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Accumulation of trace metals in vegetables from allotment gardens in the city of Wrocław, SW Poland

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Abstract

The study focuses on estimating the soil–vegetable relationship (beetroot, carrot, lettuce) for trace metals such as Zn, Cu, Pb, and Cd in allotment gardens within the city of Wrocław (Poland). Indicators related to the bioaccumulation factors in plant roots (BAF_r), shoots (BAF_s), as well as the translocation factor (TF) of the shoot/root have been evaluated. A total of 45 soil samples (0–25 cm depth), along with vegetable samples (both roots and leaves), were collected from seven allotment garden complexes placed in areas with historical industrial activity. Zinc (Zn) concentration levels in soil exceeded the permissible levels of 1000 mg kg^{-1} in two allotment garden complexes in Wrocław, ranging from 1138 to 1384 mg kg^{-1}. For cadmium, the soil concentration exceeded the permissible limit of 5 mg kg^{-1} only in one allotment garden complex, reaching 6.3 mg kg^{-1}. In the case of Cu and Pb, no contamination above permissible limits was found. For the vegetables, the bioaccumulation factors (BAF) in the roots and shoots varied significantly depending on the sites, plant species, and metal. The highest values were recorded in samples from areas with high soil contamination. The highest translocation factor (TF) values were observed for Zn in beetroot leaves, ranging from 0.43 to 5.15 depending on the allotment garden. These findings emphasize the potential health risks related to consuming vegetables grown in urban and post-industrial allotment gardens due to uptake of hazardous trace metals, especially cadmium (Cd). The study emphasizes the importance of carefully monitoring and managing urban gardening sites to ensure food safety.

1. Introduction

Soils in urban areas provide very different ecosystem services depending on the spatial structure of cities (Szolginia, 1981; Wejchert, 2024). In urban environments, soils contribute to a range of services related to food production, moisture regulation, recreational and cultural functions, making them essential for sustainable urban living (Godzina, 2015; Orzepowski et al., 2017; Boluspayeva et al., 2022; Oprea et al., 2022). According to numerous authors, urban green areas, including allotment gardens, parks, and squares, contribute significantly to the aesthetic value of a city. In Poland, the total area of allotment gardens is 40,000 ha (Mokras-Grabowska, 2020). These areas are under high anthropopressure, including the impact of factories, urban infrastructure, progressive air pollution and smog, or surface water and soil (Pierścionek, 2015; Pérez-Figueroa et al., 2023). As a consequence of industrial and urban development, pollutants may accumulate in the soils and thus pose an ecological risk. Vegetables grown in these areas can absorb pollutants from the soil and keep them in their shoots or roots parts (Singh et al., 2012). According to literary sources, different vegetable crops grown on heavy metal-contaminated soil showed marked differences in metal accumulation, uptake, and distribution patterns. Crop species also showed remarkable differences in metal concentration of various plant parts (Singh et al., 2012). Leafy vegetables such as spinach tend to accumulate higher levels of heavy metals compared to other types of vegetables (Zhou et al., 2016; Latif et al., 2018). Manganese, chromium, and iron content in spinach was found to exceed the thresholds set by WHO/FAO (Dydiv et al., 2023). The peas also showed a high accumulation of heavy metals, and the levels of cadmium exceeded acceptable standards (Li et al., 2022). Leafy vegetables accumulate more heavy metals, as roots and leaves of herbaceous plants retain higher concentrations of heavy metals than stems and fruits

Supplementary materials for this paper are available at: https://www.soilsa.com/SuppFile/209948/1/

(Manzoor et al., 2018). Based on metal accumulation in edible parts and whole plants, root vegetables, namely radish and carrot, registered lower accumulation of almost all heavy metals except zinc (Zn) in radish root (Crnković et al., 2006; Singh et al., 2012; Aloud et al., 2022). Potato and onion showed lower accumulation of zinc, copper, and higher accumulation of cadmium and nickel. Cauliflower and cabbage, however, showed greater accumulation of lead and nickel but less accumulation of copper and cadmium (Singh et al., 2012). Among fruit-type vegetables, pea, soybean, and cluster bean showed greater accumulation of Pb and Ni, and very little accumulation of Cd. Among different vegetables, cauliflower and cabbage recorded highest uptake of Zn, Pb and Ni, while mustard showed higher uptake of Zn and Cd (Singh et al., 2012). This can be further explained by the translocation factor, which expresses the mobility of trace metals and nutrients from the root, stem, and leaves (Deng et al., 2004). It is used to assess the level of metal uptake by plants (Latif et al., 2018). This index provides a useful means of the quantitative description of relative differences in the biological availability of metals to plants (Pachura et al., 2015).

The soil is the primary source of trace metals for plants, animals, and humans. Elevated levels of trace metals in the soil, mainly as a consequence of human activities, therefore pose a range of environmental and health risks. Contaminated urban soils pose a long-term risk of increased plant uptake and leaching of trace metals with potentially adverse implications for the wider environment, including human health. Arsenic, Cd, Hg, Pb, and Se are the most important in terms of the food chain contamination and ecotoxicity viewpoints (McLaughlin et al., 2003). Heavy metals are present in allotment garden soils, and their contamination levels can be ranked as follows: Zn > Pb > Cu > As > Hg > Cd (Crnković et al., 2006; Aloud et al., 2022). The long-term accumulation of these elements in soils can lead to their penetration into cultivated plants and then into the food chain, which poses a threat to human and animal health (Romero-Crespo et al., 2023). Factors affecting the mobility and bioavailability of these elements include: soil pH, organic matter content, clay mineral type, and hydrological conditions (Violante et al., 2010; Caporale and Violante., 2016).

The purpose of the research was to assess the level of local soil contamination with heavy metals, as well as to analyze the content of these elements in different parts of plants grown in allotment gardens. This study was carried out on the area of 7 allotment garden complexes in Wrocław, which were identified as being contaminated with trace metals. Alongside the soil analyses, three vegetable species were analyzed: carrots (*Daucus carota*), beetroot (*Beta vulgaris),* and lettuce (*Lactuca sativa).* This approach allowed for a comparison of the degree of accumulation and translocation of heavy metals between leafy and root vegetables.

2. Materials and methods

2.1. Study area and sampling

The soils of the complexes allotment gardens under study are subject to various forms of anthropopressure, and trace metals contamination originates from a variety of sources (Fig. 1): soils of the „Lepsze jutro" complex (number 1) were contaminated by various substances introduced into the soil, such as contaminated lime or compost. In the case of soils of the complex "Złocień" (number 2), the source of soil contamination may be old rubble and other materials that were used to fill in all the

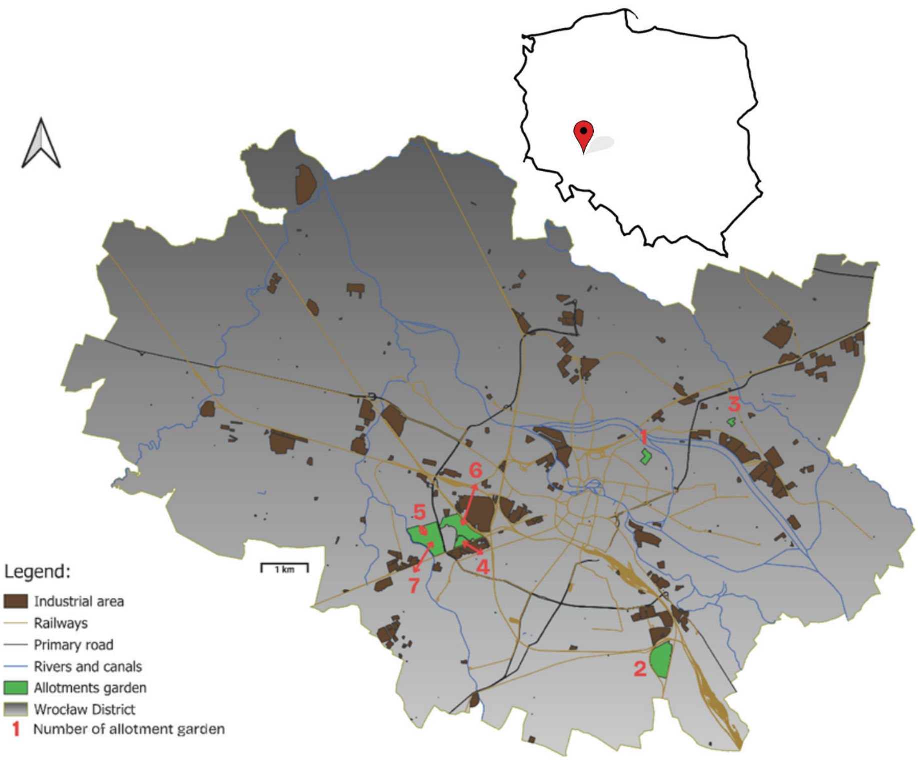

Fig. 1. Location of the studied allotment garden complexes. Note: 1 – Lepsze Jutro: soils contaminated by various substances such as contaminated lime and compost; 2 – Złocień: contamination possibly caused by old rubble and materials used to fill holes and depressions; 3 – Spółdzielca: contamination may be linked to past industrial activities in the area; 4 – Jarzębina: soils mainly polluted by emissions from the Hutmen metallurgical plant, 5 – Radość: soils polluted by emissions from the Hutmen metallurgical plant; 6 – Malina: soils polluted by emissions from the Hutmen metallurgical plant, 7 – Oświata: soils polluted by emissions from the Hutmen metallurgical plant

holes and depressions. Contamination of soils in "Spółdzielca" (number 3) may have been caused by industrial operations that took place in this area in the past. In the case of soils of allotment garden complexes: Jarzębina, Radość, Malina, Oświata (numbers 4–7 the main source of soil pollution was the former Hutmen metallurgical plant, emitting various pollutants, mainly copper (Cu).

A total of 45 soil and vegetable samples were collected from seven selected allotment garden complexes in Wrocław between July and August 2022 (Fig. 1, Sup. Tab. 1). Soil samples were taken from a depth of 0–25 cm. Each sample, weighing approximately 2–3 kg, was a composite collected from five randomly chosen locations within a single garden complex. Vegetables of one species were gathered from 3 to 4 plots within each complex (0.5 kg of biomass, 10 plants), from the same sites as the soil samples. The aboveground parts (shoots) were cut just above the crowns, while soil clumps with roots were transported to the laboratory, where roots were carefully separated from the soil.

2.2. Soil analysis

Soil samples were prepared for further analysis by air-drying and sieving through a sieve with a mesh size of 2 mm to remove the skeleton. All analyses were performed according to current soil science standards (Tan., 2005). In prepared soil samples, basic chemical and physicochemical properties of soils were determined, such as pH in distilled water and 1M KCl, the granulometric group was determined using the aerometric-sieve method and the guidelines of the Polish Society of Soil Science (PTG), total organic carbon (TOC), and total nitrogen (TN) were measured using a Vario Macro Cube CN analyzer (Elementar Analysensysteme GmbH, Langenselbold, DE). Soil pH was measured in a suspension in 1 M KCl (1:2.5; *v*/*v*). In order to assess soil contamination with trace metals, in accordance with the existing polish regulation, the land subgroup of the surveyed allotments was identified based on particle size distribution, pH, and clay fraction content. It was found that all sites belong to group II, subgroup II (in accordance with the Regulation of the Minister of Environment on how to conduct land surface pollution assessment dated 1 September 2016. Journal of Laws of Poland, Item 1395 (website 1).

Total trace metals concentrations were determined after soil digestion with *aqua regia* in a microwave system. One g of soil, ground to pass through a 0.25 mm sieve, was added to mineralization flasks, and then 10 ml of *aqua regia* was added (this is a mixture of concentrated hydrochloric and nitric acids in a 3:1 ratio). The samples prepared in this way were left overnight and then mineralization was applied in an open block. Initially lasting 3 hours at a temperature of 100°C, gradually increasing it to approx. 200°C. After mineralisation, the solutions were filtered. The concentrations of Zn, Cu, Pb, and Cd in the digests were determined by ICP-AES (iCAP 7400, Thermo Fisher Scientific, Waltham, MA, USA). All analyses were made in triplicate. The quality of determinations has been monitored using soil reference materials (sample ID: SRM 2709, SRM 2711, RTH 912, RTH 953) with certified total concentration "aqua-regia extractable" of trace metals being analyzed.

Based on geological data and measured heavy metal values, the enrichment factor of the tested soils was determined using the formula (Liao et al., 2021):

$$EF = \frac{heavy\ metal\ content\ in\ the\ soil}{geochemical\ background}$$

The geochemical background was determined based on the 1998 Geochemical Atlas of Wrocław and the Surrounding Area (Tomassi-Morawiec et al., 1998). The natural geochemical background was not considered because urban areas were transforming. According to (Rezapour et al., 2022), the enrichment factors can be interpreted as:

EF < 2 – minimum,
2 ≤ EF < 5 – moderate,
5 ≤ EF < 20 – significant/high
20 ≤ EF < 40 – very high
EF > 40 – extremely high

2.3. Vegetables analysis

The vegetables were washed thoroughly under distilled water to remove any soil or other substances. The underground part (root) was separated from the above-ground part (leaves) and then dried in a laboratory oven at 60°C. After drying, they were transferred to laboratory mills for grinding and then microwave mineralization was carried out. For this purpose, 0.10 g of each part of the vegetables was weighed, then 2 ml of perhydrol was added and the reactive mixture placed in the dryer again at 60°C. After drying, 10 ml of nitric acid (HNO_3) was added, left overnight and then microwave mineralization was carried out. After mineralization, the solutions were filtered and the Zn, Cu, Pb, and Cd were determined by ICP-AES (Sup Table 3). Analytical methods were validated with plant reference materials: BCR-414 and DC-7349.

The levels of contamination in the soils and vegetables were determined for each sample. Based on this data, the bioaccumulation factor was calculated according to the following formula:

$$BAFs = \frac{heavy\ metal\ content\ in\ the\ leaf}{heavy\ metal\ content\ in\ the\ soil}$$

$$BAFr = \frac{heavy\ metal\ content\ in\ the\ root}{heavy\ metal\ content\ in\ the\ soil}$$

Where:
BAF_s – bioaccumulation factor in the leaf
BAF_r – bioaccumulation factor in the root

According to (Gruca-Królikowska and Wacławek, 2006) the bioaccumulation factor can be divided into the following categories:

low (0.1–0.5) most often for: green beans or peas,
moderate (0.5–1.0), e.g. for cabbage or carrots,
strong (1.0–3.0), e.g. for radishes and leeks,
very strong (3.0–6.0), e.g. for spinach, lettuce or celery.

By calculating the individual bioaccumulation factors (BAF_r) and (BAF_s), it was possible to calculate the translocation factor according to the formula:

$$TF = \frac{BAFs}{BAFr}$$

Where:
TF – translocation factor
BAF_s – bioaccumulation factor in the leaf
BAF_r – bioaccumulation factor in the root

This coefficient, if TF ≤ 1, shows that there is a low ability to translocate heavy metals from the root to the above-ground parts. When this parameter is TF > 1, we say that the plant effectively transfers heavy metals to the above-ground parts, e.g. leaves (Alagić et al., 2013; Tong et al., 2022).

2.4. Statistical analysis

To assess the statistical significance of differences in the content of trace metals in the tested soils and vegetables (beetroot, carrots, and lettuce), as well as the plants' ability to accumulate and translocate pollutants, the non-parametric Kruskal–Wallis test was applied. This test was chosen due to the non-normal distribution of the data and heterogeneity of variances between groups, as confirmed by the Shapiro–Wilk and Levene's tests. The Kruskal–Wallis method is suitable for comparing more than two independent groups when the assumptions of parametric ANOVA are not met, which is often the case in environmental studies. Statistical analyses were performed using Statistica 13.3. In addition, principal component analysis (PCA) was performed using OriginPro software to identify patterns and visualize the variability of heavy metal concentrations (Pb, Cu, Cd, Zn) across the studied sites. This multivariate technique enabled the detection of correlations between variables and the grouping of samples based on their trace metal profiles

3. Results

3.1. Characteristics of examined soils

The results presented for the physical and chemical properties in selected allotment gardens show similarities (Table 1). Soils were classified as SCL (sandy clay loam – complex of gardens no.: 2,3,4,5,6), SL (sandy loam – complex of gardens no.: 2,7), LS (loamy sand – complex of gardens no.: 1,3) (according to USDA classification). The values of other parameters, such as pH (in distilled water and 1M KCl), are similar for the studies soils of allotment garden complexes. The pH of the tested soils in allotment gardens was similar, and it can be assumed that the content was close to neutral pH (Table 1). A neutral pH value may be the result of human activities, especially liming, undertaken within this type of land (based on interviews with garden owners). The highest hydrolytic acidity (average 17.1 cmol kg^{-1} was found in garden complex 3 (LS/SCL soil), while the lowest was found in garden complex 7 (SL soil), with an average of 14.1 cmol kg^{-1}. The C content varied between 2.1 and 5.9 g kg^{-1} and

Table 1
Selected average physicochemical properties of the examined soils

No of allotment garden complex	Granulometric group USDA	pH in H2O (min/max/ mean/±sd)	pH in 1M KCl (min/max/ mean/±sd)	TOC [g kg^{-1}] (min/max/ mean/±sd)	TN [g kg^{-1}] (min/max/ mean/±sd)	C/N (min/max/ mean/±sd)	Hydrolytic acidity [cmol kg^{-1}] (min/max/ mean/±sd)	Flatable fraction [%](min/max/ mean/±sd)	Fraction > 2 mm [%] (min/max/ mean/±sd)
1	LS	6.7/7.1 7.0±0.1	6.5/6.8 6.8±0.1	4.3/5.8 4.7±0.5	0.2/0.4 0.3±0.0	15.1/18.3 16.3±1.2	15.4/18.5 16.6±1.2	15.0/21.0 18.3±2.0	1.2/2.3 1.9±0.4
2	SL/SCL	6.7/7.4 7.0±0.2	6.5/7.1 6.8±0.2	2.1/3.7 2.9±0.6	0.1/0.3 0.2±0.1	13.6/17.8 14.7±1.2	13.8/17.9 14.9±1.2	11.0/26.0 19.2±5.6	0.5/6.0 2.2±2.1
3	LS/ SCL	6.7/7.4 7.2±0.2	6.7/7.1 6.9±0.1	2.5/5.9 4.1±1.4	0.1/0.4 0.2±0.1	15.2/19.1 16.9±1.1	15.4/19.2 17.1±1.1	12.0/32.0 24.9±5.8	0.2/9.0 2.4±2.5
4	SCL	7.9/8.1 8.0±0.1	7.1/7.3 7.2±0.1	3.8/4.1 3.9±0.2	0.2/0.3 0.3±0.1	12.5/18.4 15.7±3.0	12.8/18.6 16.0±2.9	21.0/23.0 22.0±1.0	6.7/8.4 7.3±1.0
5	SCL	7.0/7.6 7.3±0.5	6.9/7.1 7.0±0.1	3.7/4.2 4.0±0.3	0.2/0.3 0.2±0.0	14.8/17.0 15.9±1.6	15.0/17.2 16.1±1.5	24.0/25.0 24.5±0.7	3.0/4.4 3.7±1.0
6	SCL	6.9/8.0 7.6±0.3	6.2/7.2 6.9±0.3	2.9/3.9 3.5±0.3	0.2/0.3 0.2±0.0	13.0/17.5 15.6±1.5	13.3/17.7 15.9±1.5	22.0/33.0 27.1±3.5	1.3/7.1 3.5±1.7
7	SL	7.2/7.6 7.4±0.3	7.1/7.3 7.2±0.1	3.2/3.3 3.3±0.1	0.2/0.3 0.2±0.0	13.0/14.8 13.9±1.3	13.2/15.0 14.1±1.3	15.0/16.0 15.5±0.7	1.0/1.6 1.3±0.4

Note: According to the USDA classification, the abbreviations stand for: LS – (loamy sand), SL (sandy loam), SCL (sandy clay loam) (Soil Taxonomy, 1999). 1 – Lepsze Jutro: soils contaminated by various substances such as contaminated lime and compost; 2 – Złocień: contamination possibly caused by old rubble and materials used to fill holes and depressions; 3 – Spółdzielca: contamination may be linked to past industrial activities in the area; 4 – Jarzębina: soils mainly polluted by emissions from the Hutmen metallurgical plant;–5 – Radość: soils polluted by emissions from the Hutmen metallurgical plant; 6 – Malina: soils polluted by emissions from the Hutmen metallurgical plant; 7 – Oświata: soils polluted by emissions from the Hutmen metallurgical plant.

the N content between 0.1 and 0.4 g kg^{-1}. After analysing the soil samples collected from allotment gardens in Wrocław, it was found that these soils are rich in total organic carbon. This high content may be the result of horticultural practices employed by the gardeners (based on interviews with garden owners). The tested material is characterized by a low content of total nitrogen, as in all samples, its value does not exceed 1.0 %. The total organic carbon-to-nitrogen ratio in the tested soil samples was found to be in the range of 12.5 to 19.1. The varied C/N ratio in allotment garden soils may be related to the use of mineral fertilization (including nitrogen fertilization) and organic fertilization, which in turn will introduce significant amounts of total organic carbon into the soil.

3.2. Concentration of selected trace metals in investigated soils

The levels of heavy metal contamination in the soil depend on the location of the allotment gardens (Table 2). The highest levels of contamination and their greatest variation occur in the south-western area of Wrocław (allotment gardens complex no. 4, 5, 6, 7) (Sup Table 5). These are gardens located near the former Hutmen metallurgical plant (Map 1). The levels of contamination varied depending on the distance from the factory. High concentrations of Zn 1384 mg kg^{-1} and Cd 6.3 mg kg^{-1} were found in samples from garden complex no. 4, while in soils from garden complex no. 7 they were much lower Zn – 283 mg kg^{-1}, Cd – 1.4 kg^{-1}. In the other gardens, the levels of soil contamination were low, apart from the local Zn contamination in garden complex no. 2, where the Zn content was found to be at the level of 1138 mg kg^{-1}. The copper (Cu) content ranged from 25 to 232 mg kg^{-1}, while the zinc (Zn) content ranged from 101 to 1394 mg kg^{-1}, which also suggests a strong anthropogenic impact, including from the metallurgical and automotive industries.

The PCA (Principal Component Analysis) analysis confirms the trends presented, with the greatest variability in Zn contamination levels, followed by Cd, Cu, and Pb (Fig. 2). Zinc, related to the first ordination axis, explains most of the variability. The average values indicate elevated levels of contamination, especially in the soil from garden plot no. 4, where the highest concentrations of Zn (7.7), Cu (8.6), Pb (4.3), and Cd (0.9) were recorded. The highest enrichment factors were recorded for Zn, Cu, Pb and Cd in the soil of allotment garden complex no. 4 (Fig. 3). The soils show a certain degree of variation, as the minimum level (EF < 2) is only found in garden complex no. 3. Moderate

Table 2
Content of selected heavy metals in the dry mass of the soil samples

No of allotment garden complex	Zn [mg kg^{-1}] (min/max/mean/±sd)	Cu [mg kg^{-11}] (min/max/mean/±sd)	Pb [mg kg^{-11}] (min/max/mean/±sd)	Cd [mg kg^{-11}] (min/max/mean/±sd)
1	244/599/415±131	47/80/65±11	86/156/123±26	0.68/3.41/1.6±0.98
2	101/1138/382±335	28/72/41±13	24/78/43±17	0.62/2.35/1.1±0.52
3	117/269/186±48	25/60/41±13	20/69/35±16	0.78/1.16/0.95±0.11
4	1283/1384/1319±56	215/232/222±9	222/237/230±8	3.22/6.31/5.17±1.69
5	321/350/336±21	61/76/69±11	69/90/80±15	1.01/1.88/1.37±0.24
6	216/563/372±106	57/106/81±18	58/104/82±16	1.36/1.99/1.7±0.18
7	263/283/273±14	56/57/57±1	71/86/79±11	1.04/1.38/1.16±0.19

Note: 1 – Lepsze Jutro: soils contaminated by various substances such as contaminated lime and compost; 2 – Złocień: contamination possibly caused by old rubble and materials used to fill holes and depressions; 3 – Spółdzielca: contamination may be linked to past industrial activities in the area; 4 – Jarzębina: soils mainly polluted by emissions from the Hutmen metallurgical plant, 5 – Radość: soils polluted by emissions from the Hutmen metallurgical plant; 6 – Malina: soils polluted by emissions from the Hutmen metallurgical plant, 7 – Oświata: soils polluted by emissions from the Hutmen metallurgical plant.
The total heavy metal content was compared with Polish standards (website 1). The standard for the given group to which the soil is classified is: Zn –1000 mg kg^{-1}, Cu –300 mg kg^{-1}, Pb –500 mg kg^{-1}, Cd –5 mg kg^{-1}.

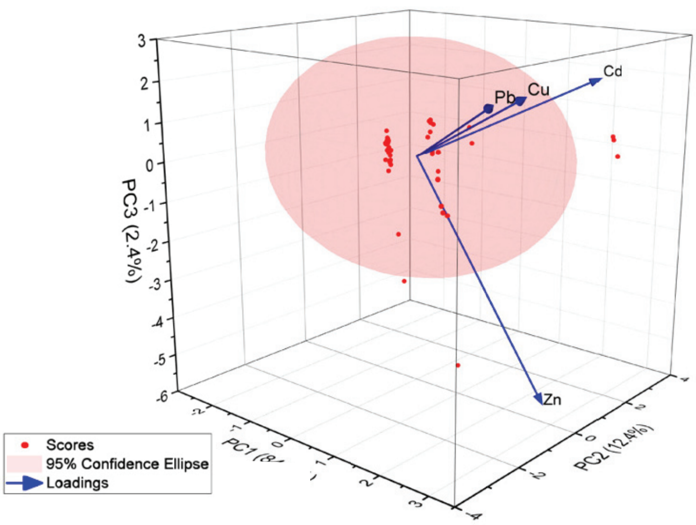

Fig. 2. Results of the PCA analysis showing variable concentrations of heavy metals (Pb, Cu, Cd, Zn) across the studied sites

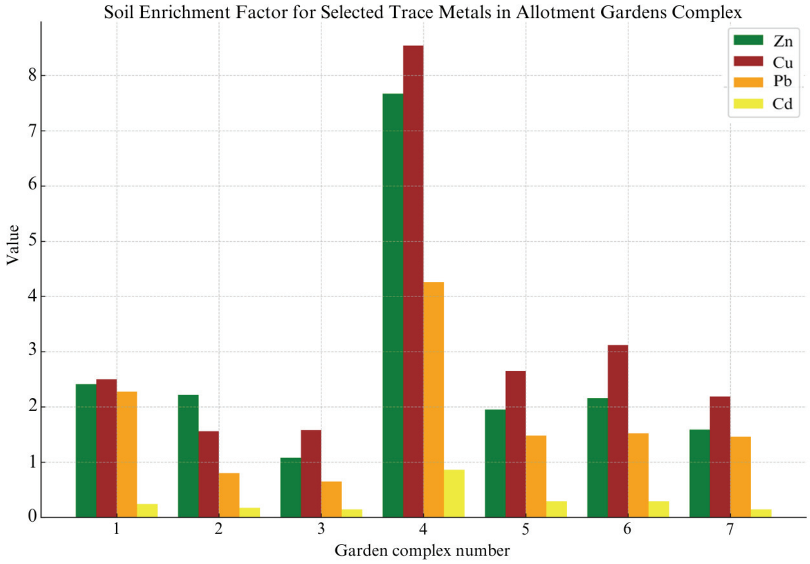

Fig. 3. Soil enrichment factors for selected heavy metals in seven complexes of allotment gardens. Note: 1 – Lepsze Jutro: soils contaminated by various substances such as contaminated lime and compost; 2 – Złocień: contamination possibly caused by old rubble and materials used to fill holes and depressions; 3 – Spółdzielca: contamination may be linked to past industrial activities in the area; 4 – Jarzębina: soils mainly polluted by emissions from the Hutmen plant, 5 – Radość: soils polluted emissions from the Hutmen metallurgical plant; 6 – Malina: soils polluted by emissions from the Hutmen metallurgical plant, 7 – Oświata: soils polluted by emissions from the Hutmen metallurgical plant

values (2 ≤ EF < 5) were observed in garden complex no. 1, 2, 5, 6 and 7, taking into account the element with the highest value. Allotment garden complex no. 4, on the other hand, shows the highest level of enrichment (5 ≤ EF < 20). These results indicate a variation in the level of heavy metal enrichment in the soil in urban allotment gardens. This relates to the impact of various anthropogenic factors on soils.

3.2. Bioaccumulation of selected trace metals in different parts of plants

In the tested vegetables, contamination with Zn, Cu and Pb was found (Fig. 4). In beetroot, Zn ranged from 28 to 133 mg kg^{-1}, in the root part and from 25 to 358 mg kg^{-1} in the shoots, in carrots from 14 to 84 mg kg^{-1} and from 23 to 147 mg kg^{-1} respectively, and in lettuce from 23 to 196 mg kg^{-1} in roots and from 24 to 95 mg kg $^{-1}$ in shoots. The Cu content in beetroot ranged from 11 to 34 mg kg^{-1} in the root part and from 10 to 35 mg kg^{-1} in the shoots, in carrots from 9 to 28 mg kg^{-1} and 9 to 27 mg kg^{-1}, while in lettuce it was 14 to 44 mg kg^{-1} in roots and 7 to 29 mg kg^{-1} in shoots (Fig. 4). The Pb content, recorded only in selected samples, in beet ranged from 1.7 to 5.2 mg kg^{-1} in the root part and from 3 to 6 mg kg^{-1} in the shoots, in carrots from 4 to 5 mg kg^{-1} and 2 to 8 mg kg^{-1} and in lettuce 2 to 8 mg kg^{-1} and 3 to mg kg^{-1}. The levels of contamination of the vegetables varied significantly for zinc (Fig. 4, Sup Table 6), with the highest content in the shoots of the beetroot and the lowest roots in the lower part of the carrot. In most cases, the amount of Cd present in the tested plants was very small below the detection threshold of the device. These results were compared with literature data (Sup Table 4).

The bioaccumulation factor in roots (BAF_r) and shoots (BAF_s) of lettuce, beetroot, and carrots varied depending on the sampling location (Sup Table 7). The most significant differences were observed for zinc (Zn) in beetroot from allotment garden complex no. 2, where BAF_s reached 2.25 and BAF_r was 0.4, and for copper (Cu) in beetroot from complex garden no. 3, with BAF_s at 1.20 and BAF_r at 1.04. In the case of lead (Pb), bioaccumulation values were relatively consistent across all vegetable types and locations, ranging from approximately 0.01 to 0.23 in both above-ground and underground parts. The lowest values of trace metals bioaccumulation were generally observed in vegetables from allotment gardens complex no. 4, while the highest were recorded in gardens complex no. 2 and 3 (Fig. 5, Sup Table 7). Among the studied species, lettuce demonstrated the highest capacity to accumulate copper, both in root and leaf tissues. Beetroot exhibited the greatest zinc accumulation in leaves, followed by copper in both roots and leaves. Carrots showed the highest copper concentrations in above-ground parts, with lower levels found in roots (Fig. 4, Sup Table 8). BAF and TF indices were not calculated for Cd because the content of this element in plants was below the detection limit for ICP-AES (Sup Table 3).

The highest translocation factor values were obtained for beetroot, reaching 5.15 for Zn, for carrots 3.92 for Zn (Fig. 6). For lettuce, this value was a maximum of 1.9 for the same element. In the case of carrots, the level of translocation was highest for Zinc in the leaf part (Sup Table 9, Sup Table 10). The translocation factor was not calculated for Cd due to the very low content of this element in plants, which made it impossible to determine using ICP-AES.

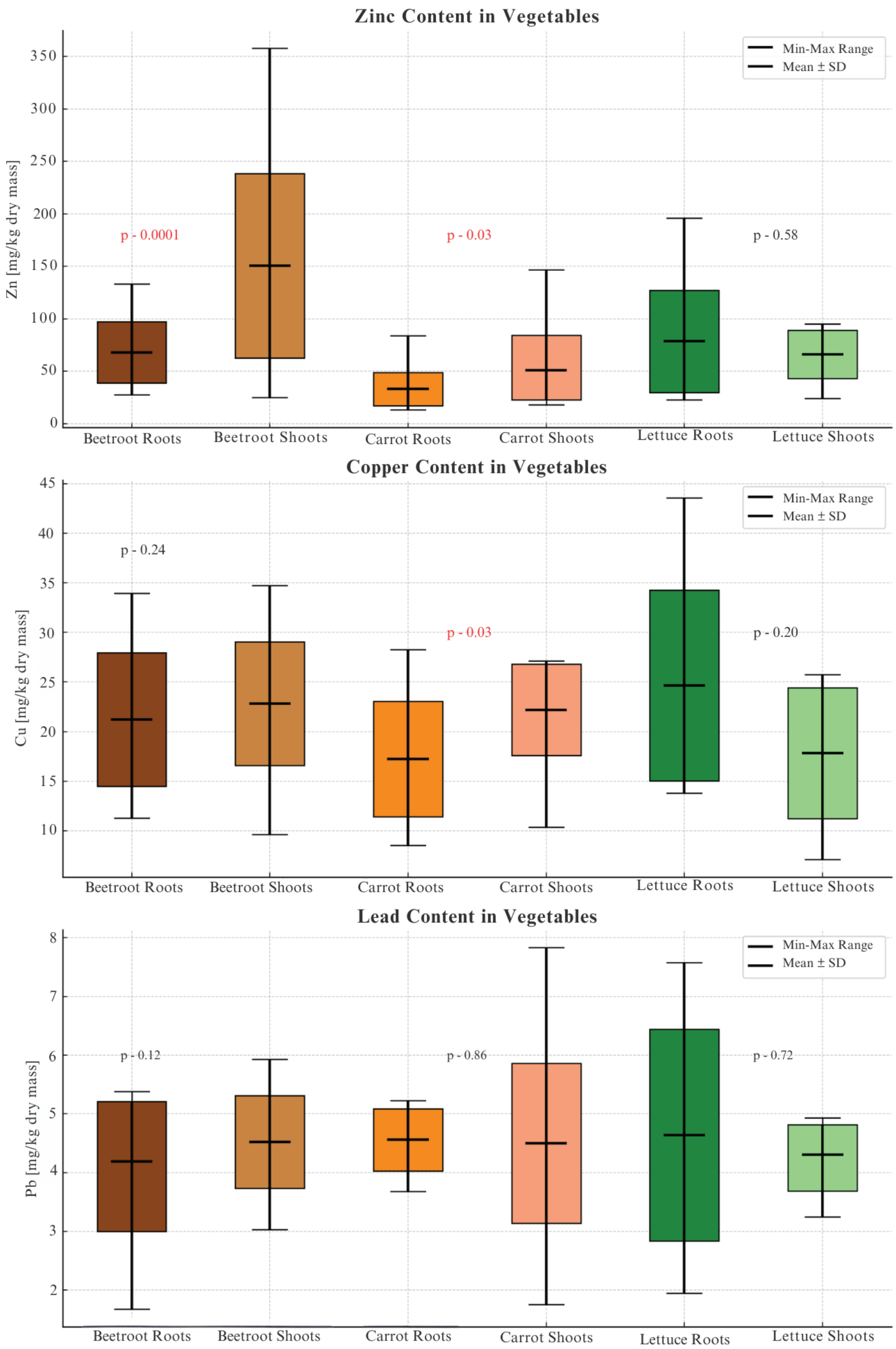

Fig. 4. Heavy metal content in selected vegetables in the examined complexes of allotment gardens

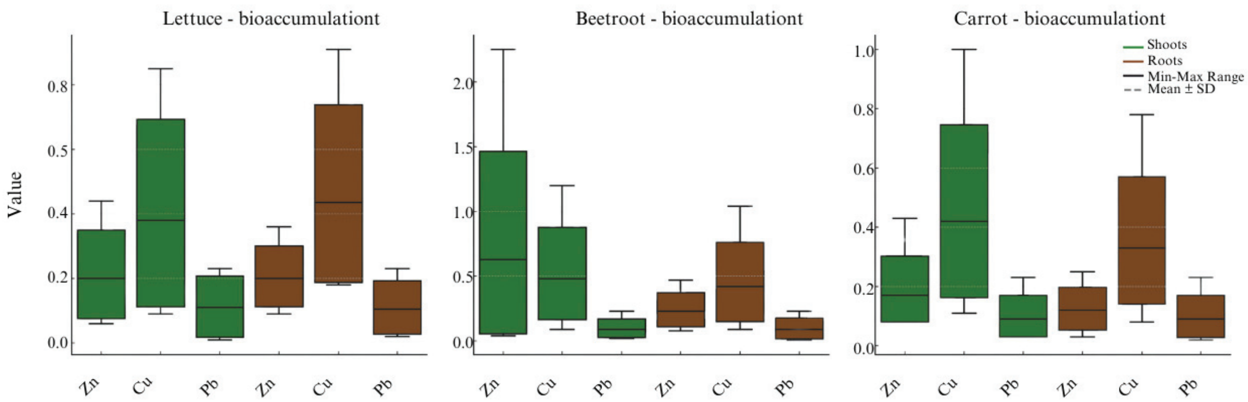

Fig. 5. Bioaccumulation factor (BAF) in shoots and roots parts in selected plants in selected allotment gardens in Wrocław

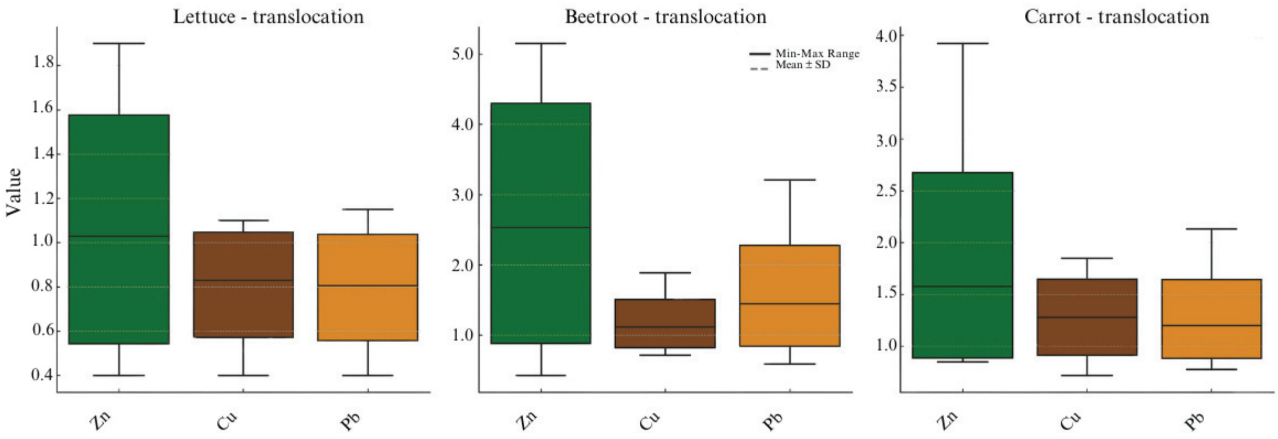

Fig. 6. Translocation coefficient in individual vegetables in selected allotment gardens in Wrocław

4. Discussion

Studies conducted in urban allotment gardens reveal significant local variations in soil contamination caused by multiple factors. Emissions from vehicles and industrial sources, as well as the use of construction materials and waste in landscaping, substantially contribute to heavy metal pollution in urban soils (Greinert, 2015). As cities expand, allotment gardens frequently become located within zones exposed to diverse sources of harmful substances, including cadmium (Cd), zinc (Zn), lead (Pb), copper (Cu), and arsenic (As) (Bidar et al., 2020). Consequently, vegetables grown in these gardens may accumulate toxic elements, posing potential health risks to consumers. Numerous studies confirm the transfer of such contaminants into the food chain through both the ingestion of contaminated soil and consumption of garden produce (El Hamiani, 2010, 2015; Tahir et al., 2022). Although risk assessments based solely on total soil metal concentrations may overestimate exposure because only a fraction of metals is bioavailable (Paltseva et al., 2020), evaluating metal transfer from soil to plants remains essential. The soil-plant system represents a primary route for human exposure to environmental heavy metals in agricultural and horticultural areas, informing land-use planning and garden management strategies, especially in urban recreational zones. However, urban gardeners often lack awareness and agency regarding potential contamination of their plots (Taylor et al., 2021).

Looking more broadly at urban areas in Europe, heavy metal contamination of soils is a widespread concern. In cities such as Wrocław (Poland), Antwerp (Belgium), and Naples (Italy), levels of Cd and Pb frequently exceed environmental standards. For example, in Wrocław, Cd concentrations reached 2.8 mg kg^{-1}, and Pb surpassed 300 mg kg^{-1} near industrial zones. Similarly, in Antwerp, Cu and Zn levels rose to 180 mg kg^{-1} and over 700 mg kg^{-1}, respectively, especially near petrochemical plants and older residential districts. These patterns are consistent with widespread contamination driven by industrial activities and urbanization across Europe and Asia (Tong et al., 2020). The spatial variability in contamination underlines the need for localized soil quality standards, particularly in areas affected by long-term industrial and transport emissions.

In Poland, contamination of garden soils by heavy metals is well-documented (Pająk and Jasik, 2010; Dziubanek et al., 2012; Qing et al., 2015; Doležalová Weissmannová et al., 2019; Gabiś, 2022; Tomczyk et al., 2023; Gruszka et al., 2024). In Wrocław, up to 35 % of surveyed allotments showed heavy metal contamination (Chodak et al., 2001). Our research aligns with these findings, indicating notable zinc contamination and moderate cadmium and lead presence. This pollution likely results from emissions of a metallurgical plant established in 1918, which produced copper pipes, bronze alloys, and other metals (Wojewódzki Inspektorat Ochrony Środowiska we Wrocławiu, 2013). Historical emissions from a 50-meter-high steel chimney (E-1) released pollutants such as Pb, Cd, Zn, Cu, NO_x, CO, and CO_2 into the atmosphere (Jackson and Alloway, 1991). Long-term industrial activity of this nature contributes to heavy metal accumulation in urban soils, presenting risks to ecosystems and human health (Pless-Mulloli et al., 2004; Le Guern et al., 2018).

Similar contamination issues have been reported in other European countries. For instance, in the Netherlands, cucumbers grown in allotment gardens contained elevated Cd and Pb levels surpassing those in adjacent agricultural areas (Prasad and Nazareth, 2000). In the UK, significant arsenic contamination has been documented in garden soils (Goni et al., 2025). These findings highlight the importance of ongoing monitoring in urban allotments (Sani and Abdulkadir, 2019). A notable contributor to elevated heavy metal levels, especially lead, in urban soils is the historical use of leaded gasoline (Guagliardi et al., 2015). This legacy pollution exacerbates the problem of contamination in garden soils, which remains a pressing issue across Europe, including Poland (Pająk and Jasik, 2010; Dziubanek et al., 2012; Qing et al., 2015; Doležalová et al., 2019; Gabiś, 2022; Tomczyk et al., 2023; Gruszka et al., 2024).

Contamination of garden soils can result in risk to consumer health which can be particularly serious; consumer exposure to lead after eating contaminated vegetables can be up to 10 times higher than the permissible daily limits (Mahakalkar et al., 2013). In our own studies, Zn, Cu and Pb contamination was found in all tested vegetables: beetroot, carrots and lettuce. Compared to the literature data (Sup Table 4), the heavy metal content in the tested vegetables was in many cases higher. The lead (Pb) levels in beetroot (root and leaf) and carrot (leaf) exceeded the values given in the literature, which indicates soil contamination. In the case of carrots (root), the results were within the literature range, while in lettuce, both the root and leaves had elevated values compared to the literature data (Chodak et al., 1995; Kawałko and Chodak, 1996; Gontarz and Dmowski, 2000; Bielicka et al., 2009). The zinc (Zn) content in beetroot (root) reached a slightly higher value than the maximum value given in the literature, while in beetroot (leaf) and carrots (root and leaf) it was significantly higher. In lettuce (leaf), Zn levels were partially within the range given in the literature, although the lower limit was lower than the values given by them. In turn, the copper (Cu) content in beetroot, carrots and lettuce (root) was higher than the literature values, which suggests a significant environmental load of this element. The high concentrations of heavy metals in the tested vegetables may indicate local soil contamination and potential health risks for consumers.

The bioaccumulation and translocation levels of the tested metals varied depending on the vegetable species and its part (root or leaves). The bioaccumulation level posed a risk where its value was equal to or greater than 1 (Gruca-Królikowska and Wacławek, 2006). In the studied complex of gardens, it was found for beetroot for the deciduous part in allotment garden complex no. 2 where for Zn in the leaves it was 1.66–2.25 and in complex allotment garden complex no. 2 for the same vegetable for Cu where this value was 1.2. For carrots, only in complex of allotment garden no. 3 for Cu in the deciduous part, a value of bioaccumulation coefficient was found on the level 1. Factors influencing metal uptake include soil bioavailability, metal type, environmental conditions, and plant species (Qureshi et al., 2016; Goni et al., 2025) conducted a study on the uptake and translocation of heavy metals in various parts of edible plants, which found that vegetables grown in heavily metal-polluted soils can accumulate these metals in large amounts. In India, the presence of metals such as Cu, Mn, Fe, Zn, Ni, and Pb has been found in vegetables (Mijinyawa et al., 2022). Also vegetables irrigated with treated water can accumulate heavy metals (Zhou et al., 2016; Mijinyawa et al., 2022). The potentially polluted areas, like cooper mine can accumulate heavy metals (Sharma et al., 2009; Tiwari et al., 2011). Additionally, plants can translocate heavy metals to the edible parts, posing health risk (Sharma et al., 2009). In our study, the highest translocation factor values were found for beetroots, reaching 5.15 for Zn, and for carrots, reaching 3.92. Owever, does not pose a risk to human health because only the root parts of these plants are consumed. Due to the low Cd content in the tested plants, below the detection limit for ICP-AES (iCAP 7400, Thermo Fisher Scientific, Waltham, MA, USA), this element was not included in further analyses/calculations.

The elevated levels of heavy metals in edible vegetables especially Zn and Cu in beetroot and lettuce indicate a need for targeted risk assessment and management strategies in urban gardening. These results highlight the importance of soil testing and site history analysis before establishing community or private gardens. Furthermore, the presence of high bioaccumulation and translocation factors in common crops underscores the potential for chronic exposure in local consumers, which may be particularly concerning for children and vulnerable populations. Therefore, urban agriculture practices should be accompanied by proper monitoring. These findings contribute to the growing body of evidence that urban soils require careful evaluation to ensure food safety and environmental sustainability.

5. Conclusions

Based on the research conducted, it can be concluded that the heavy metal content in the soil of the allotment gardens complex studied varied depending on the location. In some cases, especially in garden complexes Złocień, Jarzębina, permissible standards were exceeded, particularly for Zn and Cd, indicating zinc and cadmium contamination of these soils. This is due to the influence of the former Hutmen metallurgical plant.

Analysis of the metal content in plants showed their varied accumulation depending on the species of vegetable and its edible part. Beetroot showed the highest capacity to accumulate metals in both leaves and roots, which may be important for safe consumption. Bioaccumulation and translocation factors confirm that heavy metals can penetrate parts of plants consumed by humans, with the highest translocation values recorded for Zn in beetroot and carrots.

The results of the study indicate different levels of heavy metal accumulation in vegetables from different allotment gardens. The highest level of trace element uptake by selected vegetable species was found in allotment gardens influenced by industrial pressure, particularly the former Hutmen metallurgical plant. Particular attention should be paid to gardens where higher levels of contamination have been found in the soil, as this may pose a potential health risk to consumers. This shows that an important aspect of the research is to compare the content of heavy metals in the soil with the geochemical background in order to calculate the enrichment of the soil with a given element and then to compare the bioaccumulation and translocation rate of these heavy metals from the soil to vegetables.

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Conflict of interest

The authors declare no conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not involve human or animal subjects.

Author Contributions

Dariusz Gruszka – Conceptualization, Data curation, Visualization, Funding acquisition, Investigation, Methodology, Validation, Writing – originally draft. **Katarzyna Szopka** – Conceptualization, Investigation, Methodology, Supervision, Writing – review & editing. **Iwona Gruss** – Conceptualization, Investigation, Methodology, Supervision, Writing – review & editing. All authors read and approved the final manuscript.

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Akumulacja pierwiastków śladowych w warzywach pochodzących z ogródków działkowych we Wrocławiu

Słowa kluczowe:

Zanieczyszczone gleby
Metale ciężkie
Obszary miejskie
Bioakumulacja w roślinach
Translokacja

Streszczenie

Metale ciężkie w glebie są zanieczyszczeniami związanymi głównie z działalnością człowieka. Poszczególne części warzyw, takie jak korzenie i liście, mogą absorbować metale ciężkie. Uprawa warzyw na takich zanieczyszczonych gruntach może stanowić zagrożenie dla zdrowia konsumentów ze względu na skumulowany efekt długotrwałego spożycia warzyw z tych obszarów. Niniejsze badanie koncentruje się na oszacowaniu negatywnego wpływu zawartości w glebie wybranych form całkowitych metali ciężkich, takich jak Zn, Cu, Pb, Cd na ich pobieranie przez trzy gatunki roślin uprawiane na tych glebach (marchew, burak ćwikłowy i sałata). W pracy określono wskaźniki odnoszące się do współczynnika bioakumulacji w korzeniach roślin (BAF_r), częściach nadziemnych (BAF_s) oraz współczynnika translokacji (TF) części nadziemnej/podziemnej u roślin. Pobrano 45 próbek gleb z siedmiu kompleksów ogrodów działkowych we Wrocławiu z poziomu 0–25 cm oraz próby warzyw (części korzeniowych i liściowych) z tych samych miejsc. Przekroczenia dopuszczalnych norm zanieczyszczeń cynkiem (Zn) stwierdzono na terenie dwóch kompleksów ogrodów działkowych we Wrocławiu. Zawartości cynku na terenach gdzie wykazano zanieczyszczenia wahały się od 1138 do 1384 mg kg^{-1} (dopuszczalna zawartość 1000 mg kg^{-1}) w glebie, stwierdzono zanieczyszczenie kadmem (Cd) jedynie na terenie jednego ogrodu działkowego, gdzie jego zawartość wynosiła 6,31 mg kg^{-1} (dopuszczalna zawartość 5 mg kg^{-1}). Dla pozostałych badanych pierwiastków (Cu i Pb) nie stwierdzono przekroczenia dopuszczalnych zawartości zgodnie z Rozporządzeniem Ministra Środowiska nr 1395 z 1 września 2016 roku. Współczynniki bioakumulacji (BAF) metali ciężkich w podziemnych i nadziemnych częściach analizowanych warzyw wykazały znaczne zróżnicowanie w zależności od lokalizacji miejsc poboru roślin, gatunków roślin i rodzaju pierwiastków. Najwyższe wartości tego wskaźnika odnotowano w próbkach pochodzących z obszarów o podwyższonym zanieczyszczeniu gleb. W badanych warzywach największa wartość współczynnika TF (translokacji) stwierdzono dla cynku w liściach buraka, gdzie w zależności od badanego kompleksu ogrodu działkowego wynosiła od 0,43 do 5,15. Wartości opisanych wskaźników pokazują na zależność między działalnością przemysłową w miastach a zawartością metali ciężkich w glebach, w konsekwencji większymi ich pobieraniem przez rośliny (zwiększone współczynniki bioakumulacji, a w szczególności translokacji z części podziemnej do nadziemnej roślin). Przeprowadzone badania wskazują na ryzyko związane z użytkowaniem ogrodów działkowych do produkcji warzyw na terenach poprzemysłowych i zurbanizowanych ze względu na pobieranie przez warzywa substancji niebezpiecznych.