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Phytoremediation of contaminated urban soils spiked with heavy metals

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Abstract

Urban environments worldwide face toxic heavy metal pollution originating from industrial discharge, municipal waste disposal, vehicular emissions, and atmospheric deposition. Kazakhstan, experiencing accelerated economic growth and extensive mining activities, contends with widespread heavy metal contamination in its soil-plant-air-water ecosystems. This study explores the potential of hyperaccumulating plants for phytoremediation in urban soils of Kazakhstan contaminated with Pb, Cd, and Co. Twelve plant species, including Korean Mint (*Lamiaceae*), Ornamental Cabbage (*Brassica oleracea*), Ageratum (*Ageratum houstonianum*), Coneflower (*Echinacea purpurea*), Amaranth (*Amaranthus Perfect* and *Amaranthus Emerald*), Fescue (*Festuca glauca*), Burning Bush (*Kochia scoparia*), Marigold (*Tagetes patula nana*), White Cabbage (*Brassica-Cavolo cappuccino BIANKO*), Tepary Bean (*Phaseolus acutifolius*), and Rapeseed (*Brassica napus*), were evaluated for growth and biomass production in urban soils spiked with two maximum permissible addition (MPA) treatments of Pb, Co, and Cd. The selected plants demonstrated varied responses to heavy metal stress, with Marigold (8.4 g shoot biomass/plant), Korean mint (10.5 g shoot biomass/plant), Rapeseed (19.9 g/shoot biomass), and Tepary bean (25.9 g shoot biomass/plant) exhibiting resilience or tolerance to Pb, Co, and Cd stresses. The results highlight the significant potential of these plants for efficient phytoremediation, showcasing their unique abilities to absorb and accumulate specific metals. Marigold, particularly, displayed noteworthy Pb accumulation (40.3 mg/kg biomass), resulting in reduced residual Pb concentrations in the soil (74.7 mg/kg). Conversely, White cabbage and Amaranth showed limited efficiency in Cd extraction, while Rapeseed and Tepary bean emerged as promising candidates for Cd phytoremediation. This study emphasizes the critical role of tailored plant species selection in designing effective phytoremediation strategies for specific metal-contaminated urban sites. A comprehensive understanding of the dynamics of metal accumulation and residual concentrations is crucial for the development of sustainable and efficient environmental remediation approaches. Further research is warranted to explore the long-term effects of different plant species on soil metal concentrations, refining and optimizing phytoremediation methods for urban soils grappling with toxic heavy metal contamination.

Keywords: Pot culture, lead, cadmium, cobalt, hyperaccumulators, shoot biomass.

Introduction

Urban soils are susceptible to heavy metals pollution from both point and non-point sources, including industrial discharge and emissions, chemical plants and spillage of petrochemicals, utilities and energy

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production, burning of fossil fuels, disposal of metal wastes, municipal waste disposal, and atmospheric deposition in response to human activities globally (Wei and Yang, 2010; Kakimov et al., 2013; Tefera et al., 2018; Yelikbayev et al., 2020; Silva et al., 2021; Toishimanov et al., 2023). The movement of traffic vehicles also emits heavy metals through various sources such as exhaust gases, incomplete fuel combustion, fuel additives, oil leaks, lining rupture, tire wear, and car washing (Amato et al., 2014; Werkenthin et al., 2014). Additionally, suspended particles from atmospheric emissions contribute to soil contamination and can be re-suspended as fugitive dust into the atmosphere (Woszczyk et al., 2018).

Heavy metals commonly found in urban contaminated soil-plant-air-water ecosystems include lead (Pb), chromium (Cr), arsenic (As), zinc (Zn), cadmium (Cd), copper (Cu), mercury (Hg), and nickel (Ni) in high concentrations (Minkina et al., 2014; Doabi et al., 2018; Woszczyk et al., 2018; Ramazanova et al., 2021; Silva et al., 2021). While Pb makes up about 14.8 mg/kg of the earth's crust (Wedepohl, 1995), it enters urban soil from vehicle exhaust gases and with dust and gases from various industrial facilities (Amato et al., 2014; Werkenthin et al., 2014). In soils, Pb accumulates for a long time, because it is not biodegradable. As it accumulates in soil-plant ecosystems, it becomes toxic to soil biology and public health (Zaborowska et al., 2016; Khanam et al., 2020). Likewise, Co is about 24 mg/kg of the earth's crust (Wedepohl, 1995), but it released into urban soils mainly from industrial sites when fossil fuels are burned (Li, 2001). In contrast, Cd makes up about 100 μg/kg of the earth's crust (Wedepohl, 1995), it sourced from the mining and metallurgical industries, fertilizers, and sewage sludge (Zaborowska et al., 2016).

Soils are the major sink for heavy metals especially Pb, Cd, and Co due to their persistence against biological or chemical degradation which can lead to an increased uptake by plants and their accumulation in living organisms (Gebrekidan et al., 2013; Doabi et al., 2018; Amoakwah et al., 2022). However, these metals do not have any biological function in public health or plant nutrition and are thus considered nonessential elements. Soil contamination with these toxic heavy metals, even at low concentrations, can disrupt the activity and biodiversity of ecological systems and cause a wide range of public health disorders, including cancers (Li et al., 2018; Ramazanova et al., 2021).

Due to the accelerated economic growth and indiscriminate mining activities, soil-plant-air-water ecosystems contaminated with heavy metals is common in Kazakhstan (Diacono et al., 2008; Kaliaskarova et al., 2019; Baubekova et al., 2021; Toishimanov et al., 2023; Zhyrgalova et al., 2024). Several research studies have suggested widespread contamination of urban soils in Kazakhstan with persistent heavy metals such as Pb, Cu, Va, Zn, Cd, and Co (Iztileu et al., 2016; Aiman et al., 2018; Muzychenko et al., 2017; Baubekova et al., 2021; Naimanova et al., 2024). These contaminants pose significant environmental risks and human hazards through direct ingestion or contact with contaminated ecosystems and the food chain, necessitating urgent remediation efforts (Baubekova et al., 2021; Ramazanova et al., 2021).

While chemical and physical methods are widely used for remediating and/or neutralizing heavy metal-contaminated soils, they often entail significant environmental trade-offs. Techniques such as soil excavation, chemical leaching, and thermal desorption are expensive and labor intensive, and can substantially disrupt the ecological balance of the treated site, resulting in potential drawbacks (Naimanova et al., 2024). Given the crucial need to address the growing heavy metals pollution concerns, research efforts must concentrate on proactive remediation of toxic heavy metals pollution-laden urban soils using environmentally compatible approaches. One such approach is phytoremediation, which involves using suitable plants that are highly adaptive and capable of growing in soils contaminated with heavy metals (Cho-Ruk et al., 2006; Yelikbayev et al., 2020; Toishimanov et al., 2023). These plants produce biomass with extensive root systems that actively absorb heavy metals from the soil and translocate them from root to shoot. This process allows the plants to bind and accumulate large amounts of heavy metals in their shoots without any visible phytotoxic effects, thereby acting as hyperaccumulators to remediate and rehabilitate contaminated sites (Marques et al., 2009; van der Ent et al., 2013; Yan et al., 2020).

It is reported that more than 500 plant species in 101 families, including members of *Asteraceae, Brassicaceae, Caryophyllaceae, Cyperaceae, Cunouniaceae, Fabaceae, Flacourtiaceae, Lamiaceae, Poaceae, Violaceae*, and *Euphobiaceae*, are capable of accumulating various metals (Krämer, 2010; van der Ent et al., 2013). Accumulation of metals occurs in approximately 0.2% of all angiosperms, especially in Brassicaceae (Krämer, 2010; Marques et al., 2009; Yan et al., 2020). Previous studies have indicated that though the heavy metals like, Cd, Pb and Ni are non-essential for plant growth, they are readily taken up and accumulated by certain plants (Cho-Ruk et al., 2006). These plants can accumulate Cd, As and some other traces of metals at-least 0.01%, Co, Cu, Cr, Ni and Pb 0.1%, and Mn and Ni 1% in dry-weight of shoot biomass (Reeves and Baker, 2000).

The maximum permissible addition (MPA) of the heavy metal / metalloid content in the soil is the key criteria to standardize the soil contamination (Vodyanitskii, 2016). While the MPAs of Cd, Co, and Pb are 0.76, 34, and 55 mg/kg, respectively, the concentration of heavy metals in urban soils of Kazakhstan, in some instances, exceeded their limits. Therefore, Pb, Cd, and Co pollution of urban soils poses a great potential threat to the environment and human health in Kazakhstan. Our hypothesis was that plants with inherent tolerance and capability for increased uptake and accumulation of toxic heavy metals would provide a proactive approach to phytoextraction in contaminated urban soils. The objective of our research was to evaluate the growth and shoot biomass production of diverse plants and their performance in phytoextraction of Pb, Cd, and Co from spiked contaminated urban soils.

Material and Methods

Soil properties

The pot culture experiment was conducted at the greenhouse in the Dept. of Chemical Processes and Industrial Ecology at Satbayev University, Almaty, Kazakhstan during 2021-2022. Composite soils in metropolitan Almaty were collected at 0-30 cm depth. Initial analyses have shown that soil had total organic carbon (SOC) 17. 6 g/kg, total phosphorus 4.7 g/kg, calcium carbonate 1.21 ±%, pH 8.1, cation exchange capacity 31.6 1 $cmol_+$/kg, total silica 143, aluminum 53, magnesium 4.7, potassium 26.5, iron 5.4, and titanium 5.4 g/kg, respectively. Total cobalt (Co), lead (Pb), and cadmium (Cd) concentrations were 13, 27, and 4.1 mg/kg, respectively.

Table 1. Heavy metals type, dose (MPA, maximum permissible addition), and name of the plants used in the experiment.

Heavy metal	Soil + 2 MPA = Total (mg/kg soil) conc.	Latin or botanical name	Common name
Cobalt	13+48 = 61	*Lamiaceae*	Korean Mint
	13+48 = 61	*Brassica oleracea*	Cabbage ornamental
	13+48 = 61	*Ageratum houstonianum*	Ageratum
	13+48 = 61	*Echinacea purpurea*	Coneflower
Lead	27+110 = 137	*Amaranthus*	Amaranth Perfect
	27+110 = 137	*Festuca glauca*	Fescue
	27+110 = 137	*Kochia scoparia*	Burning bush
	27+110 = 137	*Tagetes patula nana*	Marigold
Cadmium	4.1+1.5 = 5.6	*Amaranthus*	Amaranth Emerald
	4.1+1.5 = 5.6	*Brassica-Cavolo cappuccino BIANKO*	White cabbage
	4.1+1.5 = 5.6	*Phaseolus acutifolius*	Tepary bean
	4.1+1.5 = 5.6	*Brassica napus*	Rapeseed

Experimental design and cultural practices

A completely randomized design was followed to conduct the study with 12 different locally grown plant species (Figure 1), three different heavy metals (such as Co, Pb, and Cd), and replicated six times (Table 1). Prior to initiate the experiment, about 400 g of perlite was placed in plastic pots (height 19 cm x diameter 20.5 cm, with a surface area of 330 cm^2) followed by filling with 5 kg of air-dried soil on the top of perlite layer. Required volume of distilled water was added to the pot from the top and then allowed to equilibrate the soil moisture content.

For our experiment, Pb, Cd, and Co solutions were added based on a concentration of two MPA, which was calculated based on the following equation (Vodyanitskii, 2016):

$$MPA\ (mg/kg) = NOEC : 10$$

where the NOEC stands for no observed effect concentration, i.e., the maximal concentration exerting no significant influence on the growth and reproduction of the test organisms, and 10 is a coefficient.

Pb, Cd, and Co solutions were prepared with concentrations of 2 MPA, equivalent to 110, 1.5, and 48 mg/kg, respectively. Exactly 21.98, 0.596, and 29.63 g of $Pb(NO_3)_2$, $CdSO_4.8H_2O$, and $Co(NO_3)_2.6H_2O$ salts were dissolved in 800-mL of distilled water followed by addition of 10-mL of conc. HNO_3 and volume to 1-L solution for the respective 2 MPA solution of Pb, Cd, and Co. The 2 MPA solutions of Pb, Cd, and Co were added to the soil to bring the total concentration of Pb, Cd, and Co at 137, 5.6, and 61 mg/kg, respectively (Table 1).

After 3 days, 50 ml of distilled water was added to the surface of each pot, and then poured back the drainage into each pot in four repeated cycles for unform contamination of soils. The spiked contaminated soil was allowed to equilibrate for 33 days in order for Pb, Co, and Cd to react and bind to the soil. Once the experimental soils were equilibrated with the Pb, Co, and Cd, randomly selected six seeds of each plant were sown in potted soil as per treatments. Immediately after germination, the plant seedlings were watered daily as required, based on evapotranspiration. A basal dose of NPK fertilizers was applied to maintain uniform soil fertility for all experimental plants.

Figure 1. Experimental set-up with growing plants under greenhouse condition.

Analysis of soil chemical and physical properties

Composite field-moist soils collected prior to initiate the experiment were air-dried under shade at room temperature (25 ^{0}C) for a period of 15 days, ground with agate mortar and pestle, and 2-mm sieved. Soil pH was determined soil: distilled water suspension (1:5) following the standard glass electrode method (GOST 26423-85). Total soil organic carbon was analyzed, based on wet oxidation of soil with potassium dichromate and concentrated sulfuric acid following Tyurin colorimetric method (Jankauskas et al., 2006). Determination of carbonate in soils was performed by volumetric calcimeter method. The Kappen method was used to determine cation exchange capacity of soil (GOST 27821-88). Total silica, aluminum, magnesium, potassium, iron, and titanium was determined using an X-ray fluorescence energy-dispersive spectrometer PANalytical Epsilon-3. Soil particle size analysis (sand, silt and clay contents) was performed by pipette method (GOST 12536-2014).

Plant heavy metals analysis

After 90 days of plant growth, the shoot biomass was harvested at the base, weighted, and oven-dried at 55$\pm$2^0 C for a period of 24 hr. until a constant was obtained. A portion of the oven-dried shoot biomass was ground with a Wiley Mill® grinder, sieved with a 125 µm mesh prior to digest, and analyze Cd, Co, and Pb using the standard EPA-3052 method (https://www.epa.gov/sites/default/files/2015-12/documents/3052.pdf).

Briefly, a 0.2 g processed sample was mixed with 3: 1: 1 mL ratio of HCl, HNO_3, and HF in standard Teflon tubes (vessels) for microwave digestion using the Speedwave Xpert DAP-60+ program (Table 2). After digestion, the digestates were allowed to cool and then diluted with distilled deionized water. The diluted samples were filtered using Whatman® filter paper to obtain clear aliquots. These aliquots were then analyzed for Cd, Co, and Pb using the Integrated Coupled Plasma Optical Emission Spectrophotometer Optima 8300, manufactured by Perkin Elmer Inc., USA.

Table 2. Program: Speedwave Xpert – DAP-60 +

Step	1	2	3
Time (^{0}C)	170	190	240
Pressure (bar)	50	50	50
Power (%)	80	90	100
Ta (min.)	2	2	2
Time (min)	10	20	30

Soil heavy metals analysis

After plant biomass harvest, soil samples collected from each replicated pot were air-dried under shade at room temperature (~ 25 ^{0}C) for a period of 15 days, ground with a agate mortar and pestle, and 250 µm sieved prior to analyze. Soils collected prior to establishing the experiment were also processed and analyzed for Pb, Co, and Cd concentrations in a similar manner, following the standard EPA-3052 method for heavy metals analysis (https://www.epa.gov/sites/default/files/2015-12/documents/3052.pdf).

Briefly, a 0.2 g sample of processed soil was mixed with 3: 1: 1 mL ratio of HCl, HNO_3, and HF in standard Teflon tubes (vessels) for microwave digestion at high power using the Speedwave Xpert DAP-60+ program (Table 2). After digestion, the Teflon tubes were allowed to cool at room temperature, and the digestates were diluted with distilled deionized water, filtered with Whatman filter paper, and analyzed for Cd, Co, and Pb concentration by the Perkin Elmer Optima 8300 Integrated Coupled Plasma-Optical Emission Spectrometry.

Quality analysis / quality control

After every 10 samples, a QC/QA sample prepared from certified standard solutions of Cd, Co, and Pb were determined to verify the analytical stability and quality with a relative standard deviation of QA/QC (5 to 10%). The detection limits of heavy metals such as Cd, Co, and Pb were 0.2, 0.2, and 0.3 µg/L, respectively. Analytical precision as determined by QA/QC procedures, reagent blanks, and internal standards, was better than ±10%.

Statistical analysis

One-way analysis of variance (ANOVA) was performed to evaluate the effects of selected plants (independent variable) on phytoremediation of heavy metals (dependent variable). Three separate ANOVAs were used for Cd, Co, and Pb, respectively. The plants used as an independent variable were considered as a fixed effect. Prior to the analysis, the normality of the data distribution was checked. Significant effects of the independent variable associated with Pb, Co, and Cd on plant shoot biomass production, Pb, Co, and Cd uptake in shoot biomass, and residual Pb, Co, and Cd concentrations in soil were separated by the Least Significant Difference (LSD) Test (Table 3). The software SAS 9.4 was employed for all statistical analyses, while graphs were created using SigmaPlot.

Table 3. Heavy metals effect on shoot biomass production and their residual distribution in soil and shoot uptake by plants (Mean data were presented with F values and one-way analysis of variance).

Heavy metal	Plants used (common name)	Shoot biomass (g/plant)	Residual metal (mg/kg soil)	Metal uptake (mg/kg plant)
Cobalt	Korean Mint	10.6	21.3	25.8
	Ageratum	7.0	40.0	13.7
	Cabbage ornamental	5.6	32.7	18.4
	Coneflower	1.8	27.0	22.1
	F-value	194.1	71.6	45.8
	Probability > F	0.001	<0.0001	<0.0001
Lead	Marigold	8.5	58.7	27.5
	Amaranth Perfect	2.0	95.0	26.0
	Burning bush	1.4	86.0	28.4
	Fescue	1.2	92.0	29.9
	F-value	445.2	3.0	6.0
	Probability > F	0.015	0.049	0.047
Cadmium	Tepary bean	26.1	5.1	0.56
	White cabbage	20.1	5.6	0.20
	Amaranth Emerald	0.77	5.4	0.32
	Rapeseed	0.25	5.0	0.63
	F-value	461.1	1.7	1.22
	Probability > F	0.002	0.043	0.036

Results and Discussion

Plant shoot biomass production

The application of 2 MPA Pb, Co, and Cd treatments significantly influenced the growth and shoot biomass production of tested plants used for phytoremediation (Table 3; Figure 2-4). Marigold demonstrated the highest shoot biomass production (8.4 g/plant) among Pb-treated plants, while Fescue (1.2 g/plant), Burning bush (1.4 g/plant), and Amaranth (1.9 g/plant) exhibited lower shoot biomass production, indicating their increased susceptibility to Pb toxicity (Table 3; Figure 2). These findings align with studies suggesting that Amaranth, Burning bush, and Fescue are adversely affected by Pb, experiencing decreased shoot biomass due to heightened Pb toxicity susceptibility linked to water and nutritional relations, leading to oxidative damage (Navabpour et al., 2020). Pb-induced structural changes, reduction in chlorophyll pigments, and altered carbon metabolism contribute to the observed negative impact on these plants (Rahman et al., 2013; Zulfiqar et al., 2019).

Similarly, Co exerted notable negative effects on the shoot biomass production of Coneflower (1.8 g/plant), Green cabbage (5.6 g/plant), and Ageratum (6.9 g/plant), whereas Korean mint displayed higher shoot biomass production (10.5 g/plant) (Table 3; Figure 3). The reduced biomass in coneflower, green cabbage, and ageratum under Co stress is consistent with previous research indicating that elevated Co concentrations generate reactive oxygen species (ROS), inhibit root growth, and disrupt nutrient uptake by plants (Valko et al., 2005; Mahey et al., 2020). Co-induced ROS disrupts photosystem II, the electron transport chain, and reduces pigments and nitrogen metabolism, contributing to the observed decline in biomass (Tewari et al., 2002; Ali et al., 2010).

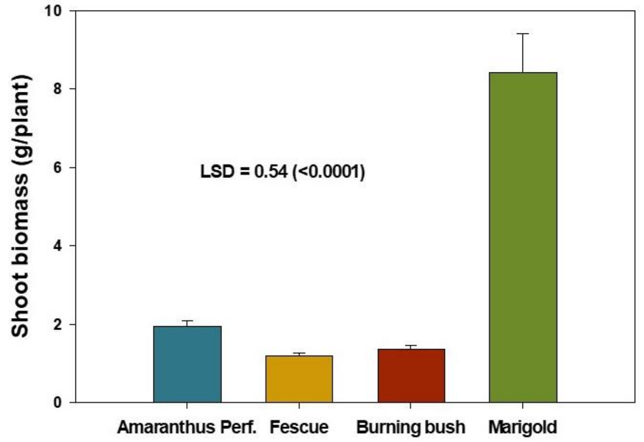

Figure 2. Effects of two maximum permissible addition (2 MPA) of lead on shoot biomass production of Amaranthus, Fescue, Burning bush, and Marigold (Mean values were presented with standard error. Means separated by same lower-case letter in the bars were not significantly different at p≤0.05 among the plants).

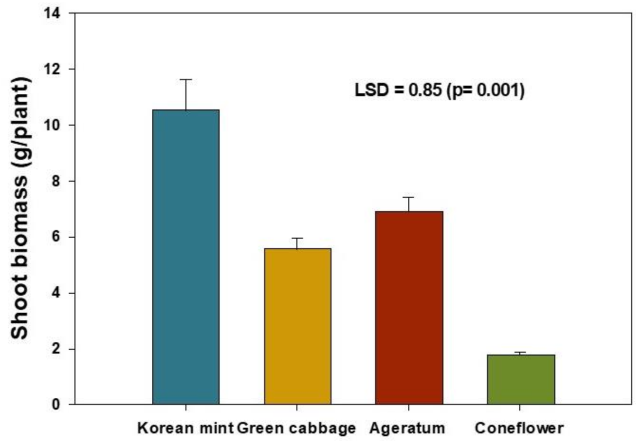

Figure 3. Effects of two maximum permissible addition (2 MPA) of cobalt on shoot biomass production of Korean mint, Green cabbage, Ageratum, and Coneflower (Mean values were presented with standard error. Means separated by same lower-case letter in the bars were not significantly different at p≤0.05 among the plants).

Furthermore, White cabbage (0.3 g/plant) and Amaranthus Emarald (0.8 g/plant) displayed significantly reduced shoot production due to the adverse effects of Cd, contrasting with the higher shoot biomass production in Rapeseed (19.9 g/plant) and Tepary bean (25.9 g/plant) (Table 3; Figure 4). The decreased shoot biomass in White cabbage and Amaranthus Emarald under Cd stress aligns with studies highlighting that Cd damages cells via ROS generation, inhibiting antioxidant enzymes and disrupting proteins (Valko et al., 2005; Bielen et al., 2013). Cd toxicity hampers nutrient uptake, induces oxidative damage, and disrupts plant metabolism, contributing to the observed reduction in shoot biomass (Gallego et al., 2012; Haider et al., 2021).

Our results suggest that Marigold, Korean mint, Rapeseed, and Tepary bean exhibit resilience or tolerance to Pb, Co, and Cd stresses, making them potential candidates for phytoremediation efforts in contaminated environments. The distinct responses observed among the tested plants underscore the importance of selecting suitable species for specific metal-contaminated sites, emphasizing their unique capacities to mitigate the adverse effects of Pb, Co, and Cd toxicity.

Plant uptake of heavy metals

The investigation into shoot biomass concentrations of Pb, Co, and Cd across diverse plant species provides crucial insights into their metal accumulation capabilities and potential roles in phytoremediation (Table 3). Marigold emerged as an outstanding accumulator of Pb, exhibiting a remarkable shoot biomass concentration of 40.3 mg/kg, surpassing Fescue and Burning bush (Table 3; Figure 5). The substantial difference is highlighted by Marigold's Pb accumulation being 1.3, 1.4, and 1.6 times higher than Fescue, Burning bush, and Amaranth, respectively. Additionally, Marigold demonstrated a noteworthy 29.6% absorption of Pb from the soil, showcasing its efficiency in lead uptake and accumulation. In contrast, Fescue, Burning bush, and Amaranth displayed lower Pb absorption percentages (22%, 20.9%, and 19.1%, respectively), suggesting their comparatively lower metal-accumulating potential.

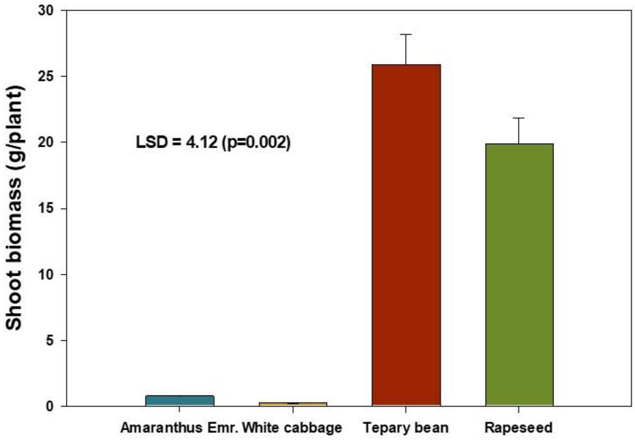

Figure 4. Effects of two maximum permissible addition (2 MPA) of cadmium on shoot biomass production of Amaranthus, White cabbage, Tepary bean, and Rapeseed (Mean values were presented with standard error. Means separated by same lower-case letter in the bars were not significantly different at p≤0.05 among the plants).

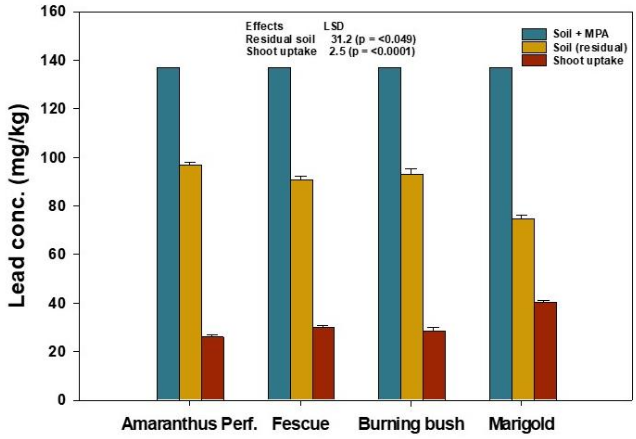

Figure 5. Lead concentration in Amaranthus, Fescue, Burning bush, and Marigold shoot biomass under two maximum permissible addition (2 MPA) of lead in the soil (Mean values were presented with standard error. Means separated by same lower-case letter in the bars were not significantly different at p≤0.05 among the plants).

Distinct responses to Co exposure were observed, with Korean mint exhibiting the highest shoot biomass concentration (25.8 mg/kg), followed by Coneflower and Green cabbage (Table 3; Figure 6). In contrast, Ageratum displayed the lowest Co concentration (13.7 mg/kg). The varying Co levels highlight the diverse abilities of these plants in Co uptake and accumulation. Korean mint, Coneflower, Green cabbage, and Ageratum absorbed 42.3%, 36.2%, 30.2%, and 22.4% of Co from the soil, respectively, showcasing their potential roles in Co phytoremediation.

Conversely, Cd concentrations in the shoot biomass remained relatively low, ranging from 0.20 to 0.63 mg/kg (Table 3; Figure 7). Rapeseed exhibited the highest Cd concentration, while Amaranth and White cabbage displayed the lowest. The modest variations in Cd levels suggest a limited uptake of this metal. Rapeseed and Tepary bean, with absorption percentages of 11.2% and 10.1%, respectively, present as potential candidates for Cd phytoremediation.

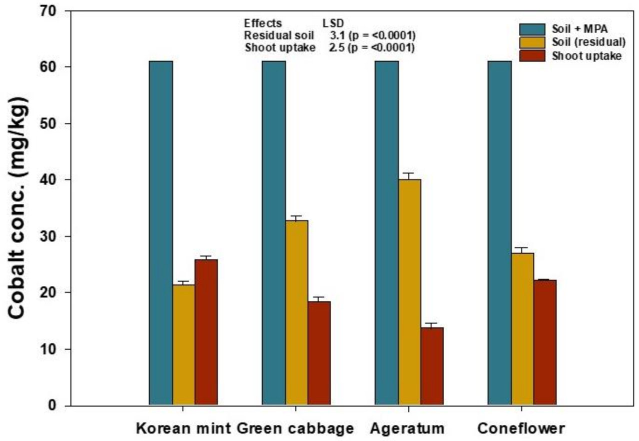

Figure 6. Cobalt concentration in Korean mint, Green cabbage, Ageratum, and Coneflower shoot biomass under two maximum permissible addition (2 MPA) of cobalt in the soil (Mean values were presented with standard error. Means separated by same lower-case letter in the bars were not significantly different at p≤0.05 among the plants).

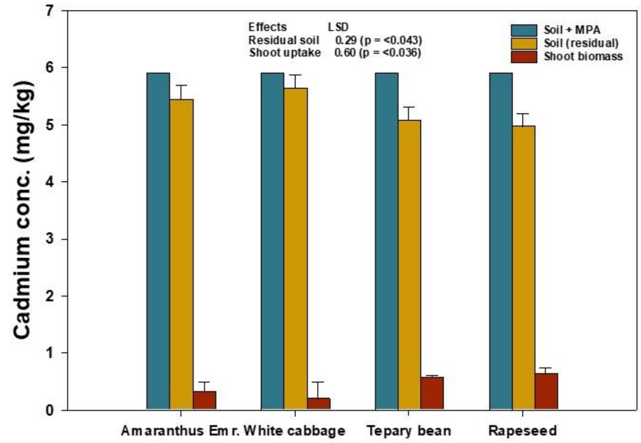

Figure 7. Cadmium concentration in Amaranthus, White cabbage, Tepary bean, and Rapeseed shoot biomass under two maximum permissible addition (2 MPA) of cadmium in the soil (Mean values were presented with standard error. Means separated by same lower-case letter in the bars were not significantly different at p≤0.05 among the plants).

The study aligns with existing literature emphasizing that increasing toxic metal levels in the soil lead to elevated uptake by plants, influencing their metal concentrations (Pb, Cu, Cd, and Zn), particularly in leaves

(Brown et al., 1995; Rahman et al., 2013). The observed differential responses among the tested plant species underscore the importance of selecting appropriate hyperaccumulators based on their metal concentrations. This information is crucial for developing effective and targeted phytoremediation strategies tailored to specific metal-contaminated environments. The ability of certain plants, such as Marigold, Korean mint, Rapeseed, and Tepary bean, to accumulate specific metals highlights their potential utility in environmental remediation efforts.

Residual heavy metals in soil

The investigation into residual metal concentrations in the soil provides valuable insights into the effectiveness of various plant species in mitigating Pb, Co, and Cd pollution (Table 3). The highest residual Pb concentrations in the soil were observed under Amaranth, Burning bush, and Fescue, measuring 96.7, 93, and 90.7 mg/kg, respectively. In contrast, Marigold exhibited the lowest residual Pb concentration of 74.7 mg/kg, relative to the total Pb concentration of 137 mg/kg in the contaminated soil (Table 3; Figure 5). These findings suggest that Amaranth, Burning bush, and Fescue may contribute to a prolonged presence of Pb in the soil due to their limited capacity for uptake and accumulation, while Marigold demonstrates potential for Pb phytoremediation by reducing residual concentrations.

Soils under Ageratum, Green cabbage, Coneflower, and Korean mint displayed the highest residual concentrations of Co compared to the total Co concentration (61 mg/kg) in the spiked contaminated soils (Tabel 3; Figure 6). This indicates that these plant species might have a limited capacity to extract and accumulate Co from the soil, leading to elevated residual Co concentrations. The persistence of Co in the soil under these plants underscores the need for careful consideration of plant selection in Co-contaminated environments.

Conversely, residual soil Cd concentrations were highest under White cabbage and Amaranth, while Rapeseed and Tepary beans exhibited the lowest concentrations, relative to the total Cd concentration in the spiked contaminated soils (Table 3; Figure 7). These results suggest that White cabbage and Amaranth may have a limited ability to extract Cd from the soil, contributing to higher residual concentrations in soil. In contrast, Rapeseed and Tepary beans demonstrate potential for Cd phytoremediation by reducing Cd concentrations in the soil.

The observed variations in residual metal concentrations in soil highlight the importance of plant species selection in phytoremediation strategies. While certain plants may effectively reduce metal concentrations in the soil, others may contribute to the prolonged presence of metals. Understanding the dynamics of residual metal concentrations is crucial for designing sustainable and efficient phytoremediation approaches tailored to specific metal-contaminated environments.

Conclusion

Marigold exhibits resilience to Pb toxicity, while Fescue, Burning bush, and Amaranth show heightened susceptibility. Similarly, Coneflower, Green cabbage, and Ageratum display reduced biomass under Co stress, contrasting with Korean mint. White cabbage and Amaranthus Emarald exhibit reduced shoot production under Cd stress, unlike Rapeseed and Tepary bean. Marigold, Korean mint, Rapeseed, and Tepary bean emerge as potential candidates for phytoremediation. The diverse responses underscore the importance of tailored species selection for specific metal-contaminated sites. Insights into metal accumulation capacities highlight the pivotal role of plant selection in effective environmental remediation strategies. Further research is needed to understand long-term effects of heavy metals concentrations in soil and to refine phytoremediation approaches.

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References

Aiman, N., Gulnaz, S., Alena, M., 2018. The characteristics of pollution in the big industrial cities of Kazakhstan by the example of Almaty. *Journal of Environmental Health Science and Engineering* 16: 81–88.

Ali, B., Hayat, S., Hayat, Q., Ahmad, A., 2010. Cobalt stress affects nitrogen metabolism, photosynthesis and antioxidant system in chickpea (*Cicer arietinum* L.). *Journal of Plant Interactions* 5: 223–231.

Amato, F., Alastuey, A., de la Rosa, J., Gonzalez Castanedo, Y., Sánchez de la Campa, A.M., Pandolfi, M., Lozano, A., Contreras González, J., Querol, X., 2014. Trends of road dust emissions contributions on ambient air particulate levels at rural, urban and industrial sites in southern Spain. *Atmospheric Chemistry and Physics* 14: 3533–3544.

Amoakwah, E., Ahsan, S., Rahman, M. A., Asamoah, E., Essumang, D.K., Ali, M., K.R. Islam., 2020. Assessment of heavy metal pollution of soil-water-vegetative ecosystems associated with artisanal gold mining. *Soil and Sediment Contamination: An International Journal* 29: 788-803.

Baubekova, A., Akindykova, A., Mamirova, A., Dumat, C., Jurjanz, S., 2021. Evaluation of environmental contamination by toxic trace elements in Kazakhstan based on reviews of available scientific data. *Environmental Science and Pollution Research* 28: 43315-43328.

Bielen, A., Remans, T., Vangronsveld, J., Cuypers, A., 2013. The influence of metal stress on the availability and redox state of ascorbate, and possible interference with its cellular functions. I*nternational Journal of Molecular Sciences* 14: 6382-6413.

Brown, S.L., Chaney, R.L., Angle, J.S., Baker, A.J.M., 1995. Zinc and cadmium uptake by hyperaccumulator *Thlaspi caerulescens* grow in the nutrient solution. *Soil Science Society of America Journal* 59: 125-133.

Cho-Ruk, K., Kurukote, J., Supprung, P., Vetayasuporn, S., 2006. Perennial plants in the phytoremediation of lead-contaminated soils. *Biotechnology* 5: 1-4.

Diacono, E., Faye, B., Meldebekova, A., Konuspayeva, G., 2008. Plant, water and milk pollution in Kazakhstan. In: Impact of Pollution on Animal Products. Sinyavskiy, Y., Faye, B. (Eds.). Springer Netherlands, Dordrecht, pp. 107–116.

Doabi, S.A., Karami, M., Afyuni, M., Yeganeh, M., 2018. Pollution and health risk assessment of heavy metals in agricultural soil, atmospheric dust and major food crops in Kermanshah province, Iran. *Ecotoxicology and Environmental Safety* 163: 153–164.

Gallego, S.M., Pena, L.B., Barcia, R.A., Azpilicueta, C.E., Iannone, M.F., Rosales, E.P., Benavides, M.P., 2012. Unravelling cadmium toxicity and tolerance in plants: insight into regulatory mechanisms. *Environmental and Experimental Botany* 83: 33-46.

Gebrekidan, A., Weldegebriel, Y., Hadera, A., Van der Bruggen, B., 2013. Toxicological assessment of heavy metals accumulated in vegetables and fruits grown in Ginfel river near Sheba Tannery, Tigray, Northern Ethiopia. *Ecotoxicology and Environmental Safety* 95: 171-178.

GOST 12536-2014. Soils - Methods of laboratory granulometric (grain-size) and microaggregate distribution. Available at [Access date: 11.03.2024]: https://www.russiangost.com/p-138335-gost-12536-2014.aspx

GOST 27821-88. Soils. Determination of base absorption sum by Kappen method. Available at [Access date: 11.03.2024]: https://www.russiangost.com/p-49750-gost-27821-88.aspx?

GOST 26423-85. Soils - Methods for determination of specific electric conductivity, pH and solid residue of water extract. Available at [Access date: 11.03.2024]: https://www.russiangost.com/p-16105-gost-26423-85.aspx

Haider, F.U., Liqun, C., Coulter, J.A., Cheema, S.A., Wu, J., Zhang, R., Wenjun, M., Farooq, M., 2021. Cadmium toxicity in plants: Impacts and remediation strategies. *Ecotoxicology and Environmental Safety* 211: 111887.

Iztileu, A., Grebeneva, O., Otarbayeva, M., Zhanbasinova, N., Ivashina, E., Duisenbekov, B., 2016. Intensity of soil contamination in industrial centers of Kazakhstan. CBU International Conference Proceedings, ISE Research Institute 1: 374-380.

Jankauskas, B., Jankauskiene, G., Slepetiene, A., Fullen, M.A., Booth, C.A., 2006. International comparison of analytical methods of determining the soil organic matter content of Lithuanian Eutric Albeluvisols. *Communications in Soil Science and Plant Analysis* 37: 707-720.

Kakimov, A., Kakimova, Z., Yessimbekov, Z., Bepeyeva, A., Zharykbasova, K., Zharykbasov, Y., 2013. Heavy metals distribution in soil, water, vegetation and meat in the regions of East-Kazakhstan. *Journal of Environmental Protection* 4: 1292-1295.

Kaliaskarova, Z., Aliyeva, Z., Ikanova, A., Negim, E., 2019. Soil pollution with heavy metals on the land of the Karasai landfill of municipal solid waste in Almaty city. *News of the Academy of Science of the Republic of Kazakhstan, series Geology and Technical Science* 6: 256-267.

Khanam R, Kumar A, Nayak AK, Shahid M, Tripathi R, Vijayakumar S, Bhaduri, D., Kumar, U., Mohanty, S., Panneerselvam, P., Chatterjee, D., Satapathy, B.S., Pathak, H., 2020. Metal(loid)s (As, Hg, Se, Pb and Cd) in paddy soil: Bioavailability and potential risk to human health. *Science of the Total Environment* 699: 134330.

Krämer, U., 2010. Metal hyperaccumulation in plants. *Annual Review of Plant Biology* 61: 517-534.

Li, X.D., Poon, C.S., Liu, P.S., 2001. Heavy metal contamination of urban soils and street dusts in Hong Kong. *Applied Geochemistry* 16: 1361–1368.

Li, G., Sun, G.X., Ren, Y., Luo, X.S., Zhu, Y.G., 2018. Urban soil and human health: a review. *European Journal of Soil Science* 69: 196-215.

Mahey, S., Kumar, R., Sharma, M., Kumar, V., Bhardwaj, R., 2020. A critical review on toxicity of cobalt and its bioremediation strategies. *SN Applied Sciences* 2: 1279.

Marques, A.P.G.C, Rangel, A.O.S.S., Castro, P.M.L., 2009. Remediation of heavy metal contaminated soils: phytoremediation as a potentially promising clean-up technology. *Critical Reviews in Environmental Science and Technology* 39: 622-654.

Minkina, T., Mandzhieva, S., Motusova, G., Burachevskaya, M., Nazarenko, O., Sushkova, S., Kızılkaya, R., 2014. Heavy metal compounds in a soil of technogenic zone as indicate of its ecological state. *Eurasian Journal of Soil Science* 3(2): 144 – 151.

Muzychenko, I., Jamalova, G., Mussina, U., Kazulis, V., Blumberga, D., 2017. Case study of lead pollution in the roads of Almaty. *Energy Procedia* 113: 369–376.

Naimanova, A., Akhmetova, S., Issayeva, A., Vyrakhmanova, A., Alipbekova, A., 2024. Phytoaccumulation of heavy metals in South Kazakhstan soils (Almaty and Turkestan Regions): An evaluation of plant-based remediation potential. *International Journal of Design & Nature and Ecodynamics* 19: 451-464.

Navabpour, S., Yamchi, A., Bagherikia, S., Kafi, H., 2020. Lead-induced oxidative stress and role of antioxidant defense in wheat (*Triticum aestivum* L.). *Physiology and Molecular Biology of Plants* 26: 793-802.

Rahman, M.M., Azirun, S.M., Boyce, A.N., 2013. Enhanced accumulation of copper and lead in Amaranth (*Amaranthus paniculatus*), Indian Mustard (*Brassica juncea*) and Sunflower (*Helianthus annuus*) *PLOS ONE* 8: e62941.

Ramazanova, E., Lee, S.W., Lee, W., 2021. Stochastic risk assessment of urban soils contaminated by heavy metals in Kazakhstan. *Science of the Total Environment* 750: 141535.

Reeves, R.D., Baker, A.J.M., 2000. Metal- accumulating plants. In: Phytoremediation of toxic metals: using plants to clean-up the environment. Raskin, I., Ensley, B.D. (Eds.). John Wiley and Sons. New York, USA. pp. 193-230.

Silva, H.F., Silva, N.F., Oliveira, C.M., Matos, M.J., 2021. Heavy metals contamination of urban soils—A decade study in the city of Lisbon, Portugal. *Soil Systems* 5: 27.

Tefera, M., Gebreyohannes, F., Saraswathi, M., 2018. Heavy metal analysis in the soils of in and around Robe town, Bale zone, South Eastern, Ethiopia. *Eurasian Journal of Soil Science* 7(3): 251 - 256.

Tewari, R.K., Kumar, P., Sharma, P.N., Bisht, S.S. 2002. Modulation of oxidative stress responsive enzymes by excess cobalt. *Plant Science* 162: 381388.

Toishimanov, M., Abilda, Z., Daurov, D., Daurova, A., Zhapar, K., Sapakhova, Z., Kanat, R., Stamgaliyeva, Z., Zhambakin, K., Shamekova, M., 2023. Phytoremediation properties of sweet potato for soils contaminated by heavy metals in South Kazakhstan. *Applied Sciences* 13: 9589.

Valko, M., Morris, H., Cronin, M.T.D. 2005. Metals, toxicity and oxidative stress. *Current Medicinal Chemistry* 12: 1161-1208.

van der Ent, A., Baker, A.J.M., Reeves, R.D., Pollard, A.J., Schat, H., 2013. Hyperaccumulators of metal and metalloid trace elements: facts and fiction. *Plant and Soil* 362: 319-334.

Vodyanitskii, Y.N., 2016. Standards for the contents of heavy metals in soils of some states. *Annals of Agrarian Science* 14: 257-263.

Wedepohl, K.H., 1995. The composition of the continental crust. *Geochimica et Cosmochimica Acta* 59: 1217–1232.

Wei, B., Yang, L., 2010. A review of heavy metal contaminations in urban soils, urban road dusts and agricultural soils from China. *Microchemical Journal* 94: 99-107.

Werkenthin, M., Kluge, B., Wessolek, G., 2014. Metals in European roadside soils and soil solution-A review. *Environmental Pollution* 189: 98-110.

Yan, A., Wang, Y., Tan, S.N., Yusof, M.L.M., Ghosh, S., Chen, Z., 2020. Phytoremediation: A promising approach for revegetation of heavy metal-polluted land. *Frontiers in Plant Science* 11: 359.

Yelikbayev, B.K., Pagano, M.C., Jamalova, G.A., 2020. Hyperaccumulator plants for phytoremediation of soil contaminated with heavy metals. *Bulletin of National Academy of Sciences of the Republic of Kazakhstan* 387: 34-40.

Zaborowska, M., Kucharski, J., Wyszkowska, J., 2016. Biological activity of soil contaminated with cobalt, tin, and molybdenum. *Environmental Monitoring and Assessment* 188: 398.

Zhyrgalova, A., Yelemessov, S., Ablaikhan, B., Aitkhozhayeva, G., Zhildikbayeva, A., 2024. Assessment of potential ecological risk of heavy metal contamination of agricultural soils in Kazakhstan. *Brazilian Journal of Biology* 84: e280583.

Zulfiqar, U., Farooq, M., Hussain, S., Maqsood, M., Hussain, M., Ishfaq, M., Ahmad, M., Anjum, M.Z., 2019. Lead toxicity in plants: Impacts and remediation. *Journal of Environmental Management* 250: 109557.