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

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ABSTRACT

Heavy metal contamination in soil has emerged as a critical environmental issue. However, research specifically addressing the distribution, pollution levels, and source analysis of heavy metals in lead-zinc mining areas remains limited. To assess the extent of soil heavy metal pollution around a lead-zinc mine in northwest Guizhou and to perform a quantitative source analysis, this study collected 56 surface soil samples and 14 samples from two different depths. The concentrations and chemical forms of Cd, Pb, Cr, Cu, Ni, and Zn were measured. Pollution levels were evaluated using the geoaccumulation index (Igeo) and the secondary-to-primary phase ratio (RSP). Sources were identified through correlation analysis, principal component analysis, and positive matrix factorization (PMF). The results demonstrated that: (1) The average concentrations of Pb, Zn, Cd, Cr, Cu, and Ni were all below Guizhou's soil background levels. While Cd and Pb reached maximum values close to background levels, their coefficients of variation were 66.56%, 413.84%, 123.04%, 195.69%, 319.98%, and 373.41%, respectively, indicating high variability and significant anthropogenic influence. Elevated levels of Cd, Cu, Pb, and Zn are closely aligned with mining locations. (2) The Igeo evaluations indicated that most areas were unpolluted; however, the RSP method revealed that 5% and 4% of sites were slightly polluted by Pb and Zn, respectively, with 4% showing slight Cd contamination, and 2% experiencing moderate to severe pollution. (3) PMF source apportionment identified five main sources: 63.7% of Cr from agriculture, 72.3% of Cd from atmospheric deposition, 59.1% of Zn and 41.9% of Ni from wastewater discharge, 52.9% of Cu, 45.4% of Ni, and 36.2% of Cr from traffic emissions, and 79.9% of Pb from mining activities. The study concluded that overall heavy metal pollution was slight, though Cd, Pb, and Zn were notably influenced by mining and associated human activities. Different sources contributed distinctly: mining primarily impacted Pb, while agriculture, atmospheric deposition, and wastewater discharge mainly affected Cr, Cd, and Zn accumulation, respectively. These findings offer a scientific basis for soil pollution prevention, control, and ecological risk management in the region.

1. INTRODUCTION

Soil, as one of the most vital natural resources for human life, serves as a fundamental material for sustainable economic and social development. Metal pollution directly affects soil quality and ecosystem stability and may also threaten human health (Kiran et al. 2022). Recently, the rapid progress of industrialization has heightened the impact of mining activities on the environment, especially around lead-zinc mine regions (Demková et al. 2017, Yang et al. 2018, Zhang et al. 2023). Southwest China, characterized by a high natural background of heavy metals, often has soil exceeding safety standards due to geological factors (Chen et al. 2024, Liu et al. 2023). As regional urbanization and industrialization advance, soils in these areas face intense human disturbance, such as agriculture, mining, and metal smelting, alongside natural weathering inputs. This region exemplifies the complex interaction between natural processes and human activities, where high geological backgrounds, combined with endogenous inputs and exogenous pollution from human actions, contribute to soil heavy metal contamination. Challenges include unclear pollution sources, ecological risks, and the lack of comprehensive prevention and control technologies, all posing significant hurdles for safe land use, precise identification of pollution sources, and effective ecological risk management in mining districts. Consequently, assessing and identifying soil heavy metal sources in mining regions is crucial for controlling pollution and safeguarding ecological health.

Northwest Guizhou is not only a well-known zinc smelting base in China but also has abundant coal resources that provide essential raw materials for zinc production (Ali et al. 2020). Heavy metal contamination in soils surrounding lead–zinc mining areas has become increasingly severe due to a high geological background, intensive mining activities, and human disturbances (Zhou et al. 2018). Magu Town in Hezhang County, located in northwestern Guizhou Province, is a typical concentrated lead–zinc ore distribution area, rich in mineral resources and playing an important role in local economic development (Li 1994). The region has a mining history of nearly 300 years, and heavy metals released from long-term mining activities continue to cause significant pollution to surrounding soils (Zhou et al. 2020). Therefore, this study aims to systematically assess soil conditions in the area, determine the level of contamination, identify pollution sources, and quantify their contribution ratios. Although many studies have investigated soil heavy metal pollution in various mining areas of Guizhou Province (Li et al. 2024, Wang et al. 2021), most have focused on single pollution assessments and preliminary source identification.

Currently, commonly used methods such as correlation analysis, principal component analysis, and cluster analysis can be applied to preliminarily identify the number and types of pollution sources (Bi et al. 2020, Jin et al. 2019, Liang et al. 2023). However, these approaches have certain limitations. A single evaluation method often fails to systematically and comprehensively reflect the overall regional pollution status. In addition, preliminary source identification alone is insufficient to clearly quantify the specific contributions and proportions of each pollution source (Chen & Lu 2017, Hu et al. 2020, Li et al. 2023, Yu et al. 2021). Therefore, it is essential to incorporate more systematic methods to achieve a comprehensive evaluation of pollution levels and to quantitatively analyze the contribution of pollution sources. In this study, the geo-accumulation index (Igeo) and the ratio of secondary to primary phases (RSP) were combined to assess the pollution status. Igeo measures the extent of human-induced accumulation, while RSP helps distinguish natural sources from anthropogenic ones and indicates the bioavailability and migration potential of heavy metals. The integration of these two indices allows for a thorough analysis of source origins and ecological risks alongside pollution levels. For source analysis, the study employs correlation analysis, principal component analysis (PCA), and the orthogonal matrix factorization model (PMF). Correlation analysis and PCA initially identify the types and quantities of pollution sources, providing a basis for determining the number of factors in PMF. The PMF model then quantitatively estimates the contribution rates of each source, with results that have clear physical significance. This combined approach leverages both qualitative identification and quantitative analysis, making source determination more scientific and results more reliable, thereby supporting accurate control of heavy metal pollution in mining soil.

Researchers selected soil samples from near a standard lead-zinc production site in Mamu Town, Hezhang District, for this study. Surface and profile soils were analyzed to determine concentrations and chemical forms of Pb, Zn, Cd, Cr, Cu, and Ni. Pollution levels were assessed using cumulative indices and a comparative analysis of secondary versus primary phase values. The origins of the heavy metals were identified through a combination of qualitative techniques, including correlation analysis and principal components, and quantitative models such as the Positive Definitive Matrix Factorization (PDMA) and PMF. This research provides valuable insights for understanding and reducing metal contamination in soils near lead and zinc mining areas. Additionally, analyzing metal sources in soils offers a scientific basis for developing environmental management strategies that balance sustainable mining with ecological protection.

2. MATERIALS AND METHODS

2.1. Research Area

Hezhang County is situated in the tilted zone of the Wumeng Mountains, at 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 northwestern Guizhou Province. This area is where the East Yunnan Plateau extends into the mountainous hills of Guizhou. It spans longitudes 104°10′28″ E to 105°01′23″ E and latitudes 26°46′12″ N to 27°28′18″ N. The region is rich in mineral resources, particularly lead and zinc, primarily found in Maigu Town. For this study, Magu Town (located at 104°33′09″ E, 26°58′42″ N) was chosen as the study area due to its abundance of mineral deposits, including high-quality lead and zinc ore deposits. Magu

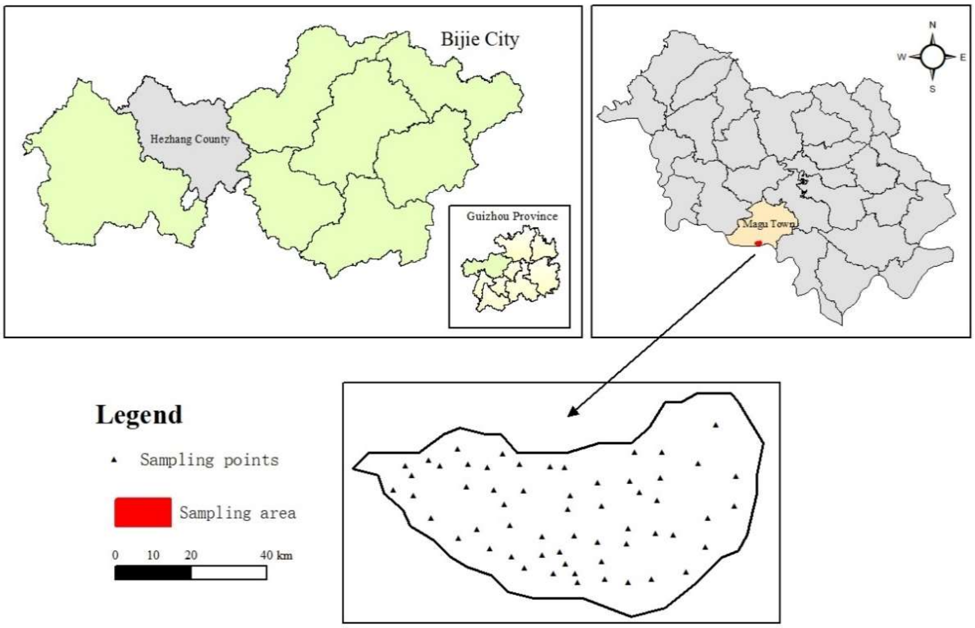

Fig. 1: Map of the study area generated using ArcGIS 10.8.2 and soil sampling points.

Town is 36 km southwest of Hezhang County, covering an area of 141.93 km², with an average elevation of 1,995 meters, a maximum of 2,588 meters, and a minimum of 1,775 meters. The region experiences an average temperature of 12°C year-round. Its soils are predominantly yellow-brown loam and brown calcareous soil, with sporadic patches of brown loam, meadow soils, and tidal soils. A location map is shown in Fig. 1.

2.2. Sample Collection and Testing

Based on the community's actual conditions, surface soil mixed samples from 20 cm were collected following the designated sampling procedures. Each sample, approximately 1 kg, was labeled and sealed in a bag. To capture variability across land use types and depths, two profiles were sampled using a uniform distribution method: Profile 1 (0–90 cm, grassland) and Profile 2 (0–60 cm, cultivated land), with samples taken at 10 cm intervals. A total of 56 topsoil specimens and 14 profile soil samples were collected. A handheld GPS device recorded the latitude and longitude of each sampling site, and a map of the sampling points was created (Fig. 1). In the laboratory, samples were seasoned, removable materials like rocks and plant debris were discarded, and the soil was crushed and sieved through 10-mesh and 200-mesh screens. The prepared samples were then sealed in labeled bags for future analysis.

This study determined the total heavy metal content in soil using an HNO_3-$HClO_4$-HCl-HF digestion method. Soil samples were processed via an improved BCR continuous extraction procedure, categorizing heavy metal forms into four fractions: acid-extractable, reducible, oxidizable, and residual, based on the extraction reagents and sequence. The extract was cooled, fixed, filtered, and analyzed with an atomic absorption spectrometer.

2.3. Evaluation Methods

2.3.1. Land Accumulation Index Method

The Index of Geoaccumulation (Igeo) is a method used to assess the pollution risk of heavy metals in sediments, proposed by Müller in 1969 (Müller 1969). Compared with other evaluation approaches, it incorporates the influence of natural geological background values as well as anthropogenic inputs on heavy metal contamination. Igeo evaluates the degree of contamination by quantifying the enrichment of metal concentrations in soil relative to geochemical background levels using the following equation.

$$I_{geo} = Log_2[C_s/(k \times C_b)] \quad \ldots(1)$$

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.

2.3.2. Secondary Phase to Primary Comparison Method (RSP)

The Ratio of Secondary to Primary Phases (RSP) method

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	$I<0$	$0\leq I<1$	$1\leq I<2$	$2\leq I<3$	$3\leq I<4$	$4\leq I<5$	$I\geq 5$

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%

is an assessment tool that indicates the activity and bioavailability of toxic metals. It also evaluates their potential to contaminate the environment and their capacity to cause pollution through their fugitive forms (Yan et al. 2016). The formula for measurement is as follows:

$$\mathrm{RSP} = \frac{F1+F2+F3}{F4} \times 100\% \quad \ldots(2)$$

where: F1, F2, and F3 are the contents of soil heavy metal acids in extractable, reducible, and oxidizable states ($mg\cdot kg^{-1}$), respectively, and F4 is the residue state ($mg\cdot kg^{-1}$). 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).

2.3.3. Positive Definite Matrix Factorization Model (PMF)

The PMF model is a source apportionment method based on factor analysis, first proposed by Paatero and Tapper (Paatero & Tapper 1994). It decomposes the receptor sample matrix through a least-squares approach and iterative calculations to obtain an optimal solution (Cui et al. 2024). During the solution process, both factor loadings and factor scores are constrained to be non-negative, ensuring that the derived source profiles and source contribution estimates are physically meaningful and interpretable (Chueinta et al. 2000). The calculation formula is as follows:

$$X_{ij} = \sum_{K=1}^{p} g_{ik} f_{kj} + u_{ij} \quad \ldots(3)$$

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

$$\mathrm{Unc} = 0.1\mathrm{C} + \mathrm{MDL}/3 \quad \ldots(5)$$

In (3), (4), and (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

Statistical analyses of soil heavy metal content, including correlation analysis and principal component analysis (PCA), were performed using Excel 2016 and SPSS 25. Maps illustrating sampling locations, study area layout, and spatial distribution of heavy metals were created with ArcGIS 10.8. Elemental morphology occupancy maps were generated using Origin 2017, while source apportionment was conducted with PMF 5.0.

2.5. Data Quality Control

To ensure the reliability of the test method and the accuracy of the results, systematic quality control measures were implemented. These included using blank samples, duplicate samples, and national standard materials (GBW07404, GBW07419) throughout the process, with heavy metal recovery rates maintained between 82.7% and 120.4%. Additionally, 15%-20% of samples were retested, and the relative standard deviation (RSD) of the results remained below 10%. Calibration involved establishing curves with standard solutions, achieving correlation coefficients of at least 0.999 for Cd, Cr, Cu, Ni, Pb, and Zn, with verification conducted before and after analysis. All reagents used were of pure, high-grade quality, and glassware was thoroughly cleaned after overnight immersion in 20% nitric acid. For the quality evaluation of soil element speciation analysis methods, accuracy was assessed by calculating the relative deviation (RE = [(C2 – C1)/C1] × 100%) of the sum (C2) based on the total elemental analysis value (C1), with RE required to be ≤40%. The actual analysis confirmed that the RE values for Cd, Cr, Cu, Ni, Pb, and Zn satisfied this criterion. The method's precision was evaluated through eight repeated measurements of the same sample, with RSDs below 30%, meeting DD2005-03 technical standards. Finally, main error sources—such as weighing (accuracy 0.0001 g), volume measurement, calibration, and repeatability—were analyzed to estimate uncertainty, providing a quantitative characterization of the reliable range of the results.

3. RESULTS AND DISCUSSION

3.1. Characterization of Soil Heavy Metal Pollution

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%

3.1.1. Analysis of Heavy Metal Concentrations in Soil

Table 4 presents the concentrations of six metal elements in the topsoil sample from the research area. The mean values for 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. These averages did not exceed typical levels found in the Guizhou region. However, the peak concentrations of Cd and Pb nearly reached the background levels characteristic 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. As shown in Table 3, soil variation intensity analysis indicates that, aside from Pb, which exhibits strong variability, the other five elements show unusually high variability. This suggests that these six elements are significantly affected by external anthropogenic activities in the study area.

Fig. 2 illustrates the vertical distribution of six heavy metal elements in soil samples. At identical depths, the profiles exhibit the following contents: Zn > Cr > Pb > Cu > Cd > Ni. Analysis of the profile reveals that the concentration trends of Cr, Cu, Cd, and Ni are consistent within the 0-60 cm depth range. In profile 1, zinc levels remain relatively stable with depth, whereas in profile 2, zinc decreases as depth increases, with a critical threshold around 30-40 cm. The lead concentration's turning point occurs at 10-20 cm in profile 1 and 20-30 cm in profile 2. Profile 1 corresponds to grassland soil, characterized by shallow surface depths, while profile 2 is from cropland soil, which undergoes long-term cultivation, fertilization, and deep tillage, leading to profile alterations. Additionally, Das et al. (2009) reported that soil heavy metal transformation capacities vary by land type, influencing heavy metal content.

3.1.2. Morphological Analysis of Soil Heavy Metals

Analyzing and calculating the recovery rate of soil heavy metal forms can effectively determine the suitability of the extraction method used for each form. The recovery rate of toxic metals in soil is calculated as the sum of the weak acid extractable soluble form (F1), reducible form (F2), oxidizable form (F3), and residual form (F4), divided by the total metal content, multiplied by 100%. The results are shown in Table 5. This table indicates that the recovery

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

Elemental	Average value (mg·kg^{-1})	Standard deviation	Coefficient of variation (CV)	Variance	Skewness	Kurtosis	Maximum (mg·kg^{-1})	Minimum (mg·kg^{-1})	Soil background values in Guizhou Province (mg·kg^{-1})
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

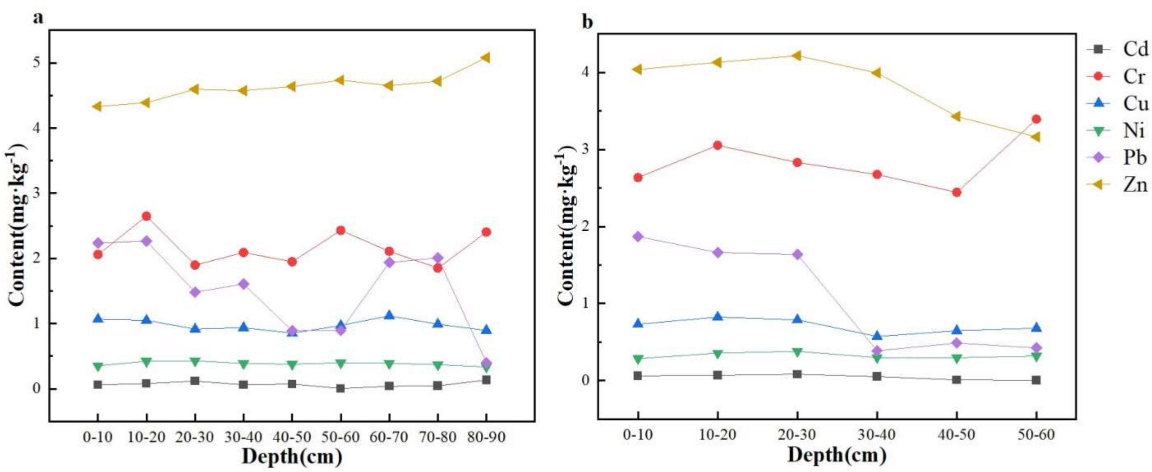

Fig. 2: Distribution map of six heavy metal elements in two profiles.

percentages for six pollutants in the research region's soil all exceed 90%, demonstrating the effectiveness of the enhanced BCR method in analyzing the chemical forms of metals in the environment. Residual form (F4) is a stable, less bioavailable form of heavy metals with limited mobility. In contrast, the weak acid extractable form (F1) is biologically active, with the highest mobility and toxicity. The reducible (F2) and oxidizable (F3) forms are potential sources that can convert into more bioavailable forms under changing environmental conditions. The chemical Forms of heavy metals in surface and profile soils within the study area are illustrated in Figs. 3 and 4. As shown, F4 is the predominant form for all six heavy

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

Element	The sum of four forms (mg·kg^{-1})	Total heavy metal content (mg·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

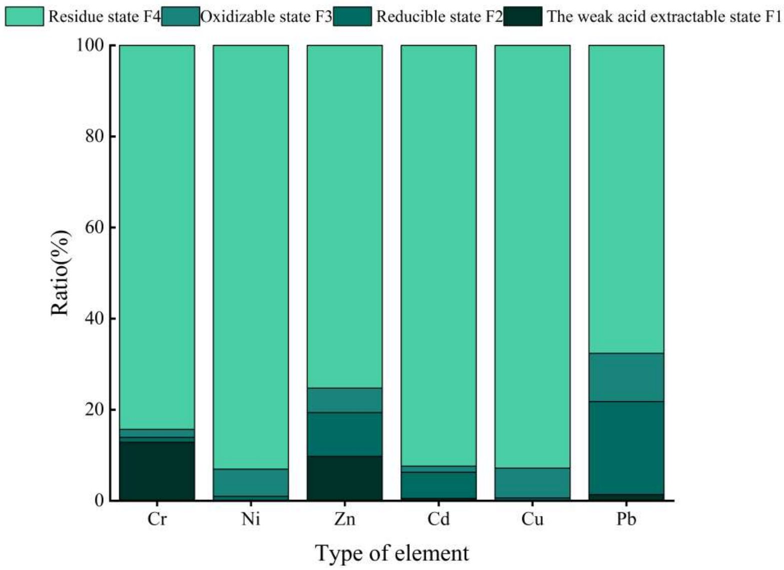

Fig. 3: The proportion of heavy metal chemical forms in surface soil in the study area.

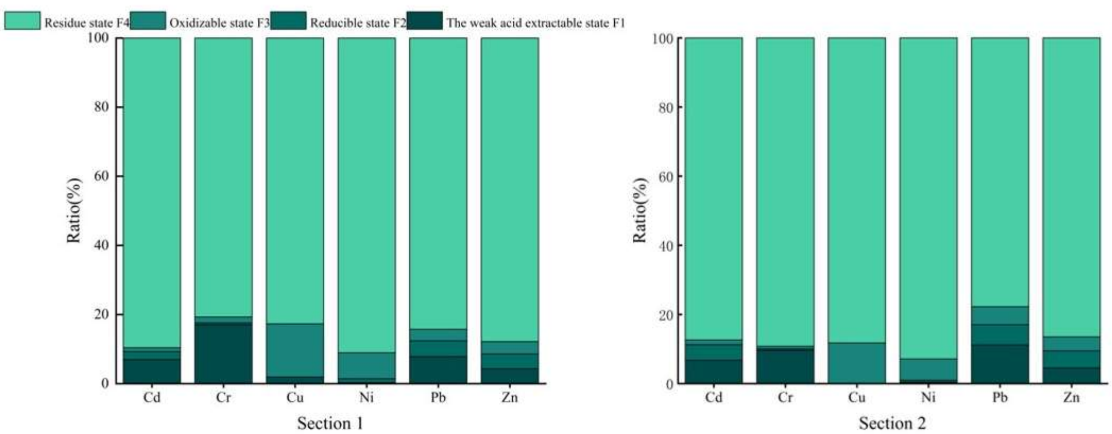

Fig. 4: Proportion map of chemical forms of heavy metals in the soil of two profiles in the study area.

metals in the soil. Elements such as Cr, Cu, Ni, Pb, and Zn each constitute over 80% of F4 in both topsoil and profiles, some exceeding 90%, signaling that the bioavailability and mobility of these metals are limited, and the ecological risk remains low. Secondary forms (F1, F2, F3) account for less than 20%, with significantly higher proportions in surface soils compared to profiles, especially for Pb, Zn, and Cr. This suggests surface layers are more affected by human activities such as agriculture and atmospheric deposition, which may increase active forms due to external inputs and changes in soil chemistry. Notably, Pb exhibits the highest proportion of secondary forms across both soil layers, with a relatively high F2 segment that could be released and toxic under reducing conditions. Cr's F1 form is the highest among the six elements, warranting attention for short-term toxicity. Zn's F3 form is comparatively high and linked to organic matter decomposition. The distribution patterns of element forms are consistent between the two profiles, with residual forms generally higher in deeper soils and minimal variation between profiles. This indicates that heavy metals in the deep soil mainly originate from geological sources, with little human interference, in stable forms, and with limited vertical migration.

3.2. Spatial Distribution Characteristics

The spatial distribution clearly highlights the high-value areas of heavy metal pollution within the study region, serving as an effective method for identifying pollution sources. Based on the content data for six heavy metal elements, this study presents a soil heavy metal distribution map using ArcGIS 10.8 (Fig. 5). As shown in Fig. 5, the high-value zones for the four elements, Cd, Cu, Pb, and Zn, are similarly arranged, primarily occupying the central and eastern parts of the area. In contrast, chromium exhibits a more dispersed distribution, while the significant concentration spots for Ni are mainly in the east, with a few in the west. Field investigations indicate that the central area consists of arable land, the eastern part is residential, and the western area was formerly a lead-zinc mining site. In the mining area, minerals are stacked through open dumping, with mining activity extending from west to east. This stacking method exposes heavy metals to surface runoff and rainfall washout, increasing soil contamination in these regions (Wu et al. 2024). The distribution of elevated levels of Cd, Cu, Pb, and Zn aligns with the Pb-Zn mining site and is significantly influenced by nearby residential farming activities. Studies have shown that the use of phosphorus, fertilizers, and organic matter can also introduce metals (Shi et al. 2010). Additionally, in the eastern part of the study area, facilities such as welding factories and coal plants are scattered around, and waste residues, water, and gases from these activities can lead to increased levels of Cr and Ni. The overlapping distribution of Cd, Cu, Pb, and Zn suggests a possible correlation among these elements, indicating a common source (Hussain et al. 2019).

In summary, the distribution and geographical distribution of the six elements (Pb, Zn, Cd, Cr, Cu, Ni) in the soils of this

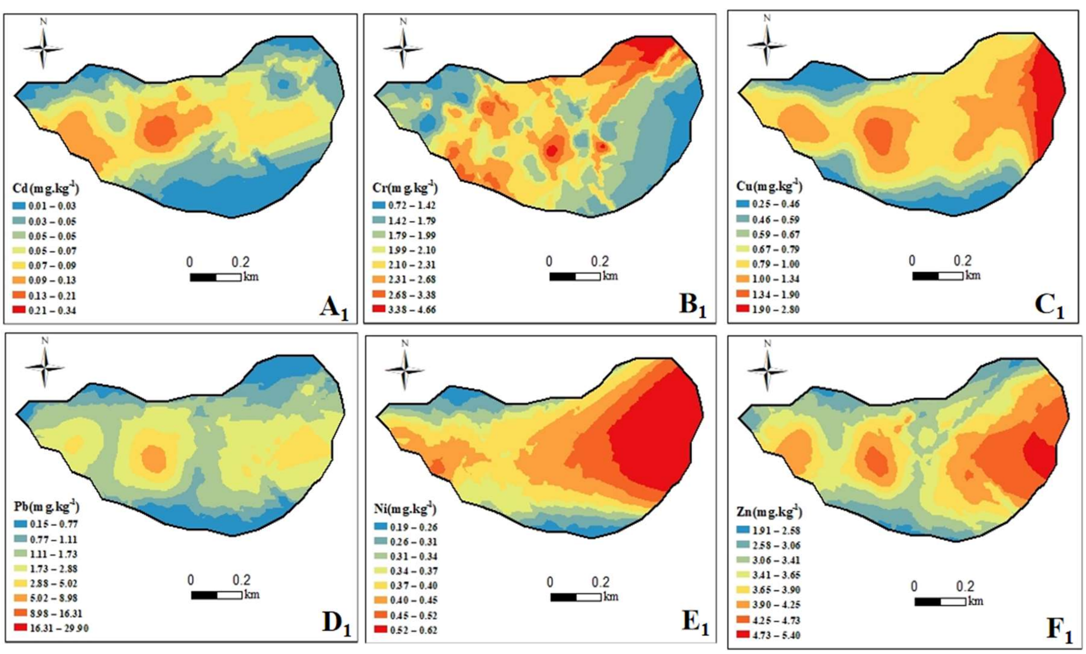

Fig. 5: Geospatial distribution of heavy metals in soil within the research area.

research area are closely linked to the waste residues from lead-zinc mining and remnants of human mining activities. However, the implications of their contamination warrant further evaluation and study.

3.3. Evaluation of Soil Heavy Metal Pollution

3.3.1. Landman Exponent Index

The Landman Exponent Index (Igeo) was used to determine the concentration of metals in the soils of the study area. The results are as follows:

From Figs. 6(a) and 6(b), the Igeo values for metal elements within the research region are all below zero, indicating a non-polluted state. However, when combined with the scatter plot, the Igeo values for Cd and Pb show greater dispersion toward the pollution threshold (0), whereas Ni deviates from this threshold. Pd and Cb exhibit the widest dispersion among all elements, followed by Cu, Cr, Ni, and Zn. This suggests that Pd and Cb are the most enriched elements in the soil, with Ni being the least, indicating it is the safest. These findings align well with the spatial distribution patterns of these elements.

3.3.2. Secondary Phase Versus Primary Comparison Method

The levels of contamination by Pb, Zn, Cd, Cr, Cu, and Ni in the research region's soils were evaluated through a comparison between the secondary and primary phases (RSP). The results of this assessment are presented below:

As shown in Fig. 7(a), only the elements Cd, Pb, and Zn have individual points exceeding the pollution threshold

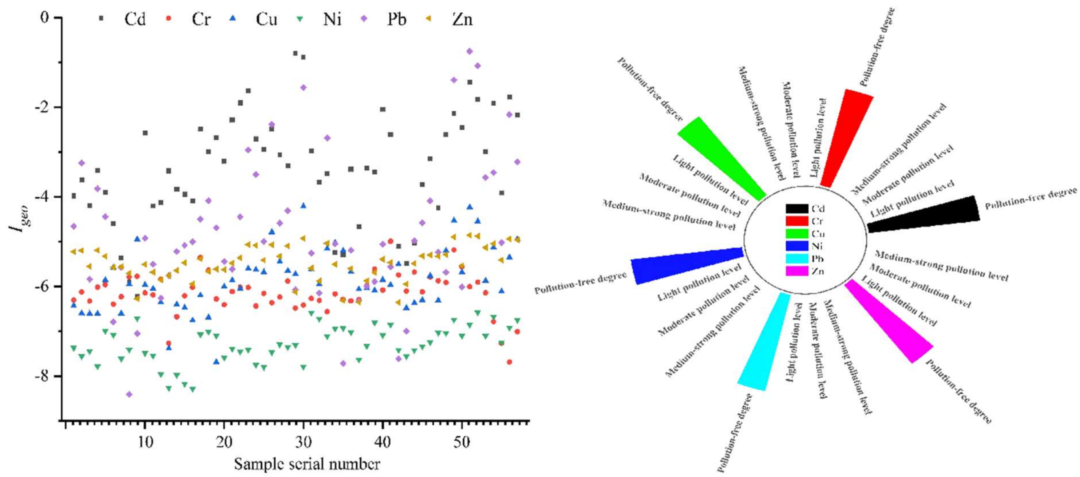

Fig. 6: Metals accumulation index in the research zone.

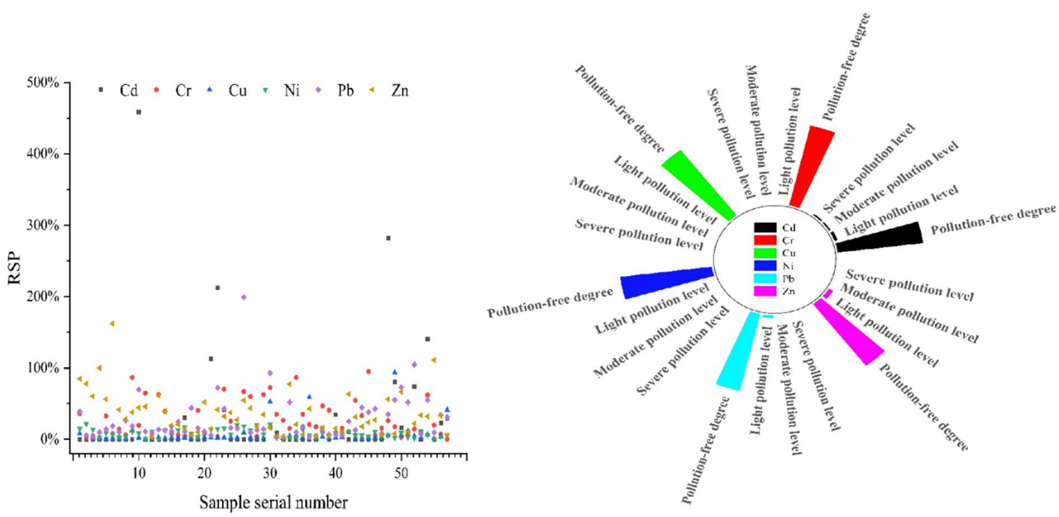

Fig. 7: Index of metal secondary and primary phases in the research area.

of 100%. The other three metals remained below the contamination level, although Cr and Cu points are closer to the pollution threshold. From Fig. 7(b), it is evident that 5% of Pb points and 4% of Zn points indicate light pollution. Additionally, 4% of Cd points show light pollution, while 2% exhibit medium to heavy pollution levels. In summary, although Cd, Pb, and Zn are not currently polluting the area, their chemical forms are contaminating the soil to some extent. Therefore, human activities should minimize the introduction of Cd, Pb, and Zn in the research region to prevent accumulation in the soil.

3.4. Analysis of Soil Heavy Metal Sources

3.4.1. Correlation Analysis

Fig. 8 presents the analysis of the behavior of metal elements in the soil within the study area. The results demonstrate that the elements Pb, Zn, Cd, and Cu exhibit a significant positive correlation at $P < 0.05$, suggesting the possible spatial overlap of multiple cumulative sources of these heavy metals, which is consistent with the findings from the geographical spread analysis. In contrast, the correlations of Cr and Ni with other elements are weak; only the correlations between Cr-Ni ($r = 0.24$) and Ni-Cu ($r = 0.44$) indicate potential disparate sources. The study indicates that the origins of metal elements in the soil are diverse. Therefore, further exploration of their compositional relationships and cumulative sources through principal component analysis or receptor modeling is recommended.

3.4.2. Principal Component Analysis

The soil heavy metal concentration data were evaluated using the KMO test and Bartlett's sphere test, which resulted in a KMO value of 0.659 (above 0.5) and a Bartlett's test p-value of 0.001 (below 0.05). These outcomes suggest a significant correlation among the elements, confirming that the data are suitable for principal component analysis, as shown in Table 6. Two principal components were extracted, with eigenvalues of 2.929 and 1.191, both exceeding 1. The combined explained variance of these two components was 68.66%, indicating they effectively capture most of the variability in the data and are reasonably representative of the overall dataset.

The variance explained by the first principal component (PC1) was 48.82%. Elements such as Cd, Cu, Pb, and Zn exhibited high positive loadings of 0.756, 0.829, 0.895, and 0.817, respectively, on PC1. A significant positive correlation was observed among these elements, indicating their homology. The study found that the mean concentrations of Cd, Cu, Pb, and Zn in the soils of the research region did not exceed the background levels observed in Guizhou. Despite this, the high variability suggests substantial influence from human activities. The mining of Pb and Zn exposes underground deposits to the surface, increasing the release flux of associated minerals. Additionally, field investigations revealed that mine slag in the study area consists of open piles, which, over time, can cause heavy metals to enter the surrounding soil. Areas with elevated levels of Cd, Cu, Pb, and Zn correspond with original mining sites and active mining zones (Ma et al. 2023). Consequently, PC1 is likely indicative of emissions from mining activities and seepage.

The variance explained by the second principal component (PC2) was 19.85%. Elements Cr and Ni exhibited significant positive coefficients of 0.822 and 0.731, respectively, on PC2. Although there was no significant correlation between them, Cr showed the strongest association with Ni among the six elements considered. It is generally assumed that human activities have minimal impact on soil Cr levels, which primarily originate from the parent material during soil formation (Duan et al. 2018). However, as shown in Table 4, the average concentrations of Cr and Ni did not surpass the soil background levels in Guizhou Province, but their variability was notably high, suggesting a greater influence

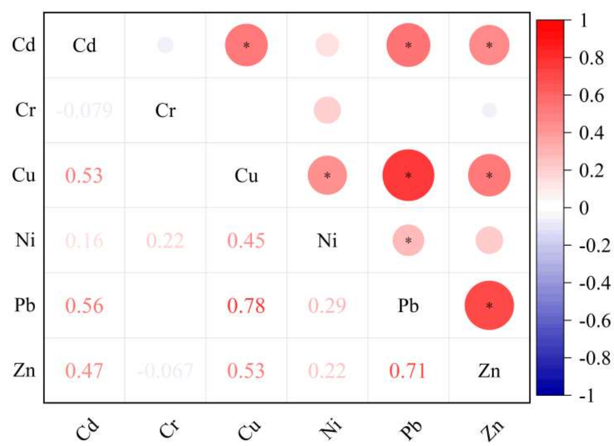

Fig. 8: Correlation coefficient of metals in the ground adjacent to the mining area.

Table 6: Rotation component matrix of metals factor analysis for the topsoil 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

from anthropogenic sources. Spatial distribution analysis indicates that Cr is mainly found in cultivated lands, while Ni is present in both cultivated areas and mining tracks. According to Ai et al. (2014), chemical fertilizers often contain elevated levels of Cr, with concentrations ranging from 50 to 250 mg·kg^{-1} in calcium superphosphate and 5 to 3000 mg·kg^{-1} in nitrogen fertilizers. Globally, the annual Cr input to soils via fertilizers is estimated to be between 0.03 and 0.38 t-a^{-1} (Ai et al. 2014, Chen et al. 2022).

Over time, excessive fertilizer application leads to the accumulation of numerous Cr elements in the soil. Additionally, the overuse of calcium superphosphate-based insecticides and herbicides may result in Ni buildup (Alengebawy et al. 2021). Field observations indicate that this area has only one entrance and exit, and heavy vehicle traffic can release Ni from exhaust into the atmosphere, which eventually deposits into the soil. Consequently, PC2 is likely caused by agricultural activities and transportation.

3.4.3. PMF Source Resolution

The PMF model is employed for the quantitative source analysis of six metals in soil samples. Fig. 8 illustrates the contribution rates of various sources to the heavy metals present in the soil around the mining area. By incorporating the concentration and uncertainty into the PMF model, the signal-to-noise ratios (S/N) for chromium, nickel, copper, and cadmium are identified as 8.8, while those for lead and zinc are 9.0, both labeled with the default name "Strong." After selecting 2-6 factors over 100 iterations, it was determined that when five factors are used, all but one, R^2 for nickel at 0.69, exceed 0.8. The other elements, Cr, Cu, Pb, and Cd, have R^2 values above 0.9, indicating that this component count effectively captures the data's underlying information and yields a robust analysis. Factor 1 accounts for 63.7% of the Cr, suggesting a dominant anthropogenic influence, which aligns with regional conditions and PC2 analysis. Therefore, it is hypothesized that Factor 1 originates from agricultural activities. Factor 2 significantly correlates with Cd, whose sources are diverse in the Pb-Zn region, including air deposition, dust, agricultural production, and industrial emissions. Notably, atmospheric deposition may contribute more to soil Cd levels since fine particles can be transported by airflow to neighboring areas and deposited into soil and water bodies. Chen et al. (2021) observed a gradual increase in atmospheric Cd deposition flux in agricultural and rural areas from 2000 to 2018, highlighting the risk posed by heavy metal Cd contamination in agricultural soils (Chen et al. 2021). Near the lead-zinc mining area, comparisons between mulched and open-air conditions revealed that atmospheric deposition primarily caused the increased heavy metal levels in the aboveground parts of Chinese cabbage (Zhan et al. 2010). Thus, it is inferred that Factor 2 represents an atmospheric deposition source. Factor three contributed more significantly to the elements Zn and Ni, accounting for 59.1% and 41.9%, respectively. Research has confirmed the presence of the three major metals, Cu, Zn, and Pb, in wastewater used for irrigation (Liu et al. 2021). This mining area primarily engages in lead and zinc ore extraction and smelting, with wastewater, exhaust gases, and slag emissions during production serving as key sources of Pb, Zn, Cd, and Cu in the soil. The open storage of raw materials and tailings in the region may lead to heavy metal pollutants spilling over into surrounding areas following rainwater runoff and leaching, posing potential environmental safety risks. Studies by Ma et al. and Wei et al. have shown that the content of Cd, Pb, and Zn in soils around the Pb-Zn mine is influenced by non-ferrous metal mining and processing activities (Ma et al. 2014, Wei et al. 2018). The main source of Ni is transportation; however, other sources also contribute. Li et al. identified high Ni levels in samples taken from the mining site and nearby river channels (Li et al. 2024). Therefore, it is hypothesized that factor three represents the wastewater discharge source.

Factor 4 accounts for 52.9%, 45.4%, and 36.2% of the elements Cu, Ni, and Cr, respectively. These findings align with the PC2 results, where tire wear contributes to Cu accumulation during transportation. Consequently, factor four is likely linked to transportation activities.

Factor 5 accounts for 79.9% of Pb contributions. Mineral resources such as lead and zinc ores are particularly abundant in Ma-Gu town. The region suffers from intensified heavy metal contamination due to mining, smelting, and tailings dumping in the watershed. Consequently, it is hypothesized that Factor 5 originates from mining emissions.

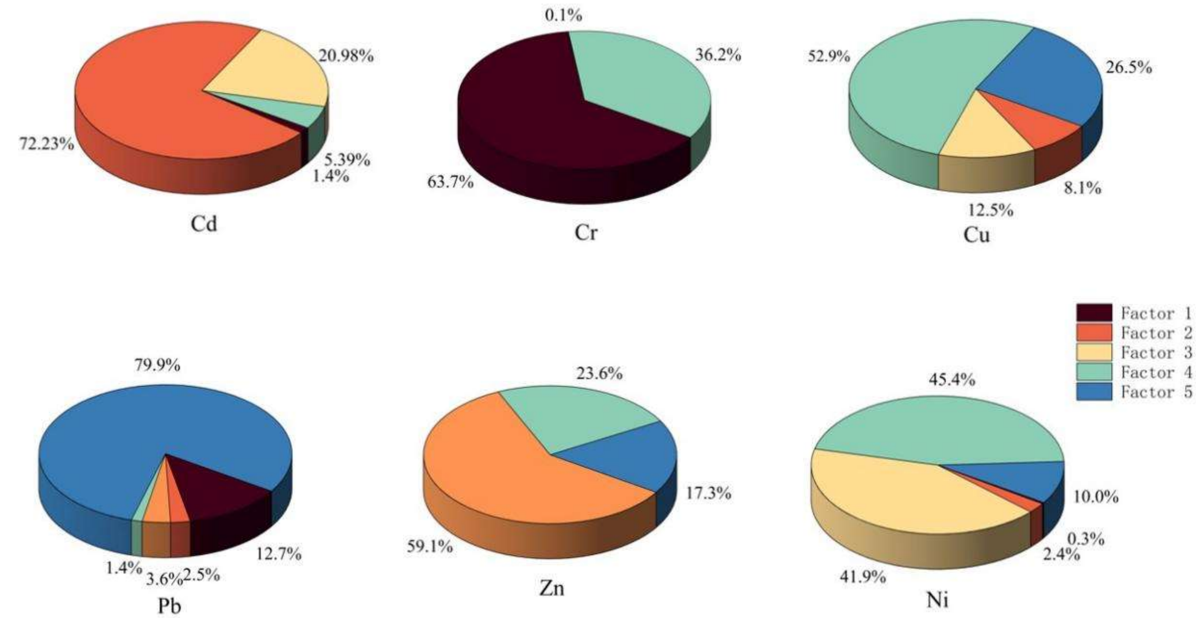

Fig. 8: Dedication rate for various causes of metal pollution in soil surrounding mining regions.

4. CONCLUSIONS

The average concentrations of six metals (Cd, Cu, Pb, Cr, Ni, and Zn) in the soils of the research area did not exceed the baseline levels established in Guizhou Province, although they exhibited significant variability. This indicates that external activities heavily influence these six metal elements. At the same depth, the concentrations followed the order Zn > Cr > Pb > Cu > Cd > Ni. Chemically, Cr, Zn, and Pb are generally stable in the soil; however, there remains a potential risk of bioaccumulation. The spatial distribution of high-concentration areas for all six metals is similar, closely linked to residuals and sites from former mining operations, but further investigation is needed to understand pollution impacts better. The geological accumulation index analysis shows that the Igeo values for all six elements are below zero, indicating no pollution. Nonetheless, cadmium and lead show the greatest dispersion and enrichment in the soil, whereas nickel has relatively low enrichment levels. RSP analysis reveals that while copper, nickel, and chromium are not polluted, lead and zinc show slight pollution, with cadmium present at light, moderate, and even heavy pollution levels. Correlation, principal component, and PMF analyses suggest that pollution sources include five main pathways: agricultural activities contribute 63.7% of chromium (Cr), atmospheric deposition accounts for 72.3% of cadmium (Cd), wastewater discharge contributes 59.1% of zinc (Zn) and 41.9% of nickel (Ni), traffic emissions account for 52.9% of copper, 45.4% of nickel, and 36.2% of chromium, and mining activities contribute 79.9% of lead.

5. ACKNOWLEDGEMENT

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