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Soil contamination and soil-mediated human health risks associated with household coal combustion in residential areas of Zavkhan Province, Mongolia

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Abstract

Soil contamination by heavy metals represents a growing environmental and public health concern in cold–dry rural settlements where coal-based household heating remains dominant. This study investigates how coal combustion alters soil element dynamics and associated human health risks by applying a process-oriented, integrated soil system assessment in a residential area of Uliastai city, western Mongolia.

Surface soils (0–10 cm) from 38 sites were analyzed using ICP-OES and ICP-MS to determine major and trace element concentrations. Multivariate statistical analysis (principal component analysis, PCA) was combined with contamination indices (enrichment factor and geo-accumulation index) and human health risk assessment to explicitly link contamination sources, transport pathways, soil retention processes, and potential human exposure.

Results reveal a clear separation between anthropogenically influenced metals (As, Pb, Cd, Zn, and Cu) and elements predominantly controlled by geogenic background conditions (Cr, Co, and Ni). Very high to extreme enrichment and geo-accumulation levels for As, Pb, Zn, Cd, and Cu indicate substantial anthropogenic alteration of surface soil metal pools. Comparison of soil, coal, and ash compositions identifies coal combustion ash as the primary source of metal enrichment, acting as a concentrated reservoir that is redistributed to soils via atmospheric deposition and surface processes. Human health risk assessment shows that the most enriched metals, particularly As and Pb, dominate both non-carcinogenic and carcinogenic risks, with inhalation and ingestion pathways contributing most strongly to potential exposure.

The findings demonstrate that soil contamination in Uliastai reflects systemic changes in soil functioning driven by household energy practices rather than isolated concentration exceedances. By integrating source identification, contamination intensity, and health risk within a unified soil system framework, this study provides mechanistic insight into soil–human interactions and offers a transferable approach for assessing soil impacts in coal-dependent rural environments.

Keywords: soil system impact; heavy metals; coal combustion; enrichment factor; geo-accumulation index; human health risk; Mongolia

1. Introduction

Soil contamination has become an increasingly significant environmental and public health concern in rural regions of Mongolia. In many countryside settlements, the combined impacts of coal-based household heating, insufficient waste management infrastructure, and the expansion of cultivated land have contributed to the accumulation of pollutants in soils (Lkhagvasuren et al., 2019; Batjargal and Kim, 2020). Such contamination not only degrades soil quality but also poses potential risks to human health, highlighting the need for integrated assessments that link environmental contamination with human exposure pathways (Li et al., 2014).

Uliastai city, one of the oldest permanent settlements in western Mongolia with a history spanning more than 300 years, provides a unique setting for evaluating the long-term influence of anthropogenic activities and natural processes on soil quality. The basin-like topography of the area promotes the accumulation of geochemical

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materials transported by the Bogd and Chigestei rivers originating from the Otgontenger mountain range. These geomorphological and hydrological conditions favor the deposition and redistribution of sediments and associated trace elements within the urban environment (Dorjgotov, 1976).

In addition to natural factors, land-use practices have played an important role in shaping soil contamination patterns in Uliastai. Riverbank agricultural lands surrounding the city have experienced decades of irrigation development and periodic application of agrochemicals, which may contribute to the gradual buildup of contaminants in surface soils (Purevsuren et al., 2017). The interaction between historical land use, river dynamics, and urban expansion makes Uliastai an important case study for understanding soil contamination processes in rural Mongolian settlements.

Uliastai was first established in 1733 as a military administrative center during the Manchu Qing Dynasty and subsequently evolved into a commercial and administrative hub. These stages of urban development have influenced the sources and spatial distribution of soil contaminants, including heavy metals such as Pb, Cu, and Zn, as well as dust and household-derived pollutants within residential areas (Dorjgotov, 1976).

As of 2024, Zavkhan Province has a population of approximately 71 800, of which about 22.5 % reside in Uliastai city (Zavkhan Province Statistical Yearbook, 2022). The city comprises 4 871 households, and recent statistics indicate that approximately 83.5 % of households rely on coal for domestic heating. This heavy dependence on coal represents a major source of both atmospheric and soil contamination.

Coal is extensively used in household stoves and centralized heating boilers in Uliastai. Limited heating network coverage, high connection costs, substantial heat loss, and inadequate thermal insulation of buildings all contribute to the continued reliance on solid fuel combustion (Meteorology and Environmental Monitoring Center, 2022). Coal combustion has been shown to enrich heavy metal concentrations several-fold relative to natural geological materials, facilitating the accumulation of these elements in air, soil, and water and increasing potential risks to human health (Batjargal and Kim, 2020; Frankel et al., 2025).

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The Uliastai Meteorology and Environmental Monitoring Center conducts biennial monitoring of selected heavy metals (Cd, Pb, Zn, Co, and Sr) at 16 soil sampling locations within the city. Monitoring results from 2011 to 2022 indicate elevated concentrations of strontium and zinc in residential areas compared to background sites, suggesting persistent environmental contamination.

Despite the long history of settlement, complex land-use patterns, and relatively high population density, comprehensive assessments of soil contamination and associated human health and ecological risks in Uliastai remain limited.

Therefore, the objectives of this study are to (i) quantify the concentrations of heavy metals in surface soils from residential areas of Uliastai city and compare them with regional background values and national soil quality standards, (ii) characterize the contamination intensity and enrichment levels of individual metals using enrichment factor and geo-accumulation index, (iii) identify potential anthropogenic and geogenic sources of soil contamination through principal component analysis, (iv) evaluate the contribution of coal ash and coal combustion–related activities to soil heavy metal accumulation, and (v) assess associated non-carcinogenic and carcinogenic human health risks within an integrated multivariate and multi-criteria assessment framework.

2. Methodology

This study assessed the level of heavy metal contamination in the urban soils of Uliastai, Zavkhan Province, by collecting and analyzing surface soil samples from a total of 38 sites. Sampling locations were selected based on population density, land-use intensity, and settlement structure, and were arranged in a grid pattern with an interval of 500 meters between points. To enhance the reliability and comparability of the results, 16 existing monitoring points from the Zavkhan Meteorology and Environmental Monitoring Center (MEMC) were also included. Figure 1 shows the study area and the distribution of sampling points.

2.1 Field Survey and Soil Sampling

The field survey was conducted between 20 and 27 March 2022 across the residential zones of six khoroos (subdistricts) of Uliastai. Using the 16 regular monitoring

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stations operated biennially by MEMC, a total of 38 soil samples were collected (Figure 1).

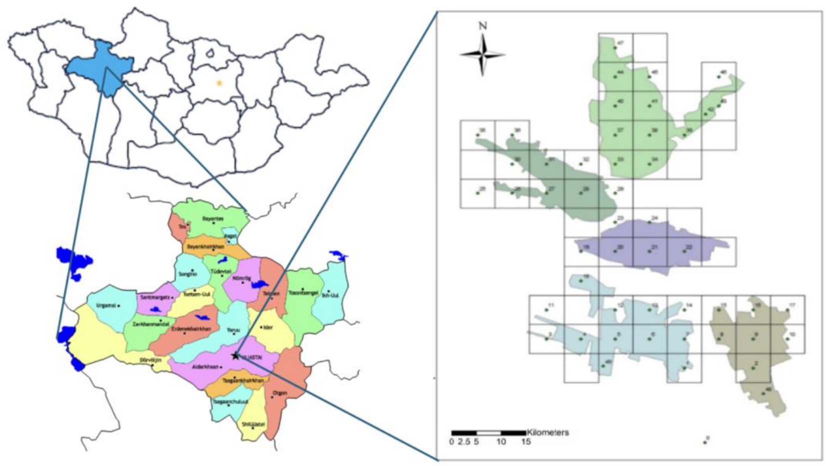

Fig1. Location of sampling points in Uliastai, Zavkhan Province

Soil sampling procedures followed the ISO 18400-104:2018 standard, using an envelope sampling method to collect samples from a depth of 0–10 cm. Approximately 300 g of soil was collected from each sampling point, placed in polyethylene bags, securely sealed, and georeferenced using a Garmin GPS device.

Prior to laboratory transport, soil samples were pre-processed at the laboratory of the National University of Mongolia (NUM). Samples were cleaned by removing stones, roots, and coarse debris, then air-dried at room temperature (20°C) for three days. The dried samples were sieved through a 2 mm mesh to achieve homogeneity and subsequently stored in airtight polyethylene bags for one week to stabilize moisture content. After pre-treatment, samples were shipped to Kanazawa University in Japan for further laboratory analysis.

2.2 Chemical Analysis of Soil

Chemical analysis of the soil samples was conducted at the Geochemistry Laboratory, Institute of Environmental Technology, Kanazawa University, Japan. Heavy metal concentrations were determined using inductively coupled plasma mass spectrometry (ICP-MS; iCAP RQ, Thermo Fisher Scientific, Waltham, MA, USA) and inductively

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coupled plasma optical emission spectrometry (ICP-OES; ES-710, Varian Inc., Palo Alto, CA, USA).

Sample preparation for instrumental analysis followed a standardized analytical protocol consisting of five sequential steps. The procedure was adapted from a previously published method (Battsengel Enkhchimeg, 2020), with minor modifications to accommodate the characteristics of the studied soils.

Soil samples (0.05 g) were subjected to sequential acid digestion using 3 mL of 60% HNO_3 and 3 mL of 48% HF at 120 °C until dryness, followed by a second digestion with 3 mL of 30% HCl. The digested residue was extracted with 10 mL of 0.6 vol% HNO_3 and shaken for 24 h. The extracts were then filtered through a 0.20 μm membrane filter and diluted 50-fold with HNO_3 prior to elemental analysis by ICP-MS and ICP-OES.

2.3 Contamination Index Assessment

To assess the level of heavy metal contamination in soils, widely used international pollution indices such as the Enrichment Factor (EF) and the Geo-accumulation Index (I_geo) were applied. These indices are effective tools for distinguishing anthropogenic contributions from natural background concentrations and for evaluating the extent to which metal levels deviate from their geochemical baseline values (Müller, 1969; Abdullah, M.I.C., 2000).

The Igeo is calculated using the following equation (Equation 1).

$$Log_2 = \left(\frac{C_n}{1.5\ x\ B_n}\right)$$

The Enrichment Factor (EF) is used to assess the degree of contamination and identify the influence of anthropogenic sources on the concentration of specific elements in soil. In contrast, the Geo-accumulation Index (I_geo) allows for a more detailed evaluation of anthropogenic impacts by comparing current concentrations with natural background levels.

In EF calculations, elements such as aluminum (Al) or iron (Fe), which are stable and strongly associated with soil mineral composition, are typically used as normalizing elements. In this study, iron (Fe) was selected as the reference element for the

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following reasons: it is widely distributed in nature, occurs consistently in soil mineral structures, it is sensitive to anthropogenic disturbances, it is strongly associated with clay minerals, making Fe a widely recommended normalizer in international studies (Barbieri, M. et al., 2016; Taylor, S.R et al., 1964).

The Enrichment Factor is calculated using the following equation (Equation 2).

$$EF = \frac{\left(\frac{M}{Fe}\right) sample}{\left(\frac{M}{Fe}\right) background}$$

For the EF computation, the Fe background concentration was derived from the control sampling site within the study area, and a value of 1125 mg/kg was used. The categories applied for evaluating contamination severity based on enrichment factor (EF) and geo-accumulation index (Igeo) are presented in **Table 1**.

Table 1. Category of EF (enrichment factor) and I_{geo} (geo-accumulation).

EF		**I_{geo}**	
EF < 2	no enrichment	$0 < I_{geo}$	uncontaminated
EF = 3–5	moderate enrichment	$0 < I_{geo} < 1$	uncontaminated to moderately uncontaminated
EF = 5–10	moderately severe enrichment	$1 < I_{geo} < 2$	moderately contaminated
EF = 10–25	severe enrichment	$2 < I_{geo} < 3$	moderately to heavily contaminated
EF = 25–50	very severe enrichment	$3 < I_{geo} < 4$	heavily contaminated
EF > 50	extremely severe enrichment	$4 < I_{geo} < 5$	heavily to extremely contaminated
		Igeo > 5	extremely contaminated

2.4 Soil–Coal–Ash Comparative Study Using PCA

Principal Component Analysis (PCA) is a multivariate statistical technique widely used to reduce the dimensionality of complex datasets while preserving the maximum amount of variance. In environmental studies, PCA is particularly effective for identifying relationships among heavy metals (e.g., Cr, Cu, Pb, Zn, Cd), determining contamination patterns, and distinguishing between natural (geogenic) and anthropogenic sources.

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In this study, PCA was employed to compare the heavy metal concentrations measured in: Surface soils from residential areas of Uliastai, Coal samples from the "Mogoin Gol" coal deposit, commonly used by residents, and Coal ash produced during combustion.

The objective was to detect common patterns, correlations, and possible source linkages among soil, coal, and ash samples. PCA was used to: Identify whether heavy metals found in soil are associated with coal or coal ash; Determine clustering patterns across soil, coal, and ash samples; Assess the degree of metal enrichment due to coal combustion; Differentiate geogenic and anthropogenic contributions; Reveal dominant sources of contamination using statistical evidence, etc.

2.5 Human health risk assessment

Residents living in the urban area of Uliastai, Zavkhan Province, were evaluated for potential human health risks using the United States Environmental Protection Agency (US EPA) risk assessment framework. For each heavy metal detected in soil, exposure pathways were quantified based on the Average Daily Intake (ADI), calculated using Equations 3-5.

$$ADI_{Ingestion} = \frac{Cx\ IngR\ x\ EF\ x\ ED\ x\ CF}{BWx\ AT} \quad (3)$$

$$ADI_{dermalcontact} = \frac{CxSAxFExABSxEFxEDxCF}{BWxAT} \quad (4)$$

$$ADI_{inhalation} = \frac{CxInhRxEFxEDxPEF}{BWxAT} \quad (5)$$

Here, ADI represents the average daily intake of a heavy metal from soil (mg/kg·day), and *C* denotes the concentration of the metal in soil (mg/kg). The assessment considered exposure through three primary pathways: (i) ingestion of soil particles, (ii) inhalation of resuspended soil dust, and (iii) dermal absorption through skin contact. Table 2 presents the exposure parameters used in the human health risk assessment, differentiated between children and adults.

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Table 2 presents the exposure parameters used for the human health risk assessment, categorized for both children and adults.

Table 2. Parameters of risk assessment.in soil

Parameters	Adult	Children	Unit
ADI, average daily intake	-	-	[mg/kg day]
IngR, soil ingestion rate	100	200	[mg/day]
EF, exposure frequency	350	350	[day/year]
ED, exposure duration	30	6	[year]
BW, body weight	70	15	[kg]
SF, skin area exposed to soil contact	5700	2800	[cm^2]
AF, soil to skin adherence factor	0.07	0.2	[kg/cm day]
ABS, contact factor	0.1	0.1	none
InhR, inhalation rate	15	10	[m^3/day]
PEF, particle emission factor	1.36×10^9	1.36×10^9	[m^3/kg]
AT, average time non-carcinogenic	10,950	2190	[days]
AT, average time carcinogenic	25,550	25,550	[days]
CR, Conversion factor	1×10^{-6}	1×10^{-6}	[mg/kg]
FE, Dermal exposure ratio	0.61	0.61	-

Non-carcinogenic risk was assessed using the Hazard Index (HI), which is calculated based on the Average Daily Intake (ADI) of each element and its corresponding Reference Dose (RfD). In contrast, carcinogenic risk (CR) was evaluated using the ADI together with the Slope Factor (SF), provided by USEPA (1997).

The equations used to calculate non-carcinogenic and carcinogenic risks are presented in Equations (6)–(8). The non-carcinogenic risk of each metal was expressed as the Hazard Quotient (HQ). To obtain the total carcinogenic risk, the risks associated with each heavy metal through the three exposure pathways were calculated according to Equation (8).

For risk assessment, the acceptable threshold for non-carcinogenic effects (HI) was set at **1**, whereas the acceptable limit for carcinogenic risk was set at 10^{-4} (Ma et al., 2018).

$$HQ = \frac{ADI}{RfD} \quad (6)$$

$$HI = \sum HQ = \sum \frac{ADI_i}{RfD_i} \quad (7)$$

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$$Risk\,(total) = \sum Risk\,\,(inh)\,\, + Risk\,(ing)\,\, + Risk\,(dermal) \qquad (8)$$

Among the 26 elements analyzed in this study, only eight had available RfD values; therefore, these elements were included in the non-carcinogenic risk assessment (HI). For carcinogenic risk assessment, SF values were available for only four elements, and thus carcinogenic risk (CR) was calculated for these four elements.

The RfD and SF values used in this study are presented in Table 3.

Table 3. RfD (reference dose) and SF (slope factor) values

	Elements	Pathways	RfD [mg/kg day]	
		Ingestion	Dermal	Inhalation
1	Cr	3×10^{-3}[a]	3×10^{-3}[a]	2.86×10^{-5}[a]
2	Pb	1.4×10^{-3}[a]	5.25×10^{-4}[a]	3.52×10^{-3}[a]
3	Zn	3×10^{-1}[c]	6×10^{-2}[c]	3×10^{-1}[a]
4	Cd	3×10^{-1}[a]	2.3×10^{-5}[a]	1×10^{-5}[a]
5	As	1×10^{-4}[a]	1.23×10^{-4}[a]	1.23×10^{-4}[a]
6	Co	2×10^{-2}[a]	NA	NA
7	Cu	4×10^{-2}[a]	1.2×10^{-2}[a]	4×10^{-2} [a]
8	Mo	5×10^{-3}[a]	NA	NA
	Elements		SF [mg/kg day]	
		Ingestion	Dermal	Inhalation
1	Cr	5×10^{-1}[a]	20[a]	42[a]
2	Pb	8.5×10^{-3}[a]	NA	4.2×10^{-2}[c]
3	Cd	NA	NA	6.3[a]
4	As	1.5[a]	3.66[a]	4.3×10^{-3}[a]

NA represents data not available. [a] USEPA, 2007; [b] Huang, 2017; and [c] Kamunda, 2016 .

3. Results

3.1. Concentrations of heavy metals in surface soils

Concentrations of 11 heavy metals (Cr, Co, Cu, Zn, As, Se, Cd, Pb, V, Sr, and Ni) measured in 38 surface soil samples (0–10 cm) exhibited substantial spatial variability across the residential areas of Uliastai. Mean concentrations of all analyzed elements were below the national soil quality limits (MNS 5850:2019); however, maximum values of Zn, Cu, Pb, and Co showed pronounced local enrichments, indicating the presence of contamination hotspots rather than uniform area-wide pollution. This contrast between mean and extreme values highlights the importance of spatially

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explicit assessment for identifying site-specific soil degradation that may be masked in aggregated statistics.

Descriptive statistics, including minimum, maximum, mean, median, standard deviation, and range values, are summarized in Table 4, together with the corresponding threshold values defined in the Mongolian national soil quality standard (MNS 5850:2019).

Table 4. Concentrations of heavy metals in surface soils

№	Elements	Min	Max	Mean	Median Std. Dev.	Std. Dev.	Range	Mongolian Standard (MNS) (5850:2019)		
		(мg/кg)	(мg/кg)					Acceptable limit	Hazardous	Dangerous
1	Cr	0.8	13.4	2.8	1.8	2.7	12.6	150	400	1500
2	Co	0.7	5.9	1.9	1.7	0.9	5.1	50	500	1000
3	**Cu**	**0.2**	**155**	**11**	**4.3**	**26**	**155**	**100**	**500**	**1000**
4	**Zn**	**8.7**	**2757**	**147**	**38**	**456**	**2749**	**300**	**600**	**1000**
5	**As**	**0.2**	**29**	**2.8**	**0.7**	**5.4**	**29**	**20**	**50**	**100**
6	Se	0.1	3.5	0.5	0.4	0.6	3.4	10	50	100
7	Cd	0.04	1.6	0.2	0.2	0.3	1.5	3	10	20
8	Pb	0.1	90	12.0	6.7	17.3	90.4	100	500	1200
9	V	2.1	89	9.9	5.6	14.7	86.8	150	600	1000
10	Sr	0.2	4.2	1.0	0.7	0.9	4.0	800	3000	6000
11	Ni	1.60	14.20	1.9	1.7	0.9	5.1	150	1000	1800

Elevated concentrations of Zn, Cu, Pb, and As in soils collected near ger districts, central heating facilities, and densely populated residential zones. These areas are characterized by intensive household heating, frequent ash handling, and limited surface sealing, all of which facilitate direct deposition and accumulation of combustion-derived particulates in surface soils. In contrast, samples from peripheral and less densely inhabited areas showed lower and more homogeneous concentrations, reflecting weaker anthropogenic pressure and stronger influence of natural background conditions.

Elements such as Cr, Co, and Ni displayed relatively narrow concentration ranges and weak spatial gradients. Their distributions showed limited association with settlement structure or heating facilities, suggesting dominant control by parent material and regional lithology. This spatial divergence between anthropogenically enriched metals

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and geogenically controlled elements provides initial evidence for multiple controlling processes within the soil system.

3.2. Multivariate structure of soil contamination

Principal Component Analysis (PCA) extracted two principal components explaining the majority of variance in the dataset, indicating that a limited number of dominant processes govern soil metal variability. The first component (PC1) was characterized by strong positive loadings of As, Pb, Cd, Zn, and Cu, indicating a coherent assemblage of elements with similar spatial behavior and shared controlling factors. These elements are commonly associated with coal combustion residues and settlement-related activities, suggesting a dominant anthropogenic signal.

The second component (PC2) was dominated by Cr, Co, and Ni, reflecting a contrasting geochemical association. These elements are typically linked to soil parent material and mineralogical composition, and their grouping along PC2 indicates a predominantly lithogenic origin. The clear separation between PC1 and PC2 demonstrates that anthropogenic and geogenic controls on soil chemistry can be statistically distinguished despite spatial overlap within the settlement.

Figure 2 shows Principal Component Analysis (PCA) biplot of soil heavy metals. PC1 is dominated by As, Pb, Cd, Zn, and Cu, representing an anthropogenic component associated with coal combustion and settlement activities. PC2 is dominated by Cr, Co, and Ni, reflecting geogenic control by natural background conditions.

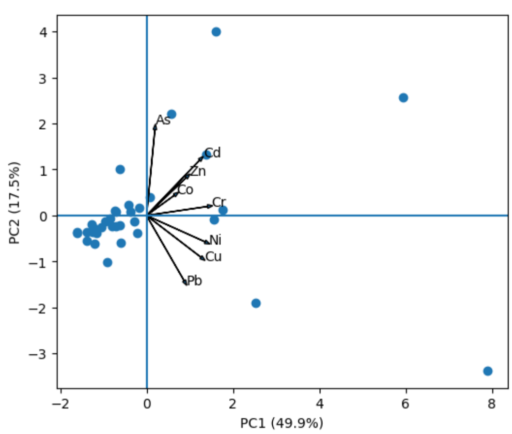

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Figure 2. Multivariate structure of soil contamination

Sample score distributions further showed that sites with high PC1 scores correspond to locations with elevated concentrations of anthropogenically enriched metals, particularly near heating facilities and densely populated ger areas. Samples clustered along PC2 represent areas where soil chemistry remains largely governed by natural background signatures. This multivariate structure confirms that soil contamination in the study area results from the superposition of anthropogenic inputs on an underlying geogenic baseline.

3.3. Contamination intensity based on pollution indices

3.3.1. Enrichment factor (EF)

Enrichment factor analysis revealed very high to extreme EF values for As, Pb, Zn, Cd, and Cu at the majority of sampling sites, indicating substantial enrichment relative to background conditions (Fig. 3). In contrast, Cr, Co, and Ni exhibited low to moderate EF values, suggesting minimal anthropogenic influence. The spatial distribution of EF values highlights distinct enrichment hotspots coinciding with residential heating zones and areas influenced by coal ash deposition.

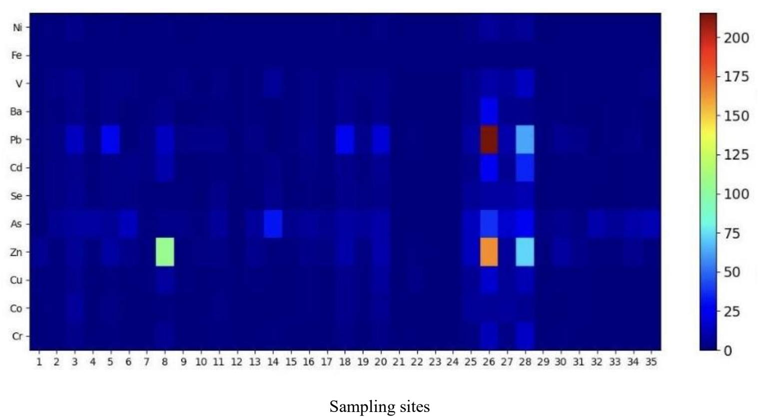

Figure 3. Spatial distribution of enrichment factor (EF) values for selected heavy metals

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The contamination patterns identified using EF are further examined using the geo-accumulation index (Igeo) to evaluate contamination intensity and to cross-validate the observed anthropogenic enrichment.

3.3.2. Geo-accumulation index (Igeo)

The Igeo values classified As, Pb, Zn, Cd, and Cu predominantly within the heavily to extremely contaminated categories, whereas Cr, Co, and Ni were generally classified as uncontaminated to moderately contaminated (Fig. 4). Elevated Igeo values for As, Pb, Zn, Cd, and Cu were observed at multiple sampling sites, indicating pronounced spatial variability and the presence of localized contamination hotspots. The clear contrast between anthropogenically influenced and geogenically controlled elements, together with the strong agreement between EF and Igeo results, confirms the robustness of the contamination intensity assessment and reinforces the differentiation between anthropogenic and geogenic element groups.

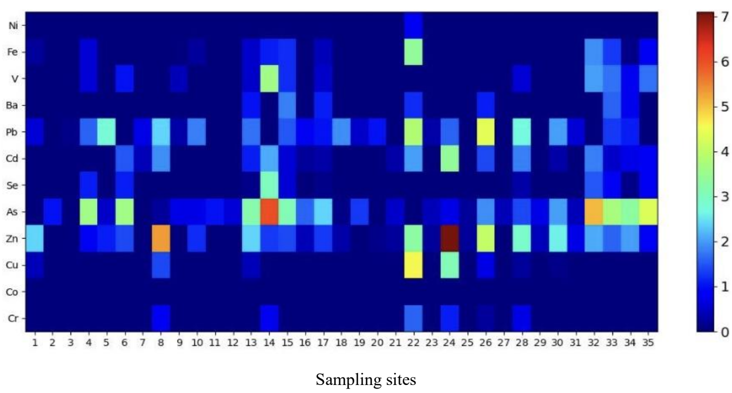

Figure 4. Classification of soil contamination intensity based on the geo-accumulation index (Igeo) for selected heavy metals.

3.4 Human Health Risk Assessment Results

3.4.1 Non-carcinogenic Risk Assessment

The results of the non-carcinogenic risk assessment for Cr, Co, Cu, Zn, As, Cd, and Pb are summarized in Table 5. Hazard index (HI) values were calculated for children and adults through oral ingestion, dermal contact, and inhalation exposure pathways.

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Table 5. Non-carcinogenic risk (hazard index, HI) for selected heavy metals

Risk	Pathways	Elements						
		Cr	Co	Cu	Zn	As	Cd	Pb
Noncarcinogenic	Child							
	Oral	1.2E-02	1.2E-03	3.2E-03	6.2E-03	3.5E-01	1.1E-05	3.7E-02
	Dermal	2.1E-03		1.8E-03	5.3E-03	4.2E-03	2.0E-03	3.2E-04
	Inhalation	2.6E-05		2.5E-02	1.8E-02	2.8E-04	1.3E-04	2.1E-03
	Adult							
	Oral	1.3E-03	1.3E-04	3.5E-04	6.7E-04	3.8E-02	1.1E-06	3.9E-03
	Dermal	3.2E-04		2.8E-04	8.1E-04	3.2E-03	1.5E-03	9.9E-04
	Inhalation	1.9E-06		7.6E-02	5.7E-02	8.8E-04	3.9E-04	6.6E-03

For both population groups, children exhibited higher non-carcinogenic risk values than adults across all exposure pathways. Among the analyzed elements, arsenic (As) and lead (Pb) were the dominant contributors to total non-carcinogenic risk, accounting for the majority of cumulative HI values. In contrast, Cr, Co, Cu, Zn, and Cd contributed relatively lower proportions to the overall risk.

Across exposure pathways, oral ingestion of contaminated soil and dust was the primary contributor to non-carcinogenic risk, followed by inhalation of resuspended particulates, while dermal contact contributed comparatively little to total HI values. Elevated HI values were spatially associated with sampling sites characterized by higher metal concentrations in surface soils, indicating a close linkage between localized soil contamination and potential human exposure.

3.4.2 Carcinogenic Risk Assessment

The results of the carcinogenic risk assessment for Cr, As, Cd, and Pb are presented in Table 6. For both children and adults, inhalation was the dominant exposure pathway, contributing substantially higher carcinogenic risk values than oral ingestion or dermal contact. Among the analyzed elements, Cr and As exhibited the highest carcinogenic risk values, particularly via inhalation, whereas Cd and Pb contributed comparatively lower risks.

Table 6. Carcinogenic risk (CR) for selected heavy metals

Risk	Pathways	Elements			
		Cr	As	Cd	Pb

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Carcinogenic	Child				
	Oral	1.6E-06	4.5E-06		1.1E-07
	Dermal	1.1E-05	1.9E-06		
	Inhalation	1.3E+01	1.3E-02	1.7E+00	5.5E-01
	Adult				
	Oral	8.4E-07	2.4E-06		6.0E-08
	Dermal	8.1E-06	1.4E-06		
	Inhalation	7.0E+00	7.0E-03	9.2E-01	3.0E-01

Carcinogenic risk values estimated for children were consistently higher than those for adults across all pathways, reflecting differences in exposure parameters. Oral and dermal pathways generally resulted in carcinogenic risk values below the acceptable benchmark, while inhalation-related risks for Cr and As exceeded the threshold (10^{-4}) at several sites, indicating potential long-term health concern associated with soil-derived airborne particulates.

4.Discussion

The integrated interpretation of multivariate analysis, contamination indices, and human health risk assessment provides a comprehensive understanding of soil-related environmental risks in Uliastai. PCA clearly distinguishes between anthropogenic and geogenic sources, with As, Pb, Cd, Zn, and Cu strongly associated with the dominant anthropogenic component. This pattern is consistent with EF and Igeo results, which demonstrate severe enrichment and pollution for the same elements.

Coal combustion residues, ash deposition, and settlement-related activities are identified as the primary drivers of soil contamination. These findings are consistent with studies from other cold-climate regions where solid fuel combustion is a dominant source of heavy metals in residential soils. In contrast, Cr, Co, and Ni are largely controlled by natural geological background conditions and contribute minimally to overall health risk, highlighting the importance of distinguishing between anthropogenic and geogenic contributions.

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The source apportionment and contamination patterns identified in this study are consistent with findings reported from other cold-climate and coal-dependent regions worldwide. Previous studies have demonstrated that coal combustion and ash deposition are dominant sources of arsenic, lead, cadmium, zinc, and copper in residential soils, particularly in areas with intensive household heating and limited pollution control (e.g., Liu et al., 2016; Chen et al., 2018). Similar enrichment patterns and anthropogenic signatures have been observed in urban and peri-urban soils in northern China and Central Asia, where solid fuel use remains prevalent.

The predominance of geogenic control for chromium, cobalt, and nickel observed in this study is also in agreement with international soil contamination studies, which report that these elements are often closely associated with parent material and lithogenic background rather than direct anthropogenic inputs (Alloway, 2013; Reimann and Garrett, 2005). The separation between anthropogenic and geogenic components identified through PCA in the present study reflects a common multivariate pattern reported in soil geochemistry literature.

In terms of health implications, the elevated non-carcinogenic and carcinogenic risks associated with arsenic and lead are comparable to those reported in residential soil studies from other developing and transition economies, where soil exposure pathways contribute significantly to overall human health risk (Li et al., 2014; Hu et al., 2017). These similarities highlight that soil contamination driven by household energy practices represents a broader environmental and public health challenge beyond the local context of Mongolia.

The integration of contamination indices with human health risk assessment reveals a direct linkage between pollution severity and potential adverse health outcomes. Metals exhibiting the highest enrichment and pollution levels are also responsible for elevated non-carcinogenic and carcinogenic risks, emphasizing the relevance of soil contamination for public health in residential environments.

Spatial heterogeneity in contamination and risk patterns reflects uneven distribution of anthropogenic emissions and site-specific accumulation processes. Localized contamination hotspots underscore the need for targeted mitigation measures rather than uniform soil management strategies. From a policy perspective, the findings

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highlight the importance of promoting cleaner household energy alternatives, improving coal ash management, and implementing focused soil remediation in high-risk areas.

Overall, this study demonstrates that soil contamination in Uliastai is a multifaceted environmental and public health challenge. The integrated multivariate and multi-criteria framework applied here offers a robust and transferable approach for soil risk assessment in rural settlements facing similar environmental pressures.

Despite the comprehensive nature of the integrated assessment, several limitations should be acknowledged. First, the health risk assessment relied on USEPA default exposure parameters, which may not fully represent local lifestyle characteristics, soil ingestion rates, or behavioral patterns in rural Mongolian communities. Second, the study focused on surface soils collected during a single sampling campaign, and therefore temporal variability in contamination levels could not be assessed.

In addition, while PCA, EF, and Igeo provide robust indicators of contamination sources and intensity, uncertainties remain regarding the relative contributions of overlapping anthropogenic activities, such as traffic emissions and small-scale industrial operations. Future studies incorporating seasonal sampling, site-specific exposure parameters, and isotopic or source-tracing techniques would further refine source attribution and risk estimation.

Conclusion

This study applied an integrated multivariate and multi-criteria environmental and human health risk assessment framework to evaluate soil heavy metal contamination in a rural settlement of Mongolia. By combining principal component analysis, enrichment factor, geo-accumulation index, and human health risk assessment, the study provides a coherent and systematic interpretation linking contamination sources, pollution intensity, and potential human health impacts.

The results demonstrate that arsenic, lead, zinc, cadmium, and copper are the dominant contaminants in the investigated soils. These metals exhibit strong anthropogenic signatures, characterized by very high to extreme enrichment and heavy to extreme pollution levels. The strong agreement between multivariate source identification and contamination indices confirms that coal combustion residues, ash deposition, and settlement-related human activities are the primary drivers of soil contamination. In contrast, chromium, cobalt, and nickel are largely controlled by geogenic background conditions and contribute comparatively little to overall human health risk.

Human health risk assessment further reveals that the most enriched and polluted metals are also responsible for elevated non-carcinogenic and carcinogenic risks. High hazard index values for arsenic, lead, and cadmium, together with carcinogenic risks exceeding acceptable thresholds for arsenic and lead, indicate that soil contamination poses a tangible public health concern in rural communities. These findings highlight a direct linkage between the severity of environmental contamination and adverse human health outcomes.

Overall, the integrated assessment framework proved effective in synthesizing complex datasets and providing a holistic understanding of soil-related environmental and human health risks. The results underscore the need for targeted mitigation measures, including the promotion of cleaner household energy practices, improved coal ash management, and focused remediation of identified high-risk areas. The methodological approach and findings of this study offer a valuable reference for environmental risk assessment and evidence-based decision-making in rural regions facing similar contamination challenges.

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Code and data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Heavy metal concentration data for surface soils, together with associated sampling coordinates, were generated during the field campaign conducted in Uliastai, Zavkhan Province, Mongolia. All data processing, statistical analyses, and figure preparation were carried out using standard scientific software. No proprietary code was used in this study.

If applicable, derived datasets used for multivariate analysis, contamination indices, and human health risk assessment can be provided to facilitate reproducibility of the results.

Supplement

The supplement related to this article includes additional tables and figures supporting the main text, including detailed statistical outputs and supplementary spatial visualizations. The supplement is available online upon publication.

Author contributions

E.Btse. conceived and designed the study, conducted field sampling, performed laboratory analysis, contributed to data analysis, statistical interpretation, and visualization, and led data interpretation and manuscript preparation. C.S. contributed to the conceptualization of the study. B.G and K.F were responsible for laboratory

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analysis and instrumental measurements. D.D. and A.D. E.Btu assisted with fieldwork, soil sample preparation for measurement, data validation, and mapping. All authors reviewed and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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