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Chromium (VI) accumulation in different plant organs of Lacy Phacelia (*Phacelia tanacetifolia* Benth.): Implications for phytoremediation

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Abstract

Lacy Phacelia (*Phacelia tanacetifolia* Benth.) is a very beneficial nectar source for honeybees, contributing to their foraging activities and honey production. Chromium (Cr) is a toxic metal that may be taken up by plants through roots and accumulates in different organs. The accumulation of Cr in nectars can affect nectar production and subsequently bee health. This study investigated whether Lacy Phacelia accumulates Cr in different plant organs. A pot experiment was conducted under controlled conditions with five different Cr concentrations (0, 5, 10, 20 and 40 mg kg^{-1}). The plants were grown for 110 days, and Cr, manganese (Mn) and iron (Fe) contents accumulated in different plant organs (root, leaf, stem, flower and stamen) were examined. Similalry, the impact of different Cr concentrations on plant height, stem diameter, and dry weights of root, stem, leaf, and flower was also recorded. The highest and lowest Cr(VI) accumulation was recorded in roots and flowers respectively. The mean Cr concentration in different organs was, i.e., root (7.13 mg kg^{-1}) > leaf (3.25 mg kg^{-1}) > stem (2.53 mg kg^{-1}) > flower (1.62 mg kg^{-1}) = stamen (1.54 mg kg^{-1}). Translocation factor was < 1 in all Cr concentrations, indicating that it is not a suitable candidate for phytoremediaiton. The Mn concentration in different organs generally increased with increasing Cr concentrations, while Fe concentration, plant height, and dry weights of root, stem, and flower decreased. Lacy Phacelia should not be grown on Cr-contaminated soils for agricultural purposes or phytoremediation. The accumulation of Cr in the stamens may possibly contaminate bee products obtained through the bees collecting nectar from Lacy Phacelia grown on Cr-contaminated soils. The transfer of Cr from Lacy Phacelia plants grown on Cr-contaminated soils to honeybee and honey products should be investigated in future studies to safeguard honeybee health.

Keywords Chromium, Pollen, Metal accumulation, Phacelia

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Introduction

Heavy metals are metallic elements that cause significant damage to human health and the environment because of their high density, potential toxicity, and capacity to accumulate in living organisms. Heavy metal is defined in the literature to describe soil contamination and characterized as elements with a density of > 5 g cm^{-3} [1]. Chromium (Cr), with 7.19 g cm^{-3} density, is regarded as the most potent pollutant in the ecosystem among heavy metals [2, 3]. It is a natural element of soil consisting of rocks and volcanic ash [4]. Cr may exist in several oxidation states ranging from − 2 to + 6. However, the most prevalent and stable forms of in the natural environment are hexavalent chromate Cr(VI) and trivalent chromite Cr(III) [5]. The Cr(VI) is used in various industrial operations, including electroplating, textile dyeing, leather processing and tanning, and steel manufacturing. Consequently, this results in the creation of waste materials containing Cr, which subsequently causes environmental pollution [6]. The Cr(VI) is 10–100 times more harmful than Cr(III), which can cause allergies and skin problems [7]. Moreover, Cr(VI) is easily soluble in soil and causes toxicity to animals and plants [8, 9]. Nevertheless, Cr is designated as a class 1 carcinogen by the International Agency for Research on Cancer [10]. Cr(VI) is regarded as a dangerous ion due to its high solubility, which leads to contamination of groundwater and transmission to the food chain. It has been reported that the permissible Cr concentration in soils and plants by WHO is 100 mg kg^{-1} and 1.30 mg kg^{-1}, respectively [11, 12], respectively, while Ibrahim et al. [13] reported that this value is 2.30 mg kg^{-1} for plants (WHO/FAO).

Cr toxicity causes ultra-structural changes in the cell membrane and chloroplast, damages root cells, reduces pigment content, causes leaves' chlorosis, disrupts mineral nutrition, and reduces plant growth [7]. Generally, the movement of Cr from the roots to the aboveground parts of a plant is restricted and influenced by its specific chemical composition in the plant tissue [14]. Cr(VI) is converted to Cr(III) in plant tissues, which tends to bind to cell walls, preventing further transport of Cr within plant tissues [9]. Therefore, Cr concentration in roots is sometimes 100 times higher than in shoots [15].

Heavy metal pollution from fertilizers used in agricultural production (along with all other chromium contamination risks) is quite important in Türkiye [16, 17]. While unconscious fertilization is common in the country [18], excessive use of phosphatic fertilizers causes Cr and cadmium (Cd) accumulation in soil [19].

The interaction among metals in the soil is important for determining the metal contents and yield. Several studies have indicated that Cr affects the concentration and absorption of manganese (Mn) in plants. Furthermore, Cr toxicity is known to develop the symptoms of iron (Fe) deficiency [20]. Moreover, it has been reported that Cr toxicity significantly reduced extractable Fe and raised the Mn in the soil [20]. Coexistence of Cr with vital plant nutrients in soil and plant cells may result in antagonistic interactions that have a negative impact on plant health and nutrients' absorption [14, 21]. Excessive Cr has been shown to reduce the number of sites available for adsorption and create insoluble compounds in the rhizosphere. This, in turn, impedes the accumulation of essential nutrients including Fe, copper (Cu), and calcium (Ca) [21].

Lacy Phacelia (*Phacelia tanacetifolia* Benth.) is an annual, long-day plant in the Hydrophillaceae family originating from North America [22]. It is widely acknowledged as one of the leading honey-producing plants globally, primarily because it serves as a crucial supply of pollen and nectar for honeybees [23]. Various parts of this plant are used as fresh animal feed, dried animal feed, as well as for making silage. Additionally, they may also be employed as green fertilizers after the flowering stage. Due to the large quantity of pollen and nectar found in its flowers, it is used as a source for nourishment for bees [24].

Metals' accumulation in floral organs (anthers, nectar, and pistils) varies depending on the type and amount of the heavy metal. However, plants transport the absorbed metals to their floral organs, including pollen and nectar [25]. Heavy metals' transport from vegetative organs affects the reproductive function and viability of pollen [26, 27]. Metal accumulation in flowering plants may negatively impact plant reproductive performance indirectly by changing the foraging behaviour of pollinators [28, 29]. Pollen has been proposed as a useful bioindicator of heavy metal pollution because it is more sensitive to pollutants than the vegetative parts [30].

Several earlier studies have investigated the impacts of Cd, Pb, Zn, As, and Cu on the development of Lacy Phacelia [31–33]. However, no studies have examined the effect and accumulation of Cr in different plant organs of Lacy Phacelia. Therefore, the major objective of this study was to determine the Cr accumulation in different plant organs (root, stem, leaf, flower, and stamen) of Lacy Phacelia. Furthermore, the accumulation of Fe and Mn was also investigated. The results would help to identify the phytoremediation potential of Lacy Phacelia and possible implications for honeybee health.

Materials and methods

This study was conducted under controlled conditions (climate room) at Bingöl University Faculty of Agriculture (Bingöl/Turkey) during 2022. Lacy Phacelia seeds were obtained from a commercial company. Commercially available $K_2Cr_2O_7$ (Merck) was used as Cr source in the study. The soil used in the study was taken from

Table 1 Chemical properties of the soil used in the experiemnt

pH	6.98
EC (µs cm^{-1})	151.4
Organic matter (%)	0.48
$CaCO_3$ (%)	2.2
Cr (mg kg^{-1})	2.62
Extractable Cr (mg kg^{-1})	0.06
Fe (mg kg^{-1})	2025.33
Extractable Fe (mg kg^{-1})	19.8
Mn (mg kg^{-1})	75.77
Extractable Mn (mg kg^{-1})	21.15

Bingöl University campus (38°54'0" N- 40°29'18" E). The chemical properties of the soil used in the experiment are presented in Table 1.

Plant cultivation and chromium treatments

Lacy Phacelia seedlings were grown for 5 weeks in trays. Afterwards, seedlings were transferred to pots containing 2 kg of soil (neutral, non-saline and calcareous). The experiment was established according to completely randomized design with four replicaitons. The Cr concentrations were selected based on its phytotoxic reported for different plant species (10–100 mg kg^{-1} Cr) [8]. The Cr concentrations included in the study were 0, 5, 10, 20 and 40 mg kg^{-1}. Chromium concentrations calculated based on the dry weight of the soil were weighed and added to the soil once. The soil was irrigated for 4–5 days and then the seedlings were transferred to the pots. The pots were irrigated to field capacity until harvest. A single plant was grown in each pot.

Stamen collection

Stamen collection started with the first flower appearance on the plants and terminated when the flowers started to dry (24 days). Stamens were collected daily at the same time of the day. Stamens were collected with clean scissors using a new paper for each pot and stored in glass bottles (Fig. 1).

Harvesting

The experiment started with seed germination and terminated with the blooming of the flowers. The plants were grown for a total of 110 days. Plant height and stem diameter were measured before harvesting. The aboveground parts of the plants were cut separately into flowers, stems, and leaves. Afterwards, pot soil was taken out in a clean basin and the roots were removed, sorted, and washed. All plant organs were dried in an oven at 70 °C for 24 h. The dried plant organs were weighed using a precision scale (g) and prepared for analysis by grinding in a mill.

Determination of Cr, Fe and Mn concentrations

The plant samples prepared for analysis were burnt with nitric acid (HNO_3) in a microwave digestion system [34]. The concentrations of Cr, Fe and Mn were determined by NexION 2000 ICP-MS (Inductively Coupled Plasma-Mass Spectrometer) (PerkinElmer Inc., Shelton, Connecticut, USA) after filtration and necessary dilution. Concentrations were calculated by substituting the values in Eq. 1.

$$Cr/Fe/Mn\ mg\ kg^{-1} in\ plant = It \times F \qquad (1)$$

Fig. 1 Collection and storing of stamens

Table 2 Chromium accumulation (mg kg^{-1}) in different plant organs (root, stem, leaf, flower and stamen) of Lacy Phacelia grown under different chromium concentrations

Cr dose (mg kg^{-1})	Root	Stem	Leaf	Flower	Stamen	Mean
0	0.39 ± 0.06 d**	0.04 ± 0.00 d**	0.08 ± 0.02 d**	0.09 ± 0.01 d**	0.03 ± 0.01 c**	**0.13D****
5	3.10 ± 0.65 c	0.29 ± 0.05 cd	0.27 ± 0.03 cd	0.50 ± 0.07 c	0.59 ± 0.05 c	**0.95CD**
10	4.36 ± 0.78 c	1.19 ± 0.08 c	0.76 ± 0.00 c	0.45 ± 0.14 c	1.50 ± 0.05 b	**1.65 C**
20	9.22 ± 0.12 b	4.48 ± 0.37 b	4.93 ± 0.20 b	1.96 ± 0.21 b	1.78 ± 0.47 b	**4.47B**
40	18.57 ± 1.25 a	6.64 ± 1.23 a	10.22 ± 0.59 a	5.10 ± 0.31 a	3.79 ± 0.69 a	**8.87 A**
Mean	**7.13 A****	**2.53BC**	**3.25B**	**1.62 C**	**1.54 C**	
$LSD_{0.05}$	1.52	0.97	0.48	0.36	0.79	

** = significant at $p < 0.01$, Uppercase letters show significant differences between the means of plant organs and doses, whereas lowercase letters show differences between Cr concentrations for the same organ

It = value of the plant solution adjusted according to the witness solution, and F = dilution factor/sample quantity.

The average LOD (limit of detection) and LOQ (limit of quantitation) values were 1.7–5.4 µg/L for Cr, 1.9–6.24 µg/L for Fe, and 1.04–4.01 µg/L for Mn. The recovery percentage (R %) is critical as it denotes the ratio of the the measured resultd to the theoretical value [35]. The R % values for Cr, Fe and Mn were 99.1%, 100.02% and 97.5%, respectively.

Translocation factor (TF)

Translocation Factor (TF) expresses the extent of metal uptake by plants. TF is an indicator of the movement of heavy metals from the root to the shoot and calculated by the ratio of heavy metal concentration in the stem of the plant to that in the root (Eq. 2) [36]. Bioconcentration Factor (BCF) quantifies the accumulation of a chemical substance within an organism in relation to its concentration in the surrounding environment, usually water or soil. The BCF was calculated as the ratio of the heavy metal concentration in the plant (root or shoot) to the heavy metal concentration in the soil (Eq. 3) [37].

$$\mathrm{TF} = \text{Shoot Cr concentration}/\text{Root Cr concentration} \quad (2)$$

$$\mathrm{BCF} = (\mathrm{Cr})_{\text{shoot or root}}/(\text{total Cr})_{\text{soil}} \quad (3)$$

Statistical analysis

The collected data were subjected to analysis of variance (ANOVA) using JMP (2018) statistical software program [38]. Treatment means were then compared according to the least significant difference (LSD) test at 95% probability.

Results

Chromium accumulation (mg kg^{-1}) and translocation factor

The distribution of Cr concentrations (mg kg^{-1}) in plant organs (root, stem, leaf, flower, stamen) after Cr (VI) treatment is shown in Table 2. Average Cr accumulation among different organs was in the order, root > leaf > stem > flower = stamen.

The ANOVA indicated that different Cr concentrations significantly ($p < 0.01$) affected Cr acumulation among all plant organs (Table 2). The highest Cr accumulation was recorded in roots, while the lowest was noted in flowers and stamens. Chromium accumulation increased in different plant organs with the increase in Cr doses. The lowest Cr accumulation in roots, stems, leaves, flowers and stamens was recorded in 0 mg kg^{-1} Cr treatment while the highest Cr accumulation was recorded in 40 mg kg^{-1} Cr treatment (Table 2).

Table 3 Translocation factor (TF) and bioconcentration factor (BCF) values of Lacy Phacelia plants grown under different chromium concentrations

Cr concentrations (mg kg^{-1})	TF (Translocation Factor)	BCF Root	BCF Shoot
0	0.16 C**	0.15 E**	0.09 E**
5	0.13 D	0.40 C	0.21 D
10	0.22 B	0.34 D	0.31 C
20	0.36 A	0.41 B	0.58 A
40	0.35 A	0.44 A	0.45 B

** = significant at $p < 0.01$, Uppercase letters show significant differences between Cr concentrations for the relevant trait

Translocation factor (TF) and bioconcentration factor (BCF) values (for root and shoot) of Phacelia plants are presented in Table 3. The highest TF values (0.36 and 0.35) were calculated for 20 and 40 mg kg^{-1} concentrations, whereas the lowest value was noted for 5 mg kg^{-1}. The TF was < 1 for all Cr concentrations used in the current study (Table 3). Root BCF values varied between 0.15 and 0.44, while shoot BCF values varied between 0.09 and 0.58. BCF values were < 1 in all Cr concentrations included in the study (Table 3).

Fe concentration (mg kg^{-1})

Different plant organs significantly differed ($p < 0.01$) for Fe uptake (Table 4). The highest Fe concentration was measured in the roots, while the lowest was measured in the stem. Similarly, the highest and the lowest

Table 4 Iron concentrations (mg kg^{-1}) in different plant organs (root, stem, leaf, flower and stamen) of Lacy Phacelia grown under various chromium concentrations

Cr dose (mg kg^{-1})	Root	Stem	Leaf	Flower	Stamen	Mean
0	166.34 ± 4.85a**	56.32 ± 14.37a**	137.47 ± 26.79a**	151.62 ± 14.38^{ns}	122.59 ± 15.99a*	**126.87 A****
5	130.57 ± 6.71b	44.17 ± 11.98ab	74.04 ± 10.02b	79.51 ± 8.17	55.22 ± 4.82ab	**76.70B**
10	112.55 ± 17.82bc	28.65 ± 4.72bc	53.00 ± 8.82b	66.22 ± 0.27	39.04 ± 5.73b	**59.89BC**
20	94.36 ± 22.66c	18.55 ± 0.91c	51.41 ± 7.92b	65.52 ± 0.94	14.04 ± 0.06b	**48.78CD**
40	94.98 ± 14.05c	15.12 ± 0.93c	12.14 ± 3.21c	54.20 ± 8.41	6.03 ± 0.05b	**36.50D**
Mean	**119.76 A****	**32.56D**	**65.61BC**	**83.42B**	**47.38CD**	
$LSD_{0.05}$	29.75	18.06	38.58	-	67.54	

** = significant at $p < 0.01$, * = significant at $p < 0.05$**, ns = non-significant. Uppercase letters show significant differences between the plant organs and Cr doses, whereas lowercase letters show significant differences between Cr doses for the same organ

Table 5 Manganese concentrations (mg kg^{-1}) in different plant organs (root, stem, leaf, flower and stamen) of Lacy Phacelia grown under various chromium concentrations

Cr dose (mg kg^{-1})	Root	Stem	Leaf	Flower	Stamen	Mean
0	7.15 ± 0.46 a**	25.53 ± 0.47 b**	12.63 ± 0.88 e**	33.06 ± 6.06 b*	43.30 ± 6.33^{ns}	**24.34 C****
5	4.67 ± 0.80 bc	20.57 ± 5.96 c	19.59 ± 2.86 d	31.34 ± 4.47 b	56.47 ± 6.59	**26.53BC**
10	3.54 ± 0.85 c	23.96 ± 1.98 bc	25.28 ± 4.38 c	31.65 ± 1.11 b	39.49 ± 3.57	**24.78 C**
20	4.87 ± 0.34 b	26.27 ± 1.09 b	29.40 ± 2.60 b	41.10 ± 1.52 ab	49.24 ± 0.42	**30.18AB**
40	4.09 ± 0.23 bc	33.37 ± 4.25 a	38.48 ± 4.57 a	51.26 ± 4.01 a	40.08 ± 0.14	**33.46 A**
Mean	**4.86D****	**25.94 C**	**25.08 C**	**37.68B**	**45.71 A**	
$LSD_{0.05}$	1.21	4.53	4.11	11.59	-	

** = significant at $p < 0.01$, * = significant at $p < 0.05$**, ns = non-significant. Uppercase letters show significant differences between the plant organs and Cr doses; Lowercase letters show significant differences between Cr doses for the same organ

Fe concentration were recorded for 0 mg kg^{-1} and 40 mg kg^{-1} Cr treatments, respectively. Fe concentration decreased with the increase in Cr doses. Generally, Fe concentration decreased in roots, stems, leaves and stamens as Cr doses increased, but did not cause a statistically significant change in flowers (Table 4).

Mn concentration (mg kg^{-1})

Different plant organs and Cr doses significantly ($p < 0.01$) differed for Mn concentrations. The highest Mn concentration was determined in the stamens while the lowest Mn concentration was determined in the roots. The highest Mn concentration was determined in 40 mg kg^{-1} Cr treatment while the lowest Mn concentration was determined in 0 mg kg^{-1} Cr treatment. At higher Cr doses, Mn concentrations increased in roots, stems, leaves and flowers, while there was no statistically significant change in stamens (Table 5).

Effects of cr treatment on Fe and Mn concentrations in plant organs

The Fe and Mn concentrations in the plant organs were analyzed after Cr exposure. The data obtained (normalized between 0 and 1) were graphed using the Python Seaborn library to interpret the association between Cr with Fe and Mn. The Cr showed antagonistic relationship with Fe and Mn in the roots at 5 and 10 mg kg^{-1} Cr concentrations. Similarly, Cr and Mn showed antagonistic relationship with Fe under 20 mg kg^{-1} Cr concentration (Fig. 2a). Likewise, Cr showed antagonistic relationship with Fe and Mn accumulation in stem at 5 mg kg^{-1} Cr concentraiton. The Cr and Mn showed antagonistic relationship with Fe under 10, 20 and 40 mg kg^{-1} Cr concentrations (Fig. 2b). Cr and Mn showed an antagonistic relationship with Fe in leaves under all Cr concnetrations. Mn concentration increased with increasing Cr concentration, but Fe concentration decreased in parallel with this increase (Fig. 2c).

In flowers, Cr showed antagonistic relationship with Fe and Mn under 5 mg kg^{-1} Cr concentration. The Cr showed antagonistic relationship with Fe under 10 mg kg^{-1} Cr concentration, while Mn remained unaffected by this relationship. Cr and Mn showed antagonistic relationship with Fe under 20 and 40 mg kg^{-1} Cr concentrations (Fig. 2d). In the stamens, Cr and Mn showed antagonistic relationship with Fe under 5 mg kg^{-1} Cr concentration. Similarly, Cr showed antagonistic relationship with Fe and Mn under 10 and 40 mg kg^{-1} Cr concentrations, while Mn remained unaffected by this relationship. Likewsie, Cr and Mn showed antagonistic relationship with Fe under 20 mg kg^{-1} Cr concentration (Fig. 2e).

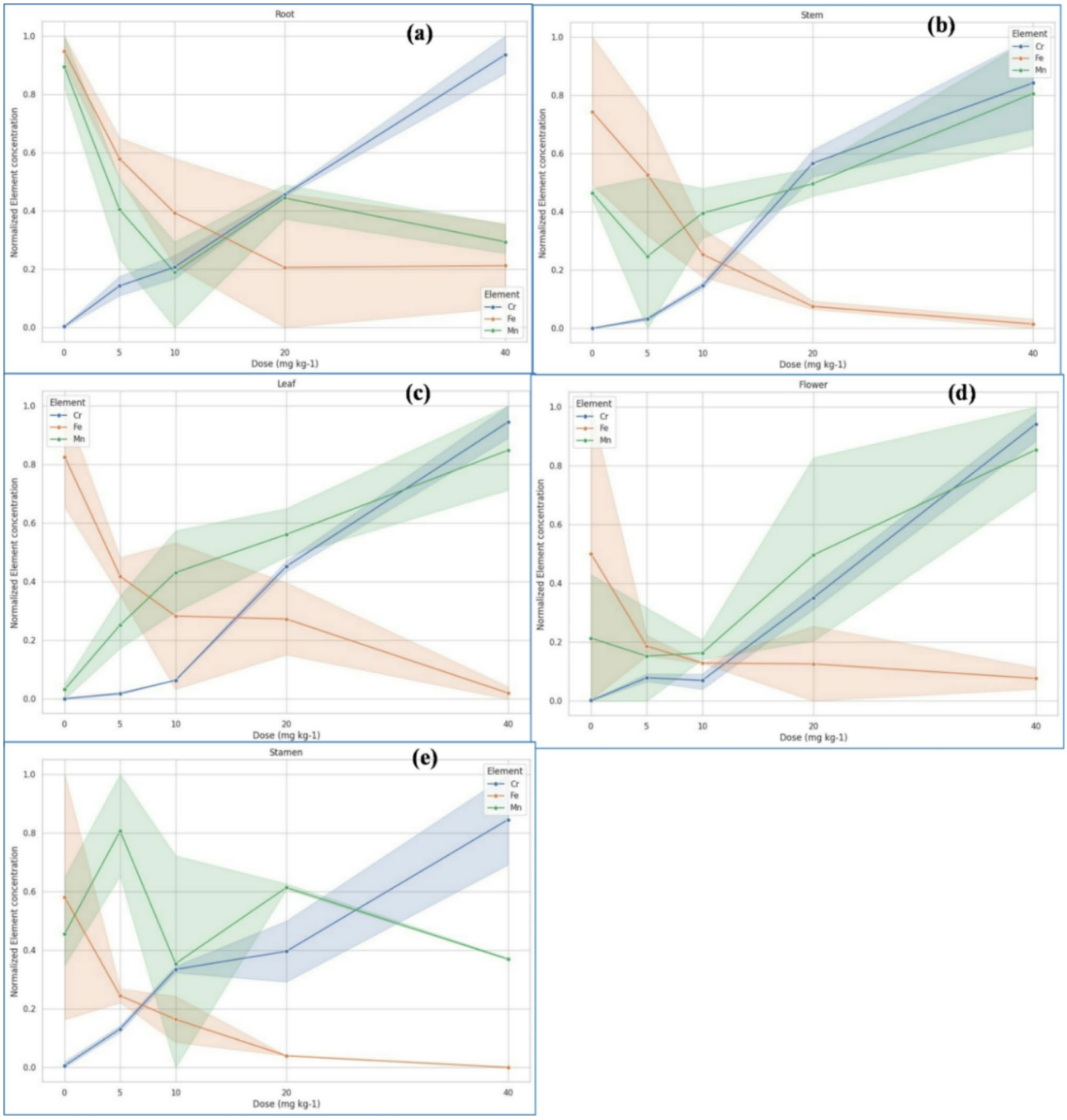

Fig. 2 Relationship of Cr accumulation with Fe and Mn concentrations in the root (**a**), stem (**b**), leaf (**c**), flower (**d**) and stamens (**e**) of Lacy Phacelia grown under different chromium concentrations

Effects of cr treatment on morphological attributes

Plant height of Phacelia was negatively affected by Cr stress and a regular decrease in plant height was observed in parallel with increasing Cr concentrations. The highest and the lowest plant height was recorded for 0 and 40 mg kg^{-1} Cr concentrations, respectively. Stem diameter remained unaffected by Cr concentrations included in the study. Root dry weight was negatively affected by all Cr concentrations. Similarly, stem dry weight was negatively affected by Cr concentrations and linearly decreased with increase concentrations. Leaf dry weight remained unaffected by different Cr concentrations included in the study. Flower dry weight was negatively affected by Cr concentrations with the highest and the lowest weight recorded for 0 and in 40 mg kg^{-1} Cr concentrations, respectively (Table 6).

Table 6 Effects of cr exposure on some morphological properties of Lacy phacelia

Cr dose (mg kg^{-1})	Plant height (cm)	Plant stem diameter (mm)	Root dry weight (g)	Stem dry weight (g)	Leaf dry weight (g)	Flower dry weight (g)
0	115.00 ± 10.52 A**	3.23 ± 0.05^{ns}	0.36 ± 0.05 A*	2.64 ± 0.58 A*	1.51 ± 0.61^{ns}	1.39 ± 0.33 A**
5	115.25 ± 11.58 A	3.32 ± 0.31	0.24 ± 0.06 B	2.43 ± 0.48 AB	1.69 ± 0.27	1.07 ± 0.40 AB
10	102.25 ± 6.18 B	3.03 ± 0.33	0.23 ± 0.04 B	1.83 ± 0.44 BC	1.21 ± 0.33	1.01 ± 0.10 B
20	93.25 ± 2.06 B	3.03 ± 0.27	0.22 ± 0.07 B	1.55 ± 0.69 C	1.17 ± 0.48	0.77 ± 0.20 BC
40	91.50 ± 3.42 B	2.93 ± 0.31	0.22 ± 0.07 B	1.48 ± 0.52 C	0.89 ± 0.17	0.46 ± 0.12 C
$LSD_{(0.05)}$	12.62	-	0.09	0.74	-	0.37

** = significant at $p < 0.01$, * = significant at $p < 0.05$**, ns = non-significant. Uppercase letters show significant differences between Cr concentrations for the examined traits

Discussion

This study aimed to investigate the impact of various Cr concentrations on morphological attributes of Lacy Phacelia plants, Cr(VI) accumulation in the roots, stems, leaves, flowers, and stamens, and relationship of tested Cr concentrations with Fe and Mn. Cr accumulation among different plant organs was in the order, root > leaf > stem > flower = stamen. The highest and the lowest Cr accumulation was recorded in the roots and flowers, respectively. Chromium transfer from roots to above-ground organs generally vary with plant species, content and valence forms of Cr in soil [39]. Higher Cr was accumulated in the roots of Lacy Phacelia plants compared to shoots in the current study. Plant roots may produce organic acids such as malate and citrate, which increase the solubility of metals and convert inorganic Cr into organic complexes that can be readily taken up by plants [40–42]. Similarly, higher Cr accumulation in root cell vacuoles causes limited Cr translocation to shoots [43]. In addition, Cr translocation to shoots depends on its chemical form within plant tissues [44]. Cr(III) cannot be translocated to aboveground plant parts as it bind to the cell wall, whereas Cr(VI) can be easily translocated [45]. Sejad et al. [46] reported that *Nonea edgeworthii* A. DC and *Onosma hispida* Wall. ex G. Don species accumulated 94.0 and 60.67 and 125.0 and 34.67 mg kg^{-1} Cr in their roots and shoots, with TF values of 0.65 and 0.28, respectively. Similarly, *Leersia hexandra* accumulated Cr in root cell wall and leaf vacuoles [47]. Likewise, Cr localization study revealed that *Coptis chinensis* accumulated the least amount of Cr in petioles, while the highest accumulation was noted in roots and rhizomes [48]. Similarly, *Capsicum annum* accumulated the highest Cr in the roots (roots > leaves > shoots > fruit) [49]. Cr accumulation has been observed in root cells of several crops, including *Vicia faba* [50] and *Brassica napus* [51, 52].

Unfortunately, Cr was transferred from the roots to the above-ground organs of the Lacy Phacelia plant in the current study, especially to the flowers and stamens that add importance to the plant. Approximately 5 times more Cr was accumulated in the flowers and 20 times more in the stamens compared to the control even at the lowest Cr concentraion. Cr toxicity has not been previously studied in Lacy Phacelia, which limits the interpretation of the results of current study. Evidence indicates that excess heavy metals in soil can be taken up by non-hyperaccumulator plants and subsequently translocated to floral organs [53]. However, adaptation mechanisms of non-hyperaccumulator plants that can translocate heavy metals into their reproductive organs and associated consequences are unclear due to limited information on the translocation of metals and metalloids to the flowers [25]. Heavy metals accumulated in pollen can adversely affect the germination and development of pollen [54]. Plants grown in Ni-contaminated soil accumulated more Ni in floral rewards than non-treated plants. Moreover, Ni concentration was higher in pollen (400%) than in nectar (100%) of Ni-treated plants compared to those grown without Ni treatment [55]. Selenium (Se) can be accumulated in the floral rewards of *R. sativus* and subsequently collected by pollinators [56]. Short-term exposure to Pb, Ni, Zn, and Cu-contaminated soil can lead to increased metal contents in floral organs (pistils, anthers) and rewards (nectar and pollen) of the non-hyperaccumulator *Cucurbita pepo*, suggesting that it can transfer heavy metals to floral parts [25]. The transfer of metals such as Ni, Zn, Cu, and Pb from soil to floral rewards (pollen, nectar) can have ecological consequences by creating reproduction problems in plants because of heavy metals' toxicity to pollinators [28]. The results of the current study indicated that Lacy Phacelia can transfer Cr from soil to stamens, which raises the question whether metal accumulion in the floral organs can cause negative physiological consequences for plant reproduction. Since excess heavy metals are toxic to plants [57], their accumulation in reproductive parts of plants may cause reproduction problems.

The TF and BCF values were < 1 under all Cr concentrations included in the current study. TF values > 1 indicate that plants efficiently transfer metals from the roots to the above-ground parts [58]. BCF is divided into four categories, i.e., < 0.01 plants with no accumulator properties, 0.01–0.1 plants with low accumulator properties, 0.1-1.0 plants with moderate accumulator properties, 1–10 plants with high accumulator properties or hyperaccumulators [59, 60].

The effects of various Cr concentraations on Fe and Mn accumulation in Lacy Phacelia plants were also investigated in the current study. Cr accumulation in plant tissues increased with increasing Cr concentrations applied (Table 2); however, Fe concentration decreased (Table 4). Although Mn concentration did not change statistically ($p > 0.01$) in 0, 5, and 10 mg kg^{-1} Cr concentrations, it linearly increased with increase in Cr concentration from 20 to 40 mg kg^{-1} Cr (Table 5). Interactions among elements can be both antagonistic and synergistic, and their unbalanced reactions can cause chemical stress in plants. Antagonism and/or synergism interactions may also refer to the capacity of an element to inhibit or induce the uptake of other elements in plants [8]. Synergistic interactions between Cr and some elements (Fe, Ca, Mn, Cu, Mg) have been observed in some cases [61]. High Cr concentrations are known to reduce Fe, S, and P content in some plant species [62, 63]. Plant biomass (dry root, dry stem, dry leaf, and dry flower) of Lacy phacelia was negatively affected by increased Cr exposure in the current study. The highest Cr concentration decreased plant height, root dry weight, stem dry weight and flower dry weight by 20%, 38%, 44%, and 67%, respectively compared to control (Table 6). Cr toxicity leads to reduced plant growth [7]. In *Brassica juncea* L., plant height decreased by about 50% because of Cr treatment [64]. The biomass and length of the shoot were also decreased upon exposure to the high content of Cr(VI) in lemongrass [65]. Cr treatments had a negative effect on the morphological characteristics (shoot length, shoot and root fresh and dry weights) of *Ipomoea carnea* Jacq. Root growth arrest/inhibition caused by Cr toxicity may be mainly due to inhibition of root cell division and function [66]. Cr(VI) treatments were toxic to plant growth and biomass production in *Arabidopsis thaliana* [67]. In tomato plants, Cr reduced root dry weight by 16% compared to the control [68]. The root length, and dry root weight of Zea *mays* L. plants subjected to Cr (VI) treatment were drastically reduced [69]. Growth and biomass of *Suaeda maritimar* L. were significantly affected by Cr exposure [70].

Conclusion

Lacy Phacelia was grown under five different Cr doses and accumulation of Cr, Fe and Mn in different plant organs, and morphological attributes were studied. Lacy Phacelia accumulated Cr in the roots and translocated it to the above-ground organs (root > leaf > stem > flower = stamen). Furthermore, plant TF and BCF were < 1 at all Cr doses, indicating that Lacy phacelia is not suitable for phytoremediation. Although the highest Cr dose applied (40 mg kg^{-1}) did not exceed the WHO permissible limit for soils (100 mg kg^{-1}), a significant amount (3.79 mg kg^{-1}) of Cr translocated to the stamens, exceeding the permissible limit (1.30 mg kg^{-1}/2.30 mg kg^{-1}). As a result, Cr(VI) was translocated to all organs of Lacy Phacelia, raising the possibility of Cr contamination of bee products through pollen collected by bees. Furthermore, Cr exposure caused a decrease in plant biomass (dry root 38%, dry stem 44% and dry flower 67%). Considering all these circumstances, it may not be appropriate to recommend phacelia cultivation for bee products, fodder, or phytoremediation in Cr-contaminated areas. Furthermore, Lacy Phacelia cultivation for forage purposes in Cr-contaminated areas will be negatively affected.

Abbreviations

Cr chromium
TF Translocation Factor
BCF Bioconcentration Factor

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Author contributions

Conceptualization, H.S.I.; methodology, H.S.I.; software, H.S.I.; validation, H.S.I.; formal analysis, H.S.I.; investigation, H.S.I.; resources, H.S.I.; data curation, H.S.I.; writing—original draft preparation, H.S.I.; writing—review and editing, H.S.I.; visualization, H.S.I. All authors have read and agreed to the published version of the manuscript.

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Data availability

The data will be available from the corresponding author on request.

Declarations

Ethics approval and consent to participate

Not applicable. This is not a clinical study and no patients were involved.

Consent for publication

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Competing interests

The authors declare no competing interests.

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6 References

1. Adnan M, Xiao B, Ali MU, Xiao P, Zhao P, Wang H, et al. Heavy metals pollution from smelting activities: A threat to soil and groundwater. Ecotoxicol Environ Saf. 2024;274:116189.
2. Gill RA, Ali B, Cui P, Shen E, Farooq MA, Islam F, et al. Comparative transcriptome profiling of two *Brassica napus* cultivars under chromium toxicity and its alleviation by reduced glutathione. BMC Genomics. 2016;17:885.
3. Sharma P, Singh SP, Tripathi RD, Tong YW. Chromium toxicity and tolerance mechanisms in plants through cross-talk of secondary messengers: an overview of pathways and mechanisms. Environ Pollut. 2023;320:121049.
4. Bhat MA, Mishra AK, Jan S, Shah SA, Asgher M, Rahman S, et al. Chromium and plant health: A prospective study of toxicity to remediation and restoration of the environment. South Afr J Bot. 2023;162:505–18.
5. Ashraf A, Bibi I, Niazi NK, Ok YS, Murtaza G, Shahid M, et al. Chromium(VI) sorption efficiency of acid-activated banana Peel over organo-montmorillonite in aqueous solutions. Int J Phytorem. 2017;19:605–13.

6. Joutey NT, Sayel H, Bahafid W, El Ghachtouli N. Mechanisms of Hexavalent Chromium Resistance and Removal by Microorganisms. In: Reviews of Environmental Contamination and Toxicology. 2015. pp. 45–69.
7. Sharma A, Kapoor D, Wang J, Shahzad B, Kumar V, Bali AS, et al. Chromium bioaccumulation and its impacts on plants: an overview. Plants. 2020;9:100.
8. Kabata-Pendias A. Trace elements in soils and plants. CRC; 2010.
9. Kabata-Pendias A, Szteke B. Trace elements in abiotic and biotic environments. Boca Raton: CRC; 2015.
10. Overall evaluations of. Carcinogenicity: an updating of IARC monographs volumes 1 to 42. IARC monographs on the evaluation of carcinogenic risks to humans Supplement /. Volume 7. World Health Organization, International Agency for Research on Cancer; 1987.
11. DT O, AA A. OE O. Heavy metal concentrations in plants and soil along heavy traffic roads in North central Nigeria. J Environ Anal Toxicol. 2015;05.
12. Iqbal MA, Chaudhary MN, Zaib S, Imran M, Ali K, Iqbal A. Accumulation of Heavy Metal (Ni,Cu,Cd,Cr,Pb) in Agricultural Soils and Spring Seasonal Plants, Irrigated by Industrial Waste Water. Technology, Environmental Vol, Management. 2011;2.
13. Ibrahim M, Daniel AK, Kiyawa SA, Kutama AS. Phyto-Accumulation of Lead and Chromium in Common Edible Green-Leafy Vegetables Consumed in Dutse Metropolis, Jigawa State, Nigeria. International Journal of Chemical, Material and Environmental Research. 2017;4.
14. Shahid M, Shamshad S, Rafiq M, Khalid S, Bibi I, Niazi NK, et al. Chromium speciation, bioavailability, uptake, toxicity and detoxification in soil-plant system: A review. Chemosphere. 2017;178:513–33.
15. Gupta AK, Sinha S. Chemical fractionation and heavy metal accumulation in the plant of *Sesamum indicum* (L.) Var. T55 grown on soil amended with tannery sludge: selection of single extractants. Chemosphere. 2006;64:161–73.
16. Taşpınar K, Ateş Ö, Özge Pınar M, Yalçın G, Kızılaslan F, Fidantemiz YF. Soil contamination assessment and potential sources of heavy metals of Alpu plain Eskişehir Turkey. Int J Environ Health Res. 2022;32.
17. Akkan T, Mutlu T. Assessment of heavy metal pollution of Çoruh river (Turkey). Karadeniz Fen Bilimleri Dergisi. 2022;12.
18. Şahin G. Türkiye'de Gübre Kullanım Durumu ve Gübreleme Konusunda Yaşanan problemler. Tarım Ekonomisi Dergisi. 2016;22:19–32.
19. Söyler O. Türkiye'de Tarımsal üretimde Kimyasal Gübre Kullanımı Ile Ilgili problemler ve Çözüm Yolları Üzerine Bir Araştırma. 5. Uluslararası Uygulamalı bilimler Kongresi Tam Metin Kitabı. 2020;:26–7.
20. Bjørklund G, Aaseth J, Skalny AV, Suliburska J, Skalnaya MG, Nikonorov AA et al. Interactions of iron with manganese, zinc, chromium, and selenium as related to prophylaxis and treatment of iron deficiency. J Trace Elem Med Biol. 2017;41.
21. Zulfiqar U, Haider FU, Ahmad M, Hussain S, Maqsood MF, Ishfaq M et al. Chromium toxicity, speciation, and remediation strategies in soil-plant interface: A critical review. Front Plant Sci. 2023;13.
22. Okant M. Arıotu (*Phacelia tanacetifolia* Bentham)'nda Farklı tohum Miktarlarının Bitkisel Özellikleri Ile kalitesi Üzerine Etkisi. Harran Tarım ve Gıda. Bilimleri Dergisi. 2019;23:47–51.
23. Carreck NL, Williams IH. Observations on two commercial flower mixtures as food sources for beneficial insects in the UK. J Agric Sci. 1997;128.
24. Akbay F, Kamalak A, Erol A. Arı Otu (*Phaceliatanacetifolia* Bentham)'nun vejatatif Dönemlerinin Ot verimine, Besin madde içeriğine ve Metan üretimine Etkisi. Kahramanmaraş Sütçü İmam Üniversitesi Tarım ve Doğa. Dergisi. 2020;23:981–5.
25. Xun E, Zhang Y, Zhao J, Guo J. Translocation of heavy metals from soils into floral organs and rewards of *Cucurbitapepo*: implications for plant reproductive fitness. Ecotoxicol Environ Saf. 2017;145:235–43.
26. Sénéchal H, Visez N, Charpin D, Shahali Y, Peltre G, Biolley J-P et al. A Review of the Effects of Major Atmospheric Pollutants on Pollen Grains, Pollen Content, and Allergenicity. The Scientific World Journal. 2015;2015.
27. Li Y, Rahman SU, Qiu Z, Shahzad SM, Nawaz MF, Huang J, et al. Toxic effects of cadmium on the physiological and biochemical attributes of plants, and phytoremediation strategies: A review. Environ Pollut. 2023;325:121433.
28. Søvik E, Perry CJ, LaMora A, Barron AB, Ben-Shahar Y. Negative impact of manganese on honeybee foraging. Biol Lett. 2015;11:20140989.
29. Hladun KR, Di N, Liu T, Trumble JT. Metal contaminant accumulation in the hive: consequences for whole-colony health and brood production in the honey bee (*Apis mellifera* L). Environ Toxicol Chem. 2016;35:322–9.
30. Coakley S, Cahill G, Enright A-M, O'Rourke B, Petti C. Cadmium hyperaccumulation and translocation in *Impatiensglandulifera*: from foe to friend?? Sustainability. 2019;11:5018.
31. Evangelou MWH, Kutschinski-Klöss S, Ebel M, Schaeffer A. Potential of Borago officinalis, *Sinapisalba* L. and phacelia boratus for phytoextraction of cd and Pb from soil. Water Air Soil Pollut. 2007;182:407–16.
32. Neagoe A, Iordache V, Bergmann H, Kothe E. Patterns of effects of arbuscular mycorrhizal fungi on plants grown in contaminated soil. J Plant Nutr Soil Sci. 2013;176:273–86.
33. Maciejewska A, Kwiatkowska-Malina J. Elucidating the effect and mechanism of the brown coal-based amendment on plant availability of zinc, lead and cadmium in a haplic Luvisols. Environ Sci Pollut Res. 2022;29:23383–91.
34. Miller R. Microwave digestion of plant tissue in A closed vessel. Handbook of reference methods for plant analysis. CRC; 1997.
35. Taner O, Kayiş AF, Yalçınkaya Ö. Atık Sularda ICP-MS Cihazı Ile Cıva Tayini ve geçerli Kılınması. 21 Yüzyılda. Fen Ve Teknik. 2020;1:1–14.
36. Li F, Ni L, Yuan J, Daniel Sheng G. Cultivation practices affect heavy metal migration between soil and *Viciafaba* (broad bean). Chemosphere. 2010;80.
37. Ladislas S, El-Mufleh A, Gérente C, Chazarenc F, Andrès Y, Béchet B. Potential of aquatic macrophytes as bioindicators of heavy metal pollution in urban stormwater runoff. Water Air Soil Pollut. 2012;223.
38. Jones B, Sall J. JMP statistical discovery software. Wiley Interdiscip Rev Comput Stat. 2011. https://doi.org/10.1002/wics.162.
39. Stambulska UY, Bayliak MM, Lushchak VI. Chromium(VI) toxicity in legume plants: modulation effects of rhizobial symbiosis. Biomed Res Int. 2018;2018:1–13.
40. Kaur R, Yadav P, Thukral AK, Sharma A, Bhardwaj R, Alyemeni MN, et al. Castasterone and citric acid supplementation alleviates cadmium toxicity by modifying antioxidants and organic acids in *Brassica juncea*. J Plant Growth Regul. 2018;37:286–99.
41. Khanna K, Jamwal VL, Sharma A, Gandhi SG, Ohri P, Bhardwaj R, et al. Supplementation with plant growth promoting rhizobacteria (PGPR) alleviates cadmium toxicity in *Solanum lycopersicum* by modulating the expression of secondary metabolites. Chemosphere. 2019;230:628–39.
42. Deng P, Wan W, Azeem M, Riaz L, Zhang W, Yang Y et al. Characterization of Biochar derived from bamboo and its application to modulate the toxic effects of chromium on wheat plant. Biomass Convers Biorefin. 2024;14.
43. Mohanty M, Patra HK. Attenuation of Chromium Toxicity by Bioremediation Technology. In: Reviews of Environmental Contamination and Toxicology. 2011. pp. 1–34.
44. Srivastava D, Tiwari M, Dutta P, Singh P, Chawda K, Kumari M, et al. Chromium stress in plants: toxicity, tolerance and phytoremediation. Sustainability. 2021;13:4629.
45. Masinire F, Adenuga DO, Tichapondwa SM, Chirwa EMN. Phytoremediation of Cr(VI) in wastewater using the vetiver grass (*Chrysopogon zizanioides*). Min Eng. 2021;172:107141.
46. Sajad MA, Khan MS, Bahadur S, Naeem A, Ali H, Batool F et al. Evaluation of chromium phytoremediation potential of some plant species of dir lower, Khyber Pakhtunkhwa, Pakistan. Acta Ecol Sin. 2020;40.
47. Liu J, Duan C-Q, Zhang X-H, Zhu Y-N, Hu C. Subcellular distribution of chromium in accumulating plant *Leersiahexandra* Swartz. Plant Soil. 2009;322:187–95.
48. Huang W, Jiao J, Ru M, Bai Z, Yuan H, Bao Z, et al. Localization and speciation of chromium in *Coptis chinensis* Franch. Using synchrotron radiation X-ray technology and laser ablation ICP-MS. Sci Rep. 2018;8:8603.
49. Ahmed F, Fakhruddin ANM, Fardous Z, Chowdhury MAZ, Rahman MM, Kabir MM. Accumulation and translocation of chromium (Cr) and lead (Pb) in Chilli plants (*Capsicum annuum* L.) grown on artificially contaminated soil. Nat Environ Pollution Technol. 2021;20:63–70.
50. Khadra A, Pinelli E, Ezzariai A, Mohamed O, Merlina G, Lyamlouli K, et al. Assessment of the genotoxicity of antibiotics and chromium in primary sludge and compost using *Viciafaba* micronucleus test. Ecotoxicol Environ Saf. 2019;185:109693.
51. Zaheer IE, Ali S, Saleem MH, Imran M, Alnusairi GSH, Alharbi BM, et al. Role of iron–lysine on morpho-physiological traits and combating chromium toxicity in rapeseed (*Brassicanapus* L.) plants irrigated with different levels of tannery wastewater. Plant Physiol Biochem. 2020;155:70–84.
52. Patra HK, Patra DK, Acharya S. Chromium-induced phytotoxicity and its impact on plant metabolism. Acta Physiol Plant. 2024;46:20.
53. Meindl GA, Bain DJ, Ashman T-L. Nickel accumulation in leaves, floral organs and rewards varies by serpentine soil affinity. AoB Plants. 2014;6.
54. Mohsenzadeh F, Chehregani A, Yousefi N. Effect of the heavy metals on developmental stages of ovule, pollen, and root proteins in *Reseda lutea* L. (Resedaceae). Biol Trace Elem Res. 2011;143:1777–88.

55. Meindl GA, Ashman T-L. Nickel accumulation by streptanthus Polygaloides (Brassicaceae) reduces floral visitation rate. J Chem Ecol. 2014;40:128–35.
56. Hladun KR, Parker DR, Tran KD, Trumble JT. Effects of selenium accumulation on phytotoxicity, herbivory, and pollination ecology in radish (*Raphanus sativus* L). Environ Pollut. 2013;172:70–5.
57. Yadav SK. Heavy metals toxicity in plants: an overview on the role of glutathione and phytochelatins in heavy metal stress tolerance of plants. South Afr J Bot. 2010;76:167–79.
58. Matanzas N, Afif E, Díaz TE, Gallego JR. Phytoremediation potential of native herbaceous plant species growing on a paradigmatic brownfield site. Water Air Soil Pollut. 2021;232:290.
59. Zayed A, Gowthaman S, Terry N. Phytoaccumulation of trace elements by wetland plants: I. Duckweed. J Environ Qual. 1998;27.
60. Sürmen B, Kılıç DD, Kutbay HG, Tuna EE. Doğal Olarak Yayılış gösteren *Lepidiumdraba* L. Türünün fitoremediasyon Yönteminde Kullanılabilirliğinin Araştırılması. Eur J Sci Technol. 2019;:491–9.
61. Dong J, Wu F, Huang R, Zang G. A Chromium-Tolerant plant growing in Cr-Contaminated land. Int J Phytorem. 2007;9:167–79.
62. Saleem Mh, Afzal J, Rizwan M, Shah Z-U-H, Depar N, Usman K. Chromium toxicity in plants: consequences on growth, chromosomal behavior andmineral nutrient status. Turkish J Agric Forestry. 2022;46:371–89.
63. Jobby R, Sarkar M, Bose R, Srivastava S, Suprasanna P. Chromiomics: chromium detoxification and approaches for engineering tolerance in plants. Environ Pollut. 2024;350:123991.
64. Gupta S, Srivastava S, Pardha Saradhi P. Chromium increases photosystem 2 activity in *Brassica juncea*. Biol Plant. 2009;53:100–4.
65. Patra DK, Pradhan C, Patra HK. Chromium stress impact on Lemongrass grown in over burden soil of Sukinda chromite ore mine (Odisha), India. Annals Plant Sci. 2018;7:2394.
66. Shanker A, Cervantes C, Lozatavera H, Avudainayagam S. Chromium toxicity in plants. Environ Int. 2005;31:739–53.
67. Castro RO, Trujillo MM, López Bucio J, Cervantes C, Dubrovsky J. Effects of dichromate on growth and root system architecture of *Arabidopsisthaliana* seedlings. Plant Sci. 2007;172:684–91.
68. Al-Huqail AA, Ali HM, Kushwaha BK, AL-Huqail AA, Singh VP, Siddiqui MH. Ascorbic acid is essential for inducing chromium (VI) toxicity tolerance in tomato roots. J Biotechnol. 2020;322:66–73.
69. Mahajan P, Sharma P, Singh HP, Rathee S, Sharma M, Batish DR, et al. Amelioration potential of β-pinene on Cr(VI)-induced toxicity on morphology, physiology and ultrastructure of maize. Environ Sci Pollut Res. 2021;28:62431–43.
70. Fatnani D, Patel M, Parida AK. Regulation of chromium translocation to shoot and physiological, metabolomic, and ionomic adjustments confer chromium stress tolerance in the halophyte *Suaeda maritima*. Environ Pollut. 2023;320:121046.

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