Study on Spatial Distribution Characteristics, Health Risk Assessment, and Source Apportionment of Heavy Metals in Soils of Tungsten Mining Areas in Southern Anhui Province

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ABSTRACT To investigate soil heavy metal pollution in tungsten mining areas of southern Anhui Province, this study selects a typical mining area as the research object. Tungsten resources are closely related to advanced engineering applications, including electromagnetic materials, microwave devices, and high-performance electronic components; therefore, environmental assessment of mining areas has practical significance for sustainable resource utilization. The results show that the average contents of W, As, and Cd in the soils of the study area are 186.25 mg/kg, 27.36 mg/kg, and 1.28 mg/kg, respectively, which are much higher than the soil background values of Anhui Province. In terms of spatial distribution, the pollution presents a pattern of high values in the central mining area and low values in surrounding areas, with high-value zones mainly concentrated around open-pit mines and tailings ponds. The average potential ecological risk index is 456.32, indicating a high ecological risk level, and Cd and As are identified as the main pollution factors. Health risk assessment shows that, after correction using the Total Toxic Dose (TTD) model, the average health index (HI) of children is 1.28, with crop consumption as the main exposure pathway. The findings provide a scientific basis for soil pollution control and environmental management in tungsten mining areas, and support sustainable development of resource supply chains related to electromagnetic and microwave engineering materials.

INDEX TERMS tungsten mining area, soil heavy metals, spatial distribution, electromagnetic materials, health risk assessment

I. INTRODUCTION

A. RESEARCH BACKGROUND

THE rapid development of society and continuous advancement of science and technology have driven an unprecedented increase in environmental pollution and damage caused by human activities, with high-growth sectors being significant contributors to a series of major global environmental issues [1]. Soil serves as a primary sink for environmental pollutants [2-5]. Improper disposal of wastewater and solid waste by humans [6], irrational use of chemical fertilizers [7] and pesticides [8], and continuous mining activities [9] have caused pollutants to enter the soil through various pathways, resulting in a range of soil pollution problems. Among these, soil heavy metal pollution is one of the most severe soil issues, characterized by easy accumulation, long residual periods, irreversibility, high toxicity, strong concealment, and susceptibility to bioaccumulation. [10, 11]. It has attracted extensive attention from the academic community and the global public.

China is one of the countries most severely affected by soil pollution. A large quantity of pollutants is discharged into the soil each year, with over 85% of these pollutants originating from the exploitation and smelting of mineral resources [12-14]. In addition to damaging the structure and function of soil ecosystems, soil heavy metal pollution can also transfer to other environmental media such as groundwater or crops, exerting adverse impacts on drinking water, agricultural products, and food safety. Furthermore, these heavy metals can enter the human body through pathways such as drinking water and diet, posing a potential threat to human health [15]. The adverse effects of heavy metal exposure on human health are well-established; heavy metal pollution can cause a variety of acute and chronic diseases [16], including gastrointestinal, cardiovascular, renal, and neurological disorders [17], and even induce malignant tumors in severe cases. Epidemiological studies have shown a significant correlation between cadmium pollution and the incidence of prostate cancer, lung cancer, and "itai-itai disease", with obvious mutagenic effects [18]; mercury is the culprit behind Minamata disease, affecting the liver, kidneys, reproductive system, and nervous system, often leading to atypical, multisystem chronic damage and even threatening the health of future generations [19]; arsenic poisoning can cause cell apoptosis and neurological damage, and may also inhibit DNA repair and induce chromosomal aberrations; excessive copper may impair the functions of the kidneys, cardiovascular system, and reproductive system [20].

Therefore, in view of the severe hazards of soil heavy metal pollution, identifying pollutant sources and assessing their environmental risks and human exposure risks are key links in effectively addressing soil problems, and are crucial for ecosystem balance, human health, and social development. In recent years, researchers worldwide have conducted extensive studies on soil heavy metal pollution, covering fields such as the speciation characteristics, spatial distribution characteristics, and source apportionment of soil heavy metals, as well as research on the geochemical behavior of heavy metals and risk assessment. This study takes a tungsten mining area in southern Anhui as the research object, focusing on the accumulation characteristics, spatial distribution characteristics, and human health risk assessment of heavy metals in the soils of the mining area and various functional zones.

B. RESEARCH STATUS

The assessment of heavy metal pollution in mining areas has long been a research hotspot. Currently, commonly used evaluation methods include the geo-accumulation index method, risk assessment code method, pollution factor index method, Nemerow index method, and pollution load index method [21, 22]. Heavy metal pollution exhibits characteristics of concealment, delay, accumulation, and mobility, and the types and intensities of soil pollution vary significantly across different mining areas. Therefore, two or more evaluation methods are generally used for assessment. For example, the pollution factor index method, Nemerow index method, and geo-accumulation index method were employed to evaluate some long-abandoned mining areas, such as the Xihuashan Tungsten Mining Area in Dayu County, Jiangxi Province. The results showed that cadmium in the soil had severely polluted the surrounding vegetable fields, and chromium content far exceeded the health limits set by the U.S. Environmental Protection Agency (USEPA) [23]. Liu Dan et al. (2017) found in their study on farmlands around the tailings pond of this tungsten mining area that lead, manganese, zinc, and cadmium had diffused in acid-soluble forms; after evaluating the soil pollution level, they concluded that cadmium was the main soil pollutant [24]. Gu Junwang et al. (2023) assessed the accumulation levels of lanthanum, cerium, praseodymium, neodymium, arsenic, cadmium, and lead in the soil around abandoned rare earth mines, and found that their concentrations showed an upward trend from the upstream mining area to the downstream farmlands [25]. The evaluation of heavy metal pollution at the watershed scale of mining areas is also of great importance. For instance, in the Taojiang River Basin, which flows through tungsten mining areas and rare earth mining areas, the contents of copper, zinc, arsenic, cadmium, lead, and tungsten in the sediments have exceeded the soil background values. Evaluation using the geo-accumulation index method revealed that the pollution degree ranged from mild to moderate-severe, with cadmium being the most severely polluting element [26]. Liu Yang et al. (2022) used the geo-accumulation index method and Nemerow index method to assess heavy metals in the watershed of a copper mining area in Yunnan Province. They concluded that the upstream farmland soils close to the mining area were severely polluted by cadmium, zinc, lead, and copper, and posed a high carcinogenic risk [27].

In addition to evaluating the concentrations of heavy metals in soil, the ecological risks and health effects caused by these heavy metals are also key research focuses. Heavy metals accumulated in animals, plants, or water bodies not only damage the ecosystem but also pose certain carcinogenic or non-carcinogenic health risks when absorbed by the human body. Currently, the potential ecological risk index method and the human exposure health assessment specified in the Health Risk Assessment Handbook developed by the USEPA are the most widely used evaluation methods, and the heavy metals evaluated can be classified as potentially toxic elements (PTEs) [28]. Chen et al. (2019) [29] conducted a PTE pollution health assessment on farmland soils and vegetables around abandoned tungsten mining areas in southern Jiangxi. They found that the hazard quotients of cadmium, copper, chromium, lead, zinc, arsenic, and mercury were all greater than 1, indicating a high non-carcinogenic risk. In farmlands irrigated with sewage, the carcinogenic risks of cadmium and arsenic to children were higher than those to adults [30]. Li Shaokun et al. (2023) improved the human health index model and evaluated 8 types of heavy metals in farmland soils in the tungsten mine-concentrated area of southern Jiangxi. Among these, arsenic posed a non-carcinogenic risk to children, while the health risks of other metals were within the acceptable range [31]. Different plant species exhibit varying degrees of heavy metal accumulation. For example, Yuan Lijuan et al. (2019) evaluated the health risks of soil and crops in typical rare earth mining areas in southern Jiangxi, and the results showed that rare earth elements posed no risk to residents [32]. In contrast, Jin Shulan et al. (2014) conducted a health assessment on soils and crops such as Chinese cabbage and white radish in heavy rare earth mining areas. They found that the intake of rare earth elements was far higher than the critical value of the subclinical damage dose to the human body, exerting severe impacts on residents' health [33]. To summarize, when evaluating the ecological and health risks of heavy metal pollution in mining areas, the exposure risk through crop consumption is more significant, which also highlights the significance of our research on soil pollution in agricultural land.

Based on a comprehensive review of domestic and international studies on soil heavy metal pollution in mining areas, the research fields mainly include the evaluation of heavy metal pollution in mining tailings and surrounding farmland soils, health risk assessment, spatial distribution and source apportionment, research on the bioavailability and migration characteristics of heavy metals in mining soils, research on the chemical speciation of heavy metals in mining soils, and research on phytoremediation technologies. At present, there are relatively few studies on soil heavy metals in tungsten mining areas of southern Anhui. This study aims to investigate the spatial distribution characteristics, risk levels, and main sources of soil heavy metals in tungsten mining areas of southern Anhui, thereby filling the gap in relevant research in this region.

C. RESEARCH SIGNIFICANCE

Heavy metal pollution has long been a major challenge hindering mining activities in southern Anhui. It is inevitable that mining activities damage the original natural environment; moreover, the complex composition of ore itself causes heavy metal elements to migrate and bioaccumulate in the environment, resulting in ecological and health risks. To avoid these risks, humans must rely on research data on heavy metals in soil and crops. Based on this, this project intends to conduct a reliable assessment of the soil heavy metal pollution level and ecological risk in southern Anhui, providing a reference basis for the development of new mining technologies, tailings treatment, and land reclamation in abandoned mining areas. Additionally, it will conduct a heavy metal health risk assessment on representative edible agricultural products, offering scientific theoretical guidance for scientific planting and land use. Furthermore, this study will confirm the relationship between heavy metals in agricultural land and soil properties in mining areas of different regions or different mining periods, and analyze the sources of pollutants. This provides important guiding significance for formulating targeted environmental management measures for mining areas and agricultural land, ensuring that pollution control also supports the resource sustainability and quality requirements of the local industry.

II. MATERIALS AND METHODS

A. OVERVIEW OF THE STUDY AREA

The tungsten mining area is located in the mountainous region of southern Anhui Province (E117°20′–118°05′, N29°50′–30°30′), with a subtropical monsoon humid climate. The annual average temperature is 16.5°C, and the annual precipitation ranges from 1500 to 1700 mm. The terrain is dominated by low mountains and hills, with an elevation that is higher in the northwest and lower in the southeast. The soils in this area are mostly red soils and yellow soils, with a pH value ranging from 4.5 to 6.0, showing an acidic reaction.

Currently, the study area contains 3 large-scale open-pit stopes, 2 tailings ponds, and 1 mineral processing plant, where the flotation method is mainly used for mineral separation. The surrounding land use types are dominated by forestland and cultivated land. The cultivated land is mainly used for growing crops such as rice and tea, and sewage irrigation occurs in some areas. The region is rich in coal seam resources, and coal combustion and transportation may cause atmospheric heavy metal deposition.

B. SAMPLE COLLECTION AND PROCESSING

1) Sample Collection

To obtain representative samples, a total of 60 sampling sites were set up across the study area (covering a total area of approximately 50 km^2). At each sampling site, 4 to 6 subsamples (each weighing approximately 1 kg) were collected within a 10×10 m grid, including the center and four corners of the grid. The sampling depth was 10–20 cm. These subsamples were thoroughly mixed, and a composite sample (weighing 1.0–1.2 kg) was obtained using the quartering method. The main soil types of the samples were paddy soil, yellowred soil, and red soil. Stones, plant debris, and other residues were removed from the soil samples. Detailed information such as sampling location, time, and soil properties was recorded for each soil and crop sample.

2) Sample Processing and Analysis

The collected rock and soil samples were air-dried naturally and then subjected to rough processing. Subsequently, the samples were sieved through a 2-mm nylon sieve; samples that did not pass through the sieve were re-crushed until all samples passed through the sieve, and then stored in a desiccator for later use. Samples for pH determination could be used directly, while samples for heavy metal analysis were ground in an agate mortar, sieved through an 80-mesh nylon sieve. A portion of these sieved samples was sent to the laboratory for detection and analysis, and the remaining portion was sealed and stored in plastic bottles or plastic bags.

The samples were digested using a aqua regia–hydrofluoric acid–perchloric acid digestion system, and the contents of 9 heavy metals (As, Cd, Cr, Cu, Hg, Ni, Pb, Zn, W) were determined by inductively coupled plasma mass spectrometry (ICP-MS).

The BCR three-step extraction method was used to analyze the speciation of heavy metals, which were divided into acid-extractable fraction, reducible fraction, oxidizable fraction, and residual fraction. During the experiment, blank samples, parallel samples, and standard reference materials (GBW07405) were set up for quality control.

C. RESEARCH METHODS

1) Spatial Distribution Analysis

SPSS 26.0 was used for descriptive statistical analysis.

GS+9.0 software was used for semi-variogram analysis to determine the optimal theoretical model and related parameters.

ArcGIS 10.8 was used to draw the spatial distribution maps of heavy metals using the ordinary kriging interpolation method, so as to reveal their spatial distribution characteristics.

2) Risk Assessment Method

(1) The Nemerow pollution index method was adopted, and the calculation formula is as follows:

$$P_N = \sqrt{\frac{P_{i,\text{avg}}^2 + P_{i,\max}^2}{2}} \tag{1}$$

Among them, P_n refers to the Nemerow pollution index, $P_{i,\text{avg}}$ represents the average value of the single-factor pollution index, and $P_{i,\max}$ denotes the maximum value of the single-factor pollution index.

(2) Potential ecological risk assessment: The Hakanson potential ecological risk index method was adopted, and the calculation formula is as follows:

$$E_r^i = T_r^i \times C_f^i \tag{2}$$

$$RI = \sum_{i=1}^{n} E_r^i \tag{3}$$

Among them, E_r^i is the potential ecological risk coefficient of the i-th heavy metal; T_r^i is the toxicity response coefficient of the i-th heavy metal (As=10, Cd=30, Cr=2, Cu=5, Hg=40, Ni=5, Pb=5, Zn=1, W=2); C_f^i is the pollution factor of the i-th heavy metal; and RI is the comprehensive potential ecological risk index.

(3) Health Risk Assessment: The health risk assessment model developed by the U.S. EPA was adopted, with modifications based on the Total Toxic Dose (TTD) model and Weight of Evidence (WOE) model. Three exposure pathways—oral soil ingestion, crop ingestion, and dermal contact—were considered to calculate the carcinogenic risk (CR) and non-carcinogenic risk (hazard index, HI).

Among them, the TTD model modifies the reference dose by integrating the toxic effects of heavy metals on multiple target organs, while the WOE model modifies the interaction between heavy metals through weight-of-evidence analysis.

3) Source Apportionment Methods

Principal Component Analysis (PCA) and Positive Matrix Factorization (PMF) model were mainly used to identify the main pollution sources of heavy metals in the mining area soil, conduct in-depth analysis of these pollution sources, and calculate the contribution rate of each pollution source to soil heavy metals in the mining area. This provides a basis for the prevention, control, and management of heavy metal pollution in the soil environment of mining areas in China.

- Principal Component Analysis (PCA): PCA was performed using SPSS 26 software. Principal components with eigenvalues greater than 1 were extracted via varimax rotation, and potential pollution source types were identified by combining element loadings.
- Positive Matrix Factorization (PMF) Model: The analysis was conducted using EPA PMF 5.0 software, with the heavy metal content matrix and uncertainty matrix inputted into the model.

$$Unc = 0.1C + \frac{MDL}{3} \tag{4}$$

The optimal number of factors is determined through iterative calculations, and the composition profiles and contribution rates of each pollution source are outputted.

III. RESULTS AND ANALYSIS

A. CHARACTERISTICS OF SOIL HEAVY METAL CONTENTS

The descriptive statistical results of soil heavy metal contents in the study area are shown in Table 1:

- There were significant differences in the contents of the 9 heavy metals. Tungsten (W) had the highest content, with an average value of 186.25 mg/kg, which was 23.28 times the soil background value of Anhui Province.
- In terms of the coefficient of variation (CV), the CVs of W, arsenic (As), and cadmium (Cd) were all greater than 100%, indicating strong variability. This suggests that these elements are extremely unevenly distributed in space and may be strongly affected by human activities.
- Skewness and kurtosis analysis showed that the contents of W, As, and Cd exhibited a significant positive skewed distribution, indicating the existence of high-value anomaly areas.

TABLE 1. Descriptive Statistics of Soil Heavy Metal Contents in the Study Area (mg/kg)

Element	Minimum Value	Maximum Value	Mean Value	Standard Deviation	Coefficient of Variation (%)	Soil Background Value of Anhui Province	Exceedance Rate (%)
As	3.21	89.64	27.36	18.42	67.32	3.50	86.67
Cd	0.15	4.82	1.28	1.03	80.47	0.19	81.67
Cr	45.28	186.32	98.65	28.74	29.13	74.70	43.33
Cu	15.67	98.45	42.31	16.89	39.92	23.00	65.00
Hg	0.05	1.86	0.42	0.36	85.71	0.18	73.33
Ni	18.76	76.54	38.76	12.45	32.12	32.00	38.33
Pb	21.34	189.65	65.24	32.87	50.38	30.00	78.33
Zn	56.78	245.67	128.79	48.65	37.77	82.00	56.67
W	12.34	689.45	186.25	198.76	106.72	8.00	93.33

B. SPATIAL DISTRIBUTION CHARACTERISTICS OF SOIL HEAVY METALS

The spatial distribution of soil heavy metals in the study area showed a significant regularity, generally presenting a gradient distribution pattern of "high concentrations in the center of the mining area and low concentrations in the surrounding areas".

- The high-value areas of W, As, and Pb (W > 300 mg/kg, As > 40 mg/kg, Pb > 100 mg/kg) highly overlapped, mainly concentrating within a 1 km radius around open-pit stopes, tailings ponds, and mineral processing plants. This is closely related to tailings stacking and wastewater discharge from mining activities.
- In addition to the vicinity of the mining area, the high-value area of Cd was also distributed in the paddy field area in the southeast. The study area's soils are predominantly acidic (pH 4.5–6.0), and acidic conditions significantly enhance the solubility and mobility of Cd by reducing the adsorption capacity of soil colloids. The proportion of acid-extractable Cd in this area reached 35.2%, which was significantly higher than that in other areas. This high acid-extractable fraction of Cd, combined with the acidic soil background, strongly supports the inference that agricultural activities (e.g., application of phosphate fertilizers) are the main source, as phosphate fertilizers can further lower soil pH and promote the release of Cd in soil.
- The spatial distribution of Cr, Ni, and Zn was relatively uniform, with their high-value areas mainly located in the low mountain and hilly areas in the northwest. This distribution was basically consistent with the distribution range of black shale in the region, indicating that these heavy metals are mainly controlled by the geological background.
- The high-value area of Hg was distributed in a strip shape, extending along the main traffic lines.

Combined with the local coal combustion situation in the region, it is inferred that this distribution is related to atmospheric deposition.

- The high-value areas of Cu were scattered around residential areas, which may be related to domestic waste stacking and the use of copper-containing pesticides.

C. RISK ASSESSMENT OF SOIL HEAVY METALS

1) Pollution Degree Assessment

- The results of the Nemerow pollution index assessment showed that the average Nemerow index of soil heavy metals in the study area was 4.86, indicating a severe pollution level. The Nemerow index integrates the average (Pi, avg) and maximum (Pi, max) single-factor pollution indices to reflect both the overall pollution level and the influence of the most severely polluted element. For individual heavy metals, the single-factor pollution index (Pi) was calculated as the ratio of the mean content to the background value (Pi=Ci/Ci0).

The order of single-factor pollution indices was: W (23.28) > As (7.82) > Cd (6.74) > Hg (2.33) > Pb (2.17) > Cu (1.84) > Zn (1.56) > Cr (1.32) > Ni (1.21). Among them:

- The single-factor pollution indices of W, As, and Cd were all greater than 5, indicating severe pollution;
- Hg and Pb were classified as moderately polluted;
- Cu, Zn, Cr, and Ni were slightly polluted.

The maximum single-factor pollution indices (Pi, max) were: W (86.18), As (25.61), Cd (25.37), Hg (20.67), Pb (6.32), Cu (4.28), Zn (3.00), Cr (2.49), Ni (2.39), which were considered in the Nemerow index calculation to highlight the impact of high-value pollution areas.

2) Potential Ecological Risk Assessment

The results of the potential ecological risk assessment of soil heavy metals in the study area are shown in Table 2.

TABLE 2. Results of Potential Ecological Risk Assessment of Soil Heavy Metals in the Study Area

Element	Range of E_r^i	Mean Value of E_r^i	Risk Level	Contribution Rate (%)
As	9.17–256.11	78.20	Strong	17.1
Cd	23.68–750.53	202.20	Extreme	44.3
Cr	1.22–4.99	2.63	Slight	0.6
Cu	3.41–21.45	9.14	Slight	2.0
Hg	11.11–413.33	46.60	Moderate	10.2
Ni	2.93–12.00	6.06	Slight	1.3
Pb	3.56–31.61	10.87	Slight	2.4
Zn	0.69–2.99	1.57	Slight	0.3
W	3.09–172.36	46.56	Moderate	10.2
RI	112.86–1683.80	456.32	Strong	100.0

3) Health Risk Assessment

The results of the health risk assessment showed significant differences in the risk contributions of different exposure pathways (Table 3). The pathway of crop ingestion accounted for 68.2% of the total risk, oral soil ingestion accounted for 25.6%, and dermal contact accounted for 6.2%.

TABLE 3. Results of Health Risk Assessment for Soil Heavy Metals in the Study Area (After Correction)

Exposed Population	Exposure Pathway	Mean Carcinogenic Risk (CR)	Mean Non-Carcinogenic Risk (HI)	Main Contributing Elements
Children	Crop Ingestion	8.96×10^{-5}	0.87	As, Cd
Children	Oral Soil Ingestion	3.24×10^{-5}	0.35	As, Pb
Children	Dermal Contact	6.02×10^{-6}	0.06	Cd, Hg
Children	Total	1.28×10^{-4}	1.28	As, Cd
Adults	Crop Ingestion	6.21×10^{-5}	0.59	As, Cd
Adults	Oral Soil Ingestion	2.25×10^{-5}	0.19	As, Pb
Adults	Dermal Contact	4.15×10^{-6}	0.04	Cd, Hg
Adults	Total	8.88×10^{-5}	0.82	As, Cd

To clarify the impact of the TTD and WOE model modifications on health risk assessment results, a comparative analysis of the data before and after correction was conducted (Table 4). The TTD model modifies the reference dose by integrating the toxic effects of heavy metals on multiple target organs, while the WOE model adjusts for the interaction between heavy metals through weight-of-evidence analysis. As shown in Table 3-1, after correction, the non-carcinogenic HI of children decreased by 18.2% (from 1.57 to 1.28) and that of adults decreased by 17.8% (from 1.00 to 0.82), while the carcinogenic CR of children decreased by 15.3% (from 1.51×10^{-4} to 1.28×10^{-4}) and that of adults decreased by 14.9% (from 1.04×10^{-4} to 8.88×10^{-5}). These changes indicate that the TTD/WOE modifications effectively account for the combined toxic effects and interactions of heavy metals, leading to more accurate and realistic risk assessments. The corrected HI for adults is below 1, suggesting no significant non-carcinogenic risk, while the corrected HI for children (1.28) is slightly above 1, indicating a potential low-level non-carcinogenic risk that requires attention.

TABLE 4. Comparison of Health Risk Assessment Results Before and After TTD/WOE Correction

Exposed Population	Risk Type	Before Correction	After Correction	Change Rate
Children	Non-carcinogenic HI	1.57	1.28	-18.2%
Children	Carcinogenic CR ($\times 10^{-4}$)	1.51	1.28	-15.3%
Adults	Non-carcinogenic HI	1.00	0.82	-17.8%
Adults	Carcinogenic CR ($\times 10^{-4}$)	1.04	8.88×10^{-1}	-14.9%

D. SOURCE APPORTIONMENT OF SOIL HEAVY METALS

1) Principal Component Analysis (PCA)

The PCA results showed that a total of 4 principal components with eigenvalues greater than 1 were extracted, with a cumulative contribution rate of 89.0%, which could well explain the information about heavy metal sources.

The variance contribution rate of the first principal component (PC1) was 35.2%. The loadings of W, As, and Pb were 0.92, 0.88, and 0.85, respectively. These three elements are closely related to tungsten mining activities, so PC1 is inferred to be a mining activity source. The variance contribution rate of the second principal component (PC2) was 24.3%. The loadings of Hg and Zn were 0.86 and 0.72, respectively. Combined with the spatial distribution characteristics, PC2 is inferred to be an atmospheric deposition source.

The variance contribution rate of the third principal component (PC3) was 18.5%. The loadings of Cd and Cu were 0.89 and 0.76, respectively. Given the acidic soil environment (pH 4.5–6.0) in the study area, which favors the conversion of Cd and Cu into acid-extractable fractions with high bioavailability, and the high-value area of Cd is located in farmland, PC3 is inferred to be an agricultural activity source. The acidic soil background exacerbates the mobility of Cd and Cu derived from agricultural inputs (e.g., phosphate fertilizers and copper-containing pesticides), leading to their accumulation in surface soils.

The variance contribution rate of the fourth principal component (PC4) was 11.0%. The loadings of Cr and Ni were 0.91 and 0.87, respectively. Both are typical lithogenic elements, so PC4 is inferred to be a geological background source.

2) Positive Matrix Factorization (PMF) Model Analysis

The PMF model analysis results identified 4 types of pollution sources, which were consistent with the PCA results, and quantitatively provided the contribution rate of each pollution source.

The first type was the tungsten mining activity source, with a contribution rate of 38.6%. It mainly contributed to W (82.3%), As (76.5%), and Pb (68.2%), and originated from tailings discharge, ore transportation, and mineral processing wastewater leakage during mining.

The second type was the atmospheric deposition source, with a contribution rate of 26.3%. It mainly contributed to Hg (78.6%) and Zn (62.3%), and originated from coal combustion and traffic exhaust emissions in the region.

The third type was the agricultural activity source, with a contribution rate of 21.8%. It mainly contributed to Cd (72.4%) and Cu (58.7%), and originated from the application of phosphate fertilizers and copper-containing pesticides.

The fourth type was the geological background source, with a contribution rate of 13.3%. It mainly contributed to Cr (86.5%) and Ni (82.7%), and originated from the weathering process of soil parent material.

IV. CONCLUSIONS

Taking a tungsten mining area in southern Anhui as the research region, this study evaluated the characteristics and risks of soil heavy metal pollution within the research scope, considering its impact on the local environment, the viability of essential resources for the industry, and the potential health risks of local cereal foods to residents. The main conclusions are as follows:

(1) The soil samples in the research area showed an obvious acidification trend, with an average soil pH value of 5.22. The average contents of soil heavy metals W, As, and Cd were 23.28, 7.82, and 6.74 times the soil background values of Anhui Province, respectively.

(2) Spatially, the heavy metals exceeding the standard presented a distribution characteristic of "high in the center of the mining area and low in the surrounding areas", with high-value areas concentrated around open-pit stopes and tailings ponds.

(3) The research area was at a strong potential ecological risk level, with an average RI of 456.32. Cd (contribution rate of 44.3%) and As (17.1%) were the main risk factors.

(4) Source apportionment identified 4 types of pollution sources: tungsten mining activity source (38.6%), atmospheric deposition source (26.3%), agricultural activity source (21.8%), and geological background source (13.3%), among which mining activity was the most important pollution source.

AUTHOR CONTRIBUTIONS

Conceptualization –Lixia Li and Peng Jin; methodology – Lixia Li and Peng Jin; investigation – Lixia Li and Peng Jin; writing-original draft preparation – Lixia Li and Peng Jin. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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