The Accumulation and Translocation of Harmful Sb, Se, and Tl in Certain Vegetables Grown in Contaminated Areas

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Heavy metal accumulation in food produced in polluted areas can reach high levels, posing a health risk. In this study, the variation in Sb, Se, and Tl concentrations was determined on a species and organ basis in tomatoes, peppers, eggplants, cucumbers, and corn grown near an industrial area in Düzce, one of Europe's most polluted cities. The concentrations of these elements in the soil were also determined, and the bioconcentration factor and translocation factor in the organs of the plants were calculated, thus attempting to determine the risks in terms of food safety. The study found that the concentrations of these elements in the soil were quite high, while their translocation and accumulation in the above-ground parts of plants, especially fruit organs, were at lower levels compared to other organs. Nevertheless, their concentrations in fruit organs were still quite high. In many countries, limit values for Sb, Se, and Tl in vegetables have not been established. This is considered a major deficiency. However, the values obtained in this study are well above the limit values permitted by countries such as China and Italy. This poses a significant risk to human health.

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INTRODUCTION

Food safety has become a major global issue in recent years. Factors such as soil salinization and degradation, the conversion of agricultural land to residential areas, and various biotic and abiotic pests, are reducing the amount of agricultural land and degrading its quality (Şen *et al*. 2018; Xing and Wang 2024; Velilla *et al*. 2025). These factors also cause significant product loss and resource waste. It is stated that food loss due to pests, such as insects, mites, rodents, and mycotoxins, consumes 1/4 of the world's fresh water resources and 1/5 of the total arable land (Junaid and Af 2024).

One of the factors that most threatens food security is global climate change. Global climate change is defined as an irreversible problem and is stated to affect all living things on earth (Erturk *et al*. 2024; Canturk *et al*. 2025; Zeren Cetin *et al*. 2025). It is stated that global climate change will also significantly affect agricultural production, potentially reducing agricultural productivity by 10 to 25% (Junaid and Af 2024). These factors are said to significantly threaten food security. According to the United Nations' 2022 World Food Security and Nutrition Report, approximately 828 million people worldwide suffer from hunger (Sharma *et al*. 2024). It is stated that approximately 3.14 billion people do not have a healthy diet (Melgar-Quiñonez 2025). This situation is predicted to worsen.

Another factor threatening food security is pollution. Many researchers consider pollution to be the most significant global threat after irreversible global climate change and urbanization (Mutlu and Aydın Uncumusaoğlu 2018; Ozturk Pulatoglu *et al*. 2025; Şimşek *et al.* 2025). It has even been stated that some pollution factors, such as nanoparticles, may soon affect even the most remote ecosystems (Özel *et al*. 2024). Similarly, it is stated that the release of heavy metals into nature and the threats they pose, which can be harmful and toxic to humans even at very low concentrations, is constantly increasing (Kuzmina *et al*. 2023; Key *et al*. 2023; Sevik *et al*. 2025).

Selenium (Se), antimony (Sb), and thallium (Tl), which are among the most dangerous heavy metals for human health, are heavy metals whose industrial use and release into the environment are increasing. Moreover, due to their potential hazards, these heavy metals have been included in the priority pollutant list by both the ATSDR and the EPA (Canturk *et al*. 2024; Şevik *et al*. 2024). When heavy metals are absorbed into the human body through respiration or food, they can be much more threatening, harmful, and deadly (Ghoma *et al*. 2023; Gültekin *et al*. 2025). However, in recent years, the intermingling of agricultural areas with residential and industrial areas has caused serious health concerns in food products grown in these areas. This is because heavy metals enter plant tissues from the air or soil and enter the food chain, which can cause potentially fatal health risks (Angon *et al*. 2024). Therefore, determining heavy metal accumulation in food products grown in areas with high levels of heavy metal pollution and identifying which heavy metals accumulate in which organs is of great importance for food safety. This study aimed to determine the accumulation and translocation of the heavy metals Sb, Se, and Tl, which can be toxic and harmful to humans even at low concentrations, in the plant organs of certain vegetables grown in areas with high levels of pollution.

EXPERIMENTAL

Materials

The study was conducted in Düzce province, one of Turkey's most polluted cities and ranked among Europe's five most polluted cities according to the 2021 World Air Pollution Report. Previous studies in the region have identified Cr (Koc *et al*. 2024; Ozturk Pulatoglu *et al*. 2025), Cd (Isinkaralar *et al.* 2025a), Pb, Al, Cu, and Ni (Koc *et al.* 2025a, 2025b; Isinkaralar *et al*. 2025a), Ba (Sevik *et al*. 2025), Tl (Şen 2025), Sb (Canturk *et al*. 2024), As (Yaşar Ismail *et al*. 2025), V (Cebi Kilicoglu and Zeren Cetin 2024), Pd (Sevik *et al*. 2024), Sr and Sn (Erdem 2023; Yigit 2024; Kulac *et al*. 2025) as being at high levels, which are quite dangerous for human health. In studies conducted in the region, Tl has been associated with agricultural activities (Canturk 2023), Se with pollution from traffic and urban settlements (Koç *et al.* 2026), and Sb with traffic-related pollution (Canturk *et al*. 2024).

Within the scope of the study, five vegetables (tomatoes, peppers, eggplants, corn, and cucumbers) were grown in Düzce in agricultural areas adjacent to industrial zones. The vegetables grown from seeds were planted in the Düzce industrial area in mid-May, and no fertilizers, hormones, or pesticides were used on the plants, which underwent routine watering and maintenance. At the end of August, the plants were uprooted along with their soil and brought to the laboratory. In the laboratory, the roots were first cleaned of soil. The soil was sifted to separate it from debris and placed in glass Petri dishes. For plant samples, the roots were separated from the soil and thoroughly washed with tap water to

remove soil particles adhering to the roots, followed by three rinses with deionized water. The plants were separated into roots, stems, leaves, and fruits. After thorough washing, the plant parts were rinsed with deionized water. This washing procedure was performed to remove surface dust and airborne particulate matter, ensuring that the measured heavy metal concentrations accurately reflect root uptake rather than external contamination. After washing, the plant samples were chopped with stainless steel knives, placed in Petri dishes, and labeled.

Methods

The samples were kept for 15 days in Petri dishes with open lids in a well-ventilated laboratory away from direct sunlight. They were then pre-dried in an oven at 45 ± 2 °C for two weeks. After pre-drying, the samples were ground into powder using a steel blender, weighed to 0.5 g, and placed in special tubes designed for microwave use. A total of 10 mL of 65% HNO was added to the samples, which were then heated in a microwave oven at 280 PSI pressure and 180 °C for 20 min. After the process, deionized water was added to the cooled samples to make up 50 mL, and they were filtered through filter paper. Cr and Cd concentrations were determined using a GBC Integra XL –SDS-270 ICP-OES (inductively coupled plasma - optical emission spectroscopy) device (GBC Scientific Equipment Pty Ltd., Melbourne, Australia). This pretreatment and heavy metal analysis have been frequently used in the analysis of plant samples in recent years (Erdem *et al*. 2024; Isinkaralar *et al*. 2025b). The obtained data were analyzed using the SPSS software package. Variance analysis was applied to the data, and the Duncan test was performed for factors with an F value, error rate, and statistically significant differences at a confidence level of at least 95%.

The bioaccumulation factor (BCF) and translocation factor (TF) were also calculated in the study. Thus, it was attempted to determine in which species and in which organs the elements were more accumulated. The following formulas were used in the calculations (Ergül and Kravkaz Kuşçu 2025):

$$BCF = (\text{Concentration in the organ}) / (\text{Concentration in the soil}) \quad (1)$$

$$TF = (\text{BCF of the organ}) / (\text{BCF of the root soil}) \quad (2)$$

RESULTS AND DISCUSSION

Change in Sb Concentration

The results of the variance analysis and Duncan test regarding the changes in Sb concentration in vegetables based on species and organ are presented in Table 1.

Table 1. Change in Sb (ppb) Concentration

Species	Organ						
	Stem	Fruit	Leaf	Root	F Value	Average	Soil
Pepper	7674.26 cB	7056.09 dA	8247.13 bC	12698.43 aD	1579.5***	8918.98	18677.33 a
Tomato	9659.23 dB	6356.13 bA	13734.49 eC	14704.36 bD	7021.5***	11113.55	63628.49 c

Corn	6236.16 aA	5598.50 aA	5908.26 aA	70458.58 dB	17352.2***	22050.37	69689.50 d
Eggplant	7512.29 cB	6724.40 bA	9462.76 cC	17844.50 cD	4541.3***	10385.99	62616.58 b
Cucumber	6803.93 bB	6515.20 cA	10325.09 dC	13072.30 aD	2348.8***	9179.13	69507.08 d
F Value	425.5***	101.5***	2172.6***	12503.4***		2.024 ns	6090.8***
Average	7577.17 A	6450.06 A	9535.55 B	14579.89 C	51.2***		

According to Duncan's test results, numbers followed by the same letters are not statistically different at P > 0.05

As shown in Table 1, Sb concentration varied significantly among all species in terms of organs and among all organs in terms of species ($p < 0.001$). The lowest values were obtained in fruits in all species. According to the average values, the lowest values were obtained in fruits and stems, while the highest values were obtained in roots. The highest values in organs were obtained in the stem and leaves of tomatoes, in the fruit of peppers, and in the roots of corn. The lowest values in soils were obtained in peppers and eggplants, and the highest values in corn and cucumbers. The variation in BCF values for Sb by species and organ is given in Table 2.

Table 2. BCF Values for Sb

Species	Organ				Average
	Stem	Fruit	Leaf	Root	
Pepper	0.411	0.378	0.442	0.680	**0.478**
Tomato	0.152	0.100	0.216	0.231	**0.175**
Corn	0.089	0.080	0.085	1.011	**0.316**
Eggplant	0.120	0.107	0.151	0.285	**0.166**
Cucumber	0.098	0.094	0.149	0.188	**0.132**
Average	**0.174**	**0.152**	**0.209**	**0.479**	**0.253**

When examining the BCF values for Sb, they were found to range from 0.080 (corn fruit) to 1.011 (corn root). It was determined that BCF values were quite low (maximum 0.411) except for peppers and corn roots. According to the average values, the lowest BCF values were calculated for fruit as an organ (0.152) and for cucumber as a species (0.132), while the highest values were calculated for root as an organ (0.479) and for pepper as a species (0.478). The TF values calculated for Sb are given in Table 3.

Table 3. BCF values for Sb

Species	Organ			Average
	Stem	Fruit	Leaf	
Pepper	0.604	0.556	0.650	**0.603**
Tomato	0.658	0.433	0.935	**0.675**

Corn	0.088	0.079	0.084	**0.084**
Eggplant	0.421	0.375	0.530	**0.442**
Cucumber	0.521	0.500	0.793	**0.605**
Average	**0.458**	**0.389**	**0.598**	**0.482**

When TF values for Sb are examined, it is seen that the lowest values were obtained in fruit for all species. The TF values in fruit were calculated as 0.079 in corn. The TF values calculated in fruit for other species ranged from 0.375 (eggplant) to 0.556 (pepper). The highest TF values in species other than corn were calculated in leaves, with the highest TF values in leaves calculated in tomatoes (0.935) and cucumbers (0.793).

Change in Se (ppb) Concentration

The results of the variance analysis and Duncan test regarding the changes in Se concentration in vegetables based on species and organ are presented in Table 4.

Table 4. Change in Se (ppb) Concentration

Species	Organ						
	Stem	Fruit	Leaf	Root	F Value	Average	Soil
Pepper	3332.29 cB	3069.10 cA	3760.29 BC	5167.63 AD	445.4***	3832.33	7765.43 a
Tomato	4336.13 dB	2782.53 bA	5,836.63 eC	6006.56 cD	1210.6***	4740.46	25768.58 c
Corn	2478.83 aAB	2270.53 aA	2715.36 aB	27,974.33 eC	16,116.5***	8,859.76	27857.24 d
Eggplant	3385.56 cB	3016.43 cA	4,046.93 cC	7,217.06 dD	1498.6***	4416.50	25016.33 b
Cucumber	3055.00 bA	3210.63 dB	4,533.06 dC	5,475.76 bD	884.3***	4068.61	27962.66 dB
F Value	384.2***	72.2***	750.3***	10,279.5***		1.897 ns	10416.8***
Average	3317.56 A	2869.84 A	4178.46 B	5966.75 C	42.6***		

According to Duncan's test results, numbers followed by the same letters are not statistically different at P > 0.05

As a result of the variance analysis, it was observed that the Se concentration changed significantly in all types of organs and in all organs in terms of type ($p < 0.001$). The lowest values were obtained in corn in organs other than the roots. The lowest value in the roots was obtained in peppers. The highest values were obtained in the stems and leaves of tomatoes, in the fruit of cucumbers, and in the roots of corn. In the soil, the lowest value was obtained in peppers, and the highest value was obtained in corn. The variation in BCF values for Se by species and organ is given in Table 5.

Table 5. BCF Values for Se

Species	Organ				Average
	Stem	Fruit	Leaf	Root	
Pepper	0.429	0.395	0.484	0.665	**0.493**
Tomato	0.168	0.108	0.227	0.233	**0.184**
Corn	0.089	0.082	0.097	1.004	**0.318**
Eggplant	0.135	0.121	0.162	0.288	**0.177**
Cucumber	0.109	0.115	0.162	0.196	**0.146**
Average	**0.186**	**0.164**	**0.226**	**0.477**	**0.264**

As shown in Table 5, BCF values for Se range from 0.082 (corn fruit) to 1.004 (corn root). The lowest values were obtained in the fruit, with the exception of the cucumber. The highest values were obtained in the roots of all species. The change in average BCF values among species is as follows: cucumber < eggplant < tomato < corn < pepper. The TF values calculated for Se are given in Table 6.

Table 6. BCF Values for Se

Species	Organ			Average
	Stem	Fruit	Leaf	
Pepper	0.645	0.594	0.728	**0.656**
Tomato	0.721	0.464	0.974	**0.720**
Corn	0.089	0.082	0.097	**0.089**
Eggplant	0.469	0.420	0.563	**0.484**
Cucumber	0.556	0.587	0.827	**0.657**
Average	**0.496**	**0.429**	**0.638**	**0.521**

The lowest TF value for Se was obtained in corn fruits with 0.082, while the highest TF value was obtained in tomato leaves with 0.974. The lowest values were obtained in corn. The TF values in corn ranged from 0.082 to 0.594, with an average of 0.429. No organ had a TF value exceeding 1, with the highest values obtained in tomato leaves (0.974), cucumber leaves (0.827), and pepper leaves (0.728).

Change in Tl (ppb) Concentration

The average data regarding the variation in Tl concentration, along with the results of the variance analysis and Duncan test, are presented in Table 7.

Table 7. Change in Tl (ppb) Concentration

Species	Organ						
	Stem	Fruit	Leaf	Root	F Value	Average	Soil
Pepper	2437.30 cB	2222.30 cA	2696.03 bC	3781.73 aD	1042.7***	2784.34	5648.23 a
Tomato	3050.60 dB	1947.16 bA	4178.10 eC	4354.30 bD	1804.3***	3382.54	18,712.08 c
Corn	1772.66 aAB	1623.96 aA	1953.60 aB	19789.83 dC	10,919.6***	6285.01	19,349.75 cd
Eggplant	2423.66 cB	2184.30 cA	2894.56 cC	5288.73 cD	1376.9***	3197.81	17,637.58 b
Cucumber	2208.73 bA	2283.23 dA	3223.70 dB	3834.90 aC	799.8***	2887.64	20098.25 d
F Value	184.5***	133.5***	826.3***	7847.1***		1.830 ns	632.6***
Average	2378.59 A	2052.19 A	2989.20 B	4314.91 C	43.3***		

As with the other two elements, it was determined that the change in the Tl element was statistically significant in all types of organs and in all organs in terms of type ($p < 0.001$). The highest values were obtained in the stem of tomatoes (3050.60 ppb), in the fruit of cucumbers (2283.23 ppb), in the leaves of tomatoes (4178.10 ppb), and in the roots of corn (19789.83 ppb). The change in Tl concentration in fruits was corn < tomato < pepper < eggplant < cucumber. The change in Tl concentration in soils was pepper < eggplant < tomato < corn < cucumber. The change in BCF values for Tl based on species and organ is given in Table 8.

Table 8. BCF Values for Tl

Species	**Organ**				**Average**
	Stem	**Fruit**	**Leaf**	**Root**	
Pepper	0.432	0.393	0.477	0.670	**0.493**
Tomato	0.163	0.104	0.223	0.233	**0.181**
Corn	0.092	0.084	0.101	1.023	**0.325**
Eggplant	0.137	0.124	0.164	0.300	**0.181**
Cucumber	0.110	0.114	0.160	0.191	**0.144**
Average	**0.187**	**0.164**	**0.225**	**0.483**	**0.265**

It was determined that BCF values in TL ranged from 0.084 (corn fruit) to 1.023 (corn roots). According to the calculations, the lowest values were obtained in cucumber stems, while the highest values were obtained in the roots of all species. The TF values calculated for Tl are given in Table 9.

Table 9. BCF Values for Tl

Species	Organ			Average
	Stem	Fruit	Leaf	
Pepper	0.645	0.594	0.728	**0.656**
Tomato	0.721	0.464	0.974	**0.720**
Corn	0.089	0.082	0.097	**0.089**
Eggplant	0.469	0.420	0.563	**0.484**
Cucumber	0.556	0.587	0.827	**0.657**
Average	**0.496**	**0.429**	**0.638**	**0.521**

When examining the table values, the highest values were calculated as 0.957 for tomato leaves, 0.838 for cucumber leaves, and 0.712 for pepper leaves. The highest values in fruits were obtained for cucumber (0.597) and pepper (0.587). The lowest values were calculated for corn fruits (0.082) and corn stalks (0.090).

Within the scope of the study, the concentrations of Sb, Se, and Tl in some of the most commonly consumed vegetables were evaluated. It is stated that Sb, one of these elements, alters hormone levels in the human body and increases the risk of cancer (Lai *et al*. 2022). It is also stated that it causes symptoms such as conjunctivitis, upper respiratory tract inflammation, chronic bronchitis, chronic emphysema, and pleural adhesions (Gad 2014). As a result of the study, it was determined that Sb concentrations ranged from 5598 ppb to 7056 ppb in fruit organs consumed as food. The US Food and Drug Administration (FDA) or other international organizations have not set specific regulatory limits for Sb in food. The WHO has set a guideline value of 20 μg L^{-1} for Sb in drinking water. However, the FDA has set a guideline level of 0.1 ng L^{-1} for Sb in bottled water (Elik *et al*. 2024). The Food Safety and Standards Authority of India (FSSAI) has set the limit for Sb concentration in vegetables at 1.00 mg/kg (1000 ppb) (Kashyap and Jain 2024). In Italy, the permitted Sb limit in foods is also 1.0 mg kg^{-1}dw (Wei *et al*. 2024). The values obtained in the study are approximately 5.5 to 7 times this limit.

Another element covered in the study, Se, can cause vomiting, pain, nausea, garlic breath, and heart symptoms. In severe toxicity cases, cardiac and pulmonary symptoms may occur and lead to death (Hadrup and Ravn-Haren 2020). It is stated that Se is found at an average level of 0.110 mg kg^{-1}dw in leafy vegetables and 0.054 mg kg-1dw in vegetable fruits (Fordyce 2013). China has set Se concentration limits for products, such as grains, vegetables, fruits, edible mushrooms, *etc.*, at 20.0 to 200.0 μg/100 g (Ren *et al*. 2024). Within the scope of the study, Se concentrations in the fruit organs of plants were determined to be 2270 ppb to 3210 ppb. These values are well above the limits set by China. Because 1 μg/kg = 1 ppb, the Chinese standards can be evaluated as 200 to 2000 ppb.

The final element discussed in this study, Tl, is extremely hazardous to human health. Tl is an element that is not essential for humans and has no biological use in the human body. It is one of the most toxic metals and is more toxic to humans than Hg, Cd, Pb, Cu, and Zn (Blain 2022). Tl can cause fatigue, muscle and joint pain, visual impairment, gastrointestinal dysfunction, ascending paralysis, and mental disorders in humans, and polyneuritis may occur (Duri *et al*. 2020; Şevik *et al*. 2024). In Italy, the

permitted Tl limit in food is set at 0.50 mg kg^{-1}dw (Wei *et al*. 2024). Within the scope of the study, Tl concentrations in fruit organs ranged from 1624 ppb to 2283 ppb. These values are approximately 3.2 to 4.4 times the permitted Tl concentrations.

Studies have determined that heavy metal contamination in the region's soils is quite high, and consequently, heavy metal concentrations in plants are also high (Guney *et al*.; Dışbudak *et al*. 2026). In a study conducted on vegetables grown in the region, it was determined that Cd concentrations in fruit organs ranged from 0.22 mg/kg to 0.33 mg/kg, and that these values exceeded the limit values set by international standards by more than twofold. The same study highlighted that chromium (Cr) concentrations in fruit organs ranged from 178.5 to 579.8 mg/kg, with these values being hundreds of times higher than the limit set by international standards (Sevik *et al*. 2026). Similarly, it was determined that Al concentrations in the fruit organs of vegetables significantly exceeded the limit values set by the WHO and the EU, and that there is a potential non-carcinogenic health risk associated with the consumption of tomatoes, cucumbers, and peppers, primarily due to nickel (Demirci *et al*. 2026).

In many countries, legal limits for the elements studied have not been specified in detail for vegetables. According to the ATSDR, the acceptable daily intake (minimal risk level) is 1 µg/g/day for Sb and 0.005 µg/g/day for Se; the limit value for Se, as per the Turkish Food Codex Contaminants Regulation, is 250 µg/day (Şahin and Türksoy 2024). Daily Sb intake is reported to be 3,471 µg/day (IQR 2,801 to 4,395 µg/day), and daily Tl intake is reported to be 533.7 ng/day (414.6 to 676.0 ng/day) (Filippini *et al*. 2020). Using results from similar studies, limits for Se, Sb, and Tl in foods can be determined. However, compared to elements, such as Pb, Cu, Cd, and Zn, for which limit values have been established, it can be said that the elements studied can be much more harmful at lower concentrations. The WHO and EU have set limit values for Cd in leafy vegetables at 0.1 mg/kg. The WHO has set a limit value of 0.3 mg/kg for Pb, while the EU has set a limit value of 0.1 mg/kg (Ejaz *et al*. 2023). The values obtained in the study are well above these limits.

The study focused on the accumulation of heavy metals in the fruit organs of vegetables. According to the study results, the lowest concentrations were generally obtained in the fruit organs, while concentrations in other organs were generally higher. However, the leaves and stems of these plants are used as animal feed in some regions. Corn, in particular, is ensiled in many regions, and the above-ground parts of the plant are used as animal feed (Shuo *et al*. 2024). Within the scope of the study, the Se concentration in corn leaves and stems was approximately 2.5 ppm (mg/kg), while it was calculated to be above 5 ppm in tomatoes. However, while the minimum Se requirement in animal husbandry is 0.05 to 0.10 mg/kg dry feed, the toxic Se concentration in animal feed is 2 to 5 mg/kg dry feed (Gupta and Gupta 2017). The same applies to other heavy metals. The use of the above-ground parts of these plants as animal feed poses a risk of toxicity in animals and can also threaten human health through the food chain.

As seen, the concentrations of the elements studied in the fruit organs of vegetables were well above the permissible levels for health. Furthermore, the determined heavy metal concentrations in other organs were even higher. Heavy metals can enter the plant body from the soil, air, or stem sections (Cobanoglu *et al*. 2023; Kulac *et al*. 2025). However, the transport of heavy metals within plants is a complex process that varies with many factors, primarily plant species. Many studies have shown that heavy metal concentrations vary significantly across plant species (Lin *et al*. 2025; Isinkaralar *et al*. 2025a; Ismail *et al*. 2026). In this study as well, it was determined that there was a significant difference

between maize, a monocot, and other dicot species regarding both heavy metal accumulation and translocation. Plants manage metals through uptake, transport, storage, and detoxification. Numerous studies have shown that monocotyledonous and dicotyledonous plants differ in anatomical and physiological characteristics, and that these differences can alter where and how much metal accumulates. For example, monocotyledonous plants generally accumulate less Pb in their roots compared to dicotyledonous plants. This may be attributed to the fact that dicotyledonous plants have more divalent cation-binding sites in their root tissues (Rahman *et al*. 2024). Many dicotyledonous plants strongly acidify the rhizosphere and secrete chelators under iron deficiency. In contrast, monocotyledonous grasses employ different iron strategies. This leads to distinct uptake pathways and the co-uptake of other metals via shared transporters (Wallace 2008; Andresen *et al*. 2018). Dicotyledonous plants typically secrete organic acids (citrate, malate), monocotyledonous plants secrete phytosiderophores, which alter metal chelation and availability at the root-soil interface (Balagopa *et al*. 2025). Due to these differences between monocotyledonous and dicotyledonous plants, it is natural that their potentials for heavy metal uptake and accumulation differ.

The primary route of entry of many heavy metals into the plant body is through the roots from the soil (Yuan *et al*. 2024). Therefore, heavy metal concentrations in soils are also important. Within the scope of the study, it was determined that the Sb concentration in soils ranged from 18700 ppb to 69700 ppb, the Se concentration ranged from 7770 ppb to 27,900 ppb, and Tl concentrations ranged from 5,650 ppb to 20,100 ppb. These values are well above the permitted limits. For example, in Italy, the permitted limit for Tl in soil is 2.0 mg kg^{-1}dw, and the limit for Sb is 10.0 mg kg^{-1}dw (Wei *et al*. 2024). The permitted Se concentration in soils is 10 mg/kg in countries such as Mongolia and France (Fordyce 2013; Bataa *et al*. 2022). Furthermore, when the results of this study were compared with similar studies, it was determined that the values obtained were higher than those obtained in similar studies. For example, a study conducted in China found average concentrations in soils to be 2.78 mg/kg for Sb and 0.84 mg/kg for Tl (Li *et al*. 2025). It has been reported that the Tl concentration in contaminated soils can reach up to 7 mg/kg (Karbowska 2016; Grösslová *et al*. 2018; Minnikova *et al*. 2023). In a study conducted in the Mediterranean region, the average Se concentration was found to be 0.43 $mg.kg^{-1}$ in natural soils, 0.40 $mg.kg^{-1}$ in agricultural soils, and 0.93 $mg.kg^{-1}$ in industrial soils (Roca-Perez *et al*. 2010). A study conducted in mining areas in Peru reported that the average Se concentration was 1.1 mg/kg, exceeding the limit values set by both the Ministry of the Environment of Peru (MINAM) and the Canadian Council of Ministers of the Environment (CCME) (GómezOquendo *et al*. 2026).

One of the most important factors influencing heavy metal accumulation in plants is the concentration of these heavy metals in the soil (Wu *et al*. 2024; Sevik *et al*. 2026). Heavy metal contamination in soils, however, is shaped by the influence of numerous and interrelated factors. The most significant factor contributing to uncertainty in studies on this topic is the heterogeneity of the soil's physicochemical properties. Consequently, inconsistent responses in soil adsorption capacity may be observed. Failure to account for these factors can lead to serious interpretation errors. The adsorption and desorption of heavy metals at the soil interface is a highly complex, nonlinear process influenced by the interactive effects of multiple physicochemical properties (*e.g*., initial concentration, ionic strength, and solid-liquid ratio). Understanding these nonlinear, interactive, and multifactorial effects is of great importance for accurately predicting the potential migration of heavy metals to plant roots. For example, clay particles can significantly alter

the physicochemical environment (*e.g*., pore size distribution, moisture retention) that facilitates long-term metal retention (Wu *et al*. 2025a). Similarly, ion exchange capacity (IEC) has a significant effect in this process. IEC controls the amount of metal ions adsorbed onto biomaterials (Hubbe *et al*. 2011). For every mole of a divalent metal element adsorbed, one mole of Ca is displaced (Crist *et al*. 2003). In other words, depending on the valence of the metal species, it is expected that each adsorbed metal ion will displace other ions such as hydrogen or sodium (Hubbe 2013). Thus, the presence and concentration of other elements in the soil can significantly influence heavy metal uptake by plants (Hubbe *et al*. 2022; Ergül and Kravkaz Kuşçu 2024).

Studies have shown that contaminant behavior in the unsaturated zone is shaped not by individual chemical parameters but also by the combined effect of multiple environmental factors. Factors such as pH, oxidation-reduction potential (ORP), moisture content, and electrical conductivity jointly and simultaneously control contaminant distribution. Furthermore, it has been determined that these factors are spatially heterogeneous and interact with one another. In this context, the bioavailability of heavy metals in soil is similarly regulated not only by solubility parameters but also, and particularly, by the surface properties and distribution coefficients of reactive mineral phases such as iron (Fe), manganese (Mn), and aluminum (Al) oxides. These oxides can immobilize heavy metals by binding them through microscopic mechanisms such as adsorption, complexation, and surface precipitation, thanks to their high specific surface areas and variable surface charges. However, changes in environmental conditions (such as a decrease in pH or reduced redox conditions) can weaken these bonds and release metals back into the soluble phase. The combined variation in environmental factors causes contaminant concentrations to exhibit different responses across regions, and a single factor's value can be associated with varying contaminant levels. This situation demonstrates that heavy metals retained on Fe-Mn-Al oxides do not exhibit static behavior; rather, they exist within a dynamic sorption–desorption equilibrium that depends on environmental conditions. Consequently, these microscopic processes directly influence metal concentrations in soil solution, thereby determining uptake by vegetables via the root system (Wu *et al*. 2026a).

Therefore, the accurate assessment of heavy metal bioavailability requires holistic approaches that consider mineral phases and environmental factors together and hierarchically. For example, soil pH plays a decisive role in the mobility of heavy metals and in associated risk assessments. However, studies have shown that the risk of heavy metal mobility, particularly in relation to pH, can be systematically overestimated, leading to significant deviations in soil quality assessments. This situation highlights the inadequacy of treating pH as a standalone control parameter. This is because interactions with pH, mineral phase equilibrium, complexation processes, and other environmental variables shape metal mobility. Consequently, risk assessments based on fixed threshold values or univariate approaches may overestimate or underestimate actual mobility, particularly under alkaline or variable pH conditions (Wu *et al*. 2025b). In this context, holistic assessment frameworks based on explainable modeling approaches that consider environmental factors collectively and interactively are critical for accurately and context-sensitively assessing heavy metal risk. However, current risk assessment approaches have significant limitations in explaining contaminant behavior, particularly in the unsaturated zone (vadose zone). This is because these methods primarily rely on generalized predictions based on individual parameters or limited hydrogeological variables, and they fail to represent the environment’s highly heterogeneous nature adequately (Chen *et al*.

2025; Liu *et al*. 2025). Indeed, studies have clearly demonstrated that contaminant concentrations cannot be reliably back-calculated from a single environmental factor, and that the same parameter values may correspond to different concentration scenarios. Furthermore, the extensive data requirements of traditional physical and mathematical models, along with their temporal and spatial limitations and their reductionist approach to complex processes, increase uncertainties in risk assessments. In this context, the joint and hierarchical evaluation of environmental factors (such as moisture content, pH, redox potential, and electrical conductivity) is of critical importance for capturing the multidimensional nature of contaminant transport (Wu *et al*. 2026b).

The study found high levels of Tl, Se, and Sb contamination in the soils of the study area. Studies conducted in the region have shown that heavy metals such as Cu, Ni, Cd, Zn, and Pb in the soil—originating from vehicle emissions, industrial processes, ferroalloy industries, and coal-fired power plants—are present at levels high enough to pose a risk to human health (Dışbudak *et al*. 2026). It has been determined that this situation leads to the accumulation of heavy metals, including Al, Cr, Cd, Ni, and Zn, at very high levels in vegetables grown in the region (Demirci *et al*. 2026; Sevik *et al*. 2026). It is recommended to use the latest soil remediation strategies to mitigate the risks posed by high levels of heavy metal contamination. For example, the use of new environmentally friendly solidification/stabilization materials could be recommended to reduce the bioavailability of heavy metals and prevent their entry into the food chain at the source. Studies have indicated that red mud, biochar, phosphate rock (Derakhshan Nejad *et al*. 2018), liming materials, phosphates, minerals, and various industrial byproducts (Lwin *et al*. 2018) have been identified as potential solutions for this purpose; however, recent studies have yielded promising results from innovative applications such as amino-modified gangue-derived zeolite (Zhu *et al*. 2026) and even fungal inoculation (Zhang *et al*. 2025). Such applications can immobilize heavy metals in the soil, thereby preventing their entry into the food chain.

The study found that TF values were generally higher in leaves than in other organs. The TF value did not exceed 1 in any vegetable fruit organ. The TF value is an important criterion indicating a species' potential for heavy metal accumulation. The higher this value, the greater the species' potential for heavy metal accumulation in that organ (Wang *et al*. 2019). Plants with TF values greater than 1 are considered strong accumulators of the relevant metals (Takarina and Pin 2017). Based on these results, it can be said that the plants studied accumulate Sb, Se, and Tl at lower levels in fruit organs compared to other organs. However, the values obtained in fruit are still well above the health threshold values.

CONCLUSIONS

1. The study determined that TF values in vegetables remained at low levels in above-ground organs and did not reach a value of 1 in fruit organs. At first glance, this situation may be considered as positive. This is because it is understood that Sb, Se, and Tl accumulate at lower levels in fruit organs compared to other organs. However, when the average values were examined, it became apparent that despite the low TF value, the concentrations of Sb, Se, and Tl in the fruit organs were very high relative to some regulatory limits. This situation poses a great risk to health.

2. The study found that the concentrations of Sb, Se, and Tl in plant organs were quite high. Although these elements are known to be extremely harmful to human health, limit values for Sb, Se, and Tl in vegetables have not yet been established in many countries. However, these elements are much more harmful than many other pollutants for which limit values are specified in relevant laws. The fact that limit values have not been legally determined limits the power of legal sanctions. For this reason, limit values for these elements in food products, including the vegetables studied, must be determined urgently.
3. It has been determined that the concentrations of Sb, Se, and Tl in the soils of the study area are much higher than those in plants. Although it is known that heavy metal pollution is high in the study area, intensive agriculture and animal husbandry are still practiced. This situation poses a major risk to food safety. Food safety must be ensured by taking the necessary measures urgently.
4. Among the vegetables studied, the highest values for all elements in the edible parts of the fruit were found in peppers and cucumbers, while the lowest were in corn. Based on these results, it is recommended to avoid growing peppers and cucumbers in the region or to cultivate them in clean soil, while prioritizing corn cultivation in open fields.

DATA AVAILABILITY

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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