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The potential of selected ornamental plants for remediating heavy metal-contaminated soil: A case study at the Zenica Steel Mill, Bosnia and Herzegovina

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Abstract: In this study, a greenhouse experiment was carried out from April to July 2024 to assess the effectiveness of four ornamental plants in removing heavy metals from the polluted soil surrounding the Zenica steel mill in Bosnia and Herzegovina. The selected ornamental plants - blue mink (*Ageratum houstonianum* Mill.), marigold (*Tagetes erecta* L.), impatiens (*Impatiens walleriana* Hook. f.), and begonia (*Begonia semperflorens* - Cultorum Group) - demonstrated potential for addressing soil contamination. These plants were cultivated in grow bags filled with soil collected from different areas surrounding the Zenica steel mill. The concentrations of heavy metals (Cu, Zn, Pb, Cd, Cr, Mn, and Fe) in both soil and plant samples were analyzed using atomic absorption spectrophotometry. The findings of this study reveal that soils adjacent to the Zenica steel mill are heavily contaminated with Zn, Cd, and Pb and also contain notable levels of Mn and Fe. The bioaccumulation factor (BAF) and translocation factor (TF) were calculated to determine the potential of the selected ornamental plants to uptake and transport heavy metals from the soil to its aboveground parts. The BAF values for all heavy metals in all studied plant species were consistently below 1, indicating a limited capacity to remove heavy metals from the soil. This limited effectiveness can be attributed, among other factors, to the high pH levels of the tested soils. Despite the limitation, the findings revealed a significant difference in the plants' capacity to uptake and accumulate heavy metal ions from the examined soils. Among the tested plants, blue mink demonstrated the highest ability to absorb Cu, Pb, Cr and Fe, while the highest concentrations of Zn and Cd were found in begonia.

Introduction

Soil pollution caused by heavy metals is a significant global environmental issue (Zhao et al. 2024, Adnan et al. 2025). It results from both natural processes and anthropogenic activities such as rapid urbanization, mining, industrial operations, and certain agricultural practices (Jutsz & Gnida 2015, Adnan et al. 2024). Contamination of soil with heavy metals poses serious risks to soil productivity and biodiversity, and adversely affects surrounding air and water ecosystems. Furthermore, heavy metals can threaten human health through bioaccumulation in the food chain involving soil, plants, and animals. One potential solution lies in the use of horticultural plants – either as ornamental species or within the framework of a "good neighbor" policy in organic food production. Therefore, investigating the responses of horticultural plants to various pollutants present in urban environments is crucial, particularly with regard to their capacity to extract heavy metals from food chain and reduce associated health risks. Further research should prioritize herbaceous horticultural plants with high aesthetic value that are cultivated in contaminated urban areas, aiming to identify potential heavy metal accumulators or hyperaccumulators.

Soil pollution by heavy metals is particularly severe in point-source locations such as mining sites, oil refineries, steel mills, foundries, and other heavy metal-based manufacturing facilities. Numerous studies have reported that soils in industrial regions often contain elevated levels of toxic heavy metals, with mining and smelting activities identified as major contributors (Adnan et al. 2022, Gawroński et al. 2022). Therefore, the removal of toxic heavy metals from contaminated soil is essential to minimize human health risks

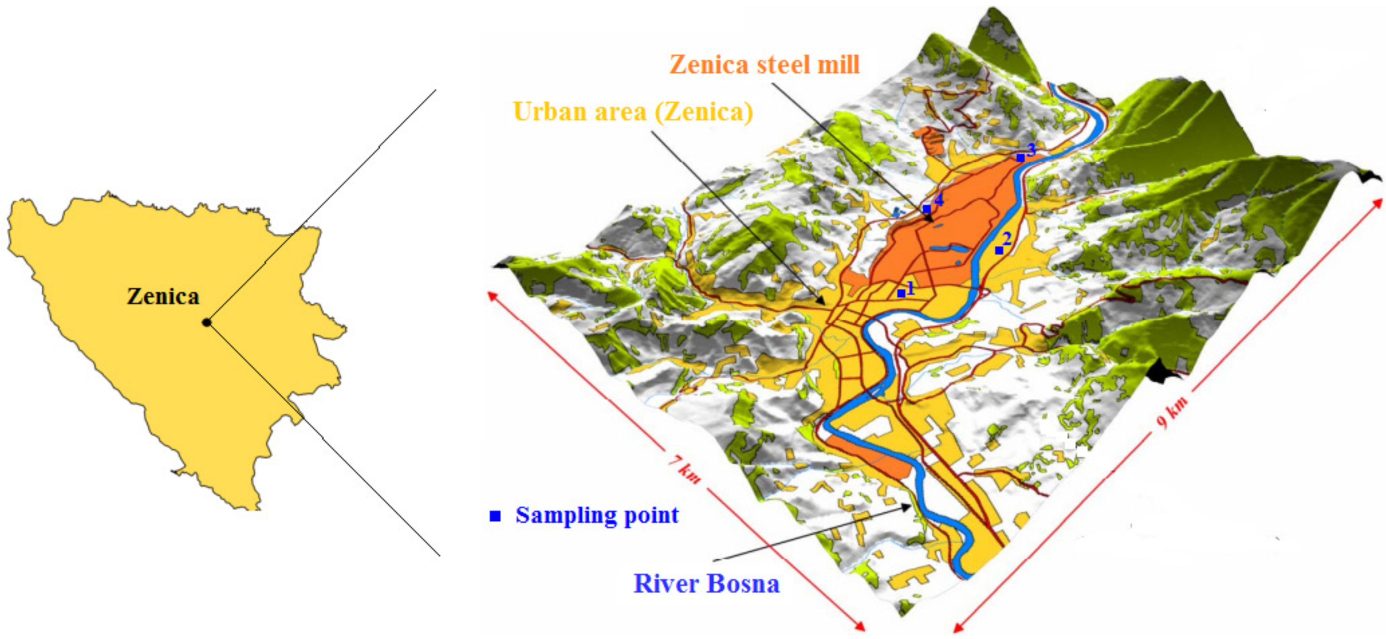

Figure 1. Location map of the study area and sampling points.

and mitigate environmental harm. To address this issue, a variety of remediation methods have been developed and implemented, including both biological and physicochemical techniques. However, physicochemical approaches, such as filtration, coagulation, adsorption, solvent extraction, and chemical precipitation, are often expensive, impractical for large-scale use, and may adversely impact soil biological activity and fertility. In contrast, biological methods provide accessible, cost-effective, and environmentally friendly alternatives, making them viable and sustainable options for remediating heavy metal-contaminated soils (Lin et al. 2022).

Biological techniques use the natural properties of microorganisms, plants and biopolymers to remove heavy metals from contaminated soil. Among these, phytoextraction is one of the most commonly employed methods. Phytoextraction involves the uptake and accumulation of heavy metals from soil or other substrates by plants. This technique offers significant advantages over traditional remediation methods, especially in terms of cost-effectiveness and efficiency (Bosiacki et al. 2013).

Ideal plant species for phytoextraction should exhibit high metal tolerance, a short life cycle, substantial biomass production, and a strong capacity for heavy metal uptake. Several studies have shown that certain edible crops, such as sunflowers, maize, rapeseed, and soybeans, effectively remove various heavy metals from contaminated soil (Ali et al. 2018, Kniuipytė et al. 2023). However, the use of edible crops for phytoextraction is not advisable, as the accumulated heavy metals can enter the food chain and pose health risks. In contrast, ornamental plants, which are primarily inedible, represent a valuable group of higher plants that could be employed to remediate heavy metal-contaminated soils. Despite their potential, the use of ornamental plants in phytoremediation has been relatively underexplored, and the effects of heavy metals on these plants remain insufficiently studied. Identifying ornamental plants capable of tolerating and accumulating high levels of heavy metals is essential for effectively cleaning up contaminated soil and supporting sustainable ecosystems, particularly in industrial areas. To date, limited research has been conducted in Bosnia and Herzegovina regarding the phytoremediation potential of ornamental plants, particularly in soils surrounding steel mills.

This study aims to evaluate the effectiveness of four ornamental plants in removing heavy metals from polluted soil near the Zenica Steel Mill in Bosnia and Herzegovina. The selected species - blue mink (*Ageratum houstonianum* Mill.), marigold (*Tagetes erecta* L.), impatiens (*Impatiens walleriana* Hook. f.), and begonia (*Begonia semperflorens* - Cultorum Group) - are not only aesthetically appealing but also exhibit rapid growth, short life cycles, and high biomass production. These traits make them particularly promising candidates for phytoremediation, with the potential to contribute significantly to environmental restoration and sustainability.

Material and methods

Study area and experimental design

The Zenica steel mill is located in the Bosnia River Valley, within the city of Zenica (coordinates: 44°13′8″ N, 17°53′16″ E). The steel mill occupies a total area of 291.56 hectares. It is bordered to the east by the Bosnia River, to the south by the city itself, and to the northwest and west by the regional road Zenica-Nemila.

For the purposes of this study, four composite soil samples were collected from each side of the Zenica steel mill on April 10, 2024 (Figure 1). The sampling sites were selected using a grid system with approximately equal spacing (1 km). Soil samples were taken from a depth of 0 to 30 cm using a stainless steel shovel. All samples had a predominantly loamy texture. Approximately 60 kilograms of soil were collected from each sampling point, placed in plastic bags, and transported to the experimental station of the Faculty of Agriculture and Food Sciences in Sarajevo.

Following transportation, the soil samples were passed through a 6 mm sieve to remove large fragments and were then

Figure 2. Bags containing ornamental plants growing in heavy metal-contaminated soils.

used as potting media in a pot experiment. Prior to initiating the experiment, basic chemical parameters, including the total content of heavy metals, were determined for all soil samples.

A pot experiment was carried out under greenhouse conditions in order to evaluate the ability of four selected ornamental plants to remove heavy metals from the studied soils. Blue mink, marigold, impatiens and begonia seedlings used in this study were sourced from the Garden center 'Flora' in Nedžarići and KJKP Park Sarajevo. The seedlings showed no significant differences in vigour, size and appearance. At the start of the experiment, all plants were in the pre-flowering stage.

On April 18, 2024, all investigated ornamental plants were transplanted into black plant grow bags (24 cm x 24 cm x 40 cm), with one plant per bag. The bags had been previously filled with soil collected from the area surrounding the Zenica steel mill. One day prior to filling, the soils were moistened using municipal water to enhance compaction and then thoroughly mixed. Sixteen grow bags were prepared for each plant species (four plants per soil samples), resulting in a total of 64 grow bags. Air circulation in the greenhouse was maintained by opening the roof vents and main door in the day, while a green shade cloth was used to reduce light and heat intensity on hot days. Daytime temperature in the greenhouse ranged from 18 to 27 °C , and nighttime temperatures from 15 to 22 °C , with relative humidity between 60 and 85%. The main activity during the experiment involved monitoring the growth and development of plants under study (Figure 2).

After three months of growth under these conditions, the experiment was concluded. The plants were harvested and separated into underground and aerial parts. The plant material was oven-dried at 60 °C to a constant weight, pulverized with an electric blender, and stored in paper bags until analysis.

Soil chemical analysis

Soil samples, each weighing approximately 500 g, were prepared for chemical analysis by air-drying and sieving through a 2 mm mesh. Soil pH was determined in both H_2O and 1 M KCl solution (soil-to-solution ratio of 1:2.5) using a pH meter (ISO 10390, 2021). Organic matter content and available forms of phosphorus and potassium were estimated using the potassium dichromate redox method (ISO 14235, 1998) and ammonium lactate (AL) method (Egnér et al. 1960), respectively. Heavy metals were extracted from the soil sing aqua regia solution (a 3:1 mixture of HCl and HNO_3) following ISO 11466, 1995.

Heavy metal analysis in plant samples

A mixture of HNO_3 and H_2SO_4 in a ratio of 2.5:1 was used for the extraction of heavy metals from plant samples (Lisjak et al. 2019). Briefly, 1g of dry plant material was weighed in an Erlenmeyer flask, followed by addition of 10 ml of HNO_3 and 4 ml of H_2SO_4. The mixture was left to stand for 6 hours in a fume hood. It was then gently boiled on a hot plate under reflux for 2 hours . After cooling to room temperature, the solution was filtered through quantitative filter paper (Whatman No. 42) into a 25 ml volumetric flask, and the final volume was adjusted with deionized water.

Determination of heavy metals in soil and plant samples

The concentrations of heavy metals (Cu, Zn, Pb, Cd, Cr, Mn and Fe) in soil and plant samples were determined using atomic absorption spectrophotometry (ISO 11047, 1998) with a Shimadzu AA-7000 instrument (Shimadzu Instruments, Tokio, Japan). Working standard solutions of the analyzed heavy metals were prepared by diluting certified stock solutions (Merck, Darmstadt, Germany) with deionized water as necessary.

Bioaccumulation factor

The bioaccumulation factor (BAF) refers to the ability of a plant species to absorb heavy metals from its environment and was calculated using the following equation:

$$BAF = \frac{C_{\ plant}}{C_{\ soil}}$$

Where C plant and C soil represent the concentration of heavy metal in the harvestable aboveground or belowground plant material and the corresponding soil, respectively. BAF values greater than 1 indicate a potential heavy metal hyperaccumulator plant species (Ramírez et al. 2021).

Translocation factor

The translocation factor (TF) refers to the ability of a plant species to translocate heavy metals from the roots to the aboveground parts and was calculated using the following equation (Bonanno et al. 2018):

$$TF = \frac{C_{\ aboveground\ parts}}{C_{\ belowground\ parts}}$$

C aboveground and C belowground represent the concentrations of heavy metals in the aboveground and

Table 1. Chemical properties of the studied soils

Parameter	Measure value	Soil 1	Soil 2	Soil 3	Soil 4
pH H_2O	range 1 - 14	8.2	7.8	7.5	7.7
pH KCl	range 1 - 14	7.7	7.4	7.1	7.2
Organic matter	%	5.1	2.9	3.1	3.0
Available P (P_2O_5)	mg/100 g	1.9	1.3	1.9	1.2
Available K (K_2O)	mg/100 g	13.9	11.1	11.7	9.3
Cu	mg/kg	33.2	52.4	44.8	54.2
Zn	mg/kg	389.6	251.6	244.1	257.2
Pb	mg/kg	242.9	450.3	397.1	404.2
Cd	mg/kg	1.3	2.3	1.4	1.2
Cr	mg/kg	33.6	77.5	63.2	72.2
Mn	mg/kg	2628.4	2976.1	3003.1	2878.5
Fe	mg/kg	13793.1	15076.2	14778.5	15123.1

belowground plant material, respectively. A TF value greater than 1 is a key indicator for classifying plant species as suitable for phytoextraction (Alghamdi and El-Zohri 2024).

Statistical analysis

The data were analyzed using One-Way Analysis of Variance (ANOVA), and the means were compared using the Least Significance Difference (LSD) test, with $P < 0.05$ as the threshold for statistical significance.

Results

The basic chemical properties and total concentrations of Cu, Zn, Pb, Cd, Cr, Mn, and Fe in the soil samples collected near the Zenica steel mill are presented in Table 1.

The results revealed that the investigated soil samples were neutral to alkaline in reaction, medium in organic matter content, and relatively low in available phosphorus and potassium. The only exception was soil sample 1, which exhibited a high organic matter concentration. The chemical analysis of the soils also revealed that the concentrations of Zn, Cd and Pb in all soil samples greatly exceeded the limits established by legislation in Bosnia and Herzegovina (Official Gazette of FBiH, 2009), indicating that the soils in the vicinity of Zenica steel mill are heavily polluted with these heavy metals. According to national legislation of Bosnia and Herzegovina, the maximum permissible concentrations for Cu, Zn, Pb, Cd and Cr in soils are 40, 200, 100, 1 and 100 mg/kg, respectively. Limit values of Fe and Mn for soils are not defined by legislation, because they are not considered direct contaminants . However, the Mn and Fe concentrations in the tested soil samples were much higher than the average values reported in the scientific literature. According to Kabata-Pendias and Pendias (2001), average concentrations of Mn and Fe in soils range from 500 to 900 mg/kg for Mn and from 6,000 to 12,000 mg/kg for Fe. The ranking order of mean heavy metal concentrations in the soil samples from the area of Zenica steel mill followed the sequence: Fe > Mn > Pb > Zn > Cr > Cu > Cd.

The concentrations of various heavy metals (Cu, Zn, Pb, Cd, Cr, Mn and Fe) in the aboveground and underground parts of studied ornamental plants are presented in Tables 2 and 3.

The data indicated that the heavy metal content in the aboveground parts of ornamental plants varied. Blue mink exhibited the highest tendency to absorb Cu, Pb, Cr, and Fe from the tested soil. In contrast, the aboveground parts of begonia contained the highest concentrations of Zn and Cd, regardless of the soil in which they were grown. Additionally, the highest Mn content was observed in marigold plants.

The results indicated differences in the ability of the tested ornamental plants to accumulate heavy metals in their roots. Begonia roots exhibited the highest levels of all the studied heavy metals. Additionally, the contents of Cd, Cr, Pb and Mn in blue mink roots were higher than those found in impatiens and marigold, regardless of the soil in which they were grown. In contrast, the Fe content in impatiens roots was significantly higher than that in the marigold and blue mink. Furthermore, there were no significant differences in Cu and Zn contents among the roots of blue mink, impatiens and marigold plants. The bioaccumulation factor (BAF) values for the heavy metals investigated are given in Table 4.

In this study, the highest BAF value was observed for Cd, while the lowest was recorded for Fe. The overall trend in BAF values for the analyzed ornamental plants followed the order: Cd> Cu>Zn>Mn>Cr>Pb>Fe. Furthermore, blue mink plants exhibited a pronounced bioaccumulation potential for Cu, Pb, Cr, and Fe compared to marigold, impatiens and begonia plants. Conversely, begonia plants showed the highest BAF values for Cd and Zn.

Table 2. Heavy metal contents in the aboveground parts of ornamental plants

Soil	Plant species	Heavy metal contents in the aboveground parts (mg/kg dry mass)						
		Cu	Zn	Pb	Cd	Cr	Mn	Fe
Soil 1	Blue mink	10.1 ± 0.8^{a}	31.2 ± 5.1^{b}	6.2 ± 2.5^{a}	0.7 ± 0.3^{b}	2.1 ± 0.4^{a}	164.2 ± 13.3^{c}	314.2 ± 51.8^{a}
	Marigold	8.3 ± 1.1^{b}	30.9 ± 5.6^{b}	3.5 ± 1.2^{bc}	0.3 ± 0.3^{c}	1.6 ± 0.4^{b}	252.4 ± 15.5^{a}	123.1 ± 13.1^{b}
	Impatiens	8.8 ± 0.9^{b}	28.2 ± 7.2^{b}	2.6 ± 0.8^{cd}	0.4 ± 0.2^{c}	0.9 ± 0.9^{c}	138.1 ± 11.3^{d}	111.4 ± 12.2^{b}
	Begonia	8.9 ± 0.7^{b}	46.7 ± 4.9^{a}	4.4 ± 1.9^{b}	1.0 ± 0.3^{a}	1.0 ± 0.2^{c}	212.7 ± 17.9^{b}	87.4 ± 14.8^{c}
	$LSD_{0.05}$	1.72	5.07	1.37	0.22	0.44	16.58	21.67
Soil 2	Blue mink	13.0 ± 1.9	26.6 ± 3.8^{b}	6.1 ± 1.9^{a}	0.8 ± 0.3^{b}	2.8 ± 0.7^{a}	165.1 ± 28.2^{b}	318.1 ± 56.1^{a}
	Marigold	12.3 ± 2.9	24.8 ± 2.7^{b}	3.8 ± 1.4^{b}	0.5 ± 0.2^{c}	1.7 ± 0.4^{b}	244.6 ± 45.1^{a}	130.9 ± 45.7^{b}
	Impatiens	11.9 ± 2.1	23.7 ± 3.1^{b}	3.6 ± 1.5^{b}	0.5 ± 0.2^{c}	1.2 ± 0.4^{c}	141.7 ± 15.1^{b}	118.1 ± 23.1^{b}
	Begonia	12.4 ± 2.5	40.3 ± 6.2^{a}	5.1 ± 1.8^{a}	1.1 ± 0.2^{a}	1.2 ± 0.3^{v}	214.1 ± 31.9^{a}	82.3 ± 13.8^{c}
	$LSD_{0.05}$	-	3.25	1.28	0.17	0.37	30.87	31.58
Soil 3	Blue mink	13.6 ± 2.3	25.9 ± 2.9^{b}	6.5 ± 1.2^{a}	0.6 ± 0.2^{b}	2.8 ± 0.6^{a}	158.8 ± 23.7^{c}	326.5 ± 31.6^{a}
	Marigold	12.8 ± 1.4	24.9 ± 2.8^{b}	4.6 ± 1.6^{b}	0.4 ± 0.2^{b}	1.8 ± 0.4^{b}	254.6 ± 36.9^{a}	126.2 ± 9.1^{b}
	Impatiens	12.3 ± 1.4	23.8 ± 3.3^{b}	4.6 ± 1.8^{b}	0.4 ± 0.3^{b}	1.1 ± 0.6^{c}	145.9 ± 24.7^{c}	126.1 ± 17.1^{b}
	Begonia	12.8 ± 1.7	38.6 ± 2.9^{a}	4.9 ± 1.2^{b}	1.0 ± 0.3^{a}	0.9 ± 0.4^{c}	215.4 ± 32.8^{b}	90.7 ± 20.1^{c}
	$LSD_{0.05}$	-	2.63	1.22	0.27	0.41	25.58	15.81
Soil 4	Blue mink	13.2 ± 1.9	25.7 ± 2.2^{b}	6.3 ± 0.8	0.7 ± 0.2^{b}	2.5 ± 0.7^{a}	148.4 ± 15.2^{c}	311.7 ± 36.3^{a}
	Marigold	12.6 ± 2.0	25.4 ± 2.7^{b}	4.5 ± 2.1	0.4 ± 0.2^{c}	2.1 ± 0.4^{a}	248.4 ± 15.1^{a}	128.4 ± 26.9^{b}
	Impatiens	12.3 ± 1.4	24.8 ± 3.0^{b}	4.7 ± 1.1	0.5 ± 0.1^{c}	1.6 ± 0.8^{b}	137.6 ± 17.9^{c}	125.6 ± 16.7^{b}
	Begonia	12.3 ± 2.1	39.2 ± 5.3^{a}	5.4 ± 0.8	0.9 ± 0.3^{a}	1.0 ± 0.4^{b}	207.4 ± 17.2^{b}	86.4 ± 11.1^{c}
	$LSD_{0.05}$	-	3.12	-	0.18	0.42	14.48	19.39

*Averages with the same letter in the same column are not significantly different ($P < 0.05$)

Table 3. Heavy metal contents in the roots of ornamental plants

Soil	Plant species	Heavy metal contents in the roots (mg/kg dry mass)						
		Cu	Zn	Pb	Cd	Cr	Mn	Fe
Soil 1	Blue mink	11.4 ± 1.3^{b}	23.8 ± 7.1^{c}	7.0 ± 2.0^{b}	0.9 ± 0.4^{a}	4.5 ± 1.3^{b}	47.5 ± 12.4^{b}	335.1 ± 48.1^{c}
	Marigold	12.0 ± 2.0^{b}	27.1 ± 4.1^{b}	4.2 ± 2.2^{c}	0.7 ± 0.3^{b}	3.6 ± 1.7^{c}	30.8 ± 8.1^{c}	334.9 ± 41.2^{c}
	Impatiens	11.1 ± 1.1^{b}	24.3 ± 6.2^{c}	5.0 ± 2.1^{bc}	0.5 ± 0.5^{bc}	4.1 ± 1.8^{bc}	32.3 ± 7.1^{c}	375.2 ± 24.4^{b}
	Begonia	20.2 ± 8.7^{a}	62.6 ± 5.8^{a}	16.4 ± 4.5^{a}	0.9 ± 0.3^{a}	5.9 ± 1.7^{a}	64.5 ± 14.1^{a}	764.7 ± 61.9^{a}
	$LSD_{0.05}$	3.45	4.79	2.21	0.32	1.31	9.23	36.3
Soil 2	Blue mink	14.8 ± 2.4^{b}	21.7 ± 3.1^{b}	6.6 ± 1.3^{b}	1.2 ± 0.2^{b}	5.4 ± 1.1^{b}	53.4 ± 20.1^{b}	339.9 ± 34.5^{c}
	Marigold	14.5 ± 1.4^{b}	22.7 ± 3.8^{b}	5.2 ± 2.6^{c}	0.8 ± 0.3^{c}	4.1 ± 1.5^{c}	32.4 ± 15.2^{c}	343.5 ± 30.4^{c}
	Impatiens	14.1 ± 1.5^{b}	22.4 ± 3.9^{b}	6.2 ± 1.8^{bc}	0.8 ± 0.3^{c}	4.5 ± 2.3^{bc}	34.1 ± 11.2^{c}	396.1 ± 25.2^{b}
	Begonia	16.6 ± 3.6^{a}	49.1 ± 3.2^{a}	19.4 ± 4.0^{a}	1.5 ± 0.2^{a}	6.6 ± 0.9^{a}	66.6 ± 11.9^{a}	854.8 ± 93.2^{a}
	$LSD_{0.05}$	1.2	2.78	0.66	0.24	1.11	12.56	9.03
Soil 3	Blue mink	14.5 ± 2.4^{b}	24.7 ± 3.0^{b}	6.1 ± 1.2^{b}	0.9 ± 0.3^{a}	4.7 ± 1.2^{b}	51.1 ± 16.1^{b}	332.5 ± 19.1^{c}
	Marigold	14.2 ± 2.4^{b}	25.0 ± 3.1^{b}	5.8 ± 1.4^{b}	0.6 ± 0.2^{b}	3.2 ± 2.5^{c}	31.4 ± 13.2^{c}	333.1 ± 16.2^{c}
	Impatiens	13.7 ± 2.1^{b}	23.2 ± 3.5^{b}	5.9 ± 1.8^{b}	0.6 ± 0.2^{b}	3.9 ± 1.6^{bc}	36.6 ± 8.8^{c}	390.6 ± 31.5^{b}
	Begonia	16.2 ± 2.3^{a}	47.5 ± 5.4^{a}	18.5 ± 3.6^{a}	1.0 ± 0.3^{a}	6.0 ± 1.9^{a}	68.7 ± 11.1^{a}	823.4 ± 40.3^{a}
	$LSD_{0.05}$	1.73	3.04	1.73	0.21	1.21	11.22	23.62
Soil 4	Blue mink	14.6 ± 2.3^{b}	23.1 ± 3.1^{b}	6.7 ± 3.1^{b}	0.9 ± 0.2^{a}	4.5 ± 2.6^{b}	48.7 ± 10.2^{b}	329.3 ± 35.1^{b}
	Marigold	14.6 ± 2.0^{b}	26.1 ± 3.2^{b}	5.6 ± 2.6^{b}	0.6 ± 0.1^{b}	3.3 ± 1.1^{b}	38.0 ± 13.1^{c}	330.6 ± 27.2^{b}
	Impatiens	14.4 ± 1.3^{b}	24.1 ± 3.1^{b}	5.6 ± 4.1^{b}	0.5 ± 0.2^{b}	3.3 ± 1.0^{b}	37.3 ± 11.6^{c}	387.4 ± 39.7^{b}
	Begonia	17.5 ± 3.1^{a}	48.3 ± 5.3^{a}	18.5 ± 1.9^{a}	1.0 ± 0.2^{a}	5.9 ± 2.3^{a}	67.0 ± 9.9^{a}	821.0 ± 102.1^{a}
	$LSD_{0.05}$	1.82	9.29	3.48	0.16	1.36	9.18	60.68

*Averages with the same letter in the same column are not significantly different ($P < 0.05$)

Table 4. Bioaccumulation factor (BAF) of selected heavy metals in tested ornamental plants

Plant species	Bioaccumulation factor (BAF)						
	Cu	Zn	Pb	Cd	Cr	Mn	Fe
Blue mink	0.275	0.098	0.018	0.474	0.044	0.055	0.017
Marigold	0.201	0.094	0.011	0.267	0.032	0.087	0.009
Impatiens	0.249	0.091	0.011	0.307	0.021	0.049	0.008
Begonia	0.255	0.148	0.014	0.723	0.018	0.074	0.006

Table 5. Translocation factor (TF) value for the selected heavy metals in ornamental plants

Plant species	Translocation factor (TF)						
	Cu	Zn	Pb	Cd	Cr	Mn	Fe
Blue mink	0.902	1.173	0.951	0.718	0.534	3.172	0.945
Marigold	0.828	1.054	0.788	0.593	0.522	7.543	0.379
Impatiens	0.850	1.076	0.683	0.750	0.304	3.842	0.311
Begonia	0.641	0.794	0.272	0.901	0.168	2.386	0.107

Translocation factor (TF) values for the investigated heavy metals are presented in Table 5.

The translocation factors (TFs) determined for the selected heavy metals in all examined ornamental plants were highest for Mn, followed by Zn and Pb. Begonia recorded the lowest mean TF value for all selected heavy metals, except Cd, indicating its ability to effectively restrict the translocation of heavy metals from roots to aerial parts.

Discussion

The findings of this study reveal that soils adjacent to the Zenica steel mill are heavily contaminated with Zn, Cd, and Pb, and also contain notable levels of Mn and Fe. Despite the elevated concentrations of these heavy metals , the growth and development of blue mink, marigold, begonia, and impatiens were not adversely impacted. This suggests that these plants are capable of thriving in the contaminated soils surrounding the Zenica steel mill. From an ecological perspective, this is highly valuable, as ornamental plants significantly enhance the aesthetic quality of environments, particularly in industrial areas and urban traffic zones.

In this study, the levels of heavy metals absorbed by blue mink, marigold, begonia and impatiens were considerably lower than the thresholds required to classify these species as potential hyperaccumulators – plants characterized by a high capacity to uptake and accumulate one or more heavy metals. According to Verbruggen et al. (2009), a plant can be considered suitable for phytoextraction if the concentration of heavy metals in its harvestable parts reaches at least 1% for Zn, 0.1% for Cr, Cu and Pb, and 0.01% for Cd. However, the concentrations of these heavy metals in the studied ornamental plants were far from satisfying these criteria. Moreover, with the exception of Cr and Mn, the detected levels of heavy metals were either below or within the standard concentration ranges reported for plants. The standard ranges for Cu, Zn, Pb, Cd, Cr, Mn and Fe in plants are 5-20 mg/kg, 20-100 mg/kg, 0.5-30 mg/kg, 0.1-2.4 mg/kg, 0.1-1 mg/kg, 15-150 mg/kg and 20-250 mg/kg, respectively (Kastori et al. 1997).

The bioaccumulation factor (BAF) and translocation factor (TF) are important indicators for evaluating the suitability of plant species for phytoextraction. Generally, plants with BAF and TF values greater than one are considered effective for this purpose. However, in this study, the BAF values for all tested heavy metals were significantly below one, indicating that the ornamental plants examined have a limited capacity to remove heavy metals from soils in the vicinity of the Zenica steel mill. Similarly, TF values for all heavy metals in the examined plants, except for Zn and Mn, were also below one, further reinforcing the conclusion that these ornamental species are not effective in removing heavy metals from the investigated soils.

Notably, all ornamental plants tested exhibited TF values greater than one for Mn and Zn, suggesting a strong potential for the translocation of these elements from roots to the aboveground parts. This observation is consistent with findings from other studies, which have reported higher concentrations of Mn and Zn in the aboveground parts of plants compared to the roots (Kuang et al. 2022, Meng et al. 2023). These results are not unexpected, as both Mn and Zn are essential micronutrients. Manganese plays a significant role in numerous physiological processes, including photosynthesis and nitrogen assimilation (Schmidt and Husted 2019), while Zn is crucial for the activation of over 300 enzymes involved in vital biochemical pathways (Hamzah Saleem et al. 2022).

Many researchers concur that the uptake and accumulation of heavy metals in plants are strongly influenced by the physico-chemical properties of the soil. These properties include soil pH, organic matter content, clay content, cation exchange capacity, and the interactions, both antagonistic and synergistic, among heavy metal ions . Wan et al. (2024) emphasize that soil pH is a key factor governing the solubility and mobility of heavy metals in the soil, which in turns affects their uptake by plants. Generally, higher pH values (pH > 7) lead to reduced mobility and availability of heavy metals. In alkaline soils, heavy metal ions tend to bind with hydroxyl ions and carbonates, forming compounds with extremely low solubility, thereby further limiting their bioavailability to plants.

The analysis of the soil samples revealed that the high pH values significantly contributed to the low phytoextraction efficiency observed in the studied plants, as reflected by the bioconcentration factor (BAF) values. This finding supports the well-established concept that plants growing in alkaline soils typically do not accumulate substantial amounts of heavy metals, regardless of the level of soil contamination. Therefore, it is essential to carefully evaluate the necessity of implementing phytoremediation strategies in such soils.

Despite the limited ability of the tested ornamental plants to absorb heavy metals from the analyzed soils, the study revealed significant differences in their capacity to uptake and accumulate specific heavy metal ions . Among the ornamental species evaluated, blue mink demonstrated the highest ability to absorb Cu, Pb, Cr and Fe from the tested soils. Conversely, the highest concentrations of Zn and Cd were found in the aboveground parts of begonia, while marigold exhibited the highest Mn content. These findings strongly support the conclusion that the uptake and accumulation of heavy metals in plants are closely associated with their physiological characteristics.

This study also revealed that the concentration of hazardous heavy metals, such as Pb, Cr, and Cd, were higher in the roots compared to their aboveground parts, regardless of the plant species. In contrast, the concentrations of essential heavy metals, such as Mn and Zn, were higher in the aboveground parts of the plants. This finding suggests that plants have evolved various mechanisms to selectively absorb essential heavy metals and incorporate them into their metabolic pathways. At the same time, they possess the ability to limit the uptake or translocation of hazardous heavy metals from the roots to the leaves when those metals pose a threat. These findings align with the results from other studies in this field (Zhou et al. 2020, Ejaz et al. 2023).

Conclusions

The results of this study revealed that the soils surrounding the Zenica steel mill are heavily polluted with Zn, Cd and Pb, while also exhibiting high levels of Mn and Fe. Despite the elevated concentrations of these heavy metals, the growth and morphology of blue mink, marigold, begonia and impatiens were not adversely affected. This suggests that these plants can successfully thrive in the soils near the Zenica steel mill. However, all of the ornamental plants tested exhibited very low capabilities for heavy metal uptake from the investigated soils, indicating that they are not suitable for phytoextraction purposes in the studied area. This limited efficiency can be attributed to the high pH values of the soils, which notably impacted the phytoextraction efficiency observed in this study. These findings strengthen the argument that plants thriving in alkaline soils generally do not accumulate substantial amounts of heavy metals, regardless of the level of soil contamination. Therefore, it is crucial to evaluate the necessity of implementing phytoremediation measures in such soils.

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