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Heavy metal contamination, bioaccumulation, and health risk assessment in carrots from two regions of Kosovo

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ABSTRACT

This study evaluated the accumulation and potential health risks of five heavy metals – Arsenic (As), mercury (Hg), thallium (Tl), palladium (Pd), and antimony (Sb) in the carrots grown in two regions of Kosovo. The authors analyzed soil and carrot samples to determine how much metal was in them. Then, the bioaccumulation factor (BAF), estimated daily intake (EDI), hazard risk index (HRI), and total hazard index (THI) for both adults and children were established. The findings indicated that the BAF values for As, Hg, Tl, and Pd were predominantly low, signifying minimal translocation from soil to edible carrot tissues, whereas Sb demonstrated moderate bioaccumulation. Children had higher EDI values because they weighed less, and As and Sb were the main sources of dietary exposure. The HRI values for all metals were below 1 for adults, indicating a minimal non-carcinogenic risk; however, children showed notably higher HRI values, especially for arsenic. The THI assessment indicated that overall exposure remained within safe limits for most municipalities; nonetheless, Obiliq recorded the highest THI figures (7.22 for adults, 22.66 for children), highlighting the necessity for regional monitoring. In conclusion, the research demonstrated that carrot consumption in the assessed regions is generally safe for adults, while children may face elevated yet still acceptable levels of exposure. These results offer vital information for food safety evaluations and stress the importance of ongoing monitoring of heavy metal pollution in agricultural soils and crops.

Keywords: heavy metals, bioaccumulation factor, health risk assessment, Kosovo.

INTRODUCTION

Due to industrialization, mining operations, the burning of fossil fuels, wastewater irrigation, and extensive use of agrochemicals, heavy metal contamination in agricultural ecosystems has become a significant worldwide environmental problem (Mohamed et al., 2025). Heavy metals are more likely to pass into crops and then enter the human food chain than organic contaminants, because they are persistent, non-biodegradable, and able to build up in soils over extended periods of time (Mustapha et al., 2025). Arsenic (As), cadmium (Cd), lead (Pb), mercury (Hg), and thallium (Tl) are among the hazardous metals known for their high toxicity and possible negative health impacts (Balali-Mood et al., 2021). Exposure to arsenic has been linked to cardiovascular disorders and cancer (WHO, 2018) (Yu et al., 2023). Renal failure and bone damage are associated with cadmium accumulation, which mostly occurs in the kidneys (EFSA, 2009). Lead exposure poses serious dangers to children and has an impact on neurological development (WHO, 2010). (Satarug et al., 2020). While thallium is known for its acute toxicity and systemic effects even at low doses, mercury, especially in methylated forms, is a powerful neurotoxin (UNEP, 2019)

(Charkiewicz et al., 2025). Chronic health issues could result from ongoing low-dose dietary intake (Pekmezci et al., 2025). In agricultural systems, soils serve as both a source and a sink for heavy metals (Filimon et al., 2021). Soil physicochemical characteristics like pH, redox potential, organic matter concentration, cation exchange capacity, and clay composition affect metal mobility and bioavailability (Jiang et al., 2024a). Plants mostly absorb metals through their roots, though this can vary based on the kind of plant and the metal speciation (Eben et al., 2024). The edible section of root crops, like carrots, grows immediately inside the soil matrix, increasing the likelihood of metal buildup, making them especially pertinent in contamination studies. (Falae et al., 2025). Numerous studies have shown that the rates at which Cd, Pb, and As are transferred into root crops vary based on the contamination levels and soil conditions (Chețan et al., 2025). The bioaccumulation factor (BAF), which is the ratio of metal content in soil and plant tissue, is frequently used to assess the effectiveness of soil-to-plant transfer (Aladesanmi et al., 2019). However, concentration and transfer measurements alone do not accurately reflect possible effects on human health (Arnold et al., 2013). In order to determine non-carcinogenic risk related to dietary exposure, risk assessment models, including estimated daily intake (EDI), health risk index (HRI), and total hazard index (THI), are frequently used (USEPA, 2011). (Jalil et al., 2026). Acceptable risk is indicated by a THI value less than 1, whereas values more than 1 indicate possible health issues. (Abdelmontaleb et al., 2025). Despite the fact that heavy metal pollution has been well researched globally, (Yu et al., 2025), there is a dearth of comprehensive data concerning Kosovo's agricultural areas, especially when it comes to soil-plant transfer and the evaluation of related health risks. Evaluating the distribution of heavy metals in food crops is crucial for environmental management and public health protection because of the historical presence of mining and industrial activities in some areas of the nation. (Behrami and Avdiu, 2023a). Thus, the study goals were as follows:

1. Ascertain the levels of As, Cd, Pb, Hg, and Tl in soil and carrot samples from two Kosovo agricultural districts;
2. Use the BAF to measure the efficiency of soil-plant transfer.
3. Use the EDI, HRI, and THI models to assess any non-carcinogenic health concerns.

The results add to baseline environmental data and offer scientific proof in favor of sustainable farming methods and regional food safety surveillance.

MATERIALS AND METHODS

Study area description

The Prishtina and Prizren regions, two of Kosovo's principal agricultural areas, were the sites of this study (Figure 1).

Two regions of Kosovo, comprising several municipalities, were sampled. Based on spatial distribution and agricultural activity, five typical sampling locations were chosen for each municipality. Samples of dirt and matching carrots were gathered at each location. To guarantee reproducibility and representativeness, all samples were gathered in triplicate. Adequate spatial coverage of the study areas was the goal of the sampling design. Based on triplicate measurements, all data are shown as mean ± standard deviation (SD). To evaluate the variability of the data, confidence intervals (95%) were computed. IBM SPSS Statistics was used for statistical analysis. One-way ANOVA was used to assess differences between areas and sampling locations, with a significance level of $p < 0.05$. While the Prizren region exhibits a mixed agricultural–urban ecosystem with varied degrees of anthropogenic influence, the Prishtina region is distinguished by higher urban density, traffic pollution, and closeness to industrial and mining activity. (Behrami and Avdiu, 2023b). With seasonal temperature fluctuations that could affect the chemical dynamics of soil and metal mobility, both areas have continental climates. (Scalenghe et al., 2012). The intensity of agricultural activity, accessibility, and possible exposure to sources of environmental pollution were taken into consideration while choosing sampling locations (Behrami et al., 2021). The representative agricultural fields that grow carrots (*Daucus carota*) were recognized for each region. Samples of soil and carrots were gathered throughout the primary harvest season. Composite soil samples were taken from the topsoil layer (0–20 cm), which corresponds to the active root zone, at each chosen location (Awoonor et al., 2025). Using a stainless steel auger, five subsamples were randomly selected from each plot and carefully mixed to create one representative composite sample per site (Li et al., 2026). After being labeled and kept in sanitized

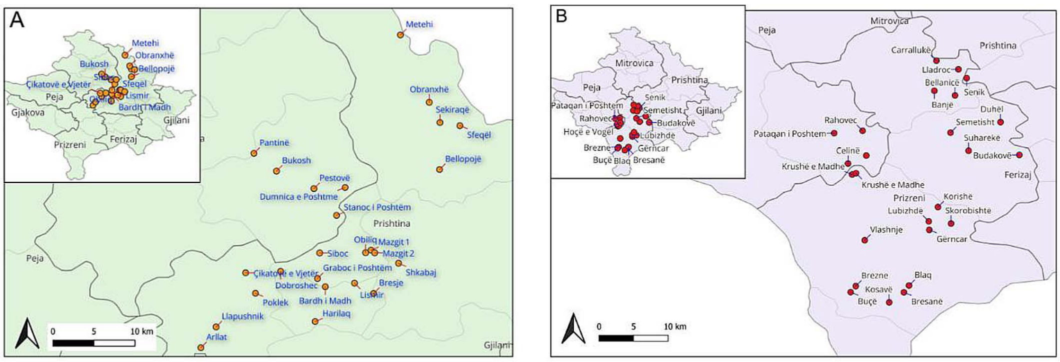

Figure 1. Map of the study area (Pristina region) with sampling locations and Map of the study area (Prizren region) with sampling locations

polyethylene bags, the samples were brought to the lab for analysis. (Beriro et al., 2025). Mature carrot samples were taken at random from the same places. After being separated, the edible root sections were air-dried, cleaned with distilled water to get rid of any remaining soil particles, and ready for laboratory examination. To remove stones and debris, soil samples were homogenized, air-dried at room temperature, then sieved through a 2 mm mesh screen (Van Genderen, 2013). For chemical analysis, a piece of the dried sample was finely powdered. Samples of carrots were oven-dried at 70 °C until they reached a consistent weight. A stainless steel mill was used to grind the dried material into a fine powder that could be consumed (Kaba et al., 2025).

Sample preparation and analysis

Each sample weighed precisely 1.0 g, which was then placed into a temperature-and acid-resistant mineralization tube. The following acid mixture was applied to each case: HNO_3 (65%) 9 ml; $HClO_4$ (70%) 3 mL; and H_2O_2 1 ml extra for challenging matrices. With the exception of mercury (Hg), which was mineralized using a mixture of 9 mL HNO_3 65% and 3 mL H_2SO_4 98%, this procedure was the same. The proper mineralization program was chosen after passing the samples and acids into the tube: DKL acid digestion program: Stage 1: Drying: To prevent acid splashing, the temperature was gradually raised to 140 °C for 15 minutes. Stage 2: Mineralization: For 60 minutes, the temperature was increased to 200 °C. The temperature was raised to 240 °C for 30 minutes for the soil samples with tougher mineral matria (depending on the reaction). The samples (tubes) were cooled progressively after mineralization (without opening them right away to prevent acid evaporation). All samples were filtered to remove any insoluble (mineralizable) particles after cooling. Following filtration, each sample was placed into a 50 ml standard flask and filled with distilled or deionized water to precisely 50 ml. To ensure the stability of the atomic absorption spectrophotometer (GFAAS) analysis, 1 ml of 3% HNO_3 was added at the end of each sample. Following the preparation of the samples for the analysis of each metal, the graphite furnace program was chosen, and the Pro 4250 instrument GFAAS handbook was used to configure these parameters. A calibration curve was created for each metal using the appropriate standards. 20 µL was the injection volume.

Analytical quality control and human health risk assessment of heavy metals

To guarantee the precision, dependability, and repeatability of the analytical data, quality assurance and control (QA/QC) protocols were employed. Throughout the experiment, duplicate samples, calibration standards, and blanks were examined. Standard solutions for each metal were used to create calibration curves, and adequate linearity ($R^2 > 0.99$) was attained. Based on signal-to-noise ratios of three and ten, respectively, the limits of detection (LOD) and limits of quantitation (LOQ) were calculated using standard analytical procedures. Recovery tests were used to assess the accuracy of the method by introducing known concentrations of metals into samples. The results showed good accuracy, with recovery rates ranging from 90% to 110%. Relative standard deviation (RSD) was used to measure precision; values less than 5% indicated that the approach was repeatable.

Health risk assessment

The risk to human health associated with consuming contaminated carrots was evaluated using a number of indices, including the BAF, estimated daily intake (EDI), health risk index (HRI), and total hazard index (THI). These markers provide insight into the movement of metals from soil to plants and the potential health effects of food exposure. Exposure parameters, including ingestion rate (IR), exposure frequency (EF), exposure duration (ED), body weight (BW), and average time (AT), were calculated using the United States Environmental Protection Agency's (USEPA) guidelines. An average adult body weight of 70 kg and typical vegetable consumption rates were used to assess dietary exposure. These assumptions could not adequately reflect regional consumption trends, even though they allow for consistent comparison with other studies.

Bioaccumulation factor (BAF)

The transport of heavy metals from soil to carrots was evaluated using the BAF, which is calculated as follows:

$$BAF = \frac{C_{plant}}{C_{soil}} \quad (1)$$

where: *C_soil* – metal concentration in soil (mg/kg) and *C_plant* – metal concentration in carrot (mg/kg). A BAF number greater than 1 indicates that the plant efficiently takes metals from the soil, indicating a high transfer potential, whereas a value less than 1 suggests inadequate uptake.

This parameter is essential for identifying crops that may be more hazardous for human consumption due to metal accumulation (Aina et al., 2024).

Human health risk assessment

To assess the potential non-carcinogenic health risks associated with carrot consumption, the EDI, HRI, and THI were calculated. These indicators compare the level of human exposure to heavy metals to safe reference limits. The EDI, or the daily quantity of metal ingested by carrot consumption, is calculated using Equation 2.

$$EDI = \frac{(C_{carrot} \times IR)}{BW} \quad (2)$$

where: *C_carrot* is the concentration of the metal in carrots (mg/kg), *IR* is the ingestion rate of carrots (kg/person/day), and BW is the average body weight (kg).

EDI provides an estimate of the exposure dose and is a critical step in evaluating potential health risks. Higher EDI values indicate greater exposure to contaminants through diet (Smical et al., 2025). The HRI was used to assess the potential non-carcinogenic risk posed by individual metals. It is calculated as:

$$HRI = \frac{EDI}{RfD} \quad (3)$$

where: *RfD* is the oral reference dose (mg/kg/day), which represents the maximum acceptable daily intake of a contaminant without significant health risk.

An *HRI* value less than 1 indicates that the exposure is within safe limits, whereas an *HRI* value greater than 1 suggests a potential health risk. This index helps identify which metals contribute most significantly to health concerns (Nag et al., 2022). The target hazard index (THI) represents the cumulative non-carcinogenic risk from multiple metals and is calculated as the sum of individual HRIs:

$$THI = \sum HRIi \quad (4)$$

A THI value greater than 1 indicates a potential health risk due to combined exposure to multiple metals, even if individual HRI values are below the threshold. This cumulative approach provides a more realistic assessment of overall health risk (Moradnia et al., 2024).

RESULTS AND DISCUSSION

Concentrations of heavy metals in soil and carrot samples from central Kosovo

Figure 2a shows the levels of heavy metals in the soil samples taken from the Drenas municipality. Arsenic (As) had the greatest quantities of the elements examined, ranging from roughly 6.4 mg/kg in Çikatovë e Vjetër to 11.2 mg/kg in Llapushnik. This variability points to regional variations in the distribution of metals, which are probably impacted by regional environmental factors and perhaps human inputs. The amounts of Hg, which ranged from 0.029 to 0.067 mg/kg, were comparatively low. The amounts of Tl in the soil showed a moderate presence, ranging from 0.18 to 0.39 mg/kg. The quantities of Pd were generally low, staying below 0.03 mg/kg at every sampling location. Llapushnik had the highest Sb concentration, which varied from 0.42 to 0.91 mg/kg. The industrial emissions and coal-related activities of central Kosovo basin may be the cause of the comparatively high amounts of arsenic and antimony. Figure 2b shows the amounts of heavy metals found in carrot samples taken from the same regions. The range of arsenic values was roughly 0.035 mg/kg to 0.071 mg/kg, with Llapushnik having the highest value. The amounts of mercury ranged from 0.0038 to 0.0091 mg/kg, which is comparatively low. The concentration of thallium varied slightly throughout the sampling locations, with Çikatovë e Vjetër having the highest value (0.00675 mg/kg). Additionally, palladium concentrations were modest, typically less than 0.01 mg/kg. The range of antimony values was 0.0105 to 0.0318 mg/kg. These findings show that although the quantities are still very low when compared to those found in soil samples, the carrots grown in this region might absorb trace amounts of heavy metals from the soil.

Figure 3a shows the amounts of heavy metals in soil samples taken from the municipality of Fushë Kosovë. The concentrations of arsenic varied from 6.9 mg/kg to 12.1 mg/kg, with Harilaq showing the highest value. The amounts of mercury ranged from 0.033 to 0.072 mg/kg, which is comparatively low. The quantities of thallium in the soil were moderate, ranging from 0.19 to 0.41 mg/kg. All sampling locations had palladium concentrations that were < 0.031 mg/kg. The range of antimony values was 0.46 to 0.95 mg/kg. These findings imply that the municipality's soils also have high levels of antimony and arsenic, which may be a result of industrial influence from adjacent energy producing plants. Figure 3b shows the heavy metal concentrations in carrot samples taken from Fushë Kosovë. Graboc, and Poshtëm had the greatest concentration of arsenic, which varied from 0.027 to 0.052 mg/kg. The range of mercury values was from 0.0055 to 0.0098 mg/kg. In general, thallium quantities were extremely low, and in certain samples, none was found. Additionally, palladium was not found in several test sites, suggesting that carrot plants absorbed very little of it. The range of antimony values was 0.010 to 0.0325 mg/kg. Overall, the findings indicate that, despite modest quantities seen in soil, there is little heavy metal accumulation in carrots.

Figure 4a shows the heavy metal concentrations in the soil samples taken from the Obiliq municipality. Mercury concentrations varied from 0.034 to 0.081 mg/kg, while arsenic concentrations ranged from 7.6 mg/kg to 12.7 mg/kg, with Shkabaj having the highest value. The range of thallium values was 0.21 to 0.44 mg/kg. Although normally modest, palladium concentrations in Shkabaj reached 0.036 mg/kg. Among the municipalities under investigation, antimony contents were among the highest, ranging from 0.48 to 1.02 mg/kg. The higher concentrations in this region could be related to past mining operations and emissions from adjacent lignite-based power units. Figure 4b displays the amounts of heavy metals found in carrot samples taken from Obiliq. Mercury concentrations ranged from 0.0065 to 0.0099 mg/kg, whereas arsenic concentrations ranged from 0.069 to 0.094 mg/kg, with Obiliq having the highest value. The concentrations of thallium varied significantly, with Obiliq having

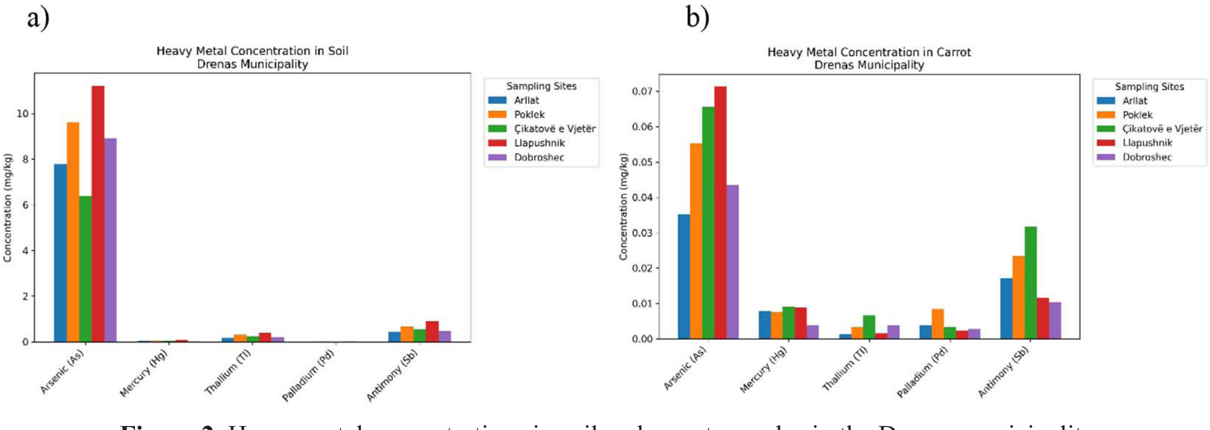

Figure 2. Heavy metal concentrations in soil and carrot samples in the Drenas municipality

a) b)

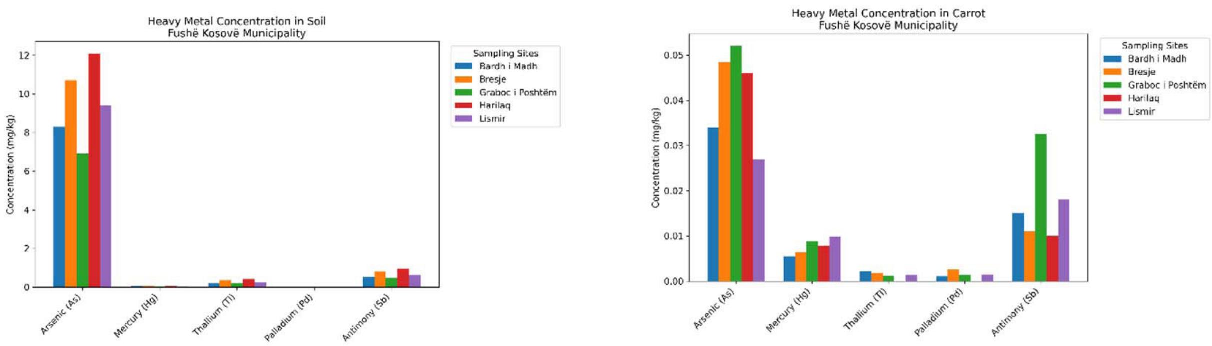

Figure 3. Heavy metal concentrations in the soil and carrot samples in the municipality of Fushë Kosovë

a) b)

Figure 4. Heavy metal concentrations in the soil and carrot samples in the Obiliq municipality.

the highest value (0.01051 mg/kg). In general, palladium concentrations were modest, staying below 0.002 mg/kg. Antimony values ranged from undetectable to roughly 0.04 mg/kg. These findings suggest that, in comparison to other parts of the central region, carrots grown in this municipality may collect higher concentrations of specific metals.

Figure 5a shows the heavy metal concentrations in the soil samples from the Vushtrri municipality. The range of arsenic values was 8.7–12.6 mg/kg. The range of mercury values was 0.039 to 0.083 mg/kg. The range of thallium values was 0.24 to 0.46 mg/kg. All sampling locations had comparatively low palladium values, often less than 0.037 mg/kg. The range of antimony values was 0.49 to 1.05 mg/kg, indicating comparatively high levels in some areas. These numbers imply that local industrial activity may have an impact on the environment. Figure 5b shows the amounts of heavy metals in the carrot samples taken from Vushtrri. The range of arsenic values was from 0.011 to 0.046 mg/kg. Mercury levels stayed comparatively low, often less than 0.004 mg/kg. The range of thallium values was from 0.0028 to 0.0061 mg/kg. Palladium concentrations varied slightly between the sampling locations; Dumnica e Poshtme had the highest value. The range of antimony values was 0.0157 to 0.0345 mg/kg. These results show that carrot plants absorb certain metals at a moderate rate.

Figure 6a shows the heavy metal concentrations in the soil samples from the Podujevë municipality. The range of arsenic contents in the study was 8.5 mg/kg to 13.1 mg/kg, which is among the highest values. The range of mercury values was 0.036–0.087 mg/kg. The range of thallium values was 0.23–0.48 mg/kg. The concentrations of palladium were often less than 0.039 mg/kg. The amounts of antimony varied from 0.49 to 1.08 mg/kg. According to these findings, the soils of Podujevë's have comparatively high levels of a number of heavy metals. Figure 6b shows the heavy metal contents in the carrot samples taken from Podujevë. The range of arsenic values was from 0.012 to 0.025 mg/kg. None of the examined samples contained mercury. The range of thallium values was from 0.0037 to 0.0069 mg/kg. Only a few samples contained palladium, and its amounts were quite low. The range of antimony values was from 0.012 to 0.018 mg/kg. These results show that, in comparison to other parts of central Kosovo, the carrot samples

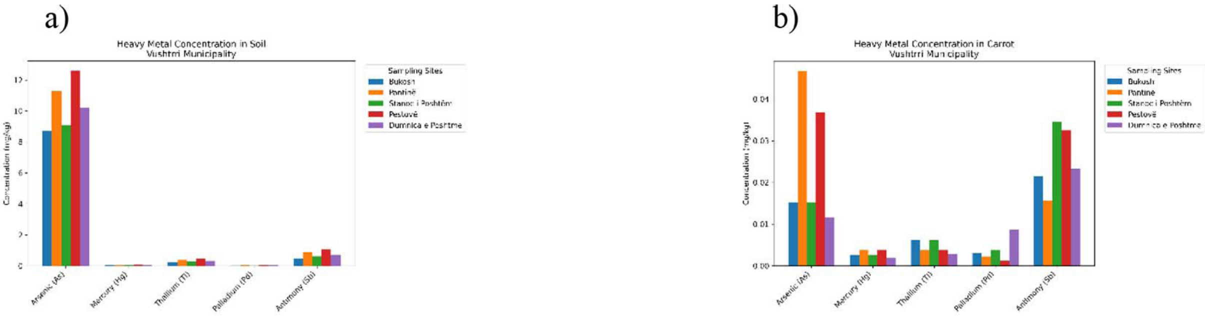

Figure 5. Heavy metal concentrations in the soil and carrot samples in the Vushtrri municipality

from this municipality show comparatively little deposition of heavy metals.

Figure 7a shows the heavy metal concentrations in the soil samples taken from the Dragash municipality. Hg values were comparatively low, ranging from 0.015 to 0.031 mg/kg, whereas As concentrations varied from 3.8 mg/kg to 6.2 mg/kg, with Blaq having the highest value. The amounts of Tl ranged from 0.09 to 0.21 mg/kg, suggesting a comparatively low presence in the soil as compared to the central region of Kosovo. At every sampling location, Pd values stayed below 0.014 mg/kg. The amounts of Sb varied from 0.19 to 0.41 mg/kg. Due to the predominantly agricultural nature of the region and lack of significant industrial sources, the soil samples from Dragash generally showed very low quantities of heavy metals. Figure 7b displays the amounts of heavy metals in the carrot samples taken from Dragash. Only a few sites had arsenic found, with amounts as high as 0.017 mg/kg. Most samples did not contain mercury or thallium. Only Kosavë had palladium (0.018 mg/kg). The amounts of antimony varied from undetectable to roughly 0.017 mg/kg. These results show that there was very little heavy metal buildup in the carrot samples grown in this municipality.

Figure 8a shows the levels of heavy metals in soil samples taken from the Prizren municipality. Mercury concentrations ranged from 0.019 to 0.034 mg/kg, while arsenic concentrations ranged from 4.2 mg/kg to 6.4 mg/kg, with Korishë having the highest value. The range of thallium values was 0.12 to 0.23 mg/kg. All sampling locations had low palladium values, which were typically less than 0.015 mg/kg. The range of antimony values was 0.22 to 0.45 mg/kg. Although they are still lower than those found in the central Kosovo region, these values show a moderate presence of heavy metals in the soil. Figure 8b shows the amounts of heavy metals found in the carrot samples taken from Prizren. The range of arsenic values was from 0.018 to 0.024 mg/kg. The amounts of mercury were generally modest, ranging from about 0.0017 to 0.0075 mg/kg. Palladium concentrations were comparatively greater in some places, especially in Lubizhdë and Gërncar, while thallium concentrations ranged from undetectable levels to about 0.03 mg/kg, with Korishë showing the highest value. Only Korishë and Vlashnje showed antimony concentrations, suggesting that carrot plants only absorbed a small amount of it.

Figure 9a shows the heavy metal concentrations in the soil samples taken from Suharekë

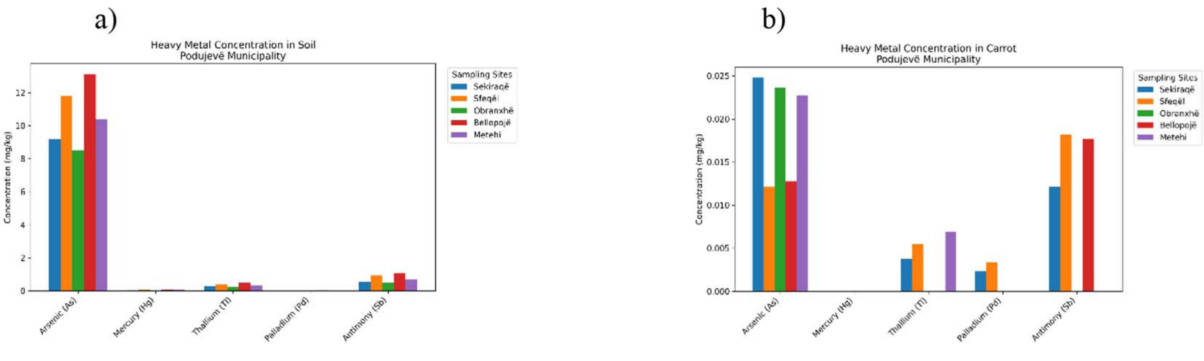

Figure 6. Heavy metal concentrations in soil and carrot samples in the Podujevë municipality are presented

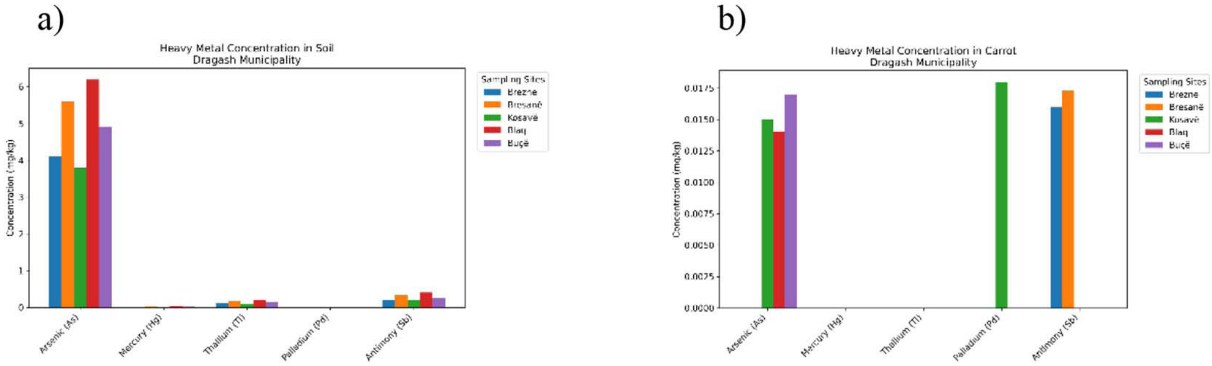

Figure 7. Heavy metal concentrations in soil and carrot samples in the Dragash municipality

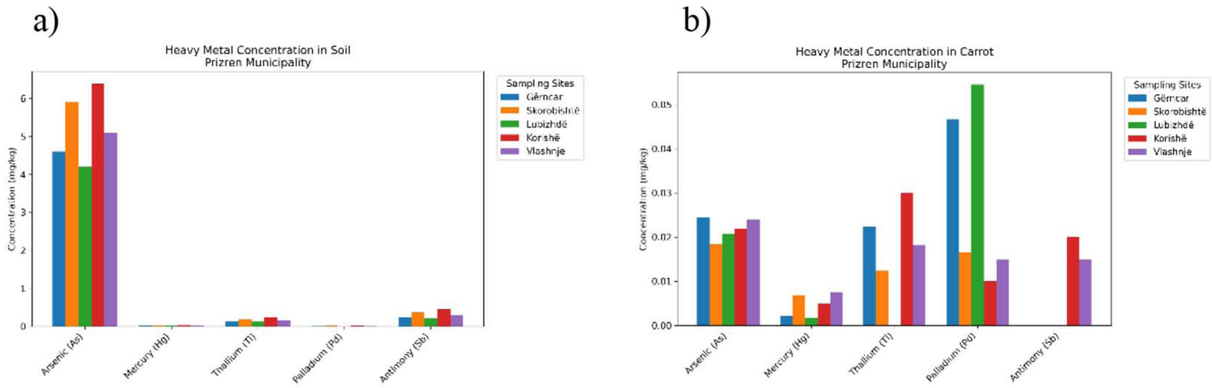

Figure 8. Heavy metal concentrations in soil and carrot samples in the Prizren municipality

municipality. The concentrations of arsenic varied from 4.3 mg/kg to 6.6 mg/kg, with Krushë e Madhe having the highest value. The range of mercury values was 0.018–0.036 mg/kg. The range of thallium values was 0.11–0.24 mg/kg. All of the sampling locations had comparatively low palladium contents. The amounts of antimony varied from 0.23 to 0.48 mg/kg. Although these numbers show moderate levels of heavy metals, they are still much lower than those found in the central part of Kosovo. Figure 9b shows the amounts of heavy metals found in carrot samples taken from Suharekë. The range of arsenic values was roughly 0.011–0.016 mg/kg. Only a small number of samples with extremely low amounts of mercury were found. In the majority of carrot samples, thallium, palladium, and antimony were not found. These findings imply that there is little heavy metal translocation from the soil to the carrot plants in this municipality.

Figure 10a displays the amounts of heavy metals in the soil samples taken from the Rahovec municipality. The range of arsenic values was 4.8–5.6 mg/kg. The range of mercury values was 0.020 to 0.028 mg/kg. The range of thallium values was 0.12 to 0.18 mg/kg. At every sampling location, palladium concentrations stayed comparatively low. The range of antimony values was roughly 0.25 to 0.35 mg/kg. These numbers show that the amounts of heavy metals in the soil are comparatively steady and mild. Figure 10b shows the heavy metal concentrations found in carrot samples taken from Rahovec. The highest value of arsenic was found in Rahovec, and values varied from roughly 0.011 to 0.06 mg/kg. The range of mercury values was between 0.0013 and 0.008 mg/kg, which is relatively low. Between undetectable levels and roughly 0.029 mg/kg, thallium concentrations varied. The amounts of palladium varied from around 0.010 to 0.025 mg/kg. Some samples had antimony contents as high as roughly 0.065 mg/kg, which is the highest amount found in the carrot samples from this area.

Figure 11a displays the heavy metal concentrations in soil samples taken from the municipality of Malishevë. The range of arsenic values was 4.7–5.3 mg/kg. The range of mercury values was 0.020 to 0.027 mg/kg. The range of thallium values was 0.12 to 0.18 mg/kg. At every sampling location, palladium concentrations stayed low. The range of antimony values was

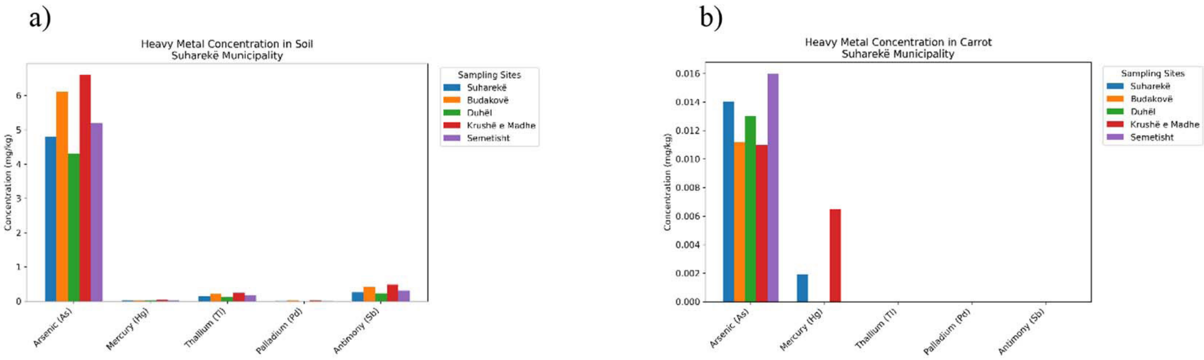

Figure 9. Heavy metal concentrations in soil and carrot samples in the Suharekë municipality

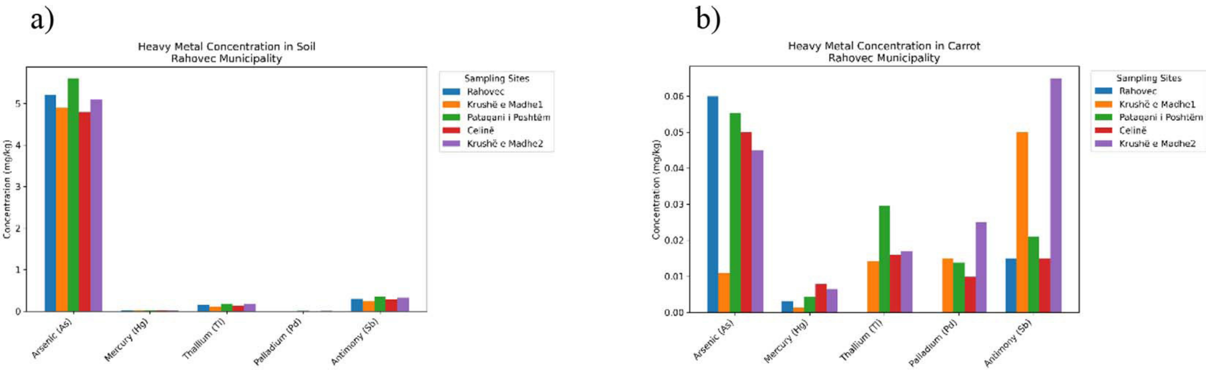

Figure 10. Heavy metal concentrations in soil and carrot samples in the Rahovec municipality

0.25 to 0.33 mg/kg. In comparison to the central Kosovo region, the soil tests from Malishevë generally revealed comparatively low quantities of heavy metals. Figure 11b shows the amounts of heavy metals in the carrot samples taken from Malishevë. The range of arsenic values was from 0.028 to 0.035 mg/kg. The range of mercury values was from 0.0065 to 0.0083 mg/kg. The range of thallium values was from 0.029 to 0.035 mg/kg. The range of palladium values was from 0.012 to 0.03 mg/kg. None of the examined samples contained antimony. These findings show that several heavy metals have accumulated in the carrot samples at low to moderate levels.

Comparative interpretation between regions

Overall, the findings show that compared to the soil samples taken from the Prizren region, those from the central Kosovo region (Prishtina region) have higher quantities of a number of heavy metals. The considerable industrial influence in the central Kosovo basin, especially from coal-fired power stations, lignite mining operations, and other anthropogenic causes, may be the cause of this discrepancy. On the other hand, heavy metal concentrations in soil and carrot samples were generally lower in the Prizren region, which is primarily known for its agricultural land usage and less industrial activity. Additionally, heavy metal buildup in carrot samples was usually minimal in both locations, suggesting that under the environmental conditions under study, there was little transfer of these elements from soil to edible plant tissues. The results are shown as mean ± standard deviation (SD), and all measurements were carried out in triplicate. IBM SPSS Statistics was used for the statistical analysis. One-way analysis of variance (ANOVA) was used to assess differences between sample locations and areas, and post hoc comparisons were performed when necessary. To identify statistically significant differences, a significance level of $p < 0.05$ was used.

Bioaccumulation, dietary exposure, and health risk evaluation of heavy metals in carrots from two regions of Kosovo

Bioaccumulation factor (BAF)

Carrot plants show little accumulation of heavy metals from the soil, according to the

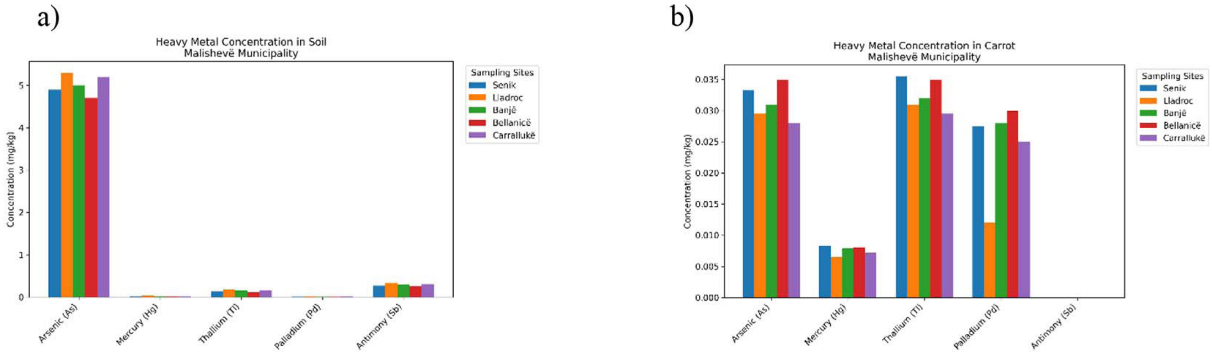

Figure 11. Heavy metal concentrations in soil and carrot samples in the Rahovec municipality

computed BAF values for all metals in the Pristina and Prizren districts. As and Pd had BAF values ranging from 0.0042 to 0.132 in Pristina, whereas Prizren had slightly higher BAF values for Pd (1.78) but low values for other metals (0.0046–0.063) (Tables 1 and 2). These findings imply that carrots are not hyperaccumulators of the studied elements, with the exception of Pd in Prizren. The comparatively increased BAF of Pd could be the result of limited contamination sources or particular soil-plant interactions. Overall, low metal transport from soil to edible carrot tissues is confirmed by BAF values <1. There are a number of reasons for the comparatively high BAF for Pd found in this investigation. First, some elements may have increased transfer efficiency to plants even at low soil concentrations, leading to higher BAF values. BAF is known to be inversely correlated with soil concentration, which means that the elements with low soil concentrations might yet exhibit comparatively high absorption ratios. Second, palladium may be present in soil in more accessible chemical forms, especially when it is associated with organic materials or soluble complexes, which can improve the ability of plant roots to absorb it. Furthermore, the mobility and bioavailability of Pd may be aided by soil physicochemical characteristics as pH, cation exchange capacity, and organic carbon content. Furthermore, because of their close interaction with soil and capacity to absorb metals through their root tissues, root vegetables like carrots are known to have a higher propensity for accumulating trace elements.

Influence of soil physicochemical properties

Soil physicochemical properties such as pH, organic matter, and texture are key factors controlling heavy metal mobility and bioavailability (Campillo-Cora et al., 2025; Chen et al., 2024).

Despite not being explicitly assessed in this study, soil physicochemical characteristics like pH, organic matter content, and texture were taken into consideration based on evidence from the literature about their possible impact on metal mobility and bioavailability. Because of increased adsorption and precipitation processes, neutral to slightly alkaline soils – typical for the central Kosovo region – generally decrease metal mobility, as Table 3 illustrates. Higher levels of heavy metals were found in this area in spite of these circumstances, indicating that human inputs are primarily responsible. On the other hand, the soils of the Prizren region frequently have neutral to slightly acidic conditions, which could improve metal mobility. However, the lower quantities found in the soil and carrot samples suggest that metal uptake is not controlled by mobility alone

Table 1. Pristina region overall average-BAF

Metal	Soil mean (mg/kg)	Carrot mean (mg/kg)	BAF
As	9.96	0.042	0.0042
Hg	0.056	0.0069	0.123
Tl	0.323	0.0038	0.0118
Pd	0.022	0.0029	0.132
Sb	0.742	0.020	0.027

Table 2. Prizren region overall average-BAF

Metal	Soil mean (mg/kg)	Carrot mean (mg/kg)	BAF
As	5.24	0.024	0.0046
Hg	0.025	0.0037	0.148
Tl	0.158	0.010	0.063
Pd	0.009	0.016	1.78
Sb	0.31	0.012	0.039

and that contamination levels are quite low. These results imply that pollution sources, rather than soil physicochemical characteristics alone, are the main factors influencing heavy metal deposition in the locations under study.

Estimated daily intake (EDI)

Due to differences in body weight and food consumption, the EDI values for adults and children show that eating these carrots contributes differently to daily metal exposure. Adults' EDI in the Pristina region varied from 8.3×10^{-2} mg/kg/day for Pd to 1.2×10^{-0} mg/kg/day for As, while children's values were higher, ranging from 1.9×10^{-1} mg/kg/day (Pd) to 2.8×10^{-0} mg/kg/day (As) (Tables 4–5). In a similar vein, children in Prizren routinely showed EDI that was two to three times greater than that of adults, highlighting their heightened susceptibility to dietary metal intake. Because of its comparatively higher abundance in carrots, arsenic continues to be the predominant contributor to food consumption.

Hazard risk index (HRI)

The HRI investigation highlights possible health hazards related to long-term metal exposure through carrot intake. Children showed greater HRI values than adults in both locations, which is consistent with their increased intake in relation to body weight. For example, HRI was 0.40 for adults and 0.93 for children in Pristina, whereas it was 0.53 for children in Prizren (Tables 6–7). Tl and Sb in Prizren also had significant hazardous contributions, with child HRI values of 0.84 and 0.19, respectively. For the majority of metals, HRI values <1 indicate no immediate non-carcinogenic danger; nevertheless, cumulative risk may increase with combined exposure. The lack of an established oral RfD prevented the calculation of palladium HRI.

The cumulative metal exposure dangers are further summarized by the THI values. Children's THI was consistently greater than that of adults; Obiliq had the greatest THI (22.66 for children) and Fushë Kosovë had the lowest (6.70 for children) (Table 8). In every municipality, adults' THI stayed below 10, indicating no risk to health from their present diet. However, children's much higher THI indicates that they are more vulnerable to potentially harmful effects. These findings highlight how crucial it is to keep an eye on the concentrations of heavy metals in food crops, especially in the regions that are contaminated by industry or agriculture.

While other metals showed similar bioaccumulation to Pristina, Prizren demonstrated higher BAF for Pd and Tl across the two regions (Table 9). Children's lower body mass and higher food consumption rates in relation to weight are reflected in the EDI and HRI data, which consistently show higher exposure. The THI reflects the cumulative impact of arsenic's dominating contribution to both EDI and HRI. These results highlight the need for risk management techniques to reduce consumption from edible crops and are in line with research, showing that children are more susceptible to dietary exposure to heavy metals. All things considered, the statistics indicate that although the individual metals present a low to moderate danger, children's cumulative exposure, especially in places like Obiliq and Vushtrri, calls for careful consideration. Potential long-term health impacts can be minimized by implementing monitoring and soil remediation techniques.

Table 10 presents the carcinogenic risk (CR) associated with arsenic exposure through carrot consumption. The calculated CR values ranged

Table 3. Potential influence of soil physicochemical properties on heavy metal mobility and bioavailability (Jiang et al., 2024b; Keshavarzifard et al., 2019; Feraguena et al., 2025)

Region	Expected soil pH	Organic matter	Soil texture	Expected metal mobility	Interpretation based on results
Prishtina Region	Neutral to slightly alkaline	Moderate	Clay–loam	Moderate to low mobility	Higher metal concentrations in soil and carrot samples suggest strong anthropogenic input rather than high mobility
Prizren Region	Slightly acidic to neutral	Moderate to high	Loam–sandy loam	Moderate mobility	Lower metal concentrations indicate limited contamination despite potentially higher mobility
General trend	pH ↑ → mobility ↓	OM ↑ → complexation ↑	Clay ↑ → retention ↑	Varies	Metal uptake is influenced by both soil properties and contamination sources

Table 4. Pristina region overall average EDI (mg/kg/day)

Metal	Adults	Children
As	1.2×10^{-4}	2.8×10^{-4}
Hg	2.0×10^{-5}	4.6×10^{-5}
Tl	1.1×10^{-5}	2.5×10^{-5}
Pd	8.3×10^{-6}	1.9×10^{-5}
Sb	5.7×10^{-5}	1.3×10^{-4}

Table 5. Prizren region overall average EDI (mg/kg/day)

Metal	Adults	Children
As	6.9×10^{-5}	1.6×10^{-4}
Hg	1.1×10^{-5}	2.5×10^{-5}
Tl	2.9×10^{-5}	6.7×10^{-5}
Pd	4.6×10^{-5}	1.1×10^{-4}
Sb	3.4×10^{-5}	7.8×10^{-5}

Table 6. Pristina region overall average HRI

Metal	Adults	Children
As	0.40	0.93
Hg	0.07	0.15
Tl	0.14	0.31
Sb	0.14	0.33

Note: HRI was not calculated for Pd due to the absence of an established oral reference dose (RfD) by international regulatory agencies.

Table 7. Prizren region overall average-HRI

Metal	Adults	Children
As	0.23	0.53
Hg	0.04	0.08
Tl	0.36	0.84
Sb	0.09	0.19

Note: HRI was not calculated for Pd due to the absence of an established oral reference dose (RfD) by international regulatory agencies.

Table 8. Results of THI

Municipality	THI Adult	THI Child
Drenas	3.19	10.01
Fushë Kosovë	2.14	6.70
Obiliq	7.22	22.66
Podujevë	3.12	9.81
Vushtrri	3.69	11.56

from 0.3×10^{-6} to 3.3×10^{-6}. The highest values were observed in Obiliq, while the lowest were recorded in Dragash. All values fall within the acceptable risk range (10^{-6}–10^{-4}), indicating that carrot consumption does not pose a significant carcinogenic risk to the population. The absence of standardized slope factors prevented the inclusion of other elements (Hg, Tl, Pd, and Sb) in the carcinogenic assessment. Although there are noticeable variations based on the degree of industrialization, the heavy metal concentrations found in this study are largely in line with those published in other areas. For example, the levels of arsenic in carrot samples (up to ~0.09 mg/kg in the central Kosovo region) are similar to those found in agricultural regions of China and Turkey, where evidence of moderate contamination associated with human activity has been reported (Singhania et al., 2024). The Prizren region's lower concentrations, on the other hand, are comparable to those seen in less industrialized regions of Spain and Italy, where vegetable heavy metal levels are generally lower because of less industrial impact (Ferré-Huguet et al., 2008). Additionally, investigations carried out in highly industrialized areas, like China's mining regions, have found far greater quantities of arsenic and other heavy metals in vegetables and soil, frequently beyond permissible levels (Yu et al., 2017). The results of this study are still within acceptable bounds and comparatively modest when compared to these investigations. Overall, the study findings classify Kosovo as having moderate pollution, with distinct geographical distinctions between areas that are mostly agricultural and those that are heavily impacted by industry. The observed levels of Hg and As) were compared to globally recognized limits set by the EU Regulation 2023/915 and the Codex Alimentarius Commission. The findings show that there was no immediate risk to consumers because the quantities of these components in carrot samples were below the maximum allowable levels (Table 11) (Garofalo et al., 2025; Fioravanti et al., 2025).

International food safety laws do not specify maximum limits for Tl, Pd, or Sb. As a result, rather than using explicit regulatory thresholds, their assessment in this study was based on comparative analysis and health risk indicators. The lack of regulatory limits for Tl, Pd, and Sb emphasizes the necessity of additional risk assessment and toxicological study.

Table 9. Summary of BAF, EDI, HRI, and THI for adults and children in two regions

Metal	BAF (Region 1)	BAF (Region 2)	EDI adults (mg/kg/day)	EDI children (mg/kg/day)	HRI adults	HRI children	THI adults	THI children
Arsenic (As)	0.047	0.043	0.0045	0.0089	0.75	1.48	1.21	2.41
Mercury (Hg)	0.007	0.008	0.0007	0.0015	0.14	0.28	-	-
Thallium (Tl)	0.003	0.004	0.0004	0.0008	0.10	0.20	-	-
Palladium (Pd)	0.003	0.004	0.0003	0.0006	–	–	-	-
Antimony (Sb)	0.020	0.025	0.0022	0.0045	0.22	0.45	-	-

Table 10. Carcinogenic risk (CR) for arsenic in carrot samples

Region	Municipality	Mean As (mg/kg)	CDI (mg/kg/day)	CR
Prishtina Region	Drenas	0.054	1.5×10^{-6}	2.3×10^{-6}
	Fushë Kosovë	0.041	1.1×10^{-6}	1.7×10^{-6}
	Obiliq	0.079	2.2×10^{-6}	3.3×10^{-6}
	Vushtrri	0.025	0.7×10^{-6}	1.0×10^{-6}
	Podujevë	0.019	0.5×10^{-6}	0.8×10^{-6}
Prizren Region	Dragash	0.009	0.2×10^{-6}	0.3×10^{-6}
	Prizren	0.022	0.6×10^{-6}	0.9×10^{-6}
	Suharekë	0.013	0.3×10^{-6}	0.5×10^{-6}
	Rahovec	0.044	1.2×10^{-6}	1.8×10^{-6}
	Malishevë	0.031	0.9×10^{-6}	1.3×10^{-6}

Table 11. Comparison with food safety limits (carrots)

Metal	This study (max)	Limit (mg/kg)	Standard	Assessment
As	0.094	0.10	EU / Codex	Below limit
Hg	0.0099	0.01–0.02	EU / Codex	Below limit
Tl	0.0105	Not established	—	No standard
Pd	0.0087	Not established	—	No standard
Sb	0.065	Not established	—	No standard

Future research perspectives

In order to provide a more thorough assessment of heavy metal distribution patterns outside of the Prizren and central areas (Prishtina region), future research should strive to expand the spatial scope of the study by incorporating more agricultural regions of Kosovo. To assess temporal fluctuations in metal content in soil and carrot samples, seasonal monitoring is also advised. Given the higher concentrations of elements like As, Sb, Tl, and Hg found in the central region, further research should look into the precise anthropogenic sources – such as industrial processes and agricultural inputs – that are causing this contamination. Furthermore, a wider variety of crops should be included in future research to evaluate species-specific absorption and bioaccumulation behavior, which would enhance our comprehension of food chain transfer in general. For a more precise understanding of plant uptake pathways, soil physicochemical characteristics, and metal bioavailability studies must be included. Finally, in order to give a more realistic assessment of potential dangers, more sophisticated human health risk assessment models that integrate various exposure pathways (ingestion, inhalation, and skin contact) are required. These methods would overcome the shortcomings of the current research and aid in the creation of focused environmental management and monitoring plans.

CONCLUSIONS

The Prizren region and the central Kosovo region (Prishtina region) exhibit distinct spatial disparities in heavy metal contamination, according to this study. As, Sb, Tl, and Hg concentrations were consistently higher in the soils of the central region, probably as a result of significant anthropogenic influence from lignite mining, coal-fired power plants, and industrial operations. Conversely, lower amounts of contamination were found in the Prizren region, which is mostly used for agriculture. The carrot samples from both regions typically had little accumulation despite moderate to elevated metal concentrations in soils, as indicated by low BAF values (<1) for the majority of metals. Pd in the Prizren region was an exception, with higher BAF values indicating localized variables impacting uptake. In general, carrots cannot be categorized as hyperaccumulators of the metals under study. The results of the HRI and EDI show that there are currently no acute non-carcinogenic health concerns for adults from carrot consumption. However, children's EDI and HRI readings were consistently higher, and the main cause of food exposure was found to be arsenic. Values nearing unity, especially for arsenic in children, indicate possible worry under long-term exposure, even though the majority of HRI values remained below the safety threshold (HRI < 1). Additionally, cumulative danger is highlighted by the THI, particularly in localities like Obiliq and Vushtrri where children displayed significantly increased values. This highlights the possibility that exposure to several metals at once could be more harmful to one's health than exposure to just one element. In conclusion, even though the risk of individual heavy metals in carrots is low to moderate, the cumulative exposure – especially for children living in the areas affected by industry – needs to be taken seriously. To reduce long-term health hazards and guarantee food safety, it is advised to apply soil management and remediation measures, monitor the environment continuously, and tighten industrial emissions regulations.

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