Prepublished copy

Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper to be published in Vol. 25, No. 3, September 2026 issue

Type of the Paper (Original Research)

Evaluation and Origin Studies of Heavy Metals in Soils Around Traditional Mining Regions in the Northwest Guizhou District

Tiantian Cai[1,2], Die Xu[3], Ji Wang[1,2]†, Shuai Zhang[1,2], Xiongfei Cai[1,2] and Huifang Zhao[1,2]

[1]School of Geography and Environmental Science, Guizhou Normal University, Guiyang 550025, China

[2]The State Key Laboratory, Incubation Base for Karst Mountain Ecology Environment of Guizhou Province, Guiyang 550001, Peoples Republic of China

[3]College of Education Science, Qiannan Normal University for Nationalities, Duyun 558000, China

† Corresponding Authors: Ji Wang; wangji@gznu.edu.cn

ORCID IDs of Authors

Shuai Zhang: 0000-0003-1501-1653

Xiongfei Cai: 0000-0002-8817-2709

Key Words	Lead-zinc mining area; Heavy metal pollution; Spatial distribution; PMF source analysis
DOI	https://doi.org/10.46488/NEPT.2026.v25i03.D1888 (DOI will be active only after the final publication of the paper)
Citation for the Paper	Cai, T., Xu, D., Wang, J., Zhang, S., Cai, X. and Zhao, H., 2026. Evaluation and origin studies of heavy metals in soils around traditional mining regions in the northwest Guizhou district. *Nature Environment and Pollution Technology*, 25(3), D1888. https://doi.org/10.46488/NEPT.2026.v25i03.D1888

Abstract: Heavy metal pollution in soil has become a highly concerning environmental issue. However, there is still a lack of research on the distribution of heavy metal content, pollution degrees, and quantitative source analysis in lead-zinc mining areas. Therefore, to assess the heavy metal pollution status of the soil around a lead-zinc mining area in northwest Guizhou and quantitatively analyze its sources, this study collected 56 surface soil samples and 14 soil samples from two different depths. The contents and chemical forms of Cd, Pb, Cr, Cu, Ni, and Zn were analyzed. The pollution status of heavy metals was evaluated by using the geoaccumulation index (I_{geo}) and the ratio of secondary phase and primary phase (RSP) method.

The sources of heavy metals were analyzed by combining correlation analysis, principal component analysis, and the positive matrix factorization (PMF) model. The results showed that (1) the average contents of Pb, Zn, Cd, Cr, Cu, and Ni were all below the background values of soil in Guizhou. Among them, the maximum values of Cd and Pb were close to the background values, but their coefficient of variation was 66.56%, 413.84%, 123.04%, 195.69%, 319.98%, and 373.41%, respectively, indicating a large variation and significant influence of human activities. The high-value areas of Cd, Cu, Pb, and Zn were highly consistent with the mining site. (2) The I_{geo} results indicated that the study area was in a non-polluted state; however, the RSP assessment indicated that 5% and 4% of the sites were slightly polluted by Pb and Zn, respectively, 4% of the sites were slightly polluted by Cd, and 2% of the sites were moderately and severely polluted. (3) PMF source analysis indicated that the pollution mainly came from five sources: agricultural activities contributed 63.7% of Cr; atmospheric deposition contributed 72.3% of Cd; wastewater discharge contributed 59.1% of Zn and 41.9% of Ni; traffic emissions contributed 52.9% of Cu, 45.4% of Ni, and 36.2% of Cr; and mining activities contributed 79.9% of Pb. This study concluded that the overall heavy metal pollution in the study area was slight, but Cd, Pb, and Zn were significantly affected by mining and related human activities in some areas. Different elements had clear source differences, with mining emissions being the main source of Pb, while agriculture, atmospheric deposition, and wastewater discharge played a dominant role in the accumulation of Cr, Cd, and Zn, respectively. The pollution status and sources of the regional soil were analyzed, providing a scientific basis for soil pollution prevention and control and ecological risk management in this area.

1. INTRODUCTION

As one of the most important natural resources in human life, soil is an important basic material for sustainable economic and social development. Metal pollution not only has a direct impact on soil quality and ecosystem stability but also may pose a potential threat to human health (Kiran et al., 2022). Recently, with the rapid development of industrialization, the impact of mining activities on the natural environment has become increasingly prominent, especially around the lead-zinc mine area (Demková et al., 2017; Yang et al., 2018; Zhang et al., 2023). Southwest China is a typical area with a high natural background of heavy metals, and the soil in this region exceeds standard levels due to its close relationship with geological factors (Chen et al., 2024; Liu et al., 2023). With the continuous progress of regional urbanization and industrialization, the soil in this kind of high geological background area has been subjected to strong human disturbance such as agricultural cultivation, mining, and metal smelting while receiving natural weathering input for a long time. As a typical interactive area between natural processes and human activities, under the superimposed influence of endogenous input and exogenous pollution caused by human activities under high geological background, heavy metals in soil in mining areas are generally limited by unclear pollution sources and causes, unclear ecological risks, and insufficient comprehensive prevention and control technology, which poses great challenges to the safe utilization of land resources in mining areas, accurate control of heavy metal pollution sources, and scientific prevention and control of ecological risks. Therefore, evaluating and analyzing the sources of soil heavy metals in the mining area is essential for effectively controlling soil heavy metal pollution.

Northwest Guizhou is not only a famous distribution center of zinc refining in China, with rich coal resources under its jurisdiction providing abundant raw materials for zinc refining (Ali et al., 2020). Heavy metal pollution in the soil around the lead-zinc mine area has increasingly become prominent due to the high geological background, mining activities, and human interference (Zhou et al., 2018). Magu Town, Hezhang County, located in the northwest of Guizhou Province, is a typical concentrated distribution area of lead and zinc deposits, which is rich in mineral resources and plays an important role in local economic development (Li, 1994). The mining history in this area is nearly 300 years, and the heavy metals left by mining activities still cause serious pollution to the surrounding soil (Zhou et al., 2020). Therefore, the purpose of this study is to systematically evaluate the soil in this area, determine its pollution degree, analyze the pollution sources, and explore their contribution ratio. Although numerous scholars have investigated land heavy metal contamination in various mining regions in Guizhou Province (Li et al., 2024; Wang et al., 2021), these works are mostly limited to single pollution assessments and preliminary identification of pollution sources.

Currently, commonly employed methodologies, such as correlation analysis, principal component analysis, and cluster analysis, can preliminarily ascertain the quantity and classification of pollution sources(Bi et al., 2020; Jin et al., 2019; Liang et al., 2023). ; however, they exhibit certain limitations: A single evaluation method struggles to systematically and comprehensively reflect the regional pollution level; furthermore, a preliminary identification of pollution sources insufficiently explains each source's specific contributions and proportion(Chen and Lu, 2017; Hu et al., 2020; Li et al., 2023; Yu et al., 2021). Therefore, it is necessary to integrate more systematic methods to realize a comprehensive evaluation of the pollution degree and a quantitative analysis of the pollution source contribution. Therefore, in this study, the geo-accumulation index (I_{geo}) and the the ratio of secondary phase and primary phase (RSP) method were combined to evaluate the pollution situation. I_{geo} focuses on quantifying the degree of human accumulation, while RSP helps to distinguish natural sources from human sources and reveals the bioavailability and migration potential of heavy metals. The combination of the two can deeply analyze the source and ecological risk while evaluating the pollution level. In the aspect of pollution source analysis, this study comprehensively uses correlation analysis, principal component analysis (PCA), and the orthogonal matrix factor analysis model (PMF). Correlation analysis and PCA are used to preliminarily identify the types and quantities of pollution sources, providing a basis for the number of factors needed in PMF analysis; subsequently, the PMF model calculates the contribution rate of each pollution source quantitatively, and the results have clear physical significance.This method system takes into account the advantages of qualitative identification and quantitative analysis, making the source analysis process more scientific and the results more reliable, thus providing a basis for accurate control of heavy metal pollution in soil in mining areas.

Consequently, researchers chose the soil in the vicinity of a standard lead-zinc production location in Mamu Town, Hezhang District, as the subject of investigation. Surface and profile soils were sampled to ascertain the amount of Pb, Zn, Cd, Cr, Cu, and Ni, along with their chemical speciation. The pollution conditions in this research area were evaluated utilizing the ground cumulative indices manner and a comparative analysis of secondary versus primary phase values. The origins of the heavy metals were elucidated through a combination of qualitative (correlation, principal components) and quantitative (Positive Definitive Matrix Factorization (PDMA) model, PMF) methodologies. This research is highly significant for comprehending and mitigating metal pollution in soils adjacent to lead and zinc mining regions. Meanwhile, a detailed analysis of the origins of metals in soil can provide a scientific basis for developing effective environmental management strategies and measures that achieve a balance between sustainable mining development and ecological protection.

2. MATERIALS AND METHODS

2.1 Research area

Hezhang County is located in the tilted zone of the Wumeng Mountains in the upper reaches of the Liuchong River, the northern source of the Wujiang River, and the Sanqiao River, the southern source of the Wujiang River, in the northwestern part of Guizhou

Province, where the East Yunnan Plateau is overstepping to the mountainous hills of Guizhou, and it is located at longitude 104°10′28″ E to 105°01′23″ E and latitude 26°46′12″ N to 27°28′18″ N. The area has rich mineral resources, including lead and zinc, which are mainly found in Maigu Town of Hezhang County. In this study, we chose Magu Town of Hezhang County as the study area (104°33′09″ E, 26°58′42″ N), which is rich in mineral resources, and the main mineral resources include lead and zinc, and the lead-zinc deposits are widely distributed, with high-quality ores. A-Ma-Gu Town is 36 km southwest of Hezhang County, with a total area of 141.93 km^2, an average elevation of 1,995 meters, a maximum elevation of up to 2,588 meters, and a minimum elevation of 1,775 meters; the average temperature for many years is 12 °C; the soils are mainly yellow-brown loam and brown calcareous soils, while there are also sporadic distributions of brown loam, meadow soils, and tidal soils. The location map is shown in Figure 1.

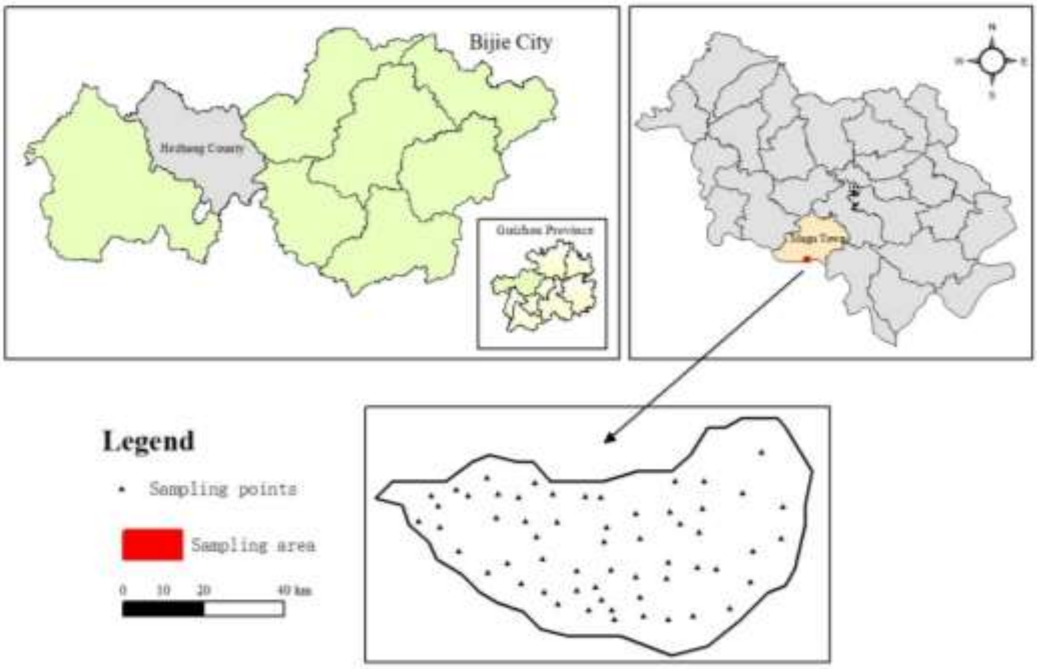

Fig.1: Map of the study area generated using ArcGIS 10.8.2 and soil sampling points.

2.2 Sample collection and testing

According to the actual situation of the community, the surface soil mixed sample of 20 cm was collected following the designated sampling procedure, and the quality was kept at about 1 kg, then it was labeled and bagged. The method of uniform distribution was used to gather two types of profiles with various land use types and depths. Profile 1 (0–90 cm, grassland type) and Profile 2 (0–60 cm, cultivated land type)， respectively, with10 cm intervals. We harvested 56 topsoil specimens and 14 profile soil samples. A handheld GPS positioning system was used to determine the latitude and longitude of the sampling spots, and a map of the soil sampling points was drawn (Fig. 1). The samples were seasoned in the laboratory, extraneous materials such as rocks and plant residue were eliminated, and the soil was crushed and sieved to 10 mesh and 200 mesh, respectively, and finally put into labeled sealing bags for spare use.

In this paper, the total content of heavy metals in soil was determined by HNO_3-$HClO_4$-HCl-HF digestion method. soil samples were processed by the improved BCR continuous extraction method, and the heavy metal element forms were classified into four form fractions, namely, acid-extractable, reducible, oxidizable and residual, according to the type of extractant added and the extraction order. The solution was cooled down, then fixed and filtered, and determined using an atomic absorption spectrometer. The specific experimental procedures are described in detail in the supporting information, among them, the reagent and instrument information used in this study are shown in Table S1 and S2, respectively.

2.3 Evaluation methods

2.3.1 Land accumulation index method

The index of geoaccumulation (Igeo) method is a method for evaluating the risk of heavy metal contamination of sediments and was proposed by Müller in 1969 (Muller, 1969). Relative to other evaluation methods, this method integrates the effects of background values from natural geological processes and anthropogenic activities on heavy metal contamination. Igeo assesses heavy metal contamination by determining the enrichment factor of total metals in the soil relative to the geochemical background using this equation.

$$I_{geo} = Log_2[C_s/(k \times C_b)] \qquad (1\text{-}1)$$

where Cs is the content of soil heavy metal elements ($mg \cdot kg^{-1}$); Cb is the average value of soil heavy metal ($mg \cdot kg^{-1}$), and the background value of soil in Guizhou Province was utilized in this investigation; k represents a correction coefficient to the natural variation of the level of metals during diagenesis, typically assigned a value of k=1.5. The grading standards of I are illustrated in Table 1.

Table 1: Grading of the geo-accumulation index（I）.

Degree of contamination	Non-polluting	Light pollution	Mid-pollution	Medium-strong pollution	Strong pollution	Strong - very strong pollution	Extreme pollution
I	$I<0$	$0 \le I < 1$	$1 \le I < 2$	$2 \le I < 3$	$3 \le I < 4$	$4 \le I < 5$	$I \ge 5$

2.3.2 Secondary Phase to Primary Comparison Method (RSP)

The Ratio of secondary to primary phases (RSP) method is an evaluative technique that reflects the activity and bioavailability of toxic metals, as well as assesses their ability to contaminate the environment, thereby determining the capacity of heavy metals to induce environmental pollution via their fugitive forms (Yan et al., 2016). The formula for measurement is as follows:

$$\mathrm{RSP} = \frac{F1+F2+F3}{F4} \times 100\% \tag{1-2}$$

where: F1, F2, and F3 are the contents of soil heavy metal acids in extractable, reducible, and oxidizable states ($\mathrm{mg{\cdot}kg^{-1}}$), respectively; F4 is the residue state ($\mathrm{mg{\cdot}kg^{-1}}$). According to the size of the calculated results of RSP, the chemical form risk can be divided into 4 levels of evaluation criteria (Table 2).

Table 2: The division grade standards of the Ratio of secondary phase and primary phase （RPS）(Chen et al., 2018).

Degree of contamination	Non-polluting	Light pollution	Mid-pollution	severe pollution
RPS	RPS <100%	100%≤RPS <200%	200%≤RPS <300%	RPS >300%

2.3.3 Positive definite matrix factorization model (PMF)

The PMF model is a source analysis method based on factor analysis technology proposed by Paatero and Tapper (Paatero and Tapper, 1994). Through the least square method and iterative calculation, the receptor sample matrix is constantly decomposed to obtain the optimal solution (Cui et al., 2024). In the process of solving, both factor load and factor score are non-negative constraints. To make the acquired origin ingredient spectrum and source contribution rate understandable and physically significant (Chueinta et al., 2000). The calculation formula is as follows:

$$X_{ij} = \sum_{K=1}^{p} g_{ik} f_{kj} + u_{ij} \tag{1-3}$$

$$Q = \sum_{i=1}^{n} \sum_{j=1}^{m} \left(\frac{X_{ij} - \sum_{k=1}^{p} g_{ik} f_{kj}}{u_{ij}} \right) \tag{1-4}$$

$$\mathrm{Unc} = 0.1\mathrm{C} + \mathrm{MDL}/3 \tag{1-5}$$

in (1-3), (1-4), and (1-5), Xij is the concentration matrix of the jth element of the ith sample; fkj is the concentration matrix of the ith heavy metal of the kth source; gik is the contribution of the kth source to the ith sample; and uij is the residual matrix of the jth heavy metal of the ith sample. The factor contributions and distributions were calculated from the PMF model. Q is the minimization objective function, Unc is the uncertainty of the jth heavy metal of the ith sample, and MDL is the method detection limit for the determination of heavy metal content.

2.4 Data processing

Soil heavy metal content statistics, correlation analysis, and principal component analysis (PCA) were done by Excel 2016 and SPSS 25; maps of sampling point locations and the study area and spatial distribution maps of heavy metals were done by ArcGIS 10.8; elemental morphology occupancy maps were done by Origin 2017; and source resolution was done by PMF 5.0.

2.5 Data quality control

To ensure the reliability of the test method and the accuracy of the results, we implemented systematic quality control measures. Specifically, it includes using blank samples, duplicate samples, and national standard materials (GBW07404, GBW07419) for the whole process quality control, and the recovery rate of heavy metals is controlled between 82.7% and 120.4%. At the same time, 15%-20% of samples are selected for repeated testing, and the relative standard deviation (RSD) of the determination results is less than 10%. In the calibration process, calibration curves are established by a series of standard solutions, and the correlation coefficients of standard curves of Cd, Cr, Cu, Ni, Pb, and Zn are all $\geqslant 0.999$, and the accuracy is verified before and after analysis. During the experiment, all reagents were excellent grade pure, and glassware was thoroughly cleaned after being soaked in 20% nitric acid overnight. Aiming at the quality evaluation of speciation analysis methods of elements in soil, based on the total analysis value (C1) of elements, the accuracy is evaluated by calculating the relative deviation (RE = [(C2-C1)/C1] × 100%) of the sum (C2), which requires RE $\leqslant$ 40%. The actual analysis shows that the RE values of Cd, Cr, Cu, Ni, Pb and Zn all meet the requirements. The precision of the method was evaluated by repeated determination of the same sample 8 times, and the RSD of each morphological determination result was less than 30%, which met the quality requirements of the DD2005-03 technical standard. Finally, through the main error sources such as quantitative weighing (accuracy 0.0001 g), constant volume (head-up concave liquid level reading), calibration, and repeatability, the uncertainty is evaluated; thus, the reliable range of the analysis results is quantitatively characterized.

3. RESULTS AND DISCUSSION

3.1 Characterization of soil heavy metal pollution

3.1.1 Analysis of heavy metal concentrations in soil

Table 4 shows the numbers for six metal elements in the topsoil swatch from the research region, and the mean values of the elements Pb, Zn, Cd, Cr, Cu, and Ni were 4.019, 3.670, 0.085, 2.182, 1.020, and 0.392 mg·kg^{-1}, respectively. The mean values for each of six variables did not surpass the normal levels of the fields in the Guizhou region; nevertheless, the peak amounts of Cd and Pb approached the background ranges of these soils.

The coefficients of variation for Pb, Zn, Cd, Cr, Cu, and Ni were 66.56%, 413.84%, 123.04%, 195.69%, 319.98%, and 373.41%, respectively. The evaluation criteria of soil variation intensity are shown in Table 3. It can be seen that except for Pb, which has a strong variation, the other five elements are unusually strong, demonstrating that the six elements in the research zone are more influenced by external anthropogenic activities.

Figure 2 shows the vertical distribution of six heavy metal elements in soil samples. At the same depth, the contents of two types of profiles are: Zn > Cr > Pb > Cu > CD > Ni. By observing the heavy metal elements in the profile, it is found that the changing trends of Cr, Cu, Cd, and Ni in the profile are consistent in the depth of 0-60 cm. The zinc concentration in profile 1 has no obvious changeregardless of deepness, whereas it diminishes with depth in profile 2, and the important threshold turning point is 30-40 cm; the turning point of Pb was 10-20 cm in profile 1 and 20-30 cm in profile 2. Combined with the location of the profiles, profile 1 was a grassland soil, and profile 2 was a cropland soil. Grassland soils usually have shallow surface depths, while cropland soils are subjected to long-term cultivation and management with fertilizer application and deep tilling, causing changes in the profile. In addition, a study by Das et al. showed that different land types have different soil heavy metal transformation capacities, which also affects the heavy metal content (Das et al., 2009).

Table 3: Evaluation criteria of soil variation intensity (Wang et al., 2020).

weak variation	Medium variation	strong variation	abnormally strong variation
＜20%	20%~50%	50%~100%	＞100%

Table 4: Statistical characteristics of metal concentration in the topsoil of the research area

elemental	average value	standard deviation	coefficient of variation	variance	skewness	kurtosis	maximum （mg·kg^{-1}）	minimum （mg·kg^{-1}）	Soil backgroun
Cd	0.085	0.069	123.04%	0.005	1.810	4.123	0.345	0.007	0.400
Cu	1.020	0.521	195.69%	0.276	1.657	3.162	2.797	0.252	34.500
Pb	4.019	6.038	66.56%	37.074	2.710	7.279	29.904	0.148	33.570
Cr	2.182	0.682	319.98%	0.473	1.056	2.783	4.664	0.722	98.980

Ni	0.392	0.105	373.41%	0.011	0.175	-0.593	0.617	0.189	39.300
Zn	3.670	0.893	413.84%	0.812	0.055	-0.652	5.400	1.907	104.210

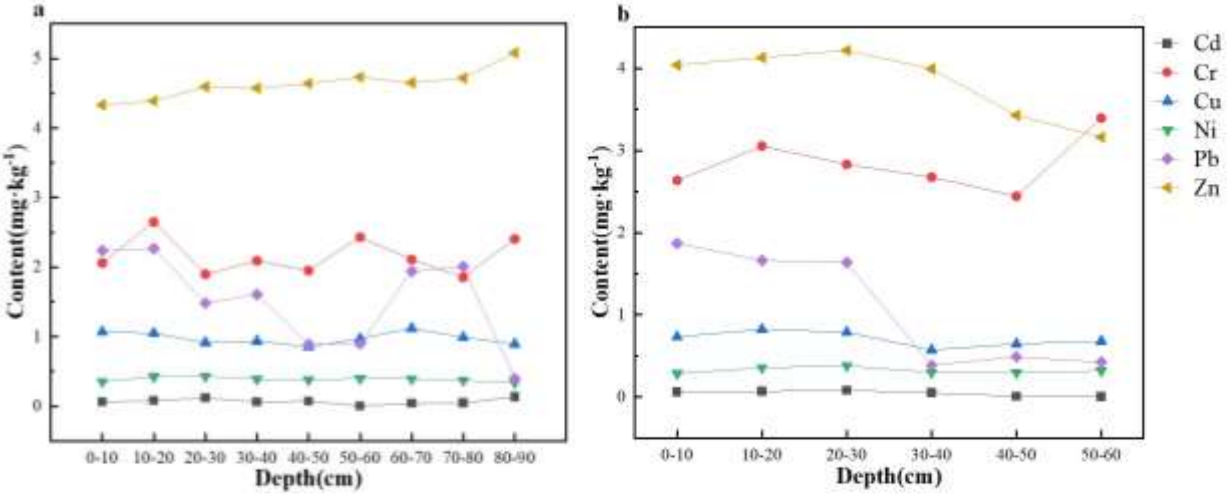

Fig. 2: Distribution map of six heavy metal elements in two profiles.

3.1.2 Morphological analysis of soil heavy metals

Analyzing and calculating the recovery rate of soil heavy metal forms can effectively determine the applicability of the method used to extract the form (Sungur et al., 2015). Recovery rate of toxic metals in soil = (weak acid extractable soluble form F1 + reducible form F2 + oxidizable form F3 + residual form F4)/total amount × 100%; the computation results are presented in Table 5. Table 5 illustrates that the recovery percentage for each of six pollutants in the ground of the research region exceeds 90%, indicating the efficacy of the enhanced BCR method for analyzing the chemical forms of metals in the natural environment. Residual state (F4) belongs to the stable form of heavy metals, which is not easy to be utilized by organisms and has weak migration ability. However, the extractable state (F1) of weak acid is biologically effective, with the strongest mobility and biotoxicity, while the reducible state (F2) and oxidizable state (F3) are potential effective states, which can be transformed into effective states when environmental conditions change.

The chemical forms of heavy metals in surface soil and profile soil in the study area are shown in Figures 3 and 4. As can be seen from Figs. 3 and 4, F4 is the absolute dominant form of six heavy metals in the soil of the study area. Cr, Cu, Ni, Pb, and Zn account for more than 80% of F4 in topsoil and two profiles (some of them are higher than 90%), indicating that the overall bioavailability and mobility of heavy metals are weak and the direct ecological risk is low. The total proportion of secondary forms (F1, F2, F3) is usually less than 20%, with the proportion of these forms in surface soil being significantly higher than in profile soil, particularly for Pb, Zn, and Cr. This indicates that the surface layer is more directly influenced by human activities such as agriculture and atmospheric subsidence, and that the proportion of active forms may increase due to external inputs and changes in the physical and chemical properties of the surface layer. From the point of element specificity, Pb is the element with the highest proportion of secondary forms in surface and profile, and its F2 is relatively high, which may be released and enhanced toxicity under reducing conditions. The F1 of Cr is the highest among the six elements, and its short-term biotoxicity should be paid attention to. The F3 of Zn is relatively high, and its release is related to the decomposition of organic matter. The distribution trend of each element form between the two profiles is highly consistent, and the proportion of residual state is generally higher than that of the surface layer, and the difference between the profiles is small, indicating that the heavy metals in the deep soil mainly come from the primary geological background, with weak human interference, stable form, and no obvious vertical active migration trend.

To sum up, the potential harm of soil heavy metal pollution in the study area is controllable as a whole, but the active forms of Pb, Cr, and other elements in the surface soil need to be paid attention to in order to prevent the ecological risks that may be caused by changes in local environmental conditions.

Table 5: Recovery rate of soil heavy metal form in the study area.

element	The sum of four forms （$mg \cdot kg^{-1}$）	Total heavy metal content （$mg \cdot kg^{-1}$）	rate of recovery（%）
Cd	0.084	0.085	99.78
Cu	0.984	1.020	96.79
Pb	4.041	4.019	100.55
Cr	2.063	2.182	94.63
Ni	0.364	0.396	91.91
Zn	3.377	3.670	91.34

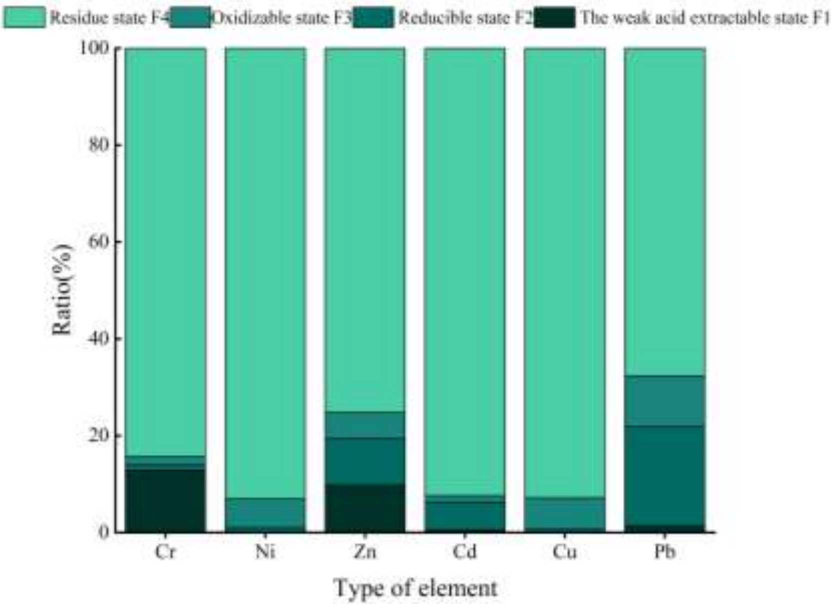

Fig. 3: The proportion of heavy metal chemical forms in surface soil in the study area.

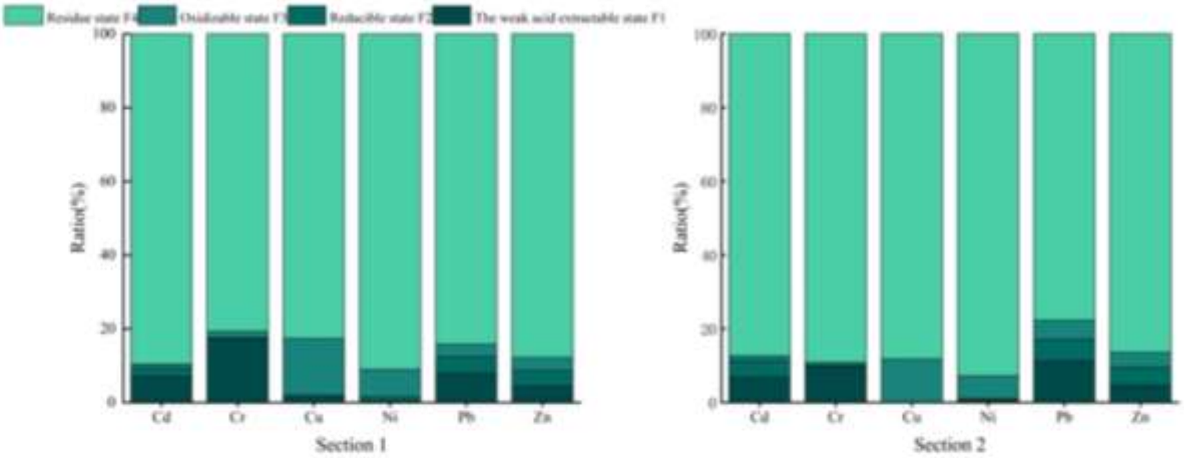

Fig. 4: Proportion map of chemical forms of heavy metals in soil of two profiles in the study area.

3.2 Spatial distribution characteristics

The spatial distribution is more intuitive to see the high-value areas of heavy metal pollution in the study area, and it is also one of the effective methods to identify the source of pollution. After obtaining the content data of six heavy metal elements, this paper draws the spatial distribution map of soil heavy metals in the study area based on ArcGIS 10.8 (Figure 5).As shown in figure 5, the arrangement of high-value zones throughout the four elements (Cd, Cu, Pb, and Zn) is similar and predominantly in the middle and eastern portions of the research region. In contrast, chromium has a looser distribution, while the significant value spots for Ni are primarily concentrated in the east, with a small portion located in the west. According to the site investigation, the land use type in the central part is arable land, the eastern part is residential living area, and the western part is the former mining area of lead-zinc ore. The way to stack minerals in the mining area is open dumping, and the mining activity extends from the west to the east. Due to the stacking method, heavy metals are greatly affected by surface runoff and rainfall washout, making the area of soil heavy metal contamination larger (Wu et al., 2024). The distribution of elevated concentrations of Cd, Cu, Pb, and Zn elements coincides with the Pb-Zn mining site and is greatly affected by residential farming near the middle region of the research area. The studies of Wang et al. and Shi et al. showed that use of phosphorus, fertilizer, compound fertilizer, and organic fertilizer may also introduce metals (Shi et al., 2010; Wang et al., 2014). Alongside residential zones in the eastern section of the research area, other facilities such as welding factories and coal plants are scattered around the area, and the waste residue, water, and gas generated from these activities can result in increased levels of Cr and Ni. The existence of spatially overlapping organisms of the elements of Cd, Cu, Pb, and Zn suggests that there may be a certain degree of correlation between the four elements, which have the same origin (Hussain et al., 2019).

In summary, the consistence and geographical position of the six elements (Pb, Zn, Cd, Cr, Cu, Ni) in the soils of this research region are intricately related to the waste residue left by lead-zinc mines and the remains of human mining activities; however, the consequences of their contamination require further assessment and analysis.

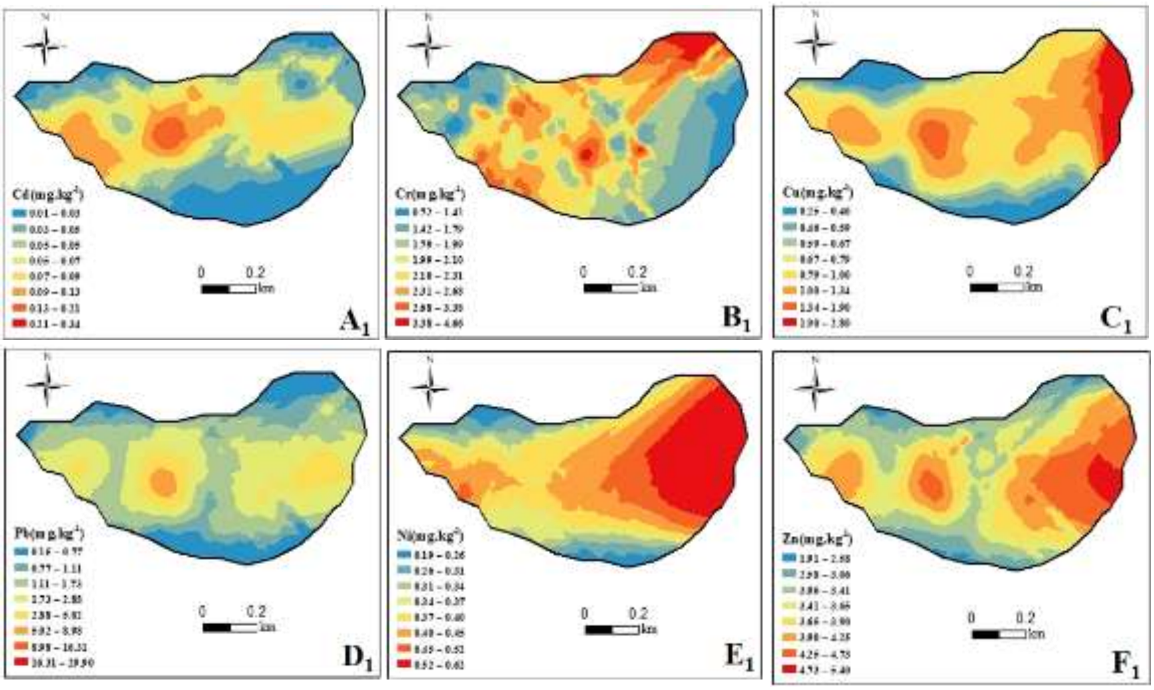

Fig. 5: Geospatial distribution of heavy metals in soil within the research area.

3.3 Evaluation of soil heavy metal pollution

3.3.1 Land amass exponent way

The land amass exponent way (Igeo) was employed to find out how many metals were in the soils of the study region. The results were described as follows:

From Fig. 6(a)(b), the Igeo values for metal elements within the research region are all lower than the pollution level (0) and are at the non-pollution level; however, in combination with the scatter plot, the Igeo values of Cd and Pb elements are more dispersed in the direction of the pollution level (0), while the Ni element deviates from it (0), and the dispersion is greatest for the Pd and Cb elements, succeeded by Cu, Cr, Ni, and Zn in that sequence. Pd and Cb had the greatest dispersion among the elements. followed by Cu, Cr, Ni, and Zn, but Ni was the most dispersed element, indicating that Cd and Pb were the elements that were more enriched in the soil, while Ni was the safest element; this is in high agreement with the characteristics of the space spread of the elements.

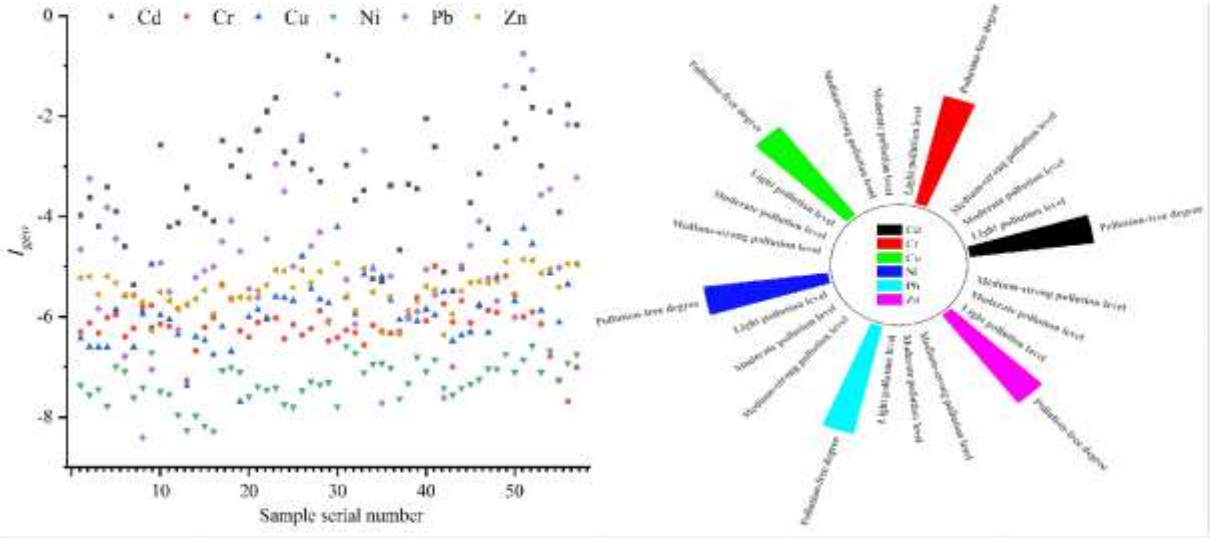

Fig. 6: Metals accumulation index in the research zone.

3.3.2 Secondary phase versus primary comparison method

The contamination levels of Pb, Zn, Cd, Cr, Cu, and Ni in the soils of the research region were assessed using the method of comparison between the secondary phase and primary phase (RSP), and the evaluation results were as follows:

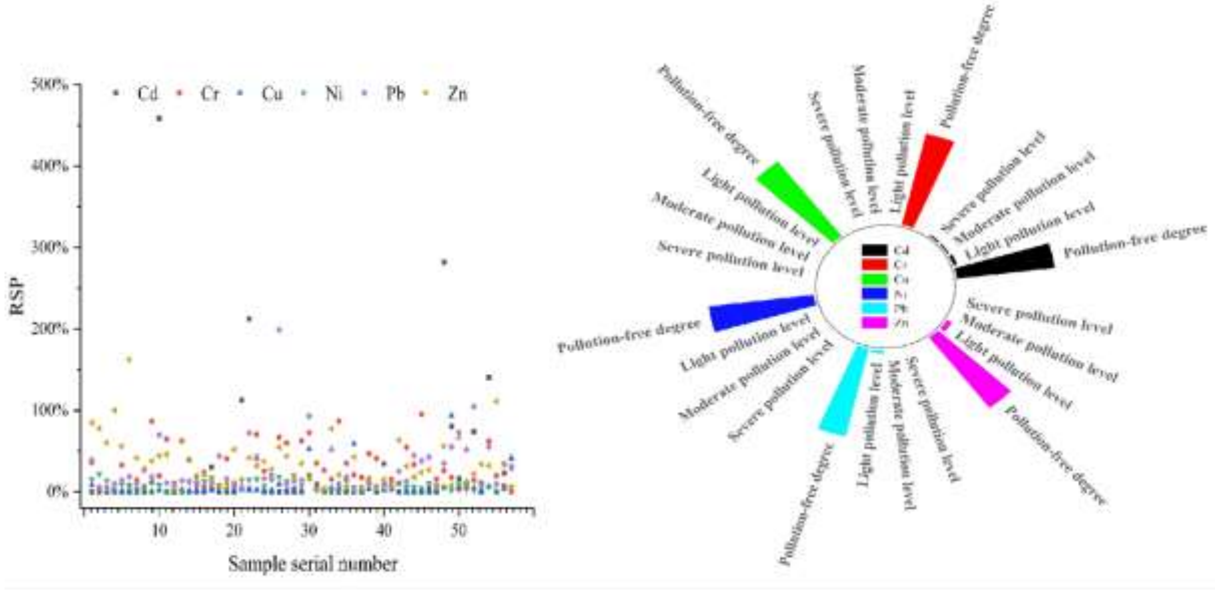

Fig. 7: Index of metal secondary and primary phase in the research area.

As can be seen from Fig. 7(a), only Cd, Pb and Zn elements have individual points exceeding the pollution level (100%), while the remaining three metals remained below the contamination threshold, however Cr and Cu elements have individual points closer to the pollution level. From Fig. 7(b), it can be seen that 5% and 4% of the points of Pb and Zn elements have light pollution level, 4% of the points of Cd elements have light pollution level, and 2% of the points have medium pollution level as well as heavy pollution level. In short, although the presence of Cd, Pb and Zn elements are not polluting the study area, the chemical forms of cadmium, lead, and zinc are contaminating the soil of the research region to a given amount. Therefore, the introduction of Cd, Pb, and Zn elements should be minimized during human activities in the research region, otherwise it could lead to the buildup of Cd, Pb, and Zn in the soil.

3.4 Analysis of soil heavy metal sources

3.4.1 Correlation analysis

Figure 8shows the related behavior analysis results of metal elements in soil in the study area.. Figure 8 illustrates that the elements Pb, Zn, Cd, and Cu have a significant positive correlation at $P < 0.05$. . indicating that there may be spatial superposition of multiple cumulative sources of these heavy metal elements, which aligns with what the geographical spread analysis found. The correlations of the elements Cr and Ni with the other elements did not show a strong correlation, and only the correlations of Cr-Ni ($r = 0.24$) and Ni-Cu ($r = 0.44$) showed that there may be inconsistent sources. The research indicates that the origins of metal elements in soil are involved. So it is necessary to continue to explore their compositional relationships and cumulative sources using principal component analysis or with the help of receptor modeling.

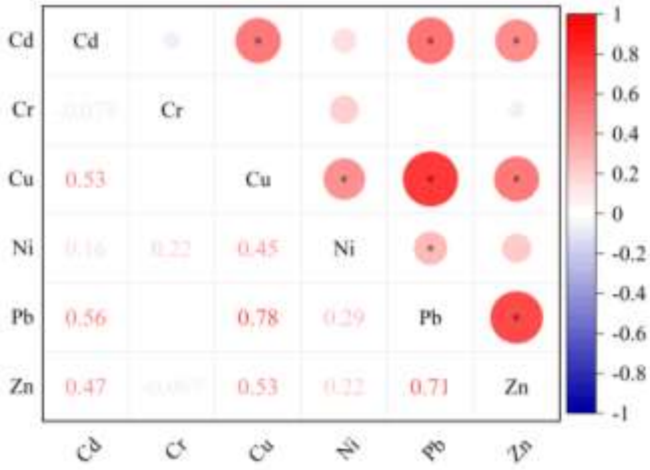

Fig. 8: Correlation coefficient of metals in ground adjacent to mining area.

3.4.2 Principal component analysis

Soil heavy metal concentration data were tested by the KMO test and Bartlett's sphere test, yielding KMO=0.659 (>0.5) and PBartlett=0.001 (<0.05). These results indicate a significant association among the elements, making the data appropriate for principal component analysis in accordance with the findings presented in Table 6. The principal components were extracted to 2 factors, and the eigenvalues of these 2 factors (2.929 and 1.191) were greater than 1, and the cumulative total explained variance of the 2 principal components was 68.66%, indicating that the first 2 principal components can better represent most of the information of all the data in the region and have a certain degree of representativeness.

The explained variance of the first principal component (PC1) was 48.82%, in which the elements Cd, Cu, Pb, and Zn had high positive loadings of 0.756, 0.829, 0.895, and 0.817, respectively, on the C1. There was an outstanding positive connection between these elements two by two, which indicated that Cd, Cu, Pb, and Zn had homology. The study demonstrated that the mean value of Cd, Cu, Pb, and Zn in the soils of the research region did not surpass the background levels seen in Guizhou.The degree of variability was large, indicating that human actions significantly affect their sources. The mining process of Pb and Zn mines exposes the underground elements such as Pb and Zn to the surface and also increases the release flux of associated minerals. In addition, the field investigation found that the slag of mines in the research zone is open piles, which will cause heavy metal elements to enter into the surrounding soil after long-term weathering, rainwater leaching, and downward seepage, coupled with the fact that the areas of high values of the elemental content of Cd, Cu, Pb, and Zn coincide with the original mining area and the area of mining activities (Ma et al., 2023). Therefore, PC1 is hypothesized to be a source of mining extraction emissions and seepage emissions.

The explained variance of the second principal component (PC2) was 19.85%, and Cr and Ni had significant favorable coefficients of 0.822 and 0.731, respectively, on the PC2. Although there was no significant correlation between the two, elemental Cr had the strongest correlation with elemental Ni when compared with the other five elements. It is generally believed that the influence of human activities on element Cr in soil is small, and its main source is the soil-forming parent material(Duan et al., 2018).. However, as can be seen from Table 4, the mean values of Cr and Ni elemental contents did not exceed the background values of soils in Guizhou Province, but the degree of variation was anomalously strong, indicating that anthropogenic activities have a greater influence on their sources. From the spatial distribution, it can be seen that the Cr element is mainly distributed in cultivated land, and the Ni element is distributed in cultivated land and mining tracks. According to Ai et al., it was found that chemical fertilizers contain high levels of elemental Cr, with (Cr) in general calcium superphosphate and nitrogen fertilizers ranging from 50 to 250 mg·kg^{-1} and 5 to 3000 mg·kg^{-1}, respectively, and that the global annual amount of elemental Cr imported to the soil through fertilizers ranges from 0.03 to 0.38 t-a^{-1} (Ai et al., 2014; Chen et al., 2022).

Over time, excessive use of fertilizers causes many Cr elements to build up in the soil. In addition, overuse of calcium superphosphate-based insecticides and herbicides may cause Ni to build up in the soil (Alengebawy et al., 2021). It was observed in the field that there is only one entrance and exit in this area, and when heavy vehicles pass by, Ni from their exhaust will enter the atmosphere with the movement and eventually be deposited into the soil. Therefore, PC2 is presumed to be an agricultural activity and transportation source.

Table 6: Rotation component matrix of metals factor analysis for the top soil in the research area.

Projects	Principal component factor（KMO=0.659 $P_{Bartlet}$=0.001）	
	PCA1	PCA2
Cd	0.756	-0.028
Cu	0.829	0.256
Pb	0.895	0.087

Cr	-0.131	0.822
Ni	0.304	0.731
Zn	0.817	0.007
eigenvalue	2.929	1.191
Explain total variance/%	48.82	48.82
Cumulative explained total variance/%	19.85	68.66

3.4.3 PMF Source Resolution

The PMF model is used for quantitative source analysis of six metals in the soil. The contribution rate of different sources to heavy metals in the soil around the mining area is shown in Figure 8. The concentration and uncertainty are brought into the PMF model, and the signal-to-noise ratio (S/N) of chromium, nickel, copper, and cadmium is 8.8, and the signal-to-noise ratio (S/N) of lead and zinc is 9.0, with the default name "Strong." Select 2-6 factors for 100 iterations, respectively, and finally determine that when the number of factors is 5, all the factors are greater than 0.8 except r^2 of the Ni element, which is 0.69, and the elements of Cr, Cu, Pb, and Cd are above 0.9, which shows that the number of selected components can better explain the information in the original data and the analysis effect is good.Factor 1 contributed more to elemental Cr with 63.7%. Elemental Cr is highly influenced by anthropogenic factors in the study area, combined with regional conditions and PC2 analysis. Therefore, it is speculated that factor 1 is the source of agricultural activities.Factor 2 contributes a lot to elemental Cd. The origins of elemental Cd in the ground of the Pb-Zn producing region are diverse, primarily encompassing air deposition, dust deposition, agricultural production, and industrial emissions. Among them, the proportion of Cd element entering the soil through atmospheric deposition may be higher because it can be transported to the neighboring areas with tiny particles through airflow and eventually deposited into the soil and water bodies. Chen et al. found that the atmospheric deposition flux of elemental Cd gradually increased in agricultural and rural areas during 2000-2018, and especially the risk of heavy metal elemental Cd in agricultural soils cannot be ignored (Chen et al., 2021). In the vicinity of the lead-zinc mining area, it was demonstrated that atmospheric deposition was the main reason why the amount of heavy metals in the aboveground portion of Chinese cabbage went up by comparing mulching and open air (Zhan et al., 2010). Thus, it is inferred that factor 2 is the source of atmospheric deposition.

Factor three contributed more to the elements Zn and Ni, with 59.1% and 41.9%. Research has demonstrated the presence of the three major metals (Cu, Zn, Pb) in wastewater irrigation (Liu et al., 2021). This mining area is mainly engaged in lead and zinc ore mining and metallurgy, while the wastewater, exhaust gas, and slag emitted during the production process are important sources of the elements Pb, Zn, Cd, and Cu in the soil. The open storage of raw materials and tailings in the area may lead to the overflow of heavy metal pollutants to the surrounding areas after rainwater washing and leaching, which is a potential environmental safety hazard. Ma et al. and Wei et al. discovered that the content of Cd, Pb, and Zn in the soil around the Pb-Zn mine is affected by the mining and metallurgy of non-ferrous metals (Ma et al., 2014; Wei et al., 2018). The main source of Ni is transportation, but there are also influences from other sources. Li et al. found high values of the element Ni in the samples from the mining location and river channel of the mining region (Li et al., 2024). Consequently, it is speculated that factor 3 is the source of wastewater discharge.

Factor 4 accounted for 52.9%, 45.4%, and 36.2% of the elements Cu, Ni, and Cr, respectively. This result is similar to the PC2 result, in which tire wear also contributes to the accumulation of elemental Cu during transportation. Therefore, factor 4 is presumed to be a transportation source.

The contribution of factor 5 to Pb is 79.9%.. It was found that mineral resources, such as lead and zinc ores, are more abundant in Ma-Gu town. The region experiences exacerbated contamination by heavy metals as a result of mining, smelting, and tailings dumping in the watershed. Therefore, it is speculated that factor 5 is the source of mining emissions.

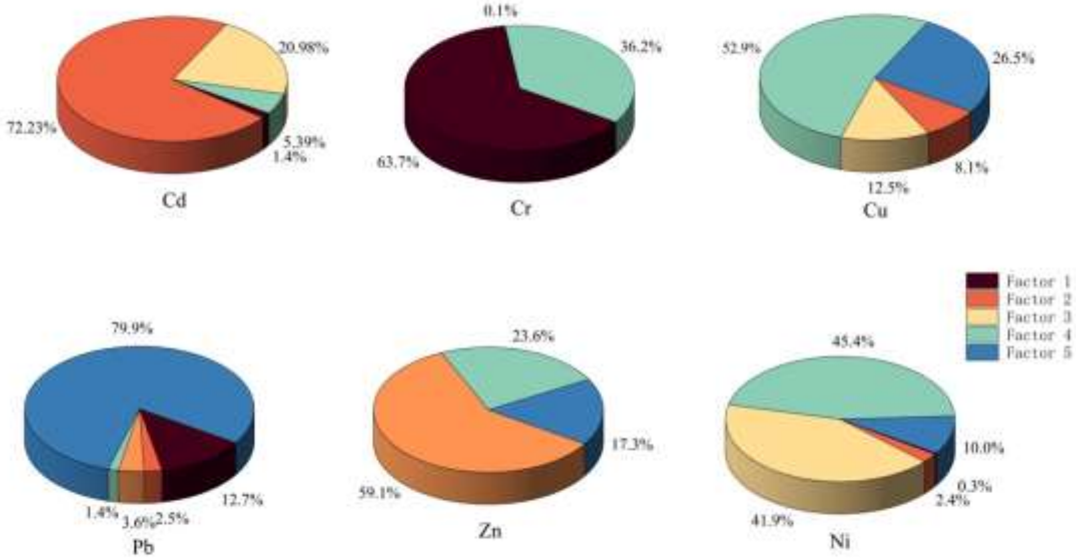

Fig. 8: Dedication rate for various causes of metal pollution in soil surrounding mining regions.

4. CONCLUSIONS

The mean concentrations of six metals (Cd, Cu, Pb, Cr, Ni, and Zn) in the research area's soils did not surpass the baseline levels found in Guizhou Province but had a high intensity of variation. It shows that the six metal elements are greatly influenced by the activities considered by the outside world. At the same depth, the size of the contents of the two profiles was Zn＞Cr＞Pb＞Cu＞Cd＞Ni. Chemically, Cr, Zn, and Pb elements are oppositely stable in the ground, but there is still a potential risk of bio-utilization. The distribution of high-value areas of the contents of six metal elements is similar, and the spatial distribution of the contents is closely related to the residues and sites left by mining areas, but the impact of pollution needs to be further explored.

The analysis of the geological accumulation index shows that the I_{geo} values of six elements in the soil samples are all lower than 0, indicating that they are in a state of no pollution. However, the dispersion degree of cadmium and lead is the largest, and the enrichment degree in soil is high, while the enrichment of nickel is relatively low. The RSP research shows that copper, nickel, and chromium in the study area are not polluted, but lead and zinc are slightly polluted. Element Cd exists in light and moderate pollution levels and also exists in heavy pollution levels.

The results of correlation analysis, principal component analysis, and PMF analysis show that pollution mainly comes from five aspects: Agricultural activities contribute 63.7% of chromium (Cr), atmospheric deposition contributes 72.3% of cadmium (Cd), and wastewater discharge contributes 59.1% of zinc (Zn) and 41.9% of nickel (Ni), respectively. Traffic emissions contributed 52.9% of copper, 45.4% of nickel, and 36.2% of chromium; mining activities contributed 79.9% of lead.

Author Contributions

“Tiantian Cai: Writing—original draft preparation, Investigation, Data curation, Methodology, Software. Die Xu: Software, Formal analysis. Ji Wang: Writing—review and editing, project administration, Funding acquisition; Shaui Zhang: Writing—review and editing, Supervision, Conceptualization. Xiongfei Cai: Conceptualization, Writing—review and editing, Huifang Zhao: Writing—review and editing, project administration, Funding acquisition. All authors have read and agreed to the published version of the manuscript.”

Corresponding author

wangji@gznu.edu.cn (Prof. Ji Wang, Guizhou Normal University, China)

Funding

This work was financially supported by Guizhou Science and Technology Plan Project (Guizhou Science and Technology

Support [2024] General 433 and Guizhou Provincial Science and Technology Projects [2022]325).

Ethics declarations

Declaration

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Conflicts of Interest

The authors declare no competing interests.

Rights and permissions

REFERENCES

Ai, J., Wang, N., and Yang, J., 2014. Source Apportionment of Soil Heavy Metals in Jiapigou Goldmine Based on the UNMIX Model. *Environmental Science, 35*(9), pp. 3530-3536. https://doi.org/10.13227/j.hjkx.202201127 (in Chinese).

Alengebawy, A., Abdelkhalek, S. T., Qureshi, S. R., and Wang, M. Q. (2021). Heavy Metals and Pesticides Toxicity in Agricultural Soil and Plants: Ecological Risks and Human Health Implications. *Toxics, 9*(3), 42. doi:https://doi.org/10.3390/toxics9030042

Ali, W., Mao, K., Zhang, H., Junaid, M., Xu, N., Rasool, A., Feng, X., and Yang, Z., 2020. Comprehensive review of the basic chemical behaviours, sources, processes, and endpoints of trace element contamination in paddy soil-rice systems in rice-growing countries. *Journal of Hazardous Materials, 397*, pp. 122720. https://doi.org/10.1016/j.jhazmat.2020.122720.

Bi, X., Zhang, M., Wu, Y., Fu, Z., Sun, G., Shang, L., Li, Z., and Wang, P., 2020. Distribution patterns and sources of heavy metals in soils from an industry undeveloped city in Southern China. *Ecotoxicology and Environmental Safety, 205*, pp. 111115. https://doi.org/10.1016/j.ecoenv.2020.111115.

Chen, J. J., Liu, B., Cai, L. G., Wang, G. Q., Yin, K., Chen, H. B., and Li, Z. M., 2018. Comparison of risk assessment based on the various methods of heavy metals in soil: A case study for the typical field areas in the Jianghan Plain. *Hydrogeology & Engineering Geology, 45*(6), pp. 164-172. https://doi.org/10.16030/j.cnki.issn.1000-3665.2018.06.24 (in chinese).

Chen, M., Li, X., Cao, X., Yang, W., Wu, P., Hao, H., Fei, Z., and Gao, Y., 2024. Soil-forming accumulation of heavy metals in geological high background areas: Constraints of structure, lithology, and overlying soil geochemistry. *Journal of Geochemical Exploration, 263*, pp. 107518. https://doi.org/10.1016/j.gexplo.2024.107518.

Chen, M., Pan, Y., Huang, Y., Wang, X., and Zhang, R., 2022. Spatial Distribution and Sources of Heavy Metals in Soil of a Typical Lead-Zinc Mining Area,Yangshuo. *Environmental Science, 43*(10), pp. 4545-4555.

https://doi.org/10.13227/j.hjkx.202201127 (in Chinese).

Chen, Q., Zhang, X., Xie, Q., Lee, Y. H., Lee, J.-S., and Shi, H., 2021. Microplastics habituated with biofilm change decabrominated diphenyl ether degradation products and thyroid endocrine toxicity. *Ecotoxicology and Environmental Safety, 228*, pp. 112991. https://doi.org/10.1016/j.ecoenv.2021.112991.

Chen, X. D., and Lu, X. W., 2017. Source Apportionment of Soil Heavy Metals in City Residential Areas Based on the Receptor Model and Geostatistics. *Huan jing ke xue= Huanjing kexue, 38*(6), pp. 2513-2521. https://doi.org/10.13227/j.hjkx.201611208 (in Chinese).

Chueinta, W., Hopke, P. K., and Paatero, P., 2000. Investigation of sources of atmospheric aerosol at urban and suburban residential areas in Thailand by positive matrix factorization. *Atmospheric Environment, 34*(20), pp. 3319-3329. https://doi.org/10.1016/S1352-2310(99)00433-1.

Cui, W. W., Dong, X. Q., Liu, J. J., Yang, F., Duan, W., and Xie, M. X., 2024. Characterization and source apportionment of heavy metal pollution in soil around red mud disposal sites using absolute principal component scores-multiple linear regression and positive matrix factorization models. *Environmental Geochemistry and Health, 46*(12), pp. 492. https://doi.org/10.1007/s10653-024-02267-x.

Das, B., Nordin, R., and Mazumder, A., 2009. Watershed land use as a determinant of metal concentrations in freshwater systems. *Environmental Geochemistry and Health, 31*(6), pp. 595-607. https://doi.org/10.1007/s10653-008-9244-z.

Demková, L., Jezný, T., and Bobuľská, L., 2017. Assessment of Soil Heavy Metal Pollution in a Former Mining Area-Before and After the End of Mining Activities. *Soil & Water Research, 12*(4).

Duan, C., Fang, L., Yang, C., Chen, W., Cui, Y., and Li, S., 2018. Reveal the response of enzyme activities to heavy metals through in situ zymography. *Ecotoxicology and Environmental Safety, 156*, pp. 106-115. https://doi.org/10.1016/j.ecoenv.2018.03.015.

Hu, B., Zhou, Y., Jiang, Y., Ji, W., Fu, Z., Shao, S., Li, S., Huang, M., Zhou, L., and Shi, Z., 2020. Spatio-temporal variation and source changes of potentially toxic elements in soil on a typical plain of the Yangtze River Delta, China (2002–2012). *Journal of Environmental Management, 271*, pp. 110943. https://doi.org/10.1016/j.jenvman.2020.110943.

Hussain, R., Luo, K., Liang, H., and Hong, X., 2019. Impact of the coal mining-contaminated soil on the food safety in Shaanxi, China. *Environmental Geochemistry and Health, 41*(3), pp. 1521-1544. https://doi.org/10.1007/s10653-018-0233-6.

Jin, Y., O'Connor, D., Ok, Y. S., Tsang, D. C. W., Liu, A., and Hou, D., 2019. Assessment of sources of heavy metals in soil and dust at children's playgrounds in Beijing using GIS and multivariate statistical analysis. *Environment International, 124*, pp. 320-328. https://doi.org/10.1016/j.envint.2019.01.024.

Kiran, Bharti, R., and Sharma, R., 2022. Effect of heavy metals: An overview. *Materials Today: Proceedings, 51*, pp. 880-885. https://doi.org/10.1016/j.matpr.2021.06.278.

Li, P., 1994. An Investigation Report of the Industrial Economy inthe Small Towns in Ethnic Areas of Guizhou. *Guizhou Ethnic Studies*(03), pp. 23-24.

Li, R. Z., Liu, Y. H., Huang, Y. H., and Wu, H. F., 2024. Contamination Characteristics and Source Apportionment of Soil Heavy Metals in an Abandoned Pyrite Mining Area of Tongling City, China. *Huan jing ke xue= Huanjing kexue, 45*(1), pp. 407-416. https://doi.org/10.13227/j.hjkx.202301058 (in Chinese).

Li, X. Q., Tang, Y. N., Wang, X. H., Song, X. D., and Yang, J. X. (2023). Heavy Metals in Soil around a Typical Antimony Mine

Area of China: Pollution Characteristics, Land Cover Influence and Source Identification. *International Journal of Environmental Research and Public Health, 20*(3). doi:https://doi.org/10.3390/ijerph20032177

Liang, J. H., Tian, Y. Q., Fei, Y., Liu, Z. Y., Shi, H. D., Qi, J. X., and Mo, L., 2023. Source Apportionment and Potential Ecological Risk Assessment of Soil Heavy Metals in Typical Industrial and Mining Towns in North China. *Huan jing ke xue= Huanjing kexue, 44*(10), pp. 5657-5665. https://doi.org/10.13227/j.hjkx.202211197 (in Chinese).

Liu, J., Li, X., Zhang, P., Zhu, Q., Lu, W., Yang, Y., Li, Y., Zhou, J., Wu, L., Zhang, N., and Christie, P., 2023. Contamination levels of and potential risks from metal(loid)s in soil-crop systems in high geological background areas. *Science of The Total Environment, 881*, pp. 163405. https://doi.org/10.1016/j.scitotenv.2023.163405.

Liu, Y. B., Ma, Z. H., Liu, G. N., Jiang, L., Dong, L. M., He, Y., Shang, Z. F., and Shi, H. D., 2021. Accumulation risk and source apportionment of heavy metals in different types of farmland in a typical farming area of northern China. *Environmental Geochemistry and Health, 43*(12), pp. 5177-5194. https://doi.org/10.1007/s10653-021-01002-0.

Ma, H. H., Zhang, L., Guo, F., Yang, Z., Wang, H. Y., Peng, M., and Zhang, F. G., 2023. Ecological Ｒisk and Migration Patterns of Heavy Metals in Soil and Crops in the LeadZinc Mining Area in Guizhou，China. *Environmental Science, 44*(05), pp. 2856-2867. https://doi.org/10.13227/j.hjkx.202204200.

Ma, Z. W., Li, T. T., Qu, C. S., Bi, J., and Huang, L., 2014. Evaluation and source identification of trace element contamination of soils in the Qixia lead-zinc mining area, Jiangsu, China. *Journal of Soils and Sediments, 14*(10), pp. 1703-1712. https://doi.org/10.1007/s11368-014-0900-x.

Muller, G., 1969. Index of Geoaccumulation in Sediments of the Rhine River. *2*(3), pp. 109-118. https://doi.org/10.1007/s11356-022-22603-x.

Paatero, P., and Tapper, U., 1994. Positive matrix factorization: A non-negative factor model with optimal utilization of error estimates of data values. *Environmetrics, 5*(2), pp. 111-126. https://doi.org/10.1002/env.3170050203.

Shi, N. N., Ding, Y. F., and Zhao, X. F., 2010. Heavy metal content and pollution risk assesanent of crop land soils around a pesticide dustrial park. *Chinese Journal of Applied Ecology, 21*(7), pp. 1835-1843. https://doi.org/10.3724/SP.J.1077.2010.10305.

Sungur, A., Soylak, M., Yilmaz, E., Yilmaz, S., and Ozcan, H., 2015. Characterization of Heavy Metal Fractions in Agricultural Soils by Sequential Extraction Procedure: The Relationship Between Soil Properties and Heavy Metal Fractions. *24*(1), pp. 1-15. https://doi.org/10.1080/15320383.2014.907238.

Wang, F. F., Guan, Q. Y., Tian, J., Lin, J. K., Yang, Y. Y., Yang, L. Q., and Pan, N. H., 2020. Contamination characteristics, source apportionment, and health risk assessment of heavy metals in agricultural soil in the Hexi Corridor. *CATENA, 191*, pp. 104573. https://doi.org/10.1016/j.catena.2020.104573.

Wang, Q. L., Song, Y. T., and Wang, C. W., 2021. Source identification and spatial distribution of soil heavy metals in Western Yunnan.China. *Environmental Science, 41*(8), pp. 3693-3703. https://doi.org/10.3969/j.issn.1000-6923.2021.08.026 (in Chinese).

Wei, Y. H., Li, G. C., Wang, Y. H., Zhang, Q., Li, B., Wang, S. C., Cui, J. H., Zhang, H., and Zhou, Q., 2018. Investigating factors influencing the PMF model：A case study of source apportionment of heavy metals in farmland soils near a lead-zinc ore. *Journal of Agro-Environment Science, 37*(11), pp. 2549-2559. https://doi.org/10.11654/jaes.2018-0492.

Wu, B., Wan, Q., Li, X., Lin, S., Jiang, Y., Yang, X., Li, J., Lin, Q., Morel, J. L., and Qiu, R., 2024. Heavy metal migration dynamics and solid-liquid distribution strategy in abandoned tailing soils. *Journal of Hazardous Materials, 468*, pp. 133794.

https://doi.org/10.1016/j.jhazmat.2024.133794.

Yan, N., Liu, W., Xie, H., Gao, L., Han, Y., Wang, M., and Li, H., 2016. Distribution and assessment of heavy metals in the surface sediment of Yellow River, China. *Journal of Environmental Sciences, 39*, pp. 45-51. https://doi.org/10.1016/j.jes.2015.10.017.

Yang, C., Wang, B., Shen, G., and Wang, M., 2018. Pb pollution characteristics and their affecting factors in different land use types in lead -zinc mining zone. *Research of Soil and Water Conservation, 25(05)*, pp. 351-357.

Yu, D. Y., Wang, Y. H., Ding, F., Chen, X., and Wang, J. R., 2021. Comparison of Analysis Methods of Soil Heavy Metal Pollution Sources in China in Last Ten Years. *CHINESE JOURNAL OF SOIL SCIENCE, 52*(4), pp. 1000 − 1008. https://doi.org/10.19336/j.cnki.trtb.2020101202.

Zhan, M. K., Liu, Z. Y., and Zhou, C., 2010. Effect of atmospheric deposition on heavy metal accumulation in vegetable crop near a lead-zinc smelt mine. *Journal of Zhejiang University(Agriculture and Life Sciences), 36*(02), pp. 221-229. https://doi.org/10.3785/j.issn.1008-9209.2010.02.016.

Zhang, F., and Li, G. H., 2016. China released the Action Plan on Prevention and Control of Soil Pollution. *Frontiers of Environmental Science & Engineering, 10*(4). https://doi.org/10.1007/s11783-016-0867-5 (in Chinese).

Zhang, Y., Feng, N. Q., Liu, Y., Xu, Z. Q., Zhang, Y., and Wang, Q., 2023. Speciation Analysis and Risk Assessment of Heavy Metals in the Soil of a Lead-Zinc Mining Area. *Multipurpose Utilization of Mineral Resources, 44*(3), pp. 199-204, 210. https://doi.org/10.3969/j.issn.1000-6532.2023.03.033.

Zhou, Y., Chen, Q., Deng, S. P., Wan, J. Z., Zhang, S. T., Long, T., Li, Q., Lin, Y. S., and Wu, Y. J., 2018. Principal Component Analysis and Ecological Risk Assessment of Heavy Metals in Farmland Soils around a Pb-Zn Mine in Southwestern China. *Huan jing ke xue= Huanjing kexue, 39*(6), pp. 2884-2892. https://doi.org/10.13227/j.hjkx.201707125 (in Chinese).

Zhou, Y., Wang, L., Xiao, T., Chen, Y., Beiyuan, J., She, J., Zhou, Y., Yin, M., Liu, J., Liu, Y., Wang, Y., and Wang, J., 2020. Legacy of multiple heavy metal(loid)s contamination and ecological risks in farmland soils from a historical artisanal zinc smelting area. *Science of The Total Environment, 720*, pp. 137541. https://doi.org/10.1016/j.scitotenv.2020.137541.