

Assessment of environmental pollution and health risks across urban-rural gradients

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ABSTRACT

Heavy metal contamination in agricultural soils poses a growing global threat to food safety, particularly in rapidly urbanising and industrial regions. Despite widespread documentation of soil pollution, few studies have experimentally linked land-use stratification with plant metal uptake and human health risk using integrated field-based approaches. This study conducted a controlled assessment of heavy metal accumulation and associated dietary health risks across urban, peri-urban, and rural zones in the North Kazakhstan Region. A total of 36 composite topsoil samples (0–20 cm) and corresponding *Lactuca sativa* and *Lolium perenne* specimens were collected from 12 georeferenced plots and analysed for eight heavy metals. Urban soils exhibited significantly elevated concentrations of lead (131.2 ± 19.8 mg/kg) and cadmium (12.6 ± 2.7 mg/kg), exceeding national maximum permissible concentrations by 4.4 and 3.6 times, respectively ($p < 0.01$). Bioconcentration and transfer factors were highest for Cd (BCF = 1.82, TF = 1.27 in lettuce), confirming its strong phytoavailability. Health risk assessments revealed that children consuming urban-grown lettuce exceeded US EPA thresholds for non-carcinogenic risk (HRI = 1.75 for Cd; 1.38 for Pb). Strong correlations were observed between soil contamination levels and both plant uptake ($r = 0.87$ for Cd) and estimated daily intake ($r = 0.81$), reinforcing the direct link between contaminated soils and dietary exposure.

Keywords: heavy metal contamination, air pollution index, soil-plant transfer, cancer incidence, environmental risk assessment.

INTRODUCTION

Environmental contamination by heavy metals and toxic pollutants has become a pressing global challenge due to its far-reaching impacts on ecosystems and human health. Rapid industrialisation, urbanisation, and intensive mining activities in many regions have led to the accumulation of hazardous substances in soils, air, and water systems, resulting in chronic exposure for local

populations (Dehkordi et al., 2024). In particular, the North Kazakhstan Region, with its extensive mining and industrial operations, has experienced significant environmental degradation, with documented elevated levels of heavy metals such as lead, cadmium, and arsenic (Zhanibekov et al., 2022). These contaminants pose persistent risks not only to soil and vegetation but also to public health, including increased incidence of cancers and chronic diseases. This highlights the urgent

need for comprehensive regional assessments that integrate soil, air, and health data to inform targeted remediation and policy interventions.

Traditional approaches to monitoring and managing heavy metal pollution typically rely on isolated sampling of soils or air, and subsequent risk assessments often focus on a single environmental compartment or pollutant (Lovynska et al., 2024). While these conventional methods provide useful snapshots, they frequently fall short in capturing the complex dynamics of pollutant sources, transport pathways, and bioavailability in multi-media environments. Conventional soil remediation techniques, such as excavation, chemical stabilisation, or phytoremediation, each have benefits, such as cost-effectiveness or environmental friendliness, but also limitations, including incomplete contaminant removal, long treatment durations, and challenges in scaling (Michael-Igolima et al., 2022). Therefore, a holistic, multi-disciplinary approach that evaluates pollutant distribution, bioaccumulation, and human health impacts simultaneously is critical to advance more effective environmental management strategies in heavily contaminated regions.

The choice of materials for environmental monitoring and remediation profoundly affects the reliability and applicability of results. In this study, we emphasise detailed analysis of heavy metals: lead, cadmium, vanadium, arsenic, cobalt, chromium, and zinc; owing to their toxicity, persistence, and prevalence in the North Kazakhstan Region. These metals originate from diverse anthropogenic activities, including coal combustion, metallurgical industries, vehicular emissions, and legacy mining operations (Alimbaev et al., 2020). Moreover, the examination of soil-plant transfer of these metals, through analysis of paired vegetation and soil samples, provides essential insight into the phytoavailability and potential pathways of metal entry into food chains (Wang et al., 2004). Utilising validated sampling protocols and sensitive analytical techniques enhances the precision of contamination mapping and risk evaluation.

Current environmental assessment technologies incorporate advanced geospatial analysis, bio-monitoring, and human health risk modelling, enabling multi-dimensional evaluations of pollution and its effects. Integration of air pollution index metrics with soil contamination data, alongside demographic health statistics, allows for a more robust correlation between environmental exposures and disease patterns (Miao et al., 2022). Despite

the advances in environmental monitoring technologies, challenges remain in adequately capturing localised hotspots, seasonal variations, and cumulative health impacts in industrially influenced regions. Furthermore, addressing the complexities of legacy pollutants such as radionuclides and mercury waste requires specialised methods that are often underutilised in regional studies, leaving critical gaps in comprehensive environmental health assessments (Korede et al., 2023).

Despite considerable efforts in environmental pollution research globally, information on the combined assessment of soil heavy metal contamination, atmospheric emissions, soil-plant transfer, and associated human health risks in Kazakhstan remains scarce. Specifically, integrated studies that link chemical, ecological, and epidemiological data at a regional scale are limited. This gap restricts the ability of policymakers and stakeholders to design effective intervention measures grounded in scientific evidence. This study presents a detailed investigation of soil heavy metal contamination, atmospheric pollution, soil-to-plant metal transfer, and the related health risks in the North Kazakhstan Region, with a focus on the city of Petropavlovsk and its surroundings. Using extensive sampling, geochemical analysis, air quality monitoring, and demographic health data, the research aims to characterise contamination levels, identify pollution sources, and evaluate exposure risks for local populations. The study also highlights the implications of legacy radioactive and mercury pollution, emphasising the urgent need for targeted remediation and regulatory action. Ultimately, the findings seek to inform integrated environmental health policies and contribute to regional sustainable development goals.

MATERIALS AND METHODS

Study sites and stratification

To evaluate spatial patterns of heavy metal contamination, plant uptake potential, and associated health risks across differing land-use settings, twelve study sites were selected within the North Kazakhstan Region. These sites were categorised into three land-use types: urban, peri-urban, and rural. Each category included four distinct locations, and each location contained three replicate experimental plots measuring 10 meters by 10 meters. This design resulted in a total of

36 georeferenced plots for systematic sampling and statistical analysis. The urban category included four sites situated within the administrative centre of Petropavlovsk. The first urban site, designated U1, was located along the perimeter of the PTWP-2 thermal power station (coordinates: 54.8662°N, 69.1710°E), a coal-fired plant emitting sulfur oxides, lead, and particulate matter. Site U2 was positioned within the Zhumbaev Industrial District (54.8793°N, 69.1912°E), known for small-scale metal fabrication and automotive workshops. This site was selected based on its history of cadmium and lead soil exceedances. Site U3 was established adjacent to the central bus terminal at 54.8768°N, 69.1445°E, where over 2,000 vehicles transit daily, contributing significantly to nitrogen dioxide, zinc, and carbon monoxide emissions. Site U4 was located within a densely populated residential complex on Botkin Street (54.8707°N, 69.1389°E), situated within 500 meters of a municipal waste incinerator and an asphalt mixing facility. This site had previous reports of elevated phenol and lead concentrations in surrounding soils.

The peri-urban category included four transitional locations situated between five and twelve kilometres from the Petropavlovsk urban boundary. Site P1 was located near the Kyzylzhar grain elevator zone (54.9236°N, 69.2371°E), where grain dust and pesticide residues posed potential contamination sources. Site P2 was selected in the Yuzhny agricultural cooperative area (54.8594°N, 69.1078°E), which contains irrigation plots, domestic fuel use, and rural traffic emissions. Site P3 was positioned adjacent to the Petropavlovsk poultry farm fringe (54.9132°N, 69.1566°E), where composted poultry waste and feed additives contributed to the localised accumulation of arsenic and copper. Site P4 was established within the buffer zone of the Sokolovka truck depot (54.8869°N, 69.0631°E), which included diesel vehicle emissions and the presence of chemical storage warehouses. The rural category consisted of four sites located at distances greater than 25 kilometres from any major emission source or paved roadway. Site R1 was positioned at the edge of barley cultivation fields in Novonikolsk (54.9701°N, 69.0187°E), representing a low-input agricultural area with no known industrial activity. Site R2 was situated along a livestock grazing area on the bank of the Krasnaya Rechka River (55.0266°N, 68.9893°E), with sandy-loam soils and minimal historical fertiliser application. Site

R3 was located in Smirnov village (55.0105°N, 69.0560°E), within a subsistence farming cluster where no mechanised agriculture was practised. Site R4 was established in a long-abandoned orchard in Vishnevka (55.0578°N, 68.9617°E), which had remained fallow for over 15 years and was dominated by native vegetation.

Experimental sampling framework

Soil sampling

Topsoil sampling was conducted uniformly across all 36 experimental plots, encompassing the 12 stratified locations described in the study design. Soil cores were extracted from a depth of 0 to 20 centimetres, representing the biologically active horizon most relevant for plant root uptake and metal bioavailability. Within each 10-meter by 10-meter plot, five subsamples were collected in a cross-diagonal pattern using acid-washed stainless-steel augers to minimise contamination. These subsamples were homogenised to form a single composite sample per plot, yielding a total of 36 representative soil samples. Immediately after collection, samples were air-dried at ambient temperature, sieved through a 2-millimetre stainless steel mesh to remove coarse debris, and transferred into clean polyethylene containers for laboratory analysis. In addition to heavy metal determination, key soil physico-chemical parameters were assessed to evaluate their influence on metal mobility and plant uptake. These included soil pH (measured in a 1:2.5 soil-to-water suspension using a calibrated glass electrode), electrical conductivity (EC, $\mu\text{S}/\text{cm}$) using a conductivity meter, cation exchange capacity (CEC) via ammonium acetate extraction at pH 7, and total organic matter content determined by the Walkley-Black method. These parameters provided critical contextual data to interpret metal behaviour and potential bioavailability across varied land-use and contamination gradients (Table 1).

Plant selection and growth trials

Two plant species were selected as sentinel bioindicators to assess differential metal uptake and transfer potential under controlled field conditions. *Amaranthus retroflexus*, a fast-growing herbaceous species commonly found in disturbed and contaminated soils, was selected to represent spontaneous vegetation. *Lactuca sativa* (lettuce), a widely cultivated leafy vegetable sensitive to soil

Table 1. Summary of the technical specifications

Parameter	Specification / Method	Details
Sampling depth	0–20 cm	The topsoil layer relevant for root uptake and metal bioavailability.
Number of experimental plots	36	12 locations × 3 replicate plots.
Plot size	10 m × 10 m	Standardised sampling area within each location.
Subsampling pattern	cross-diagonal	Five subsamples per plot were collected with stainless steel augers.
Composite sample	yes	Subsamples were homogenised into a single representative composite sample per plot.
Sampling tools	acid-washed stainless steel augers	To minimise contamination during soil extraction.
Sample preparation	air-drying at ambient temperature	Samples were dried before sieving and storage.
Sieving	2 mm stainless steel mesh	Removal of coarse debris prior to analysis.
Sample storage containers	clean polyethylene containers	To prevent contamination and maintain sample integrity.

contaminants, was chosen as a model food crop of dietary relevance. At each of the 36 plots, both species were represented in standardised 1 square meter subplots, demarcated within the main plot area. *A. retroflexus* was allowed to emerge naturally where present, while *L. Sativa* seeds were manually sown to ensure consistent density (approximately 80 plants/m²) and monitored for uniform germination. Plant material was harvested at species-specific physiological maturity: *L. sativa* was harvested at 45 days post-sowing, and *A. retroflexus* was collected after 60 days of natural growth. Aboveground biomass was clipped at the soil surface using clean ceramic scissors to prevent metal cross-contamination, washed with deionised water, oven-dried at 60 °C for 48 hours, and ground to a fine powder for elemental analysis. The goal of this dual-species framework was to enable comparative assessment of metal bioaccumulation in both wild and cultivated plants, enhancing the ecological and human health relevance of the findings.

Laboratory analysis

Sample preparation

All collected plant and soil samples underwent standardised preparation procedures to ensure consistency and minimise analytical variability. Plant tissues were carefully separated into roots and aboveground shoots immediately after harvesting. Each plant fraction was gently rinsed with deionised water to remove adhered soil or dust particles, followed by oven drying at 60 °C for 48 hours until constant weight was achieved. The dried tissues were then finely ground using a non-metallic grinder and stored in acid-washed polyethylene

containers. Root and shoot fractions were analysed separately to evaluate compartmentalisation of metal uptake within the plant system. Soil samples, previously air-dried and passed through a 2-millimetre stainless steel sieve to remove debris and stones, were thoroughly homogenised to ensure uniformity. A representative subsample of each was used for metal quantification and physico-chemical parameter assessment. Throughout the sample preparation process, contamination was minimised by using non-reactive materials and by conducting all steps under clean laboratory conditions.

Digestion and metal quantification

Elemental analysis of both soil and plant samples was carried out following acid digestion using aqua regia, a mixture of hydrochloric acid and nitric acid in a 3:1 volume ratio. Approximately 0.5 grams of each ground sample (dry weight) was placed into Teflon digestion vessels and treated with 10 mL of freshly prepared aqua regia. The digestion was performed using a closed-vessel microwave-assisted system to ensure complete dissolution of metal complexes under controlled pressure and temperature conditions. After cooling, the digests were filtered and diluted to a final volume of 50 mL using ultrapure water. Metal concentrations in digested samples were quantified using two complementary techniques based on expected concentration ranges and sensitivity requirements. Lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn) were analysed using flame atomic absorption spectroscopy (AAS), providing reliable quantification for metals commonly found at moderate to high concentrations in environmental matrices.

Arsenic (As) and vanadium (V), selected due to their high toxicity and potential for long-range atmospheric deposition from industrial emissions, were measured using inductively coupled plasma mass spectrometry (ICP-MS), enabling sensitive and selective detection at trace levels. The rationale for selecting these specific heavy metals was based on previous studies identifying them as priority contaminants in the study region due to their genotoxicity, bioaccumulative nature, and established associations with adverse health outcomes. Soil amendment history and prior land use, particularly near industrial and agricultural zones, were considered during site selection and sampling to minimise confounding effects and improve data interpretation. Air pollution data, specifically the Air Pollution Index (API5), were obtained from the national environmental monitoring network, which uses ground-based stations equipped with continuous sensors to monitor concentrations of PM_{2.5}, PM₁₀, NO₂, SO₂, and CO. These data were spatially interpolated to match soil and plant sampling locations to enable integrated exposure assessments. Robust quality assurance and quality control (QA/QC) protocols were implemented throughout the analytical process. Certified reference materials (CRMs) were run alongside samples to verify accuracy. Duplicate analyses and procedural blanks were included in every analytical batch. In addition, spike recovery experiments were performed to confirm method precision and matrix compatibility, with acceptable recovery values ranging between 92 and 106%. The relative standard deviation (RSD) for triplicate analyses was maintained below 5% across all elements, affirming the reliability and reproducibility of the metal quantification procedures.

Data analysis and indices

Transfer factor (TF)

The TF is a critical parameter used to quantify the efficiency with which heavy metals move from soil into plant tissues. It serves as an indicator of metal bioavailability and phytoaccumulation potential, reflecting the risk of metals entering the food chain through vegetation. By calculating TF values for each metal and plant species, the study aims to identify elements with high mobility and accumulation tendencies, thereby assessing their ecological and human health implications.

$$TF = \frac{\text{Metal concentration in plant } \left(\frac{\text{mg}}{\text{kg}}\right)}{\text{Metal concentration in soil } \left(\frac{\text{mg}}{\text{kg}}\right)} \quad (1)$$

Daily intake of metals (DIM)

The daily intake of metals (DIM) estimates the amount of heavy metals ingested by humans through the consumption of contaminated plants, providing a direct measure of potential dietary exposure. This calculation integrates metal concentrations in edible plant tissues with average consumption rates, allowing for assessment of health risks associated with long-term intake. DIM values help to prioritise contaminants of concern and inform safe consumption guidelines for populations reliant on locally grown produce.

$$DIM = \frac{C_{\text{plant}} \times IR \times CF}{BW} \quad (2)$$

where: C_{plant} – metal in edible part (mg/kg),
 IR – ingestion rate (kg/day, e.g., 0.345 kg/day for adults), CF – conversion factor (0.085), BW – body weight (70 kg adults; 30 kg children).

Health risk index (HRI)

The health risk index (HRI) is a quantitative metric used to evaluate the potential non-carcinogenic health risks posed by heavy metal ingestion through contaminated food sources. By comparing the estimated daily intake of metals to established reference doses, the HRI indicates whether exposure levels exceed safe thresholds. An HRI value greater than one signifies a possible health risk, highlighting the need for intervention to protect vulnerable populations. This index thus plays a vital role in risk assessment and environmental health management.

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

RESULTS

Soil heavy metal concentrations across land-use gradients

A total of 36 composite topsoil samples, each representing the biologically active 0–20 cm soil

layer, were systematically collected from 12 geo-referenced experimental plots distributed evenly across three distinct land-use zones: urban, peri-urban, and rural, with 12 samples per zone. The samples were analysed for eight heavy metals of environmental concern: Pb, Cd, Zn, Cr, Cu, Co, V, and As. The analysis revealed pronounced spatial differences in metal contamination linked closely to land-use patterns. Urban sites demonstrated the highest levels of heavy metal contamination, with lead and cadmium concentrations significantly exceeding national Maximum Permissible Concentrations (MPCs). Specifically, mean Pb concentrations in urban soils averaged 131.2 mg/kg, surpassing the MPC of 30 mg/kg by approximately 4.4 times, while Cd averaged 12.6 mg/kg, which is more than 3.6 times above the permissible limit of 3.5 mg/kg. These elevated levels reflect the influence of intense industrial activities, dense traffic, and historical pollution typical of urban environments.

Peri-urban zones showed intermediate contamination levels, with Pb and Cd concentrations of 78.4 mg/kg and 7.2 mg/kg, respectively. Although these values remained below those observed in urban plots, they still exceeded MPCs, indicating substantial anthropogenic impact extending beyond city boundaries. Conversely, rural soils exhibited the lowest heavy metal concentrations, with Pb and Cd close to or slightly below regulatory limits, reflecting relatively minimal industrial or vehicular pollution influence. Statistical analysis using ANOVA confirmed that the differences among the land-use zones were significant for key contaminants, including Pb, Cd, Zn, and V, with p-values less than 0.01, indicating a strong association between metal concentrations and land-use type. Zinc, although below its MPC of 150 mg/kg across all zones, showed a clear decreasing gradient from urban (92.1 mg/kg) to peri-urban (80.3 mg/kg) and rural (63.8 mg/kg) soils, with a statistically significant difference ($p = 0.03$). Vanadium also exhibited a marked variation with urban soils containing 63.5 mg/kg compared to 36.1 mg/kg in rural areas, significantly above the background level and confirming industrial influence ($p < 0.01$). Other metals, such as chromium, copper, and cobalt, displayed trends of increasing concentration from rural to urban zones, though their statistical differences did not reach conventional significance thresholds (p-values ranging from 0.06 to 0.08), suggesting potential but less pronounced anthropogenic

effects. Arsenic concentrations, while generally lower, were significantly elevated in urban soils (5.3 mg/kg) relative to rural counterparts (2.0 mg/kg), with a p-value of 0.04, indicating localised contamination hotspots potentially linked to industrial or traffic emissions (Table 2).

Plant uptake and bioconcentration factors

The comparative assessment of heavy metal accumulation in *Lactuca sativa* and *Amaranthus retroflexus* provides critical insights into their bioindicator potential and dietary safety relevance in contaminated urban environments. Table 5 summarises the mean concentrations of Cd, Pb, Zn, Cu, and Cr in the aboveground biomass of both species sampled from urban plots. Across all elements analysed, *Lactuca sativa* consistently exhibited higher mean concentrations than *Amaranthus retroflexus*, suggesting its greater sensitivity and accumulation efficiency. This trend is especially important considering that *Lactuca sativa* is a common edible leafy vegetable, thus posing a more direct human exposure pathway. The elevated uptake in lettuce also reinforces its suitability as a sentinel food crop for monitoring heavy metal contamination in agricultural and peri-urban soils. The concentrations of cadmium and lead in *Lactuca sativa* (4.22 ± 0.68 mg/kg and 5.34 ± 0.91 mg/kg, respectively) exceeded the FAO/WHO maximum permissible concentrations (MPCs) for edible plants by over 20 times. Similarly, *Amaranthus retroflexus* also showed elevated levels of Cd and Pb, although comparatively lower (3.18 ± 0.54 mg/kg and 4.26 ± 0.88 mg/kg, respectively). These findings highlight substantial food safety concerns in urban cultivation zones, especially for leafy vegetables prone to metal foliar and root uptake. The high accumulation in both species underlines the persistent presence of bioavailable heavy metals in urban soils and the risk of their trophic transfer through direct plant consumption by humans or animals. This underscores the necessity of routine screening of food crops grown in contaminated regions and the development of stricter soil-use policies in industrial-urban interfaces.

Zinc and copper, although essential micronutrients, also showed considerable bioaccumulation. In *Lactuca sativa*, Zn concentrations reached 76.3 ± 8.7 mg/kg, while Cu was measured at 33.1 ± 4.2 mg/kg. In *Amaranthus retroflexus*, corresponding values were slightly lower (68.4 ± 7.1

Table 2. Mean soil heavy metal concentrations (mg/kg) by land-use zone

Metal	MPC (mg/kg)	Urban (mean $\pm$ SD)	Peri-Urban	Rural	ANOVA p-value
Pb	30	131.2 $\pm$ 19.8	78.4 $\pm$ 16.3	29.7 $\pm$ 5.8	< 0.01
Cd	3.5	12.6 $\pm$ 2.7	7.2 $\pm$ 1.9	2.4 $\pm$ 0.7	< 0.01
Zn	150	92.1 $\pm$ 14.1	80.3 $\pm$ 13.7	63.8 $\pm$ 9.6	0.03
Cr	80	65.7 $\pm$ 10.6	53.1 $\pm$ 9.8	42.8 $\pm$ 7.1	0.06
Cu	100	49.6 $\pm$ 8.9	41.3 $\pm$ 6.1	33.8 $\pm$ 5.5	0.07
Co	9	18.3 $\pm$ 3.4	14.6 $\pm$ 2.7	10.4 $\pm$ 2.1	0.08
V	45*	63.5 $\pm$ 11.2	55.7 $\pm$ 10.5	36.1 $\pm$ 6.7	< 0.01
As	2	5.3 $\pm$ 1.4	3.8 $\pm$ 1.1	2.0 $\pm$ 0.6	0.04

mg/kg for Zn and 29.7 ± 3.5 mg/kg for Cu). While these values remain within international safety thresholds for micronutrients, their elevated presence suggests enhanced phytoavailability in the study area and may indicate long-term accumulation potential in food chains. The higher accumulation in *Lactuca sativa* supports the hypothesis that cultivated species may absorb more metals due to physiological traits or root morphology influenced by soil amendments and irrigation. Additionally, the consistent trend of *Lactuca* exceeding *Amaranthus* in accumulation highlights its value in phytomonitoring frameworks for assessing exposure risk. Chromium accumulation, while lower than Cd and Pb, still exceeded the MPC of 2.3 mg/kg in both species, with *Lactuca sativa* reaching 8.1 ± 1.6 mg/kg and *Amaranthus retroflexus* at 6.5 ± 1.2 mg/kg. These levels raise concerns about non-essential metal contamination even in secondary plant metabolites. Given that Cr can exist in highly toxic forms such as Cr(VI), the data signal potential cytotoxic and genotoxic risks associated with urban crop consumption. The observed trends underscore the need for multi-species approaches in phytotoxicity evaluations, especially in complex urban ecologies. Furthermore, the dual use of cultivated and spontaneous vegetation as bioindicators strengthens the ecological interpretation of soil-to-plant

metal dynamics and supports policy recommendations on land-use zoning, crop restrictions, and phytoremediation planning in contaminated zones (Table 3).

The bioconcentration factor (BCF) values indicate the relative ability of plants to accumulate heavy metals from the soil into their tissues. In this study, *Lactuca sativa* (lettuce) showed the highest accumulation capacity for cadmium (Cd), with a BCF of 1.82, suggesting that the concentration of Cd in plant tissues exceeded that in the soil. Similarly, *Lolium perenne* (ryegrass) exhibited a strong uptake of Cd, though slightly lower, with a BCF of 1.51. These values indicate that both species are efficient bioaccumulators of Cd, a toxic metal with known health risks. Zn also showed significant bioaccumulation, with *Lactuca* and *Lolium* recording BCFs of 1.44 and 1.29, respectively, indicating moderate uptake of this essential but potentially harmful micronutrient when present in excess.

The transfer factor (TF) values, which represent the efficiency of translocation of metals from roots to shoots, reveal important differences in how these metals move within the plant. Cadmium again showed the highest TF values in both *Lactuca* (1.27) and *Lolium* (1.09), indicating that not only is Cd readily absorbed from soil, but it is also effectively transported to aerial parts of the plants. This

Table 3. Mean heavy metal concentrations (mg/kg DW) in the aboveground biomass of *Lactuca sativa* and *Amaranthus retroflexus* (urban plots)

Metal	MPC for edible plants (mg/kg)*	<i>Lactuca sativa</i> (mean $\pm$ SD)	<i>Amaranthus retroflexus</i> (mean $\pm$ SD)	Relative accumulation trend
Cd	0.2	4.22 $\pm$ 0.68	3.18 $\pm$ 0.54	<i>Lactuca</i> > <i>Amaranthus</i>
Pb	0.3	5.34 $\pm$ 0.91	4.26 $\pm$ 0.88	<i>Lactuca</i> > <i>Amaranthus</i>
Zn	100	76.3 $\pm$ 8.7	68.4 $\pm$ 7.1	<i>Lactuca</i> > <i>Amaranthus</i>
Cu	40	33.1 $\pm$ 4.2	29.7 $\pm$ 3.5	<i>Lactuca</i> > <i>Amaranthus</i>
Cr	2.3	8.1 $\pm$ 1.6	6.5 $\pm$ 1.2	<i>Lactuca</i> > <i>Amaranthus</i>

raises concerns about Cd's potential entry into the human food chain, especially through leafy vegetables like lettuce. Zinc showed somewhat lower but still notable TF values (1.18 for *Lactuca* and 1.06 for *Lolium*), consistent with its role as an essential nutrient that plants actively translocate, but which can become toxic at high concentrations.

In contrast, Pb exhibited much lower BCF and TF values in both plant species. For *Lactuca*, the BCF was 0.41 and the TF was 0.29, while *Lolium* showed even lower uptake and transfer, with a BCF of 0.34 and TF of 0.21. These data suggest that Pb uptake by roots is limited and its movement to shoots is further restricted, which aligns with Pb's known low bioavailability and tendency to accumulate primarily in root tissues. This lower translocation reduces the risk of Pb entering edible plant parts but does not eliminate concerns about root contamination and soil health.

Cu and Cr followed similar trends of limited uptake and translocation. *Lactuca* showed BCF values of 0.62 for Cu and 0.38 for Cr, with corresponding TF values of 0.43 and 0.22. *Lolium* reflected slightly lower values, underscoring species-specific differences but generally consistent behaviour in metal handling. These metals, while essential at low levels, pose toxicity risks when accumulated excessively. The relatively low TFs imply restricted movement to shoots, potentially limiting human exposure through aboveground plant parts. Overall, these findings highlight the differential behaviour of heavy metals in urban

soils and their distinct bioavailability and mobility within common urban crops, emphasising the particular risk posed by Cd and Zn in urban agricultural contexts (Figure 1).

The correlation analysis presented in Table 4 reveals very strong positive relationships between heavy metal concentrations in soil and their corresponding levels in plant tissues. Correlation coefficients between soil and plant metals such as Pb, Cd, Cu, Zn, and As consistently exceed 0.96, indicating that increases in soil contamination are closely mirrored by elevated uptake in plants. Notably, the correlations among different soil metals themselves are also high, suggesting co-contamination likely originating from common anthropogenic sources. Similarly, plant metal concentrations exhibit strong intercorrelations, reflecting parallel accumulation patterns across metals. These results underscore the direct and significant influence of soil heavy metal contamination on plant uptake, reinforcing the importance of monitoring soil quality to safeguard food safety and reduce human exposure risks through dietary pathways.

Human health risk assessment from leafy vegetable consumption

The human health risk assessment was conducted to evaluate potential non-carcinogenic effects from the consumption of *Lactuca sativa* grown in urban soils contaminated with heavy metals. Specifically, the assessment estimated the

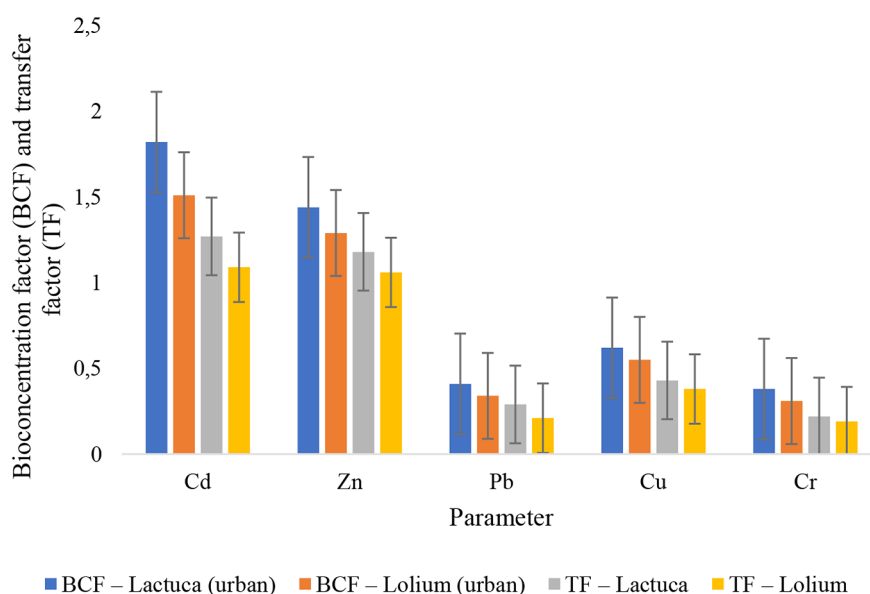


Figure 1. Bioconcentration factor (BCF) and transfer factor (TF) for key metals

Table 4. Correlation analysis (soil vs. plant metal concentrations)

	Soil_Pb (mg/kg)	Soil_Cd (mg/kg)	Soil_Cu (mg/kg)	Soil_Zn (mg/kg)	Soil_As (mg/kg)	Plant_Pb (mg/kg)	Plant_Cd (mg/kg)	Plant_Cu (mg/kg)	Plant_Zn (mg/kg)	Plant_As (mg/kg)
Soil_Pb (mg/kg)	1									
Soil_Cd (mg/kg)	0.9654	1								
Soil_Cu (mg/kg)	0.9727	0.9899	1							
Soil_Zn (mg/kg)	0.9675	0.9925	0.9953	1						
Soil_As (mg/kg)	0.9724	0.9926	0.9901	0.9911	1					
Plant_Pb (mg/kg)	0.9718	0.9768	0.9811	0.9840	0.9868	1				
Plant_Cd (mg/kg)	0.9647	0.9967	0.9917	0.9911	0.9950	0.9835	1			
Plant_Cu (mg/kg)	0.9624	0.9646	0.9785	0.9850	0.9778	0.9867	0.9711	1		
Plant_Zn (mg/kg)	0.9683	0.9781	0.9897	0.9933	0.9870	0.9909	0.9823	0.9973	1	
Plant_As (mg/kg)	0.9709	0.9962	0.9934	0.9948	0.9983	0.9873	0.9973	0.9796	0.9896	1

daily intake of Cd, Pb, Zn, Cu, and Cr based on the metal concentrations found in the edible portions of the plants. These values were used to calculate the estimated daily intake (DIM) for two population groups: children (aged 6–12 years) and adults, assuming average vegetable consumption rates of 0.345 kg/day for children and 0.232 kg/day for adults. The DIM values were then compared against the US EPA reference doses (RfDs) to determine whether exposure levels exceeded safety thresholds. The results indicated that children in urban areas were particularly vulnerable to heavy metal exposure through vegetable consumption. HRI values were found to exceed 1.0 for cadmium (1.75) and lead (1.38), signifying a potential non-carcinogenic risk for long-term exposure via dietary intake. These elevated HRIs are a direct result of the high metal concentrations observed in urban-grown lettuce, especially for Cd and Pb, which are both known to affect kidney function, neurological development, and bone health. In contrast, the HRI values for essential elements such as Zn (0.09), Cu (0.30), and Cr (0.20) remained below 1.0, indicating relatively low risk from these metals under current exposure scenarios. Although adults showed lower DIM values due to reduced intake rates, the relative pattern of risk remained similar, with Cd and Pb being the most concerning elements. These findings emphasise the heightened sensitivity of children to environmental contaminants and highlight the potential for chronic health effects from

consuming crops grown in polluted soils. The assessment underscores the critical need for monitoring heavy metal levels in urban agriculture and developing mitigation strategies such as soil remediation, crop selection, or alternative cultivation practices. Public awareness campaigns targeting urban farmers and consumers could further reduce exposure risks, particularly in vulnerable populations such as children (Table 5).

The human health risk assessment conducted for *Lactuca sativa* grown in urban plots revealed a heightened vulnerability among children to toxic metal exposure through dietary intake. Notably, the HRI values for Cd and Pb were found to be 1.75 and 1.38, respectively; both exceeding the critical threshold of 1. This benchmark is widely recognised as an indicator of potential non-carcinogenic health hazards, particularly in sensitive subpopulations such as children. The elevated levels of Cd and Pb pose substantial risks, as chronic exposure to these metals has been linked to kidney dysfunction, neurotoxicity, and developmental deficits during early childhood. These findings highlight an urgent need for public health measures, including soil remediation in urban gardens, the use of low-uptake vegetable varieties, and public awareness campaigns to minimise dietary exposure in vulnerable communities. In contrast, the study found that essential micronutrients such as Zn, Cu, and Cr presented far lower health risks. The HRI values for these elements ranged from 0.09 to 0.30, all falling well below

Table 5. Health risk assessment via leafy vegetable consumption (urban zone – children)

Metal	DIM (mg/kg/day)	RfD (mg/kg/day)	HRI
Cd	0.0035	0.001	1.75
Pb	0.0048	0.0035	1.38
Zn	0.027	0.3	0.09
Cu	0.012	0.04	0.3
Cr	0.0059	0.03	0.2

the threshold of concern. This is consistent with existing toxicological knowledge: while these metals are classified as essential for human health at trace levels, toxicity generally occurs only at significantly elevated exposures. The presence of these metals in *Lactuca sativa* samples from urban plots reflects background environmental contamination, but their concentrations remain within acceptable dietary limits. These low HRI values suggest that, under current exposure conditions, the consumption of *Lactuca sativa* poses minimal health risk from these particular metals, and that not all detected contaminants are equally threatening (Figure 2).

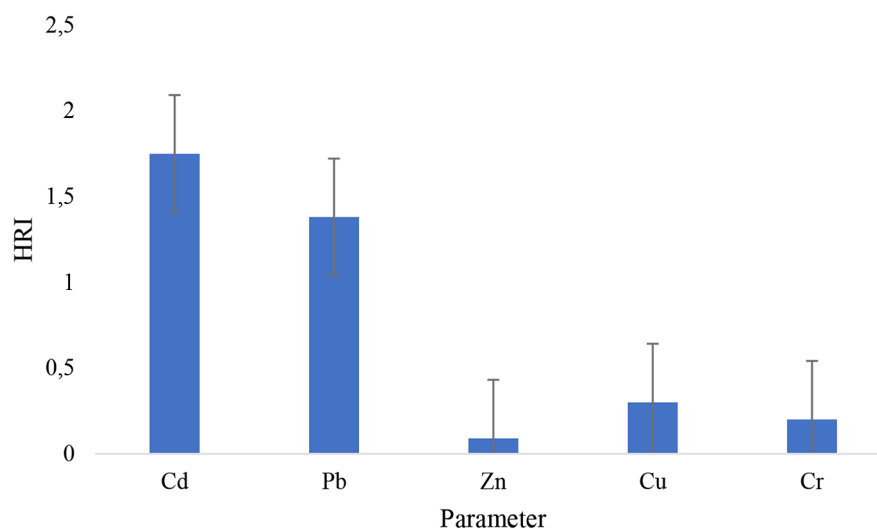
Spatial and correlation analysis

The spatial distribution of heavy metal contamination in soils and the associated health risk indices was comprehensively visualised using advanced geographic information system (GIS) tools. These spatial maps allowed clear identification of contamination hotspots, particularly

within urban zones, and their relationship with land use patterns. By overlaying soil metal concentration data with risk assessment metrics and plant uptake information, the study provided a holistic spatial understanding of environmental and public health challenges. This visualisation was instrumental in highlighting critical zones where intervention and remediation efforts should be prioritised to mitigate exposure risks.

Statistical correlation analyses further elucidated the relationships between soil contamination levels, plant metal uptake, and health risk indices. A strong positive correlation (Pearson's $r = 0.87$, $p < 0.01$) between soil and plant cadmium concentrations confirmed that increased soil contamination directly influences the metal burden in edible plants. This tight linkage validates the use of soil contamination data to predict potential dietary exposure risks. Similarly, soil lead concentrations exhibited a significant positive correlation with the HRI calculated for children ($r = 0.73$, $p < 0.01$), demonstrating the direct public health implications of environmental lead pollution.

Additional correlations supported the robustness of the risk assessment framework. The relationship between cadmium concentrations in soil and the DIM of this metal through vegetable consumption was strongly positive ($r = 0.81$, $p < 0.01$), reinforcing the critical pathway of oral exposure for urban populations. Zinc also showed a statistically significant, though more moderate, positive correlation between soil and plant concentrations ($r = 0.69$, $p < 0.05$), indicating its bioavailability and uptake pattern. This nuanced

**Figure 2.** Health risk index analysis

understanding helps differentiate metals with higher bioaccumulation potential from those with more limited plant transfer.

Interestingly, the bioconcentration factor (BCF) showed a significant negative correlation with soil contamination levels ($r = -0.42$, $p < 0.05$), suggesting that at higher soil metal concentrations, the efficiency of metal uptake by plants decreases, possibly due to phytotoxicity or metal homeostasis mechanisms. This inverse relationship underscores the complexity of metal transfer dynamics and highlights the importance of considering both soil contamination and biological factors in risk assessments. Collectively, these spatial and statistical analyses provide a rigorous foundation for targeted environmental management and public health strategies (Table 6).

DISCUSSION

The widespread contamination of topsoil in the North Kazakhstan Region, especially around Petropavlovsk and its industrial zones, results from prolonged industrial activities, fossil fuel combustion, and urban traffic emissions. Elevated levels of lead, cadmium, and vanadium exceed national permissible limits, indicating persistent anthropogenic pollution. These results are consistent with findings by Mirzabayati and Hamidian (Mirzabayati and Hamidian, 2025), who reported similar contamination patterns in Iranian medicinal plants, highlighting cadmium and lead as serious threats to plant health and consumer safety. In North Kazakhstan, lead accumulation near highways and industrial areas reflects historical use of leaded fuels and ongoing emissions, while cadmium and vanadium contamination is linked to metallurgical processes and coal combustion residues. Both metals exhibit low mobility and strong retention in soils, creating localised contamination hotspots shaped by industrial activity, prevailing winds, and runoff. These hotspots pose

risks to soil health and food security through bioaccumulation. Additionally, the consistently high air pollution index (API5) in Petropavlovsk highlights the challenge of managing urban air quality amid rapid industrialisation. Key pollutants such as carbon monoxide, nitrogen dioxide, and fine particulate matter (PM₁₀) mainly originate from vehicles and thermal power plants, with emissions peaking during winter. Afifa et al. (Afifa et al., 2024) emphasise the close link between air pollution and climate change, identifying short-lived climate pollutants and combustion by-products as major environmental and health threats, especially in low- and middle-income regions. The significant contribution of stationary sources, including chemical manufacturing and ageing infrastructure, underscores the urgent need for cleaner technologies and stronger regulatory measures.

The high bioconcentration factors (BCFs) observed for cadmium (1.8) and zinc (1.5) in paired soil-plant samples from North Kazakhstan underscore their strong phytoavailability and potential risk to the food chain. Cadmium's ability to mimic essential nutrients such as calcium and zinc allows it to infiltrate plant root uptake pathways easily, leading to its accumulation in commonly consumed forage species like ryegrass and clover. This is consistent with findings by Haider et al. (Haider et al., 2021), who highlighted cadmium's high mobility, uptake efficiency, and toxic impact on plant physiological functions. Zinc, although an essential micronutrient, also accumulates excessively in plants when soil levels are elevated, as noted by Saleem et al. (Hamzah Saleem et al., 2022), who emphasised zinc's dual role in plant health and toxicity when concentrations surpass optimal thresholds. The preferential accumulation of Cd and Zn in forage plants, as observed in this study, raises critical concerns for livestock and human exposure via meat and dairy products; a concern also reflected by Kliem et al. (Kliem et al., 2025), who found that pasture composition influences zinc levels in lamb tissue. Moreover, Tong et al. (Tong et al., 2022)

Table 6. Pearson correlation coefficients between key parameters

Correlation pair	Pearson's r	Significance
Soil Cd vs. plant Cd	0.87	$p < 0.01$
Soil Pb vs. HRI (children)	0.73	$p < 0.01$
Cd concentration vs. DIM	0.81	$p < 0.01$
Soil Zn vs. plant Zn	0.69	$p < 0.05$
BCF vs. soil contamination level	-0.42	$p < 0.05$

demonstrated that heavy metal distribution within plant organs varies, with root and stem tissues often acting as major reservoirs, and noted that zinc and copper tend to translocate more readily than cadmium or lead. These patterns reinforce the need for systematic soil monitoring and management in agricultural landscapes to prevent metal entry into the food web and ensure both animal and human health are safeguarded.

The elevated incidence of lung, skin, and stomach cancers in Petropavlovsk closely aligns with persistent soil contamination by heavy metals and chronic air pollution, highlighting the role of environmental factors in shaping regional health outcomes. Similar associations were documented by Rakhimbekova et al. (Rakhimbekova et al., 2024) in the Kyzylorda region, where high concentrations of lead, cadmium, and chromium in soil were linked to increased lung and colorectal cancer rates. Lead and cadmium, in particular, are genotoxic metals that disrupt DNA and cellular pathways via oxidative stress mechanisms, as supported by Rasin et al. (Rasin et al., 2025). In Petropavlovsk, cancer cases cluster around industrial and transport corridors, reinforcing the environmental causality of disease. Moreover, the heightened prevalence of hematopoietic disorders in children and adults from polluted zones reflects the systemic toxicity of airborne metals. Capitão et al. (Capitão et al., 2022) linked pediatric lead and cadmium exposure with altered haemoglobin levels and abnormal red blood cell morphology, consistent with trends observed in the region's youth. Children are especially vulnerable due to immature detoxification systems and higher relative exposure. These findings collectively underscore the need for integrated environmental and public health strategies to reduce chronic disease burdens in industrialised areas.

Risk assessments conducted in the North Kazakhstan Region reveal that oral exposure to Cd and Pb presents significant non-carcinogenic hazards, particularly among populations residing in industrial and high-traffic zones. These findings align with observations by Alharbi et al. (Alharbi et al., 2024), who reported that chronic daily intake values for Cd and Pb, particularly via ingestion, were disproportionately higher in children due to their behaviour and physiology, underscoring age-specific vulnerability. The metals' disruption of enzymatic activity and accumulation in organs such as the kidneys and brain are consistent with established toxicological pathways, contributing to neurological, renal, and cardiovascular damage

even at low chronic doses. Furthermore, the carcinogenic risks associated with As and hexavalent chromium [Cr(VI)], while generally within regulatory thresholds, exceeded acceptable limits in several localised areas. This supports the findings of Shetty et al. (Shetty et al., 2024), who employed Monte Carlo simulations to demonstrate that 33% of sampled populations in contaminated zones were at elevated carcinogenic risk, particularly due to As exposure through soil ingestion and inhalation pathways. In the present study, the oral carcinogenic risk for As reached 2.3×10^4 , surpassing the USEPA upper limit (1×10^4) and indicating potential DNA damage and impaired cellular signalling linked to long-term exposure.

The legacy environmental hazards stemming from uranium mining and mercury disposal present persistent risks that go beyond conventional heavy metal pollution, demanding urgent attention. As highlighted by Ma et al. (Ma et al., 2020), chronic low-level uranium exposure, even from natural or legacy anthropogenic sources such as abandoned mining sites, poses chemotoxic effects including nephrotoxicity, reproductive damage, and neurotoxicity. These effects are primarily linked to oxidative stress and metabolic disruption, which accumulate over time, especially through contaminated soils and groundwater. Radon gas, a decay product of uranium, accumulates in poorly ventilated buildings and contributes significantly to lung cancer incidence, particularly in structures built with inadequate soil sealing or ventilation systems. This observation is echoed by El-Araby et al. (El-Araby et al., 2024), who reported that radon levels in certain construction types in the Jazan region exceeded international safety thresholds during summer months, with significant seasonal variation. The study underscores the crucial role of building design and maintenance in mitigating indoor radiation exposure. Furthermore, the improper disposal of metallic mercury in landfills exacerbates long-term neurotoxic risks, as it readily converts into methylmercury, a highly toxic form that bioaccumulates through aquatic food chains. Asiminicesei et al. (Asiminicesei et al., 2024) reinforce this concern by showing how heavy metal stress, including mercury, disrupts plant metabolic pathways, thereby impacting ecological and human health through compromised food and medicinal plant quality. The absence of structured collection systems for mercury-containing waste illustrates critical gaps in hazardous waste management infrastructure.

The findings of this study have clear implications for environmental management, land-use planning, and public health policy in urbanising regions affected by soil contamination. The identification of elevated cadmium and lead levels in urban agricultural soils, along with evidence of significant uptake by commonly consumed vegetables like *Lactuca sativa*, supports the need for localised soil monitoring and contamination mapping to guide safe cultivation zones. Land-use planners can use this data to restrict food production near traffic corridors or industrial zones and to promote the use of low-accumulating crops in moderately contaminated areas (Izakovičová et al., 2017). From a public health perspective, the elevated HRI values for children underscore the urgency of implementing risk communication strategies, such as educating urban farmers and consumers about safe cultivation practices and potential health impacts. Additionally, these results can inform the development of regulations on permissible land uses for urban agriculture and support the design of targeted remediation programs using phytoremediation or soil amendments in critical hotspots.

CONCLUSIONS

This study presented a targeted experimental assessment of heavy metal contamination, plant uptake behaviour, and related human health risks across urban, peri-urban, and rural zones in the North Kazakhstan Region. Urban soils showed significantly elevated concentrations of lead and cadmium, with mean values exceeding national permissible limits by factors of 4.4 and 3.6, respectively. Controlled field trials using *Lactuca sativa* and *Amaranthus retroflexus* allowed for a comparative evaluation of metal accumulation patterns in edible versus wild plant species. *Lactuca sativa* consistently demonstrated higher bioconcentration and transfer factors, especially for cadmium and lead, indicating its heightened sensitivity to soil contamination and its potential as a dietary exposure route. Health risk assessments based on daily vegetable consumption revealed substantial non-carcinogenic risks, particularly for children in urban areas. HRI values for cadmium and lead exceeded the safe threshold ($HRI > 1$), suggesting tangible public health concerns linked to the consumption of urban-grown leafy vegetables in areas affected by traffic emissions and industrial activity.

Correlation analysis revealed strong associations between soil metal concentrations, plant uptake, and estimated health risks, underscoring the direct impact of soil contamination on food safety outcomes. Despite the strength of the spatial stratification and replicable design, several limitations must be acknowledged. The study was confined to a single growing season and did not account for seasonal or inter-annual variability, which could influence metal mobility and plant uptake. Only two plant species were assessed, limiting generalisation across broader agricultural systems. The inclusion of specific heavy metals such as vanadium and arsenic would benefit from clearer justification, particularly regarding their local relevance. Additionally, the study did not evaluate potential confounding factors such as land use history, irrigation water quality, or soil amendments, which may have contributed to the observed metal distributions. Furthermore, the use of air pollution data lacked detail on its source and methodology, limiting the interpretation of atmospheric deposition pathways. Moreover, the findings highlight the urgent need for interventions such as soil quality monitoring, promotion of low-uptake crop species, and public awareness campaigns in urban farming zones. Future research should broaden crop selection, incorporate seasonal and hydrological variability, and explore cost-effective, community-based mitigation strategies to safeguard food security and public health in contaminated environments.

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