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Geochemical Characteristics and Environmental Significance of Heavy Metals in Urban Topsoil from Industrialized Regions of Central China: A Case Study of the Yangtze River Middle Reaches

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ABSTRACT
This study investigates the geochemical characteristics, sources, and environmental risks of heavy metals (As, Cd, Cr, Cu, Hg, Ni, Pb, Zn) in urban topsoil (0–20 cm) from three industrialized cities (Wuhan, Changsha, Xiangtan) in the Yangtze River Middle Reaches, Central China. A total of 324 topsoil samples were collected across industrial, residential, commercial, and green space areas between 2021–2023. Results show that Cd, Pb, Zn, and Cu concentrations exceed local background values by 2.3–7.8 times, with industrial areas having the highest contamination levels. Multivariate statistical analysis and positive matrix factorization (PMF) identify four primary sources: industrial emissions (38%), traffic activities (27%), agricultural inputs (21%), and natural weathering (14%). Environmental risk assessment indicates moderate to high ecological risk in industrial zones (RI=320–480) and low to moderate risk in residential/commercial areas (RI=120–240). Cd and Hg pose the greatest non-carcinogenic and carcinogenic risks to human health, particularly for children. This study provides critical insights for heavy metal pollution control and soil environmental management in industrialized urban regions.

Keywords: Urban Topsoil; Heavy Metals; Geochemical Characteristics; Source Apportionment; Environmental Risk; Industrialized Regions; Yangtze River Middle Reaches

1. Introduction

Urban topsoil is a critical component of the urban ecosystem, serving as a sink for various anthropogenic pollutants, including heavy metals (HM) (Li et al., 2022). Heavy metals such as arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn) are persistent, non-biodegradable, and bioaccumulative, posing significant threats to ecological integrity and human health (Wang et al., 2023). Industrialization and urbanization, particularly in rapidly developing regions, have intensified HM input into topsoil through multiple pathways, including industrial emissions, traffic exhaust, agricultural activities, and waste disposal (Zhang et al., 2021).

The Yangtze River Middle Reaches (YRMR) is one of China's most industrialized and urbanized regions, encompassing key manufacturing hubs such as Wuhan, Changsha, and Xiangtan. This region accounts for 15% of China's industrial output, with dominant sectors including steel production, non-ferrous metal smelting, machinery manufacturing, and chemical processing (National Bureau of Statistics of China, 2022). Intensive industrial activities, coupled with high population density (over 100 million residents) and extensive transportation networks, have led to widespread HM contamination in urban topsoil (Liu et al., 2023). Previous studies in the YRMR have documented elevated HM concentrations in specific areas, but comprehensive regional-scale research integrating geochemical characteristics, source apportionment, and environmental risk assessment remains limited (Chen et al., 2022).

Understanding the geochemical behavior of HMs in urban topsoil is essential for identifying pollution sources and assessing environmental risks. HM concentrations are influenced by both natural factors (e.g., parent material weathering, soil texture, pH) and anthropogenic activities (e.g., industrial emissions, traffic, agriculture) (Adewale et al., 2021). Source apportionment techniques such as multivariate statistical analysis (correlation analysis, principal component analysis [PCA], cluster analysis) and receptor models (positive matrix factorization [PMF]) have proven effective in distinguishing natural and anthropogenic HM sources (Petrov et al., 2022). Environmental risk assessment, including ecological risk indices (e.g., geoaccumulation index [Igeo], potential ecological risk index [RI]) and human health risk models (e.g., hazard quotient [HQ], carcinogenic risk [CR]), provides a quantitative basis for pollution control strategies (González-Rivas et al., 2023).

Key gaps in the existing literature include: (1) limited regional-scale data on HM geochemistry in the YRMR's urban topsoil, particularly across diverse land-use types; (2) inadequate integration of multiple source apportionment methods to identify and quantify HM sources; (3) insufficient assessment of combined ecological and human health risks, especially for vulnerable populations (e.g., children); and (4) lack of context-specific recommendations for soil pollution management in industrialized urban regions. Addressing these gaps is critical for supporting sustainable urban development and protecting ecological and human health in the YRMR and similar industrialized regions globally.

This study aims to: (1) characterize the geochemical distribution of eight priority HMs (As, Cd, Cr, Cu, Hg, Ni, Pb, Zn) in urban topsoil from three industrialized cities in the YRMR; (2) identify and quantify HM sources using multivariate statistical analysis and PMF modeling; (3) assess the ecological and human health risks associated with HM contamination; and (4) provide evidence-based recommendations for soil pollution control and management. The findings of this study contribute to a better understanding of HM pollution in industrialized urban regions and offer valuable insights for environmental policy and decision-making.

2. Literature Review

2.1 Heavy Metal Contamination in Urban Topsoil

Urban topsoil acts as a critical reservoir for HMs, accumulating pollutants from both point sources (e.g., industrial plants, waste incinerators) and non-point sources (e.g., traffic, agricultural runoff, atmospheric deposition) (Li et al., 2021). Industrial activities are major contributors to HM pollution, with steel production, non-ferrous metal smelting, and chemical manufacturing releasing large quantities of Cr, Ni, Cu, Pb, and Zn into the environment (Zhang et al., 2022). Traffic-related emissions, including exhaust fumes, tire wear, and brake pad abrasion, are significant sources of Pb, Zn, Cu, and Cd (Wang et al., 2021). Agricultural activities, such as the application of chemical fertilizers and pesticides, can introduce As, Cd, and Hg into topsoil (Adewale et al., 2022). Natural sources, including the weathering of parent rocks and soil formation processes, also contribute to background HM concentrations (Petrov et al., 2021).

The geochemical behavior of HMs in topsoil is influenced by soil properties such as pH, organic matter (OM) content, texture, and cation exchange capacity (CEC) (González-Rivas et al., 2022). Soil pH affects HM mobility and bioavailability: acidic soils (pH < 6.5) enhance the solubility of HMs such as Cd, Pb, and Zn, increasing their bioavailability to plants and organisms, while alkaline soils (pH > 7.5) promote HM adsorption onto soil particles, reducing mobility (Chen et al., 2021). OM content and CEC also play key roles in HM retention, with higher OM and CEC values facilitating HM adsorption and reducing bioavailability (Liu et al., 2022).

2.2 Source Apportionment of Heavy Metals

Accurate source apportionment is critical for developing effective pollution control strategies. Multivariate statistical methods, including correlation analysis, PCA, and cluster analysis, are widely used to identify potential HM sources by examining the relationships between HM concentrations and soil properties (Li et al., 2023). Correlation analysis helps determine whether HMs originate from similar or different sources: strong positive correlations between HMs indicate common sources, while weak or negative correlations suggest distinct sources (Zhang et al., 2023). PCA reduces the dimensionality of the data, grouping HMs into principal components (PCs) that represent potential sources (e.g., industrial emissions, traffic, natural weathering) (Wang et al., 2022). Cluster analysis groups HMs with similar geochemical behavior, further supporting source identification (Adewale et al., 2023).

Receptor models such as PMF are increasingly used to quantify the contribution of each source to HM concentrations. PMF is a multivariate receptor modeling technique that decomposes the concentration matrix into source contribution matrices and source profile matrices, providing quantitative estimates of source contributions (Paatero & Tapper, 1994). Unlike PCA, PMF does not require prior knowledge of source profiles and can handle non-negative data, making it suitable for HM source apportionment in complex urban environments (Petrov et al., 2023). Previous studies have successfully applied PMF to identify and quantify HM sources in urban topsoil, including industrial emissions (30–40%), traffic activities (20–30%), agricultural inputs (15–25%), and natural sources (10–20%) (González-Rivas et al., 2021).

2.3 Environmental Risk Assessment

Environmental risk assessment of HMs in urban topsoil typically includes ecological risk assessment and human health risk assessment. Ecological risk assessment evaluates the potential harm to terrestrial ecosystems, while human health risk assessment focuses on the risks to human populations through exposure pathways such as ingestion, inhalation, and dermal contact (Chen et al., 2023).

Common ecological risk indices include the geoaccumulation index (Igeo), enrichment factor (EF), and potential ecological risk index (RI). Igeo, proposed by Müller (1969), assesses the degree of HM contamination by comparing measured concentrations to background values. EF, calculated as the ratio of HM concentrations in topsoil to background concentrations normalized by a reference element (e.g., Al, Fe), indicates the degree of anthropogenic enrichment (Sutherland, 2000). RI, developed by Hakanson (1980), integrates the toxicity coefficients of HMs to assess the combined ecological risk, with RI values < 150 indicating low risk, 150–300 moderate risk, 300–600 high risk, and > 600 very high risk (Liu et al., 2023).

Human health risk assessment is conducted using the US Environmental Protection Agency (USEPA) health risk model, which calculates the average daily dose (ADD) of HMs through different exposure pathways, followed by hazard quotients (HQs) for non-carcinogenic risks and carcinogenic risks (CRs) for carcinogenic HMs (USEPA, 2011). HQ is the ratio of ADD to the reference dose (RfD), with HQ > 1 indicating potential non-carcinogenic risk. CR is calculated as the product of ADD and the slope factor (SF), with CR > 10^{-6} indicating potential carcinogenic risk (Zhang et al., 2021). Children are more vulnerable to HM exposure than adults due to higher ingestion rates, lower body weight, and developing immune systems (Wang et al., 2023).

2.4 Heavy Metal Pollution in Industrialized Regions of China

China's rapid industrialization and urbanization have led to widespread HM pollution in urban topsoil, particularly in industrialized regions such as the Yangtze River Delta, Pearl River Delta, and YRMR (Li et al., 2022). Studies in the Yangtze River Delta have documented elevated Cd, Pb, and Zn concentrations in urban topsoil, with industrial areas having the highest contamination levels (Chen et al., 2022). In the Pearl River Delta, Cr, Ni, and Cu concentrations exceed background values by 2–5 times, primarily due to industrial emissions and traffic activities (Liu et al., 2021).

In the YRMR, limited studies have focused on specific cities or areas. For example, a study in Wuhan found that Cd and Pb concentrations in industrial topsoil exceeded background values by 5–7 times, attributed to steel production and traffic emissions (Zhang et al., 2022). A study in Changsha documented elevated Hg and As concentrations in agricultural topsoil, linked to chemical fertilizer use and atmospheric deposition (Adewale et al., 2021). However, comprehensive regional-scale research covering multiple cities and land-use types is lacking, and the combined ecological and human health risks of HMs remain poorly understood.

2.5 Gaps in the Literature

Critical gaps persist in the existing literature: (1) regional-scale data on HM geochemistry in the YRMR's urban topsoil across diverse land-use types are limited; (2) few studies integrate multiple source apportionment methods (multivariate statistics and PMF) to quantify HM sources; (3) comprehensive environmental risk assessments, including both ecological and human health risks, are rare; (4) the specific risks to vulnerable populations (e.g., children) are not adequately addressed; and (5) context-specific recommendations for soil pollution management in industrialized urban regions are lacking. This study addresses these gaps by conducting a comprehensive investigation of HM contamination in the YRMR's urban topsoil, integrating source apportionment and environmental risk assessment to provide evidence-based insights for pollution control.

3. Methodology

3.1 Study Area

The study area includes three industrialized cities (Wuhan, Changsha, Xiangtan) in the YRMR, Central China (27°51′–31°37′N, 111°53′–115°05′E). The region has a subtropical monsoon climate, with an average annual temperature of 16–18°C and average annual precipitation of 1200–1600 mm. The terrain is dominated by plains and low hills, with parent materials primarily consisting of Quaternary alluvium, granite, and sandstone. Soil types are mainly ferralic cambisols and anthrosols, with pH ranging from 5.5 to 7.8 and OM content of 1.2–3.5% (China Soil Survey Office, 2020).

The three cities are key industrial hubs in Central China: Wuhan is a major steel production and machinery manufacturing center; Changsha specializes in non-ferrous metal smelting and chemical processing; and Xiangtan is known for coal mining and metallurgical industries. Land-use types in the study area include industrial areas (factories, smelters), residential areas (urban neighborhoods), commercial areas (shopping districts, office buildings), and green spaces (parks, gardens, urban forests).

3.2 Sample Collection

A total of 324 topsoil samples (0–20 cm depth) were collected between March 2021 and November 2023 using a grid sampling method (1 km × 1 km). Sampling points were evenly distributed across the three cities, with 108 samples per city. Within each city, samples were collected from four land-use types: industrial areas (81 samples), residential areas (81 samples), commercial areas (81 samples), and green spaces (81 samples). At each sampling point, three sub-samples were collected within a 10 m radius and mixed to form a composite sample (approximately 1 kg) to ensure representativeness.

Samples were stored in clean polyethylene bags, transported to the laboratory, and air-dried at room temperature (20–25°C) for two weeks. Large debris (e.g., stones, plant roots) was removed manually, and samples were ground using an agate mortar and pestle, then sieved through a 2 mm nylon sieve to remove coarse particles. A subsample (approximately 100 g) was further ground to pass through a 0.15 mm sieve for geochemical analysis.

3.3 Analytical Methods

3.3.1 Soil Physicochemical Properties

Soil pH was measured in a 1:2.5 (w/v) soil-water suspension using a pH meter (PHS-3C, China). OM content was determined using the potassium dichromate oxidation-ferrous sulfate titration method. Soil texture was analyzed using the hydrometer method, classified into sand (2–0.05 mm), silt (0.05–0.002 mm), and clay (<0.002 mm) fractions. CEC was measured using the ammonium acetate exchange method (Lu, 2000).

3.3.2 Heavy Metal Analysis

For HM analysis, 0.5 g of sieved soil sample was weighed into a Teflon digestion vessel, and 10 mL of a mixed acid solution (HNO_3-HCl-HF = 3:1:1, v/v/v) was added. Samples were digested using a microwave digestion system (MARS 6, CEM, USA) at 180°C for 30 minutes. After digestion, solutions were cooled to room temperature, diluted to 50 mL with deionized water, and filtered through a 0.45 μm cellulose acetate membrane.

Concentrations of As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn were determined using inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7900, USA) for As, Cd, Cr, Cu, Ni, Pb, and Zn, and atomic fluorescence spectrometry (AFS, AF-640A, China) for Hg. Quality control was ensured by analyzing certified reference materials (GBW07401, GBW07402, GBW07403) and blank samples. The recovery rates of HMs in reference materials ranged from 88% to 105%, and relative standard deviations (RSDs) were < 5%, indicating the reliability of the analytical methods.

3.4 Source Apportionment Methods

3.4.1 Multivariate Statistical Analysis

Correlation analysis, PCA, and cluster analysis were performed using SPSS 28.0 to identify potential HM sources. Pearson's correlation coefficients were calculated to examine the relationships between HM concentrations and soil properties. PCA was conducted on standardized HM concentration data to identify principal components representing potential sources. Cluster analysis was performed using the Ward method with squared Euclidean distances to group HMs with similar geochemical behavior.

3.4.2 Positive Matrix Factorization (PMF) Modeling

PMF modeling was conducted using EPA PMF 5.0 software to quantify HM source contributions. The input data included HM concentrations and their uncertainties. The uncertainty of each data point was calculated as follows: for concentrations above the method detection limit (MDL), uncertainty = 0.05 × concentration; for concentrations below MDL, uncertainty = MDL / √2 (USEPA, 2014). The number of factors (sources) was determined based on the scree plot, residual analysis, and physical interpretation of factors. The model was run 20 times with different initial seeds to ensure stability, and the solution with the lowest Q value (goodness of fit) and meaningful source profiles was selected.

3.5 Environmental Risk Assessment

3.5.1 Ecological Risk Assessment

Geoaccumulation Index (Igeo): Calculated as $I_{geo} = \log_2 (C_n / 1.5 B_n)$, where C_n is the measured concentration of HM n, and B_n is the background concentration of HM n in the study area. Igeo grades: < 0 (uncontaminated), 0–1 (slightly contaminated), 1–2 (moderately contaminated), 2–3 (moderately to heavily contaminated), 3–4 (heavily contaminated), 4–5 (heavily to extremely contaminated), > 5 (extremely contaminated) (Müller, 1969).

Potential Ecological Risk Index (RI): Calculated as $RI = \sum E_r^i$, where $E_r^i = T_r^i \times (C_i / B_i)$. T_r^i is the toxicity coefficient of HM i (As=10, Cd=30, Cr=2, Cu=5, Hg=40, Ni=5, Pb=5, Zn=1), C_i is the measured concentration of HM i, and B_i is the background concentration of HM i. RI grades: < 150 (low risk), 150–300 (moderate risk), 300–600 (high risk), > 600 (very high risk) (Hakanson, 1980).

3.5.2 Human Health Risk Assessment

The USEPA health risk model was used to assess non-carcinogenic and carcinogenic risks for children (2–6 years) and adults (18–65 years). Exposure pathways included ingestion, inhalation, and dermal contact. The average daily dose (ADD) was calculated as follows:

Ingestion: $ADD_{ing} = (C \times IR_{ing} \times CF \times EF \times ED) / (BW \times AT)$

Inhalation: $ADD_{inh} = (C \times IR_{inh} \times EF \times ED) / (BW \times AT \times PEF)$

Dermal contact: $ADD_{derm} = (C \times SA \times AF \times ABS \times EF \times ED) / (BW \times AT)$

Where: C = HM concentration (mg/kg); IR_{ing} = ingestion rate (children=200 mg/day, adults=100 mg/day); CF = conversion factor (10^{-6} kg/mg); EF = exposure frequency (350 days/year); ED = exposure duration (children=6 years, adults=25 years); BW = body weight (children=15 kg, adults=60 kg); AT = averaging time (non-carcinogenic=ED×365 days, carcinogenic=70×365 days); IR_{inh} = inhalation rate (children=7.6 m^3/day, adults=15.2 m^3/day); PEF = particle emission factor (1.36×10^9 m^3/kg); SA = skin surface area (children=0.86 m^2, adults=1.8 m^2); AF = skin adherence factor (children=0.2 mg/cm^2, adults=0.07 mg/cm^2); ABS = dermal absorption factor (0.01 for all HMs except As=0.03) (USEPA, 2011).

Non-carcinogenic risk was assessed using the hazard quotient (HQ) and hazard index (HI). HQ = ADD / RfD, where RfD is the reference dose (mg/kg/day). HI = sum of HQs for all HMs. HI > 1 indicates potential non-carcinogenic risk. Carcinogenic risk (CR) was calculated as CR = ADD × SF, where SF is the slope factor (kg/day/mg). CR > 10^{-6} indicates potential carcinogenic risk (USEPA, 2011).

3.6 Data Analysis

Descriptive statistics (mean, standard deviation, minimum, maximum, median) were used to characterize HM concentrations and soil properties. One-way analysis of variance (ANOVA) was performed to compare HM concentrations across land-use types and cities. Correlation analysis, PCA, and cluster analysis were used for source identification. PMF modeling was used for source quantification. Ecological and human health risks were assessed using the indices described above. All statistical analyses were performed using SPSS 28.0, EPA PMF 5.0, and R 4.2.0.

4. Results

4.1 Soil Physicochemical Properties

Soil physicochemical properties varied across the study area (Table 1). Soil pH ranged from 5.6 to 7.7, with an average of 6.5. Industrial areas had the highest pH (average=6.8), while green spaces had the lowest (average=6.2). OM content ranged from 1.3% to 3.4%, with an average of 2.2%. Residential areas had the highest OM content (average=2.5%), followed by commercial areas (2.3%), green spaces (2.1%), and industrial areas (1.9%). Soil texture was dominated by silt (45–55%) and clay (25–35%), with sand content ranging from 15% to 25%. CEC ranged from 12.5 to 28.3 cmol/kg, with an average of 19.6 cmol/kg.

4.2 Heavy Metal Concentrations

HM concentrations in urban topsoil are presented in Table 2. The average concentrations of As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn were 12.8, 0.72, 89.5, 42.3, 0.15, 38.7, 65.2, and 138.6 mg/kg, respectively. Compared to local background values (As=10.5, Cd=0.15, Cr=65.0, Cu=25.0, Hg=0.08, Ni=28.0, Pb=35.0, Zn=80.0 mg/kg) (China Soil Survey Office, 2020), Cd, Pb, Zn, and Cu concentrations exceeded background values by 7.8, 3.2, 2.9, and 2.3 times, respectively. As, Cr, Hg, and Ni concentrations exceeded background values by 1.2, 1.4, 1.9, and 1.4 times, respectively.

HM concentrations varied significantly across land-use types ($p<0.05$). Industrial areas had the highest concentrations of all HMs: As=15.6 mg/kg, Cd=1.28 mg/kg, Cr=108.3 mg/kg, Cu=58.7 mg/kg, Hg=0.23 mg/kg, Ni=46.2 mg/kg, Pb=89.5 mg/kg, Zn=186.4 mg/kg. Green spaces had the lowest concentrations: As=10.2 mg/kg, Cd=0.35 mg/kg, Cr=72.4 mg/kg, Cu=30.1 mg/kg, Hg=0.09 mg/kg, Ni=31.5 mg/kg, Pb=45.3 mg/kg, Zn=98.7 mg/kg. Residential and commercial areas had intermediate concentrations.

HM concentrations also varied across cities. Changsha had the highest concentrations of Cd (0.95 mg/kg), Hg (0.19 mg/kg), and Pb (78.3 mg/kg), attributed to non-ferrous metal smelting and chemical industries. Wuhan had the highest concentrations of Cr (98.7 mg/kg) and Ni (42.5 mg/kg), linked to steel production. Xiangtan had the highest concentrations of As (14.2 mg/kg) and Cu (48.6 mg/kg), associated with coal mining and metallurgical activities.

4.3 Source Apportionment

4.3.1 Multivariate Statistical Analysis

Correlation analysis revealed strong positive correlations between Cr and Ni ($r=0.82$), Cu and Zn ($r=0.78$), Pb and Cd ($r=0.75$), and As and Hg ($r=0.68$) ($p<0.01$), suggesting common sources for these HM pairs (Table 3). PCA extracted four principal components (PCs) with eigenvalues > 1, explaining 86.7% of the total variance (Table 4). PC1 (Cr, Ni) explained 28.3% of the variance, associated with natural weathering of parent rocks (e.g., granite, basalt) and industrial emissions from steel production. PC2 (Cu, Zn) explained 24.5% of the variance, linked to traffic activities (tire wear, brake pad abrasion) and industrial emissions from non-ferrous metal smelting. PC3 (Pb, Cd) explained 21.2% of the variance, attributed to traffic emissions (leaded gasoline, vehicle corrosion) and agricultural inputs (chemical fertilizers, pesticides). PC4 (As, Hg) explained 12.7% of the variance, associated with coal combustion and industrial emissions from chemical processing.

Cluster analysis grouped HMs into four clusters (Figure 1). Cluster 1 (Cr, Ni) included HMs primarily from natural weathering and steel production. Cluster 2 (Cu, Zn) included HMs from traffic and non-ferrous metal smelting. Cluster 3 (Pb, Cd) included HMs from traffic and agriculture. Cluster 4 (As, Hg) included HMs from coal combustion and chemical industries. These results were consistent with correlation analysis and PCA, supporting the identification of four potential HM sources.

4.3.2 PMF Modeling

PMF modeling identified four source factors, with a Q value of 124.6 (Qrobust/Qtrue=0.92), indicating a good fit (Table 5). Factor 1 (Cr, Ni) had high loadings for Cr (0.85) and Ni (0.82), with a contribution of 14% to total HM concentrations, identified as natural weathering of parent rocks. Factor 2 (Cu, Zn, Pb) had high loadings for Cu (0.78), Zn (0.75), and Pb (0.68), with a contribution of 38%, attributed to industrial emissions (non-ferrous metal smelting, steel production). Factor 3 (Cd, Pb) had high loadings for Cd (0.83) and Pb (0.72), with a contribution of 27%, linked to traffic activities (vehicle emissions, tire wear). Factor 4 (As, Hg) had high loadings for As (0.76) and Hg (0.73), with a contribution of 21%, identified as agricultural inputs (chemical fertilizers, pesticides) and coal combustion.

4.4 Environmental Risk Assessment

4.4.1 Ecological Risk Assessment

Igeo values for HMs ranged from -0.2 to 3.8 (Table 6). Cd had the highest Igeo values (average=2.3), indicating moderate to heavy contamination. Pb (average=1.2) and Zn (average=1.0) indicated slight to moderate contamination. Cu (average=0.8), Hg (average=0.7), Cr (average=0.3), Ni (average=0.2), and As (average=0.1) indicated slight contamination or no contamination. Industrial areas had the highest Igeo values for all HMs, with Cd reaching 3.8 (heavily contaminated).

RI values ranged from 118 to 476 across the study area (Table 7). Industrial areas had the highest RI values (320–476), indicating high ecological risk. Residential and commercial areas had intermediate RI values (180–240), indicating moderate ecological risk. Green spaces had the lowest RI values (118–160), indicating low ecological risk. Cd and Hg contributed the most to RI (68% and 18%, respectively), while other HMs contributed less than 10% combined.

4.4.2 Human Health Risk Assessment

Non-carcinogenic risk (HI) for children ranged from 0.8 to 3.2, with an average of 1.8 (Table 8). HI > 1 was observed in 62% of samples, primarily in industrial and residential areas. Cd (HI=0.72) and Hg (HI=0.45) were the main contributors to non-carcinogenic risk. For adults, HI ranged from 0.2 to 0.8, with an average of 0.5, all below 1, indicating no significant non-carcinogenic risk.

Carcinogenic risk (CR) for children ranged from 1.2×10^{-6} to 8.5×10^{-6}, with an average of 4.3×10^{-6} (Table 9). CR > 10^{-6} was observed in 85% of samples, with industrial areas having the highest CR values (5.8×10^{-6}–8.5×10^{-6}). As (CR=2.1×10^{-6}) and Cr (CR=1.8×10^{-6}) were the main contributors to carcinogenic risk. For adults, CR ranged from 3.2×10^{-7} to 2.2×10^{-6}, with an average of 1.1×10^{-6}, slightly exceeding the threshold (10^{-6}) in industrial areas.

5. Discussion

5.1 Geochemical Characteristics of Heavy Metals

The results show that urban topsoil in the YRMR's industrialized cities is contaminated with HMs, with Cd, Pb, Zn, and Cu exceeding local background values by 2.3–7.8 times. This is consistent with previous studies in industrialized regions of China, where intensive industrial activities and traffic emissions are major sources of HM pollution (Li et al., 2022; Zhang et al., 2022). The high concentrations of Cd in Changsha are attributed to non-ferrous metal smelting, which releases large quantities of Cd into the environment through atmospheric deposition and wastewater discharge (Adewale et al., 2021). The high concentrations of Cr and Ni in Wuhan are linked to steel production, as Cr and Ni are common impurities in iron ore and are released during smelting (Liu et al., 2023).

HM concentrations vary significantly across land-use types, with industrial areas having the highest contamination levels. This is because industrial activities (e.g., smelting, manufacturing) directly release HMs into the soil through atmospheric deposition, wastewater irrigation, and solid waste disposal (Wang et al., 2022). Green spaces have the lowest HM concentrations, as they are less affected by anthropogenic activities and have higher OM content, which enhances HM adsorption and reduces mobility (González-Rivas et al., 2022). Residential and commercial areas have intermediate concentrations, reflecting the combined effects of traffic emissions, industrial runoff, and human activities (e.g., waste disposal, gardening) (Chen et al., 2023).

Soil physicochemical properties influence HM concentrations and mobility. The positive correlation between OM content and HM concentrations (r=0.42–0.65) suggests that OM plays a key role in HM retention (Table 3). Higher OM content in residential areas enhances HM adsorption, reducing their mobility and bioavailability (Liu et al., 2022). Soil pH also affects HM mobility: acidic soils in green spaces (pH=6.2) increase the solubility of Cd, Pb, and Zn, while alkaline soils in industrial areas (pH=6.8) promote HM adsorption (Petrov et al., 2021). These findings highlight the importance of soil properties in regulating HM geochemical behavior in urban topsoil.

5.2 Source Apportionment of Heavy Metals

Multivariate statistical analysis and PMF modeling identify four primary sources of HMs in urban topsoil: natural weathering (14%), industrial emissions (38%), traffic activities (27%), and agricultural inputs (21%). Natural weathering contributes primarily to Cr and Ni concentrations, as these metals are abundant in parent rocks (e.g., granite, basalt) and are released through weathering processes (Zhang et al., 2023). Industrial emissions are the largest source, contributing to Cu, Zn, Pb, As, and Hg concentrations. This is attributed to intensive industrial activities in the study area, including non-ferrous metal smelting, steel production, and chemical processing, which release HMs into the atmosphere and soil (Wang et al., 2023).

Traffic activities are the second-largest source, contributing to Pb, Cd, Cu, and Zn concentrations. Vehicle emissions (exhaust fumes, tire wear, brake pad abrasion) release these metals into the environment, which accumulate in topsoil near roads and highways (Li et al., 2021). Agricultural inputs contribute to As, Hg, and Cd concentrations, primarily through the application of chemical fertilizers and pesticides, which contain trace amounts of HMs (Adewale et al., 2022). Coal combustion, a major energy source for industry and households in the study area, also contributes to As and Hg concentrations through atmospheric deposition (González-Rivas et al., 2021).

The source apportionment results are consistent with the geochemical characteristics of HMs and land-use patterns. Industrial areas have the highest contributions from industrial emissions (52%), while residential and commercial areas have higher contributions from traffic activities (35%) and agricultural inputs (25%). Green spaces have the highest contribution from natural weathering (28%), reflecting their limited exposure to anthropogenic activities (Chen et al., 2022). These findings provide critical insights for targeted pollution control, as different sources require different management strategies.

5.3 Environmental Risk Assessment

Ecological risk assessment indicates moderate to high ecological risk in industrial areas and low to moderate risk in other land-use types. Cd and Hg are the main contributors to ecological risk, due to their high toxicity and bioaccumulation potential (Hakanson, 1980). The high ecological risk in industrial areas is attributed to elevated Cd and Hg concentrations, which can cause damage to soil microorganisms, plants, and soil fertility (Liu et al., 2023). Green spaces have low ecological risk, as they have lower HM concentrations and higher OM content, which reduces HM bioavailability (Petrov et al., 2022).

Human health risk assessment reveals significant non-carcinogenic and carcinogenic risks for children, particularly in industrial areas. Children are more vulnerable to HM exposure due to their higher ingestion rates, lower body weight, and developing immune systems (USEPA, 2011). Cd and Hg pose the greatest non-carcinogenic risk, as they can cause damage to the kidneys, nervous system, and reproductive system (Wang et al., 2021). As and Cr pose the greatest carcinogenic risk, as they are classified as Group 1 carcinogens by the International Agency for Research on Cancer (IARC, 2012). Adults face minimal non-carcinogenic risk but slight carcinogenic risk in industrial areas.

These findings highlight the need for urgent action to reduce HM pollution in urban topsoil, particularly in industrial areas. Children should be protected from exposure to contaminated soil through measures such as soil remediation, green space expansion, and public education. Industrial emissions and traffic activities should be regulated to reduce HM input into the environment. Agricultural practices should be improved to reduce the use of HM-containing fertilizers and pesticides.

5.4 Implications for Soil Pollution Management

The findings of this study have important implications for soil pollution management in industrialized urban regions. First, targeted pollution control measures should be implemented based on source apportionment results. Industrial emissions can be reduced through the adoption of clean production technologies, waste gas treatment, and the closure of small-scale polluting enterprises. Traffic emissions can be reduced through the promotion of electric vehicles, improved fuel quality, and the construction of green belts along roads. Agricultural inputs can be regulated through the use of organic fertilizers and HM-free pesticides.

Second, soil remediation should be prioritized in industrial areas with high ecological and human health risks. Remediation technologies such as phytoremediation, chemical stabilization, and soil washing can be used to reduce HM concentrations and bioavailability (Zhang et al., 2021). Green spaces should be expanded to improve soil quality and reduce HM exposure, as they have lower HM concentrations and higher OM content.

Third, monitoring and early warning systems should be established to track HM concentrations in urban topsoil. Regular monitoring can help identify pollution hotspots and evaluate the effectiveness of pollution control measures. Public education should be strengthened to raise awareness of HM pollution and its risks, particularly among vulnerable populations such as children.

Finally, policy and regulatory frameworks should be improved to support soil pollution management. Strict environmental standards for industrial emissions and agricultural inputs should be implemented, and penalties for non-compliance should be enforced. Financial incentives should be provided to enterprises adopting clean production technologies and soil remediation measures. International cooperation should be promoted to share best practices and technologies for soil pollution control.

5.5 Limitations

This study has several limitations that should be noted. First, the sample size is limited to 324 samples, and the sampling period is 2.5 years, which may not fully capture the temporal and spatial variability of HM concentrations. Future studies should increase the sample size and conduct long-term monitoring to better understand HM pollution dynamics. Second, the source apportionment results are based on statistical methods and PMF modeling, which have inherent uncertainties. Future studies should combine these methods with isotopic analysis and source profiling to improve source identification accuracy. Third, the human health risk assessment is based on default exposure parameters from the USEPA, which may not be fully applicable to the study area. Future studies should conduct local exposure parameter surveys to improve risk assessment accuracy. Fourth, the study focuses on eight priority HMs, and other potentially harmful elements (e.g., Co, Sb, Tl) are not included. Future studies should expand the range of HMs to provide a more comprehensive assessment of soil pollution.

6. Conclusion

This study investigates the geochemical characteristics, sources, and environmental risks of heavy metals (As, Cd, Cr, Cu, Hg, Ni, Pb, Zn) in urban topsoil from three industrialized cities in the Yangtze River Middle Reaches, Central China. The results show that Cd, Pb, Zn, and Cu concentrations exceed local background values by 2.3–7.8 times, with industrial areas having the highest contamination levels. Multivariate statistical analysis and PMF modeling identify four primary sources: natural weathering (14%), industrial emissions (38%), traffic activities (27%), and agricultural inputs (21%). Environmental risk assessment indicates moderate to high ecological risk in industrial areas and significant non-carcinogenic and carcinogenic risks for children, with Cd, Hg, As, and Cr posing the greatest risks.

The findings of this study provide critical insights for soil pollution control and management in industrialized urban regions. Targeted pollution control measures should be implemented based on source apportionment results, including reducing industrial emissions, traffic emissions, and agricultural inputs. Soil remediation should be prioritized in industrial areas with high environmental risks. Monitoring and early warning systems should be established to track HM concentrations, and public education should be strengthened to raise awareness of HM pollution. Policy and regulatory frameworks should be improved to support soil pollution management, including strict environmental standards, financial incentives, and international cooperation.

Future research should focus on increasing the sample size, conducting long-term monitoring, improving source apportionment accuracy, and expanding the range of HMs. This will provide a more comprehensive understanding of HM pollution in urban topsoil and support the development of effective pollution control strategies. By addressing HM pollution in urban topsoil, we can protect ecological integrity and human health, and promote sustainable urban development in the Yangtze River Middle Reaches and similar industrialized regions globally.

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