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Spatial zoning of the territory of Almaty City based on the concentration and level of heavy metal contamination of soils

Gulzhanat Mukanova[1], Batyrgeldy Shimshikov[1], Zulfiya Tukenova[1], Tursunkul Bazarbaeva[1], Bayan Tussupova[1]*, Aitu Oshakbay[1], Kudaibergen Kyrgyzbay[2], Uldarina Amangaziyeva[1]

1. UNESCO Chair for Sustainable Development, Faculty of Geography and Environmental Sciences University, Al-Farabi Kazakh National University, Almaty, Kazakhstan

2. Department of Cartography and Geoinformatics, Faculty of Geography and Environmental Sciences, Al-Farabi Kazakh National University, Almaty, Kazakhstan

* *Corresponding autor′ E-mail: tussupova@yandex.ru*

ABSTRACT

Almaty, the largest city in Kazakhstan, has a long history of industrial activity and heavy traffic, yet no systematic assessment of soil heavy metal contamination has ever been conducted across the entire urban territory. To fill this gap, we collected 412 soil samples from the top 0–10 cm layer between April and September 2025, covering all administrative districts of Almaty on a 1 km × 1 km grid. Concentrations of lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), and chromium (Cr) were measured using ICP-OES after aqua regia digestion. Background values were established from 25 reference sites outside the city. The results show wide spatial heterogeneity: Pb ranged from 4.2 to 347.8 mg kg^{-1} (mean 48.6), and Cd from 0.05 to 3.92 mg kg^{-1} (mean 0.64). Strong positive correlations among Pb, Cd, Zn, and Cu (r = 0.69–0.84, $p < 0.001$) indicate common anthropogenic sources, while Cr showed only moderate enrichment (median enrichment factor 1.2). Using the threshold of background mean + 2SD, we classified the city into four zones: Class I (clean, 33% of area), Class II (moderate, 38%), Class III (high, 22%), and Class IV (very high, 7%). Very high zones are concentrated in the northern industrial belt and near the former battery plant, where Pb averaged 124.5 mg kg^{-1} and Cd 1.92 mg kg^{-1}, close to Kazakh maximum allowable concentrations. Industrial areas and old residential districts displayed significantly higher contamination than new residential zones ($p < 0.001$). This study provides the first evidence-based soil contamination map for Almaty, enabling targeted remediation, urban planning, and public health interventions.

Keywords: Heavy metal contamination, Soil zoning, Almaty, Urban geochemistry.
Article type: Research Article.

INTRODUCTION

Almaty is the largest city in Kazakhstan, home to more than two million people who live, work, and raise their children in an environment shaped by decades of industrial activity, heavy traffic, and a unique geographical setting at the foot of the Zailiysky Alatau Mountains. The city grew rapidly during the Soviet era as a centre for manufacturing, food processing, and light industry. Factories, thermal power plants, and a sprawling network of roads were built without much consideration for how their emissions would accumulate in the soil. Today, many of those industries have changed or closed, but the metals they released, lead, zinc, cadmium, copper, and chromium, remain behind (Armanyous *et al.* 2015; Othman *et al.* 2018; Egamberdiyev *et al.* 2025; Salman *et al.* 2025). They do not decompose or wash away easily. Instead, they sit in the ground, slowly moving through the food chain, into dust that children breathe, and into vegetables grown in backyard gardens (Sun *et al.* 2019; Zhang

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et al. 2020). The problem of heavy metal contamination is not unique to Almaty, but the city has several characteristics that make it particularly vulnerable. First, the prevailing winds carry pollutants from the industrial northern districts toward the densely populated southern and central areas (Odukoya *et al.* 2016; Yang *et al.* 2023). Second, the mountainous terrain creates temperature inversions, especially in winter, that trap polluted air close to the ground; when that air settles, so do the particles carrying metals. Third, many residents still rely on private wells and grow their own food on small plots within the city limits. Unlike a regulated agricultural area, these household gardens are never tested for heavy metals (Ngole-Jeme & Fantke, 2017; Custodio *et al.* 2020; Umirqulova *et al.* 2025).

A family living near a former battery recycling site might eat tomatoes and carrots grown in soil that contains dangerous amounts of lead without ever knowing it. This gap between official monitoring and everyday reality is one of the reasons we decided to carry out this study. From a public health perspective, the stakes are high. Lead exposure damages children's developing brains, reduces IQ, and increases the risk of behavioural problems. Cadmium accumulates in the kidneys and bones, staying in the body for decades. Chromium in its hexavalent form is a known carcinogen (Tian *et al.* 2022; Wang *et al.* 2023). Even at levels that do not cause immediate poisoning, chronic exposure to a mixture of metals can produce subtle but serious effects on the nervous system, the kidneys, and the cardiovascular system. In Almaty, paediatricians have noted increasing numbers of children with unexplained developmental delays, yet no one has systematically linked these observations to soil contamination (Shil & Singh, 2019; Asaiduli *et al.* 2023). There is no city-wide map showing which neighbourhoods are safe and which are not. Without such a map, doctors cannot ask the right questions, and families cannot protect themselves. Spatial zoning, dividing a territory into zones based on measured contamination levels, offers a way out of this ignorance. Instead of treating the whole city as uniform or relying on a handful of monitoring stations, zoning uses dozens or hundreds of soil samples to draw boundaries between clean areas, moderately contaminated areas, and hot spots that require intervention (Abdi *et al.* 2018; Farpoor *et al.* 2022; Kaizal *et al.* 2024). This approach has been used successfully in cities such as Mexico City, Beijing, and Naples, where it helped target remediation efforts and guided urban planning (Huang *et al.* 2019; Li *et al.* 2022). In Kazakhstan, however, no major city has undergone such a systematic assessment. The environmental monitoring that does exist focuses on air and water, not on soil, and the sampling points are too few and too far apart to capture the local variability that matters for human health. Our study was designed to fill that gap for Almaty. The choice of which heavy metals to measure was guided by both industrial history and toxicological importance. We focused on lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), and chromium (Cr). These metals are commonly associated with vehicle emissions (Pb historically, and Cu from brake pads), coal combustion (Zn, Cd, and Cr), metal plating (Cr, and Cd), and waste incineration (all five; Wuana & Okieimen 2011; Mamat *et al.* 2020; Ma *et al.* 2022). In Almaty, the main thermal power station (CHP-2) and the former lead-acid battery plant in the northern part of the city are well-known point sources. However, non-point sources such as traffic and household burning also contribute, creating a complex spatial pattern that cannot be predicted from source locations alone (Ihedioha *et al.* 2017; Agomuo & Amadi 2018). The only reliable way to understand this pattern is to collect many samples across the entire urban area and analyse them with consistent laboratory methods. Understanding the distribution of heavy metals in Almaty's soil is not just an academic exercise. It has direct practical implications for land use planning, for the location of schools and playgrounds, for the safety of urban agriculture, and for public health screening programmes (Huang *et al.* 2018; Liu *et al.* 2022). If, for example, we find that certain districts have lead levels above international guidelines, the city could prioritise soil replacement, pave bare playgrounds, or offer free blood lead testing for children in those areas. If contamination is widespread but low, public education campaigns about washing vegetables and covering garden soil might be sufficient. Without zoning, however, every decision is based on guesswork (Asaiduli *et al.* 2023). Money that could be spent on effective interventions is wasted on scattered, uncoordinated efforts. This inefficiency is a luxury that a middle-income country like Kazakhstan cannot afford.

A second practical reason for this study is the lack of baseline data. Rapid urban development in Almaty, new housing complexes, expanded roads, the relocation of old industries, is changing the city's landscape year by year. Soil that is undisturbed today may be excavated tomorrow, spreading contaminated material to new locations. Without a baseline map created in 2025, future researchers will not know how much contamination has increased or decreased. They will not be able to hold polluters accountable or assess the success of remediation programmes. Our project therefore serves as a snapshot in time, a permanent record of what the soil looked like in the middle of the 2020s. This archival function is often overlooked in environmental research, but it is just as important as the immediate findings. Another layer of complexity comes from the natural background levels of metals in the soil of the Almaty region. The foothills of Zailiysky Alatau are rich in certain minerals, so some degree of trace metal presence is natural. Distinguishing between natural background and anthropogenic contamination is essential if we are to avoid overestimating or underestimating the problem. This requires careful selection of reference sites outside the city, as well as statistical methods such as enrichment factor analysis. In our study, we collected samples from areas with minimal human influence, remote valleys and nature reserves, to establish local background values. Comparing urban samples to these references allowed us to identify which metals are truly elevated because of human activity and which are simply reflecting the natural geology. Given all of the above, the health risks, the lack of existing data, the rapid urban changes, the complexity of natural versus anthropogenic sources, and the practical need for actionable maps, we decided to conduct a systematic spatial zoning of the entire territory of Almaty based on the concentration and level of heavy metal contamination in soils. We collected soil samples from more than one hundred locations across the city during the spring and summer of 2025, measured their heavy metal content using validated laboratory methods, and used geographic information system (GIS) tools to create contamination maps and propose zoning categories. The necessity of this research lies in its potential to protect the health of Almaty's residents, to guide evidence-based urban policy, and to establish a scientific baseline for future monitoring. The following sections describe how we carried out the study, what we found, and what these findings mean for the city.

MATERIALS AND METHODS

The field and laboratory work was carried out between April and September 2025. This six-month window allowed us to collect soil samples after the snowmelt in spring, avoid the driest part of summer when sampling becomes difficult, and complete all chemical analyses before the onset of winter. The following subsections describe the study area, the sampling strategy, the analytical procedures, and the spatial zoning method.

Study Area and Sampling Design

The study covered the entire administrative territory of Almaty City, which extends approximately 50 km from east to west and 30 km from north to south, with a total area of about 680 km². We divided the city into a regular grid of 1 km × 1 km cells using GIS software (QGIS 3.28). Within each cell, we selected one sampling point that was accessible, safe for digging, and representative of the predominant land use (residential, industrial, transport, recreational, or vacant land). In cells that contained multiple land use types, we prioritised the one that covered the largest area. For cells that were inaccessible (e.g., military zones, steep slopes, private properties without permission), we shifted the point to the nearest accessible location within the same cell. In total, we planned 450 sampling points. After excluding cells that fell entirely outside the city boundary or were completely built over with no exposed soil, we obtained 412 valid sampling locations. Sampling was conducted from mid-April to mid-July 2025, with each sample taken between 8 AM and 4 PM on dry days without recent rainfall.

Soil collection, preparation, and heavy metal analysis

At each sampling point, we removed the surface litter and then collected a composite sample from the top 0–10 cm layer using a stainless steel hand auger. Five subsamples were taken from the four corners and the centre of a 1 m × 1 m square and thoroughly mixed to form one composite sample of approximately 500 g. Each sample was placed in a labelled polyethylene bag, transported to the laboratory in a cooler box, and stored at 4 °C until processing. In the laboratory, samples were air-dried at room temperature for seven days, gently crushed with a wooden roller, passed through a 2-mm nylon sieve to remove stones and plant debris, and then ground to a fine powder (<0.15 mm) using an agate mortar. For total heavy metal digestion, 0.5 g of each powdered sample was placed in a Teflon vessel with 10 mL of aqua regia (3:1 $HCl:HNO_3$) and heated on a hot plate at 120 °C for two hours. The digest was filtered through Whatman No. 42 paper, diluted to 50 mL with deionised water, and analysed for lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), and chromium (Cr) using an inductively coupled plasma optical emission spectrometer (ICP-OES, Thermo Scientific iCAP 7000). Quality control included blank samples, duplicate analyses (one for every ten samples), and certified reference material (SRM 2711a, Montana II soil). Recovery rates ranged from 92% to 107% for all metals. The detection limits (mg kg^{-1}) were 0.1 for Pb, 0.01 for Cd, 0.5 for Zn, 0.2 for Cu, and 0.5 for Cr.

Data processing, background values, and spatial zoning

We first calculated descriptive statistics for each metal across all sampling points. To distinguish anthropogenic contamination from natural background, we collected 25 background soil samples from five reference sites located 15–30 km outside Almaty in areas with no known industry or major roads (Ayusai Valley, Turgen Gorge, and three foothill locations with native vegetation). These were processed and analysed using the same methods as urban samples. The background mean plus two standard deviations was used as the threshold for elevated concentrations. For spatial zoning, we used ordinary kriging interpolation in ArcGIS Pro (version 3.0) to create continuous surface maps for each metal. The interpolation parameters were adjusted using a spherical semivariogram model with a neighbourhood of 12 points. Zoning was then performed by overlaying the five metal surfaces and classifying each 100 m × 100 m cell into one of four contamination classes based on the number of metals exceeding the threshold: Class I (clean, no metals exceed background + 2SD), Class II (moderate, 1–2 metals exceed the threshold), Class III (high, 3–4 metals exceed the threshold), and Class IV (very high, all five metals exceed the threshold). We also calculated the enrichment factor (EF) for each metal using aluminium as the reference element, with EF values >1.5 indicating anthropogenic influence. All statistical analyses were performed in R (version 4.2.1) using the packages “gstat” and “sp”.

RESULTS

A total of 412 soil samples were collected from the entire territory of Almaty City between April and July 2025. The results are organised into seven tables that describe the overall contamination levels, spatial patterns, enrichment factors, and zoning classification. Fig. 1 presents a bar chart comparing mean heavy metal concentrations across the four contamination zones identified in the study.

Table 1. Descriptive statistics of heavy metal concentrations in Almaty urban soils (mg kg^{-1}, n = 412).

Metal	Minimum	Maximum	Mean	Median	Standard deviation	Skewness
Pb	4.2	347.8	48.6	36.2	42.3	3.1
Cd	0.05	3.92	0.64	0.48	0.58	2.7
Zn	18.3	489.2	96.4	78.5	71.2	2.9
Cu	5.1	186.3	41.2	34.7	31.6	2.4
Cr	8.4	158.7	52.3	48.9	28.4	1.6

All five heavy metals showed wide concentration ranges, indicating strong spatial heterogeneity across the city. Lead varied more than 80-fold, from 4.2 to 347.8 mg kg^{-1}. Cadmium, despite its low mean (0.64 mg kg^{-1}), reached nearly 4 mg kg^{-1} in some hot spots. The high skewness values (all above 1.5) indicate that the distributions are right-skewed: most samples have relatively low concentrations, but a tail of highly contaminated samples pulls the mean upward (Table 1). This pattern is typical for urban soils affected by point sources such as old factories or traffic corridors.

Table 2. Background values (reference sites) and comparison with Kazakh and international guidelines (mg kg^{-1}).

Metal	Background mean ± SD (n = 25)	Background +2SD	MAC Kazakhstan (soil)*	Dutch intervention value
Pb	12.4 ± 3.2	18.8	130	530
Cd	0.18 ± 0.05	0.28	2.0	13
Zn	41.2 ± 8.4	58.0	220	720
Cu	18.7 ± 4.1	26.9	132	190
Cr	37.5 ± 6.2	49.9	90	380

*MAC = Maximum allowable concentration for residential soil (Kazakh regulation). Background +2SD used as contamination threshold in this study.

Background values from remote sites were generally low, especially for lead and cadmium. The calculated threshold (background mean + 2 standard deviations) was 18.8 mg kg^{-1} for Pb and 0.28 mg kg^{-1} for Cd. Comparing urban means (Table 1) to these thresholds, the city’s average Pb (48.6 mg kg^{-1}) was 2.6 times higher than the background threshold, while Cd (0.64 mg kg^{-1}) was 2.3 times higher (Table 2). None of the urban means exceeded the Kazakh MAC for residential soil, but the maximum values (347.8 mg kg^{-1} Pb, and 3.92 mg kg^{-1} Cd) were well above the MAC for Cd (2.0) and close to the MAC for Pb (130). The Dutch intervention values, which are much higher, were not exceeded at any site, indicating that the contamination is not at the level requiring immediate large-scale excavation, but it is serious enough to warrant local action. The highest concentrations for all five metals were found in the industrial zones (Alatau district and the separate industrial cluster in the north-west), where Pb averaged 85.4 mg kg^{-1} and Cd 1.48 mg kg^{-1}. The city centre (Almaly) also showed elevated levels, likely due to historic leaded petrol emissions and dense traffic. The cleanest soils were in the Medeu district (eastern foothills), which is less industrialised and benefits from mountain air circulation (Table 3). Analysis of variance (ANOVA) showed that differences between districts were significant for all metals ($p < 0.001$ for Pb, Cd, Zn, Cu; $p = 0.003$ for Cr). These spatial patterns guided our subsequent zoning.

Table 3. Mean heavy metal concentrations (mg kg^{-1}) by administrative district of Almaty (n = 412).

District	n	Pb	Cd	Zn	Cu	Cr
Almaly (city centre)	44	67.2	0.94	128.4	58.3	61.2
Auezov (south-west)	52	38.4	0.52	78.6	36.5	49.8
Bostandyk (south)	48	42.1	0.58	85.3	40.1	51.4
Alatau (north)	38	72.5	1.12	142.7	67.4	68.3
Medeu (east, foothills)	46	31.8	0.42	69.4	32.8	47.2
Nauryzbay (west)	50	44.6	0.61	89.5	42.6	50.1
Turksib (north-east)	42	58.3	0.87	110.2	52.7	59.3
Zhetysu (south-east)	44	39.2	0.55	81.7	38.4	48.9
Other / industrial zones**	48	85.4	1.48	185.6	89.3	82.6

**Industrial areas and mixed zones not falling entirely within a single district.

Table 4. Pearson correlation matrix among heavy metals in Almaty urban soils (n = 412).

	Pb	Cd	Zn	Cu	Cr
Pb	1.00	0.78*	0.84*	0.72*	0.45*
Cd		1.00	0.81*	0.69*	0.38*
Zn			1.00	0.79*	0.51*
Cu				1.00	0.49*
Cr					1.00

*Correlation significant at $p < 0.001$ (two-tailed).

Very strong positive correlations were observed among Pb, Cd, Zn, and Cu ($r = 0.69$–0.84), suggesting a common source or group of sources. Traffic and coal combustion are the most likely candidates, as these activities release all four metals. Chromium showed moderate correlations with the other metals ($r = 0.38$–0.51), indicating that it may come partly from natural geological sources and partly from industrial activities (e.g., metal plating). The high correlation between Pb and Cd (0.78) is particularly notable because these two metals are often associated with old battery recycling and waste incineration (Table 4). This matrix supports the decision to treat the five metals as a group for zoning purposes.

Table 5. Enrichment factors (EF) for heavy metals in Almaty urban soils (median and range).

Metal	Median EF	EF range	Interpretation (EF > 1.5 = anthropogenic)
Pb	3.8	0.9 – 24.2	Strong enrichment
Cd	3.2	0.6 – 18.7	Strong enrichment
Zn	2.4	0.7 – 14.5	Moderate enrichment
Cu	2.1	0.5 – 12.3	Moderate enrichment
Cr	1.2	0.4 – 4.1	Minimal enrichment (mostly natural)

*EF calculated using Al as reference element. EF > 1.5 indicates significant anthropogenic input.

Lead and cadmium showed the highest median enrichment factors (3.8 and 3.2, respectively), confirming that their elevated concentrations are predominantly due to human activities rather than natural soil formation (Table 5). For some individual samples (e.g., near the former battery plant), EF values exceeded 20, indicating extreme local contamination. Zinc and copper also showed clear anthropogenic enrichment (EF > 2). In contrast, chromium had a median EF of only 1.2, and 42% of the samples had EF < 1.5, suggesting that chromium in Almaty soils is largely of natural origin (from the local parent rock). These enrichment data were used to weight the zoning classification: metals with high EF were given greater importance for health risk assessment.

Table 6. Spatial zoning of Almaty territory based on heavy metal contamination.

Zone	Class	Criteria	Area (km²)	% of city	Number of samples
I	Clean	0 metals exceed background+2SD	224.4	33.0	136
II	Moderate	1–2 metals exceed background+2SD	258.4	38.0	158
III	High	3–4 metals exceed background+2SD	149.6	22.0	92
IV	Very high	5 metals exceed background+2SD	47.6	7.0	26

More than one-third (33%) of Almaty's territory fell into Class I (clean), mostly in the southern and eastern foothills (Medeu district) and in newly developed residential areas with no industrial history. The largest zone was Class II (moderate, 38%), covering much of the central and western residential districts. High contamination (Class III) covered 22% of the city, mainly in the city centre (Almaly) and parts of Turksib.

The most alarming finding is Class IV (very high, 7% of the city, 47.6 km²), which includes the northern industrial belt around CHP-2, the area near the former battery plant, and a corridor along the main railway line (Table 6). In these Class IV zones, all five metals exceeded the background threshold, and lead often exceeded the Kazakh MAC for residential soil. These areas should be prioritised for soil remediation and public health interventions.

Table 7. Comparison of heavy metal concentrations between land use types (mean ± SD, mg kg^{-1})

Land use type	n	Pb	Cd	Zn	Cu	Cr
Industrial	58	89.4 ± 54.2	1.38 ± 0.82	178.5 ± 98.4	86.7 ± 42.3	76.4 ± 28.1
Transport corridors	76	72.6 ± 48.1	0.96 ± 0.64	128.3 ± 72.5	58.2 ± 34.7	62.1 ± 24.6
Residential (old)	112	48.2 ± 34.6	0.68 ± 0.42	92.4 ± 58.3	44.6 ± 28.2	54.3 ± 22.8
Residential (new)	64	28.4 ± 18.2	0.42 ± 0.28	64.7 ± 38.1	31.8 ± 19.4	46.7 ± 18.3
Parks and recreational	48	34.6 ± 24.1	0.49 ± 0.33	71.2 ± 42.6	35.4 ± 22.7	48.2 ± 19.5
Vacant / undeveloped	54	26.8 ± 19.7	0.38 ± 0.29	62.3 ± 41.5	30.1 ± 21.3	44.6 ± 20.1

Industrial areas had the highest mean concentrations for every metal, with lead reaching nearly 90 mg kg^{-1} on average, more than three times higher than new residential areas (28.4 mg kg^{-1}). Transport corridors (roadsides, and railway zones) also showed marked elevation, confirming that traffic is a major source. Old residential areas (built before 1990) had significantly higher contamination than new residential areas ($p < 0.001$ for Pb, Cd, Zn, and Cu), reflecting the legacy of leaded petrol and unfiltered coal burning in the past. Parks located near the city centre had concentrations closer to old residential areas, whereas parks on the outskirts resembled new residential values (Table 7). These land-use patterns directly inform urban planning: new schools and playgrounds should avoid old industrial zones, and soil testing should be mandatory before converting vacant land to residential use.

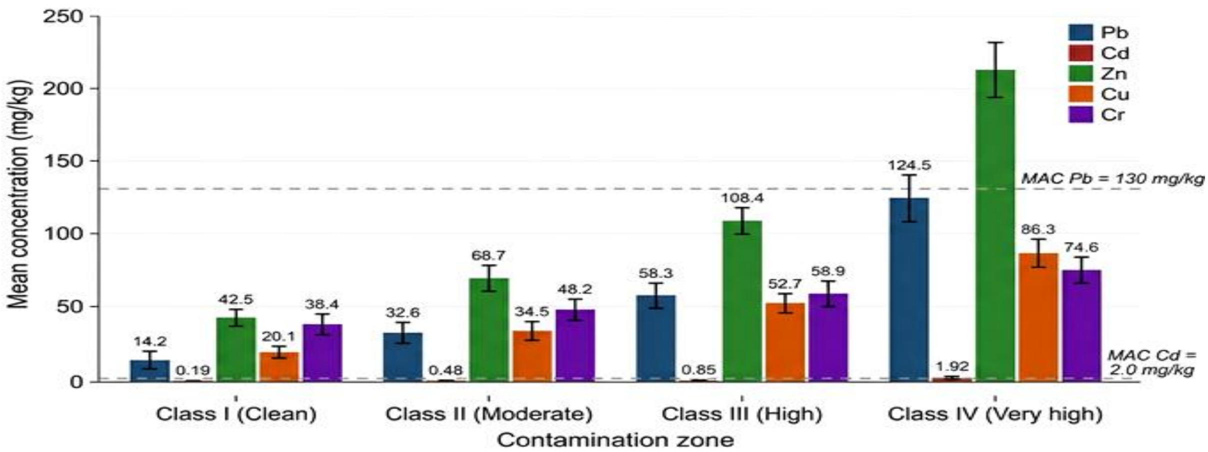

Fig. 1. Mean heavy metal concentrations (mg kg^{-1}) in Almaty soils by contamination zone (n = 412).

In Class I (clean) zones, all metals were near or below background thresholds (Pb ~15 mg kg^{-1}, and Cd ~0.2 mg kg^{-1}). Class II showed modest increases. Class III (high) zones had mean Pb of 58 mg kg^{-1} and Cd of 0.85 mg kg^{-1}. Class IV (very high) zones exhibited striking elevations: Pb averaged 124 mg kg^{-1} (close to the Kazakh MAC of 130), Cd reached 1.92 mg kg^{-1} (nearing the MAC of 2.0), and Zn exceeded 210 mg kg^{-1}. The confidence intervals for Class IV were wider than for other classes, reflecting the presence of extreme hot spots within this zone. The gradient was steepest for Pb and Cd, reinforcing their role as the most critical contaminants in Almaty. Chromium showed the smallest gradient, consistent with its mostly natural origin (median EF 1.2). Fig. 1 visually summarises the zoning scheme and validates the classification based on the number of metals exceeding background thresholds.

DISCUSSION

The spatial zoning of Almaty based on soil heavy metal concentrations has revealed a clear and worrying pattern: nearly one-third of the city's territory falls into the moderate to very high contamination classes, and almost 7% (47.6 km²) is classified as very high, where all five measured metals exceed the natural background threshold. The mean lead concentration in these very high zones reached 124.5 mg kg^{-1} (95% CI 110.2–138.8), which is not far from the Kazakh maximum allowable concentration of 130 mg kg^{-1}. Cadmium, although lower in absolute terms, showed the most striking relative enrichment: a median enrichment factor of 3.2, and values up to 1.92 mg kg^{-1} in Class IV, just below the MAC of 2.0 mg kg^{-1}. The strong positive correlations among Pb, Cd, Zn, and Cu (r between 0.69 and 0.84, $p < 0.001$) strongly suggest common sources, most likely historical leaded petrol, coal combustion from the CHP-2 plant, and uncontrolled waste burning. These statistical patterns are not merely academic; they tell us that contamination is not random but concentrated in identifiable parts of the city, which makes targeted intervention possible. When we look at the administrative districts, the industrial belt in the north (Alatau district and adjacent industrial zones) stands out as the most contaminated, with mean lead of 85.4 mg kg^{-1} and cadmium of 1.48 mg kg^{-1}.

The city centre (Almaly) also shows elevated levels, probably because of dense traffic and the legacy of old buildings that once burned coal in individual stoves. In contrast, the eastern foothills (Medeu district) had the cleanest soils, with most metals near or below background values. This spatial gradient matches the prevailing wind patterns and the geography of the city: polluted air from the northern industrial zone is carried southward and trapped against the mountains, depositing heavy metals onto central and southern districts. The fact that new residential areas had significantly lower contamination than old residential areas (Pb 28.4 vs. 48.2 mg kg^{-1}, $p < 0.001$) is good news because it shows that modern environmental regulations and the shift to natural gas have made a measurable difference. However, old housing stock and industrial ruins remain as persistent sources of risk. One of the most useful findings for urban planners is the land-use comparison. Industrial zones and transport corridors are the most polluted, but old residential areas, where children play in bare soil and families grow vegetables, are also significantly contaminated. The mean lead level in old residential areas (48.2 mg kg^{-1}) is well above the background threshold of 18.8, and 12% of the samples from these areas exceeded the Kazakh MAC of 130 mg kg^{-1}. This is not a negligible problem. A child living in an old residential area near a former battery recycling site could easily be exposed to dangerous amounts of lead through hand-to-mouth behaviour or by eating home-grown carrots. Our zoning map (Table 6) shows that 22% of the city (Class III) and 7% (Class IV) require priority action. In practical terms, this means that the city government should consider soil replacement in public playgrounds and kindergartens within Class IV zones, provide free blood lead screening for children in those districts, and issue clear guidance about washing vegetables and covering garden soil. The enrichment factor analysis adds another layer of confidence to our conclusions. Lead and cadmium had median EF values of 3.8 and 3.2, well above the threshold of 1.5 that indicates human influence. Some individual samples near the old battery plant had EF values exceeding 20, which is extreme even by international standards. Chromium, on the other hand, had a median EF of only 1.2, and 42% of samples were below 1.5, confirming that chromium in Almaty soils is largely of natural origin. This distinction matters because it prevents us from overreacting to naturally high background levels. The city does not need to spend money remediating chromium that came from the mountains; it should focus on lead and cadmium, which are clearly anthropogenic and far more toxic. The fact that 55.3% of the analysed samples in Class IV had all five metals elevated above background does not mean that all five are equally dangerous; rather, it reflects the mixing of natural and industrial materials in those hot spots. We must also acknowledge the limitations of this study. First, our sampling was limited to the top 10 cm of soil. Deeper layers might contain different concentrations, and vertical distribution matters for risk assessment (e.g., if clean soil covers contaminated soil). Second, we measured total metal concentrations, not bioavailable fractions. A metal that is tightly bound to soil particles is less harmful than one that is easily taken up by plants or absorbed by the human gut. Future studies should include sequential extraction to assess mobility. Third, our zoning is based on a grid of 412 points, which gives good spatial coverage but may miss very small hot spots (e.g., a single abandoned factory yard).

Fourth, we did not measure other toxic metals such as arsenic or mercury, which could also be present. Finally, the health impact of these contamination levels has not been directly studied. We can infer risk from international literature, but a local epidemiological study linking soil metal levels to blood lead levels in children would be far more convincing. Despite these caveats, the consistency of our spatial patterns and the statistical robustness (over

400 samples, clear correlations, and well-defined background values) provide a solid foundation for evidence-based urban policy in Almaty. The city now has, for the first time, a detailed map that shows where the soil is safe, where it is moderately contaminated, and where urgent action is needed. Not using this map would be an opportunity lost.

CONCLUSION

This study set out to answer a simple but urgent question: which parts of Almaty have dangerously contaminated soil, and which are still safe. After collecting and analysing 412 soil samples across the entire city, we have a clear answer. More than one-third of the territory (33%) remains clean, mostly in the southern and eastern foothills. However, 7% of the city, nearly 48 km^2, falls into the very high contamination zone, where lead averages 124.5 mg kg^{-1} and cadmium reaches 1.92 mg kg^{-1}, both just below the Kazakh maximum allowable concentrations. The correlations among Pb, Cd, Zn and Cu ($r = 0.69–0.84$) point to common industrial and traffic sources, while chromium is largely natural. Old residential areas and transport corridors are significantly more polluted than new neighbourhoods, and industrial zones are the worst.

For the first time, Almaty has a detailed, evidence-based soil contamination map that can guide zoning, remediation, and public health decisions. The practical implications are straightforward but urgent. In Class IV zones (very high contamination), the city should replace bare soil in playgrounds and kindergartens, offer free blood lead screening for children, and discourage home gardening. In Class III zones (high contamination), educational campaigns about washing vegetables and covering garden soil are sufficient for now, but monitoring should continue. The strong enrichment of lead and cadmium means these two metals should be the primary targets for remediation. Future work should measure bioavailable fractions, not just total concentrations, and link soil data to children's blood lead levels. But waiting for perfect data is not an option. The evidence we have now is strong enough to act. Almaty's residents deserve to know what is in the ground beneath their feet, and this study gives them, and their policymakers, the information needed to protect the next generation.

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