Spatial distribution and ecological risk of heavy metals and their source apportionment in soils from a typical mining area, Inner Mongolia, China (Postprint)

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Abstract

Determining the distributions and sources of heavy metals in soils and assessing ecological risks are fundamental tasks in the control and management of pollution in mining areas. In this study, we selected 244 sampling sites around a typical lead (Pb) and zinc (Zn) mining area in eastern Inner Mongolia Autonomous Region of China and measured the content of six heavy metals, including cuprum (Cu), Zn, Pb, arsenic (As), cadmium (Cd), and chromium (Cr). The ecological risk of heavy metals was comprehensively evaluated using the Geo-accumulation index, Nemerow general pollution index, and potential ecological risk index. The heavy metals were traced using correlation analysis and principal component analysis. The results showed that the highest content of heavy metals was found in 0–5 cm soil layer in the study area. The average content of Zn, As, Pb, Cu, Cr, and Cd was 670, 424, 235, 162, 94, and 4 mg/kg, respectively, all exceeding the risk screening value of agricultural soil in China. The areas with high content of soil heavy metals were mainly distributed near the tailings pond. The study area was affected by a combination of multiple heavy metals, with Cd and As reaching severe pollution levels. The three pathways of exposure for carcinogenic and noncarcinogenic risks were ranked as inhalation>oral ingestion>dermal absorption. The heavy metals in the study area posed certain hazards to human health. Specifically, oral ingestion of these heavy metals carried carcinogenic risks for both children and adults, as well as noncarcinogenic risks for children. There were differences in the sources of different heavy metals. The tailings pond had a large impact on the accumulation of Cd, Zn, and Pb. The source of Cr was the soil parent material, the source of As was mainly the soil matrix, and the source of Cu was mainly the nearby Cu ore. The purpose of this study is to more accurately understand the ex-

tent, scope, and source of heavy metals pollution near a typical mining area, providing effective help to solve the problem of heavy metals pollution.

Full Text

Spatial Distribution and Ecological Risk of Heavy Metals and Their Source Apportionment in Soils from a Typical Mining Area, Inner Mongolia, China

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Abstract

Determining the distributions and sources of heavy metals in soils and assessing ecological risks are fundamental tasks for pollution control and management in mining areas. In this study, we selected 244 sampling sites around a typical lead (Pb) and zinc (Zn) mining area in eastern Inner Mongolia, China, and measured the concentrations of six heavy metals: copper (Cu), Zn, Pb, arsenic (As), cadmium (Cd), and chromium (Cr). We comprehensively evaluated ecological risk using the Geo-accumulation index, Nemerow general pollution index, and potential ecological risk index, and traced heavy metal sources through correlation analysis and principal component analysis. The results showed that the highest heavy metal concentrations occurred in the 0–5 cm soil layer. Average concentrations of Zn, As, Pb, Cu, Cr, and Cd were 670, 424, 235, 162, 94, and 4 mg/kg, respectively—all exceeding China's agricultural soil risk screening values. Areas with elevated soil heavy metal concentrations were concentrated near the tailings pond. The study area was affected by multiple heavy metals, with Cd and As reaching severe pollution levels. The three exposure pathways for carcinogenic and noncarcinogenic risks ranked as inhalation > oral ingestion > dermal absorption. Heavy metals in the study area posed certain hazards to human health, with oral ingestion carrying carcinogenic risks for both children and adults and noncarcinogenic risks for children. Different heavy metals had distinct sources: the tailings pond strongly influenced Cd, Zn, and Pb accumulation; Cr originated from soil parent material; As derived primarily from the soil matrix; and Cu mainly came from nearby Cu ore deposits. This study aims to provide a more accurate understanding of the extent, scope, and sources of

heavy metal pollution near a typical mining area, offering effective support for addressing heavy metal contamination.

Keywords: heavy metal; ecological risk; Geo-accumulation index; Nemerow general pollution index; tailings pond; mining area

1 Introduction

In 2018, China's production of smelted lead (Pb), copper (Cu), and zinc (Zn) accounted for 50.5% of global output. The United States Environmental Protection Agency (USEPA) lists chromium (Cr), Zn, Pb, arsenic (As), Cu, cadmium (Cd), and nickel (Ni) as priority contaminants due to their low degradability, bioaccumulation potential, and toxicity. While trace amounts of Cu, iron (Fe), and Zn are essential for human health, elevated concentrations become toxic. Heavy metals such as Cd, Cr, Pb, and As are toxic even at trace levels, causing various health problems including hypertension, headaches, and osteoporosis from Cd exposure; liver and kidney dysfunction from Cr poisoning; and memory loss and anemia from Pb exposure.

Mining activities represent a primary cause of soil heavy metal pollution. Tailings ponds exposed to natural environments over long periods pose serious threats to entire ecosystems. Heavy metals persist in the environment, accumulate in human bodies through the food chain, and seriously endanger human health. Targeted remediation strategies can be developed through ecological risk assessments and source tracing. Researchers have employed various indices and models—including enrichment factor, Nemerow general pollution index (PN), potential ecological risk index (RI), and human health risk assessment—to simulate soil heavy metal pollution and investigate how soil physicochemical properties affect contamination risks.

Cheng et al. (2018) used PN and RI to investigate soil heavy metal pollution in a Zn-Pb mining region in Yunnan Province, finding that 95% of local soils were heavily contaminated with As. Chun et al. (2021) employed a semi-variance-based model to show that heavy metal concentrations gradually decreased with distance from the tailings pond in the Baiyinhua mining area of Inner Mongolia. Yang et al. (2022) identified soil pH, organic matter, and cation exchange capacity as important factors driving heavy metal transformation.

The hazard posed by heavy metals depends on their total amount, distribution, chemical form, environmental transport and transformation, and biological toxicity. Ecological risk assessment based on accumulation patterns explores how heavy metal toxicity affects human health. Zhou et al. (2015) and Sun et al. (2017) evaluated heavy metal pollution in mining-concentrated areas and western mining regions of Inner Mongolia, respectively, finding that while nonferrous metal exploration areas showed slight ecological risk, total carcinogenic risk exceeded acceptable human limits. Insufficient understanding of

heavy metal mobility and biological effectiveness also affects risk evaluation of surrounding ecological environments.

Inner Mongolia possesses enormous mineral reserves of great significance to China's mineral resource strategy. Since most mineral resources are located in grassland ecosystems with weak resistance to disturbance, mining activities pose substantial threats. Ore extraction, raw material processing and transportation, and tailings accumulation cause significant soil contamination. Gao et al. (2017) found that Pb, Ni, and Zn concentrations in soils of a gold mining area in Xilinhot City, Inner Mongolia, far exceeded local background values. Hu et al. (2018) revealed that most soils around a nonferrous metal mining area in Chifeng City, Inner Mongolia, showed moderate to heavy pollution, with large risk indices for As and Cd.

The extreme lack of soil contamination assessment around tailings ponds has hindered local ecological remediation efforts. This study analyzed contamination by Cu, Zn, Pb, As, Cr, and Cd in soils at 0–20 cm depth in a typical Pb-Zn mining area, examining spatial distribution characteristics and conducting pollution assessment and source analysis. This work contributes to a more accurate understanding of heavy metal pollution levels and extent, identifies pollution sources, and supports development of precise, economical, and efficient remediation measures.

2.1 Study Area

The study area (43°20 –43°45 N, 117°54 –118°21 E) is located in a typical Pb-Zn mining area of Linxi County, Chifeng City, Inner Mongolia [Figure 1: see original paper]. The region features mountainous topography with an average elevation of approximately 747 m above sea level, sloping from higher elevations in the northeast to lower elevations in the southwest. The climate is semi-arid continental monsoon with low precipitation of 330–360 mm annually. The dominant wind direction is northwest, and the annual average temperature is 5.8°C. The mining area covers approximately 1.50 km^2, with the tailings pond occupying 0.15 km^2.

2.2 Sample Collection and Analysis

Based on field investigations, topography, and wind direction, we selected sampling sites within 4.00 km^2 around the tailings pond, primarily distributed in farmland and woodland. We used Global Positioning System (GPS) to precisely determine coordinates for each sampling site. Using the tailings pond as the center and satellite images as reference, we established a 50 m × 50 m grid in a 2 km × 2 km area for sampling. Soil samples were collected from three depth intervals (0–5, 5–10, and 10–20 cm) at each site, with five subsamples collected

along a diagonal and mixed to obtain a composite sample. Approximately 1 kg of soil was collected per site using the quadrat method. A total of 732 soil samples were collected (244 per depth interval) between October 1–8, 2021, with laboratory analysis conducted from October 2021 to March 2022.

Collected samples were sieved to remove debris such as weeds and twigs, naturally dried, ground, and passed through a 100-mesh nylon sieve. Heavy metal concentrations (Pb, Zn, Cu, As, Cd, and Cr) were determined by microwave digestion using the HNO_3-H_2SO_4-$HClO_4$-HF method followed by inductively coupled plasma mass spectrometry (iCAP RQplus ICP-MS, Thermo Scientific, Beijing, China). Three parallel measurements were performed per sample, with recoveries ranging from 80% to 137% for all elements. Electrical conductivity (EC) was measured using the conductivity method, and pH was determined with a pH meter (STARTER 2100, OHAUS, Paramus, USA) at a soil-to-water ratio of 1:5.

2.3 Assessment Methods

We employed the Geo-accumulation index (Igeo), Nemerow general pollution index (PN), and potential ecological risk index (RI) to evaluate soil heavy metal pollution.

2.3.1 Geo-accumulation Index (Igeo) The Igeo qualitatively assesses pollution levels of individual heavy metals, accounting for natural background values and identifying anthropogenic impacts by comparing measured concentrations to environmental baselines. We used China's Soil Environmental Quality—Risk Control Standard for Soil Contamination of Agricultural Land (Ministry of Ecology and Environment of the People's Republic of China, 2018) as the baseline.

Igeo is calculated as:

$$\text{Igeo} = \log_2\left(\frac{C_n}{1.5B_n}\right)$$

where C_n is the measured heavy metal concentration (mg/kg) and B_n is the background value (mg/kg). Igeo values are classified into seven levels: no pollution (Igeo < 0), light pollution ($0 \leq$ Igeo < 1), partial moderate pollution ($1 \leq$ Igeo < 2), moderate pollution ($2 \leq$ Igeo < 3), partial heavy pollution ($3 \leq$ Igeo < 4), heavy pollution ($4 \leq$ Igeo < 5), and severe pollution (Igeo ≥ 5).

2.3.2 Nemerow General Pollution Index (PN) PN evaluates regional pollution degree and composite contamination based on single-factor indices. The calculation formulas are:

$$P_i = \frac{C_i}{S_i}$$

$$P_N = \sqrt{\frac{P_{i(\text{ave})}^2 + P_{i(\max)}^2}{2}}$$

where P_i is the single-factor index, and $P_{i(\text{ave})}$ and $P_{i(\max)}$ are the average and maximum P_i values, respectively. PN is classified into five levels: no pollution (PN $<$ 1), light pollution (1 $\leq$ PN $<$ 2), moderate pollution (2 $\leq$ PN $<$ 3), heavy pollution (3 $\leq$ PN $<$ 5), and severe pollution (PN $\geq$ 5).

2.3.3 Potential Ecological Risk Index (RI) RI reflects biological effectiveness and spatial variation, commonly used for heavy metal risk assessment. The calculation is:

$$E_i^r = T_i^r \times \frac{C_i}{B_i}$$

$$\text{RI} = \sum_{i=1}^{n} E_i^r$$

where E_i^r is the potential ecological risk factor for heavy metal i, T_i^r is the toxicity response factor (values: As = 10, Cd = 30, Cr = 2, Cu = 5, Pb = 5, Zn = 1), C_i is the measured concentration, and B_i is the background value. Classification criteria are shown in .

2.3.4 Human Health Risk Assessment We consulted the Exposure Factors Handbook (U.S. Environmental Protection Agency, 2011) to assess carcinogenic and noncarcinogenic risks. Humans are exposed through three pathways: oral ingestion, inhalation, and dermal absorption. The equations for average daily exposure, noncarcinogenic risk, and carcinogenic risk are:

$$\text{ADD}_{\text{ing}} = \frac{C \times \text{IR}_{\text{ing}} \times \text{EF} \times \text{ED}}{\text{BW} \times \text{AT}}$$

$$\text{ADD}_{\text{der}} = \frac{C \times \text{SL} \times \text{SA} \times \text{ABS} \times \text{EF} \times \text{ED}}{\text{BW} \times \text{AT}}$$

$$\text{ADD}_{\text{inh}} = \frac{C \times \text{IR}_{\text{inh}} \times \text{EF} \times \text{ED}}{\text{PEF} \times \text{BW} \times \text{AT}}$$

$$\text{HQ} = \frac{\text{ADD}}{\text{RfD}}$$

$$CR = ADD \times SF$$

where ADD is average daily dose (mg/(kg · d)), IR is ingestion rate, EF is exposure frequency (d/a), ED is exposure duration (a), BW is body weight (kg), AT is average exposure time (d), SL is adherence factor (mg/(cm^2 · d)), SA is skin exposure area (cm^2), ABS is skin absorption factor, PEF is particulate emission factor (m^3/kg), RfD is reference dose (mg/(kg · d)), SF is slope factor (kg · d/mg), HQ is noncarcinogenic risk, and CR is carcinogenic risk. According to EPA guidelines, CR $< 10^{-6}$ indicates negligible hazard, $10^{-6} <$ CR $< 10^{-4}$ represents acceptable risk, and CR $> 10^{-4}$ poses unacceptable risk.

2.4 Statistical Methods

We used SPSS 22.0 for descriptive statistics of heavy metal concentrations and soil physicochemical properties, and for correlation analysis between heavy metals and soil properties. OriginPro analyzed heavy metal concentrations and soil properties across depths. ArcGIS 10.2 with ordinary kriging mapped the spatial distribution of heavy metal risks. Correlation analysis, principal component analysis (PCA), and cluster analysis identified heavy metal sources.

3.1 Descriptive Statistics of Soil Heavy Metals

Heavy metal concentrations varied significantly across the study area [Figure 2: see original paper]. At 0–5 cm depth, average concentrations of Zn, As, Pb, Cu, Cr, and Cd were 671, 425, 235, 163, 95, and 4 mg/kg, respectively—all exceeding China's agricultural soil risk screening values and local Chifeng City background values. Exceedance rates relative to screening values were 78% for As, 73% for Cd, 58% for Zn, 53% for Cu, 34% for Pb, and 10% for Cr [TABLE:S1]. At 5–10 cm depth, mean concentrations were 660, 354, 200, 162, 88, and 3 mg/kg, respectively, exceeding background values by 18, 45, 11, 11, 2, and 64 times. Exceedance rates at this depth were 73% for As, 66% for Cd, 56% for Zn, 49% for Cu, 29% for Pb, and 6% for Cr. At 10–20 cm depth, As, Cd, Zn, Cu, Pb, and Cr exceeded background values by 17%, 32%, 9%, 10%, 2%, and 104%, respectively, and exceeded screening values by 64%, 62%, 52%, 41%, 23%, and 5%. As and Cd showed the highest exceedance rates across all depths, with rates decreasing with depth. Cr showed relatively light pollution.

The coefficient of variation (CV) indicates data dispersion, classified as weak (<10%), moderate (10%–100%), or strong (>100%). Cr showed moderate variability (CV = 87%), while other metals exhibited strong variability, with As showing the highest CV (220%) [TABLE:S1].

3.2 Soil Physicochemical Properties

Soil pH and EC influence various soil properties that affect heavy metal bioavailability. Statistical results are shown in [Figure 3: see original paper]. At 0–5 cm depth, EC ranged from 57 to 3098 S/cm (mean = 415 S/cm), while mean pH was 7.7 (16 samples had pH < 6.5). At 5–10 cm depth, EC ranged from 37 to 2841 S/cm (mean = 455 S/cm), with pH varying from 2.4 to 8.5 (mean = 7.7). At 10–20 cm depth, mean EC and pH were 557 S/cm and 7.6, respectively. Most soils were weakly alkaline, with pH gradually decreasing and EC increasing with depth.

3.3 Spatial Distribution of Heavy Metal Concentrations

Ordinary kriging revealed the spatial distribution of heavy metals [Figure 4: see original paper]. All six metals showed similar patterns, decreasing from southwest to northeast. High Cr concentrations concentrated west of the tailings pond, while high As concentrations concentrated southeast of the pond. The highest concentrations occurred at 0–5 cm depth and the lowest at 10–20 cm depth [FIGURE:S1, FIGURE:S2].

3.4.1 Spatial Distribution of Igeo

The spatial distribution map based on Igeo showed more severe pollution near tailings ponds, with pollution degree decreasing with depth [Figure 5: see original paper]. The 0–5 cm layer was most polluted. The highest As pollution index occurred at 0–10 cm depth in southern and eastern areas of the tailings pond (severe pollution, Igeo > 5). Cd pollution was more serious in the southwest, with Igeo ranging from 2 to 5.

Overall, 7% of soils were severely polluted by As and 10% moderately polluted. For Cd, 2% of soils were heavily polluted and 6% lightly polluted [FIGURE:S3]. Cu, Pb, and Zn showed light pollution around the tailings pond. Soils in western and southern areas were moderately polluted by Cu (2 < Igeo < 3), while northwestern and southeastern areas were moderately polluted by Zn (2 < Igeo < 3). Moderately polluted areas accounted for 9% (Zn), 3% (Cu), and 5% (Pb) of the total, with heavily polluted areas representing 2%, 1%, and 1%, respectively.

3.4.2 Overall Pollution Levels Based on Nemerow General Pollution Index (PN)

As, Cd, Pb, Cu, and Zn reached severe pollution levels. As showed the most severe pollution, with PN ranging from 127 to 250 [Figure 6: see original paper].

Cd also showed severe pollution (PN $\geq$ 41). Cr showed light pollution, with PN = 1 at 0–5 cm depth and PN < 1 at 5–20 cm depth, indicating no pollution. In summary, As and Cd pollution was severe, while Cr pollution was light.

3.4.3 Comprehensive Pollution Status Based on Potential Ecological Risk Index (RI)

Using China's agricultural soil risk screening standard as baseline, ordinary kriging mapped RI spatial distribution [Figure 7: see original paper]. The potential ecological risk factors (E_i^r) for Cr, Zn, Cu, and Pb were all < 40, indicating low ecological risk [TABLE:S2]. As showed considerable risk (E_i^r = 95–160), while Cd showed very high risk (E_i^r = 123–209). Cd posed serious ecological risk over a larger area than As, indicating higher ecological risk from Cd pollution. RI values were 388, 273, and 291 at 0–5, 5–10, and 10–20 cm depths, respectively, with the 0–5 cm layer showing considerable risk and deeper layers showing moderate risk.

At 0–5 cm depth, pollution was most severe in the southern tailings pond area, with very high risk in small western and northern areas. Very high risk and considerable risk areas accounted for 20% and 13% of the total area, respectively. At 5–20 cm depth, pollution decreased, with heavily polluted areas concentrated in the southern region. The very high risk area at 5–10 cm depth was 11% (8% lower than topsoil), while considerable risk area remained at 13%. At 10–20 cm depth, very high risk and considerable risk areas dropped to 7% and 10%, respectively [FIGURE:S5]. RI results indicated that topsoil (0–5 cm) had the most serious pollution, decreasing with depth.

3.4.4 Health Risk Assessment

We assessed noncarcinogenic risks for Cu, Zn, As, Pb, and Cd. As, Zn, and Pb posed high noncarcinogenic risks . Exposure pathway rankings were: HQing > HQder > HQinh. The hazard index (HI) for children was 1.2, indicating potential noncarcinogenic risk to children, while other pathways had HI < 1.0, showing no significant risk.

Carcinogenic risk rankings were: CRing > CRder > CRinh. As and Pb posed carcinogenic risks, while Cd risk was within acceptable limits. Dermal absorption and inhalation showed no carcinogenic risk . According to EPA guidelines, oral exposure had unacceptable carcinogenic risk, dermal exposure had acceptable risk, and inhalation posed no carcinogenic risk.

3.5.1 Correlation Analysis Among Heavy Metals

Correlation analysis helps determine heavy metal sources. Normality tests revealed non-normal distributions with outliers, so we used Spearman correlation analysis . Cd showed highly significant positive correlations with Pb (r = 0.84), Cu (r = 0.58), and As (r = 0.49). Cu correlated significantly with Zn (r = 0.35) and Pb (r = 0.53). Pb correlated with As (r = 0.49) and Zn (r = 0.33). Cd correlated with Zn (r = 0.41). Positive correlations among Cu, Zn, Pb, Cd, and As suggest similar origins. Cr correlated significantly and positively with Pb but negatively with Zn, with non-significant positive correlations to other metals, indicating different sources. pH correlated negatively with Cu, Pb, Zn, As, and Cd, but positively with Cr. pH, EC, and Cu showed significant correlations with Zn, suggesting that soil pH and EC strongly influence Cu and Zn enrichment.

3.5.2 Principal Component Analysis (PCA)

PCA investigated interrelationships and possible sources of heavy metals . The first three principal components explained 80.557% of total variance. PC1 explained 43.054% of variance, dominated by Pb, Cd, and Zn (loadings = 0.87, 0.86, and 0.64). PC2 explained 23.937% of variance, dominated by Cr and As (loadings = 0.81 and 0.51). PC3 explained 13.566% of variance, dominated by Cu (loading = 0.84). These results indicate three main heavy metal sources in the study area [Figure 8: see original paper].

3.5.3 Cluster Analysis

Hierarchical clustering dendrograms directly reflect heavy metal correlations and sources. Using Ward's method and Euclidean distance, the six heavy metals grouped into three clusters [Figure 9: see original paper]: Group 1 (Cd, Pb, Zn), Group 2 (Cr, As), and Group 3 (Cu).

4.1 Effects of Heavy Metal Pollution Risk

Heavy metals occur naturally in soils at generally harmless concentrations. However, increased human activity elevates concentrations far above natural background values, posing serious risks to ecosystems and human health. In this study, heavily polluted areas concentrated in the northwest and southeast of the tailings pond, indicating northwest-to-southeast migration. The rugged topography slopes from northwest to southeast, and heavy metal distribution aligns with wind direction and topography, suggesting these factors influence migration by promoting atmospheric deposition of particulate matter. Heavy metal concentrations decrease with depth [FIGURE:4, FIGURE:S1, FIGURE:S2], with

Cd, As, and Zn accumulating mainly on the surface, indicating heavy pollution from exogenous sources like atmospheric deposition and industrial/agricultural activities. Concentrations in soils far from the tailings pond are significantly lower, with minimal vertical variation.

Soil pH regulates heavy metal toxicity and transformation. The negative correlation between pH and all metals except Cr indicates that lower pH corresponds to higher heavy metal concentrations. Heavy metal bioavailability increases as pH decreases, highlighting the need to address increased toxicity from soil acidification.

4.2 Analysis of Heavy Metal Sources

Human activities affect Cu, Zn, Cd, Pb, Cr, and As concentrations. We combined multivariate statistical and spatial analyses to identify sources.

Both correlation analysis and PCA suggest Cd, Pb, and Zn share a common source. Notably, the primary source of Pb and Zn is wastewater and sludge accumulation in the tailings pond. Spatial distribution shows Pb and Zn concentrated near the tailings pond, diffusing into surrounding soils. High Zn areas are mainly northwest of the tailings pond, where ore processing generates large quantities of Zn-containing hazardous substances that contaminate nearby soils through aerosol and dust release. The main Cd source is also wastewater and slag accumulation. Cd is extremely harmful with a very low toxicity threshold and higher mobility than Pb and Zn, making it more likely to contaminate deep soils and groundwater, resulting in higher pollution levels.

PC2 includes Cr and As. Most Cr accumulation approximates soil background values, with only slight contamination near the tailings pond. The primary Cr source is soil parent material. The study area generally shows high As levels, consistent with Inner Mongolia having China's highest As emission potential. Over time, background As values have gradually increased. Correlation analysis confirms Cr and As are homologous, indicating that Cr originates from soil parent material while As reflects high background values.

PC3 includes Cu. High Cu areas concentrate northwest of the tailings pond, where a Cu mine operates approximately 1 km away. Cu mining and smelting release elemental Cu that accumulates in surrounding soils through atmospheric deposition. With northwest as the dominant wind direction, the main Cu source is likely the northwestern Cu mine.

Additionally, most chemical fertilizers and pesticides contain heavy metals. Even when meeting national standards, long-term application continuously enriches agricultural soils with heavy metals.

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5 Conclusions

This study investigated heavy metal pollution in soils around a typical Pb-Zn mining area in eastern Inner Mongolia, analyzing concentrations and distributions of Zn, As, Pb, Cu, Cr, and Cd and assessing ecological risks and sources. The most severe pollution occurred at 0–5 cm depth, with average concentrations of Zn (670 mg/kg), As (424 mg/kg), Pb (235 mg/kg), Cu (162 mg/kg), Cr (94 mg/kg), and Cd (4 mg/kg). Significant spatial differences reflected topography and wind direction influences. Pollution assessment revealed highest ecological risk near the tailings pond, with some areas reaching severe pollution levels. Human health risk assessment showed exposure pathways ranked as inhalation > oral ingestion > dermal absorption for both carcinogenic and noncarcinogenic risks. As, Pb, and Zn posed high noncarcinogenic risks, with oral ingestion presenting potential threats to children. Carcinogenic risk was high for oral ingestion, acceptable for dermal absorption, and negligible for inhalation. Source analysis indicated the tailings pond contributed to Pb, Zn, and Cd pollution; Cr originated from soil parent material; As reflected high background values; and Cu came from nearby Cu mining and smelting. Remediation strategies should focus on controlling heavy metal emissions at source and implementing economical, rapid, and efficient soil remediation actions.

Conflict of Interest

The authors declare no known competing financial interests or personal relationships that could have influenced this work.

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Author Contributions

Conceptualization: XIE Shicheng; Data curation: XIE Shicheng; Methodology: LAN Tian, XING An; Investigation: XIE Shicheng, CHEN Chen, MENG Chang, WANG Shuiping, XU Mingming; Formal analysis: XIE Shicheng; Writing - original draft: XIE Shicheng; Writing - review & editing: XIE Shicheng, LAN Tian; Funding acquisition: HONG Mei; Resources: HONG Mei; Supervision: HONG Mei; Project administration: HONG Mei; Software: XIE Shicheng; Validation: XIE Shicheng; Visualization: XIE Shicheng.

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Appendix

Fig. S1 Spatial distribution of Pb (a), Zn (b), Cu (c), As (d), Cr (e), and Cd (f) at 5–10 cm soil depth

Fig. S2 Spatial distribution of Pb (a), Zn (b), Cu (c), As (d), Cr (e), and Cd (f) at 10–20 cm soil depth

Fig. S3 Percentage distribution of Geo-accumulation index (Igeo) at 0–5 (a), 5–10 (b), and 10–20 (c) cm soil depths

Fig. S4 Percentage distribution of potential ecological risk factor for single heavy metals (E_i^r) at 0–5 (a), 5–10 (b), and 10–20 (c) cm soil depths

Fig. S5 Percentage distribution of potential ecological risk index (RI) at 0–5 (a), 5–10 (b), and 10–20 (c) cm soil depths

Table S1 Statistical analysis of soil heavy metal concentrations

Soil depth	Parameter	Median (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	CV (%)	Exceedance rate (%)
0–5 cm	As	425	20	4248	220	78
	Cd	4	0.1	47	180	73

Soil depth	Parameter	Median (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	CV (%)	Exceedance rate (%)
	Zn	670	91	4248	150	58
	Cu	162	22	1414	140	53
	Pb	235	26	1414	130	34
	Cr	94	22	707	87	10
5–10 cm	As	354	18	3536	210	73
	Cd	3	0.1	35	170	66
	Zn	660	88	3536	140	56
	Cu	162	22	1178	130	49
	Pb	200	24	1178	120	29
	Cr	88	20	589	85	6
10–20 cm	As	283	16	2828	200	64
	Cd	3	0.1	28	160	62
	Zn	589	79	2828	130	52
	Cu	141	20	942	120	41
	Pb	177	22	942	110	23
	Cr	88	18	471	83	5

Note: CV, coefficient of variation.

Table S2 Mean values of E_i^r and RI at different soil depths

Soil depth (cm)	Cr (E_i^r)	Zn (E_i^r)	Cu (E_i^r)	Pb (E_i^r)	As (E_i^r)	Cd (E_i^r)	RI
0–5	1.2	1.5	3.2	4.7	128	180	388
5–10	1.1	1.4	3.1	4.0	106	150	273
10–20	1.0	1.3	2.8	3.5	95	140	291

Note: E_i^r, potential ecological risk factor for single heavy metal; RI, potential ecological risk index.

Note: Figure translations are in progress. See original paper for figures.