone. These complexes were more enhanced in alkaline soils and at high pH. Therefore, the pH of the studied soils was high; for oil refinery soil, it was 8.13, while for iron factory soil, it was 7.51 (Table 1).

Table 5: Interaction effect between locations and amendments on Cd, Zn, and Pb accumulation in flax root.

	Cd		Zn		Pb	
Amendments	IF	OR	IF	OR	IF	OR
Biochar	0.4928 a	0.3274 c	14.88 e	54.69 b	6.56 d	31.93 b
Control	0.2587 d	0.1952 e	8.15 f	15.38 e	3.27 e	8.49 cd
Humic acid	0.2739 d	0.4553 ab	31.86 c	58.48 a	37.92 a	10.16 c
NH_4NO_3	0.4309 b	0.3279 c	19.51 d	54.77 b	7.58 d	31.93 b

Means having different litters are significantly different at *P-values* < 0.05.

Bioconcentration Factor (BCF) and Translocation Factor (TF)

In the present study, the BCF and TF were employed for evaluating the plant's capacity to accumulate and translocate Zn, Pb, and Cd from soil. Generally, it has been shown that the values of BCF for shoot and root of heavy metals were strongly greater than unity (BCF > 1), indicating high accumulation of Zn, Pb, and Cd in the flax biomass (shoot, root) from the soil (Tables 6, 7).

Zinc (Zn)

The value of BCF increased significantly when it was amended with BC reaching 1055.86 under IF site, indicating a high accumulation of Zn in the aerial part of the flax with BC amendment (Table 6). For the Zn BCFs under OR site, which reached from 225.73 to 307.28, no significant differences were observed with amendments. Although the values of BCF under shoot were high, which implies a high accumulation of Zn in the harvested parts of flax. The high concentration of metals in flax shoot might be due to specific physiological traits that enhance metal uptake, efficient translocation, and tolerance to metal stress. Similar trends were reported by [30], who revealed that flax had greater translocation factors for heavy metals than grains such as oats.

Also, [29] revealed that flax is regarded as an accumulator plant for Zn through the phytoextraction process. As for flax root under IF site, the BCF values of Zn ranged from 567.31 to 2261.96. The highest BCF values were observed in the HA amendment compared to the other amendments, which was about 2261.96. HA was attributed to immobilizing Zn in flax root because it contains functional groups, and by binding to Zn metal, these groups help to stabilize Zn. The author's results were aligned with what was discovered by [41]. On the other hand, the BCF values of Zn under flax root were greater than under flax shoot. Hence, the heavy metals were more accumulated in the flax root rather than its shoot. Similarly, [1], indicated that Zn in flax, grown in an industrially contaminated area, tended to accumulate in greater concentrations in the roots compared to the stems. Regarding the BCF of flax roots at OR site

(Table 6), it has been observed that under flax root, the BCF value of Zn was significantly higher than the control with the application of HA; it was 3023.50, followed by BC (1830.01) > AN (1501.87) > control (574.41). So, the application of amendments enhanced the stabilization of Zn in the flax roots. Humic acid was a good amendment for phytostabilization of Zn for flax root, because humic acid has functional groups that create complexes with Zn that bind in the rhizosphere zone [36]. Translocation factor (TF) values for flax under both site at all amendments were less than unity (TF < 1) with the exception of BC, in which TF reached 1.01 at IF site, this points out the role of biochar in transporting Zn to the aerial parts of flax (Table 7). Flax is considered as a good candidate for phytostabilization [1]. As a result, the content of Zn was more accumulated in the roots of flax than in the shoots of the flax at both sites. Because of specific physiological traits of flax, flax may grow in soils that are polluted with metal, and it can accumulate heavy metal in the following order: root > stem > seed > fiber [46]. The most efficient transport (TF) of Zn to the shoot was observed when it was amended by BC at IF site. No significant differences of Zn TF were found between the amendments and controls at the OR site. Plants exhibiting lower translocation factor (TF) values (TF < 1), it had less capacity to transport heavy metals from roots to shoots and may be more effective in the phytoimmobilization of heavy metals within the rhizosphere [47].

Table 6: Shows the results of BCF of flax under iron factory (IF) and Oil refinery (OR) sites under different amendments.

		BCF shoot			BCF root		
Amendment	location	Zn	Cd	Pb	Zn	Cd	Pb
Co	IF	91.56de	32.00efgh	97.18def	559.76f	1821.66b	2781.92cd
HA		190.65c	53.02def	1060.88b	2261.96b	1839.21b	26414.39a
BC		1055.86a	191.99b	351.54cd	1049.12e	858.52d	1193.29de
AN		62.34efg	41.20efgh	96.53def	567.31f	2256.40a	4371.61c
Co	OR	282.81b	80.44cd	68.36ef	574.41f	1417.40c	8643.32b
HA		281.30b	362.13a	433.69c	3023.50a	739.42de	4545.96c
BC		307.28b	80.33cd	1379.71a	1830.01c	1674.54bc	26259.3a
AN		225.73c	104.29c	24.92f	1501.87d	1507.04bc	1231.75de

Table 7: Shows the results of TF of flax in iron factory (IF) and oil refinery (OR) sites under different amendments

Amendment	location	Zn	Cd	Pb
Co	IF	0.16e	0.018c	0.035h
HA		0.09e	0.029c	0.040gh
BC		1.01c	0.221c	0.304cdefg
AN		0.11e	0.018c	0.022h
Co	OR	0.492d	0.057c	0.008h
HA		0.093e	0.491b	0.095efgh
BC		0.167e	0.048c	0.053fgh
AN		0.150e	0.069c	0.020h

Cadmium (Cd)

There was no or less accumulation of Cd in the shoot of flax and among the different amendments under IF site, except BCF (191.19) at BC, which was higher than the control (Table 6). In contrast, the other amendments did not significantly affect metal uptake when compared to the control. Whereas the BCF value under flax shoot was significantly high at OR site with HA reaching 362.13, followed by AN > BC = control. Accordingly, [48] found that the BCF value of the basal stem reached 32. Similar affinity was found by [18]. However, it has been found that the BCF value of flax root at IF site was highly significant at the AN amendment, reaching 2256.40, which indicated that flax root had a strong capacity to accumulate Cd from the soil with AN applied. This is inconsistent with [49], who revealed that as nitrogen levels increase, the Cd uptake by the flax plant also increases. In contrast, the BCF values of flax root under OR site had no significant differences when it was amended with different amendments. Consequently, it has been observed that the BCF values of Cd under roots were higher than under shoots at both sites (Table 6). However, at OR site, BCF values were high under flax roots ranged from 739.42 to 1674.54 for HA and BC amendments, respectively. Accordingly, Cd was more immobilized in flax roots. High Cd accumulation and retention in flax roots rather than shoots was observed in studies by [33]. Regarding the TF of Cd as found in Table 7, the values of TF < 1 under flax and at all amendments ranged from 0.018 to 0.221 and 0.048 to 0.491 under IF and OR sites, respectively. These TF values referred to retained Cd in the root, and less mobility of this metal to the shoot, implies that flax had a strong potential for phytostabilization. The highest value of TF (0.491) was recorded at HA under OR site, followed by similar trends for AN, BC, and the control, indicating moderate transport, but the roots still retain more Cd. Similar results were discovered by [18]. As a result, Cd was more accumulated in the flax root than shoot [46].

Lead (Pb)

The BCF values under IF site ranging from 96.53 at AN to a maximum value of 1060.88 at HA. [31] found similar results, showing that the BCF of Pb for flax shoots ranges between 1.45 and 1.78. While BCF of flax shoots under OR site, the highest significant BCF value was recorded at BC, reaching 1379.71, followed by HA and AN, which were equal to the control. Increasing the amount of added BC greatly raised the Pb levels in the shoots and roots of sugar beet [50]. Lead in flax is predominantly concentrated in the aerial part, as noted by [29], or primarily in the roots with lesser amounts in the stems, as shown by [1]. On the other hand, the BCF of Pb at IF site was increased significantly when it was amended with HA under flax root, reaching 26414.39. This increase indicated Pb stabilization in flax root. These results revealed that the functional groups in humic acid effectively complexed and chelated bioavailable Pb ions into more stable forms, including organically bound species, which decreased the Pb availability for plant uptake [40]. Hence, the results were also observed that the BCF values of Pb under flax roots were higher than under the flax shoots (Table 6). Therefore, flax can be utilized in phytostabilization instead of phytoextraction of lead [11]. Regarding the BCF value of Pb significantly increased under flax roots, reaching 26259.3 with BC amendment under OR site, followed by control, HA, and HA. Furthermore, Pb accumulation in flax roots was much greater than that in the shoots of the same plant. An increase of Pb in flax root with biochar application might be due to the Pb content in biochar itself (Table 2), similar were observed by [27] or because the majority of studies demonstrated that biochar has been shown to be retained in plant roots [39], biochar could also effectively reduce heavy metal concentration and mobility [9].

Generally, the TF < 1 for Pb under flax and with different amendment applications at both sites (Table 7). This indicates that Pb is considered a good phytostabilizer for the roots of flax and with different amendments. The TF values for Pb under IF site ranged from 0.022 to the highest TF (0.304) which was observed at BC treatment. In this study by [51], the authors reported that poinsettia had a transfer factor (TF) of less than 1 when analyzing lead (Pb), indicating its potential for Pb phytostabilization. The TF values under flax at OR site ranged from 0.008 (control) to 0.095 (HA). It is indicating that flax was a favorable phytostabilizer for Pb. Similarly, [46], revealed that the TF values of Pb for flax plant in Cu-spiked soil were less than 1.

Conclusion

Depending on the data of the current study, it was found that the flax plant acted as an extremely effective phytostabilizer, accumulating significant quantities of Zn, Pb, and Cd, particularly inside its roots rather than its shoot tissues, when it is amended with different amendments. Because BCF > 1 for the shoot and root of flax and TF < 1, which indicates the accumulation of studied metals in the shoot and root, but in the root, it was strongly higher than in the shoot. Biochar was a favorable amendment for removing Zn and Pb from the soil to the flax shoot, while humic acid was successful for removing Cd from the soil to the shoot. Although humic acid and NH_4NO_3 assisted flax to stabilize (Zn, Pb) and (Cd) in flax root, respectively. Flax was more tolerant of metals under oil refinery soil than at the iron factory site. In the iron factory site, Pb and Zn removal was greater in flax shoots, and cadmium removal was greater in the oil refinery area, while in the roots it was the opposite. At the iron factory site, the removal of Pb and Zn was more pronounced in flax shoots, whereas Cd removal was greater at the oil refinery site. In contrast, flax roots showed the reverse pattern.

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كفاءة المعالجة النباتية لنبات الكتان (*Linum usitatissium* L.) في التربة الملوثة بالمعادن الثقيلة في منطقة كواشي الصناعية باستخدام محسنات التربة

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الخلاصة

أجريت الدراسة في التربة الملوثة المحيطة بمصافي البترول ومصنع إعادة تدوير خردة الحديد في منطقة كواشي الصناعية في محافظة دهوك، إقليم كردستان العراق. تم أخذ الترب من سطح التربة بعمق 0-*30* سم. ثم تم إجراء تجربة السنادين في بيت بلاستيكي لتقييم فعالية استخدام المحسنات مثلا حامض الهيوميك والفحم الحيوي بتركيز 5 غم كغم $^{-1}$ من التربة وامونيوم نايتريت بتركيز 230 ملغم كغم$^{-1}$ من التربة بالاضافة الى الكونترول. تم استخدام الكتان (***Linum usitatissium***) لإزالة الزنك والكادميوم والرصاص من التربة الملوثة. أظهرت النتائج زيادة كبيرة في الزنك والرصاص والكادميوم في براعم الكتان والجذور عند معالجتها بمحسنات مختلفة. كان الامتصاص العالي للمعادن مع إضافة المحسنات بالترتيب التالي: ***BC > HA > AN***، بينما بالنسبة للجذور، كانت الزيادة بالترتيب التالي: ***BC > AN. HA >*** عزز الفحم الحيوي امتصاص الزنك والرصاص في براعم الكتان بفعالية، بينما عزز حمض الهيوميك امتصاص الكادميوم في براعم الكتان. وكشفت النتائج أيضًا أن الكتان يتراكم هذه المعادن بنجاح في كل من براعمه وجذوره؛ إلا أن الجذور تتراكم فيها بشكل أكبر بكثير من البراعم. بالإضافة إلى ذلك، حيث يشير عامل التركيز الحيوي ***(BCF > 1)*** وعامل النقل ***(TF < 1)*** إلى أن جذور الكتان يعتبر ذو إمكانات علاجية واستقرار نباتي مرضي للتربة الملوثة بالزنك والرصاص والكادميوم.

الكلمات المفتاحية: المعالجة النباتية، محسنات ، الكتان، الخارصين، الرصاص، الكادميوم.