

Article

Physicochemical Characteristics and Ecological Risk Assessment of Coal Gangue: A Case Study of Typical Coal-Resource-Based Cities in China

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Abstract

This study characterizes the physicochemical properties of coal gangue in Huainan, a typical coal resource-based city in China, and evaluates variations in its chemical composition and associated ecological risks. The results show that the coal gangue in the Huainan mining area is composed mainly of quartz and clay minerals, with SiO₂ and Al₂O₃ together accounting for over 86% of the total composition. Rare earth element concentrations are generally higher than background levels, whereas heavy metal concentrations are generally below the risk screening values for soil contamination of agricultural land. Complex associations are observed among the elements in coal gangue. The correlation coefficients between SiO₂ and the other oxides or heavy metals range from −0.750 to −0.993, indicating significant negative correlations and suggesting that the silicate mineral phase occurs independently of other element-enriched phases. The potential ecological risk index (RI) for heavy metals ranges from 33.75 to 300.71 and is driven primarily by Hg and Cd. The RI for rare earth elements ranges from 98.9 to 220.3, with Lu as the key influencing element. The predicted probability of adverse biological effects is 14–15%. Overall, classified management of coal gangue in the Huainan mining area is recommended, together with strengthened continuous monitoring of Hg and Cd and optimization of ecological disposal strategies by integrating potential ecological risk assessment with analysis of adverse biological effects, thereby further supporting the green transition of resource-depleted cities.

Keywords: Huainan mining area; coal gangue; physicochemical characteristics; correlation analysis; ecological risk assessment



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1. Introduction

China's energy structure, characterized by being "poor in oil, short of natural gas, and relatively rich in coal," determines that coal plays an important role as both the "ballast" and the "stabilizer" of the national energy supply system [1]. Coal will continue to occupy a dominant position in China's basic energy consumption structure for the foreseeable future [2]. However, the long-term intensive exploitation of coal resources has inevitably caused environmental impacts in mining areas, giving rise to a typical tension between resource development and environmental constraints [3–5]. This dual challenge is particularly prominent in resource-based cities. Therefore, in the new era of green development, the transformation of cities dominated by coal resource development faces major environmental security challenges [6,7].

Coal gangue is the main solid waste generated during coal mining and washing [8–10], accounting for 15–20% of raw coal production. It has a complex composition and is a secondary coal-associated mineral formed from plant remains incorporated during coal formation and subjected to high-temperature and high-pressure deposition [11,12]. At present, the management and comprehensive utilization of coal gangue still face multiple challenges, including difficulty in reducing solid waste, difficulty in resource utilization, and difficulty in harmless end disposal [13]. China generates more than 700 million tonnes of coal gangue each year, and cumulative stockpiles have reached 6 billion tonnes. Because coal gangue is highly diverse in type, physicochemical properties, and activity index, its pathways for resource utilization remain greatly constrained. As a result, utilization rates and quality remain low, and large quantities of coal gangue are stockpiled over long periods, creating an acute disposal dilemma due to the lack of viable disposal outlets [14]. Long-term accumulation of coal gangue not only occupies land resources but also exerts considerable ecological and environmental pressure [15–17]. Coal gangue contains heavy metals, sulfur, carbon, and other elements. Under natural stockpiling conditions, these components are prone to oxidation and decomposition in environmental media and, under the combined effects of precipitation and wind erosion, may further cause regional soil and groundwater pollution [18–20]. Although previous studies have assessed the release characteristics and environmental risks of heavy metals in coal gangue from various mining areas, they have predominantly focused on large coal bases such as Shanxi, Shaanxi, and Inner Mongolia, with insufficient attention paid to mining areas with high water tables in East China [21–23]. Meanwhile, existing assessments are generally limited to conventional heavy metals, and a systematic understanding of the environmental behavior and ecological risks of emerging contaminants such as rare earth elements (REEs) in coal gangue remains lacking. Moreover, against the backdrop of increasingly stringent environmental policies, large quantities of stockpiled coal gangue not only impose substantial operational and maintenance costs on coal enterprises but have also become a constraint on green ecological development in mining areas [24]. Therefore, there is an urgent need to analyze the physicochemical properties of existing coal gangue, clarify its pollution characteristics and potential ecological risks, and develop a risk assessment method that incorporates a broader range of factors.

The Huainan mining area, which has a long history of coal mining [25], is an important coal production base in East China. Extensive studies have been carried out in this area, but they have mainly concentrated on coal petrographic characteristics and coal quality, coal resource occurrence patterns, gas disaster prevention and control, and coal mining techniques, whereas environmental geochemical research specifically addressing coal gangue, a bulk solid waste, remains scarce [26–30]. The mining area primarily employs fully mechanized longwall mining and dense-medium separation. The coal gangue produced by raw-coal washing consists mainly of sandstone, mudstone, and carbonaceous shale. Its

complex mineralogical composition and frequent association with pyrite and other readily oxidized components result in greater potential reactivity during stockpiling. The Huainan mining area contains large quantities of coal gangue and substantial historical stockpiles, yet overall utilization remains limited [31,32]. At the same time, this region is facing the dual pressures of resource depletion and the transition toward green development, making it imperative to clarify the ecological risks of coal gangue and appropriate management strategies. Such clarification is essential for regional environmental governance and the transformation of resource-based cities. Currently, environmental risk studies on coal gangue in the Huainan mining area mostly involve only assessments of conventional heavy metal concentrations [33], while the distribution characteristics and modes of occurrence of REEs, as well as their roles as tracers and risk indicators, have rarely been investigated, leaving a distinct research gap. REEs associated with minerals in coal measures are significant both as source tracers and because of their potential ecotoxicity. Integrating REEs into risk assessments can compensate for the limitations of relying solely on heavy metals and establish a more comprehensive, multidimensional understanding of risk.

Accordingly, representative coal gangue samples were systematically collected from eight coal mines in the Huainan mining area. For the first time, risk assessments of heavy metals and rare earth elements (REEs) were integrated into a multidimensional, interdisciplinary framework to reveal the combined contamination characteristics and potential ecological risks of coal gangue in this area. By systematically comparing the results with published data from other representative mining areas, this study identifies the regional specificity of coal gangue risks in Huainan and discusses the uncertainties and limitations of the proposed assessment approach, as well as the engineering challenges associated with its application in other resource-based cities. The findings are intended to provide a precise scientific basis for the management of coal gangue in the Huainan mining area, promote the green transformation of the coal industry, and support the sustainable development of resource-based cities under the “dual carbon” goals.

2. Materials and Methods

2.1. Sample Collection

Sampling was conducted at eight major coal mines in the Huainan mining area, namely the GQ, PS, ZJD, GB, DJ, ZJ, XQ, and PE mines. Referring to the Method for Manual Sampling of Commercial Coal (GB 475-2008) [34], a multipoint sampling method was used to collect coal gangue samples. Each sample weighed approximately 25 kg, and a total of ten coal gangue samples (G1–G10) were collected. The spatial distribution of the sampling sites is shown in Figure 1. Preliminary descriptions of the collected coal gangue samples are presented in Table 1. The Huainan mining area is located in the southern part of North China and in north-central Anhui Province, spanning both sides of the Huaihe River. It extends approximately 180 km from east to west and 15–25 km from north to south, covering an area of approximately 3200 km². It is an important energy base in eastern China. The geological structure of the mining area is a nearly east–west-trending thrust structural basin. The coal-bearing strata are mainly Carboniferous and Permian, with a total thickness of approximately 900 m and about 40 coal seams. Coal resources in the area are abundant.

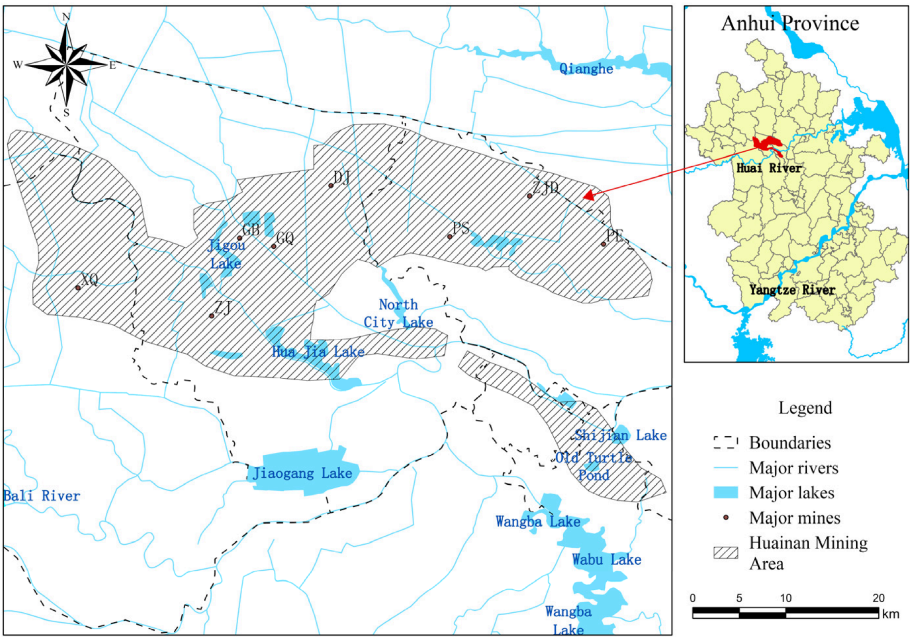


Figure 1. Location of major mines in the Huainan mining area.

Table 1. Coal gangue sampling information and sample descriptions.

ID	Coal Mine	Classification	Sample Description				Sampling Method
			Color	Main Lithology	Weathering Condition	GPS Coordinates	
G1	GQ	Excavation Gangue	Gray-black mixed with gray-white	Mudstone and fine sandstone	Relatively intact	32.8111° N, 116.5804° E	Remove the surface weathered layer (approximately 0.2–0.5 m) from the gangue dump, collect gangue samples from multiple interior locations, mix them thoroughly, and reduce the bulk sample by quartering
G2	PS	Excavation Gangue	Grayish-black	Mudstone and siltstone	Relatively intact	32.8211° N, 116.7507° E	
G3	ZJD	Parting Gangue	Grayish-black	Mudstone and siltstone	Relatively fragmented, particle size ranging from 2 to 30 cm	32.8639° N, 116.8266° E	
G4	ZJD	Excavation Gangue	Grayish-white	Siltstone and fine sandstone	Relatively intact	32.8639° N, 116.8266° E	
G5	GB	Excavation Gangue	Grayish-white	Fine sandstone	Rock intact, relatively hard, with horizontal bedding observed	32.8195° N, 116.5475° E	
G6	DJ	Excavation Gangue	Gray-black mixed with gray-white	Mudstone and fine sandstone	Relatively fragmented, particle size ranging from 1 to 10 cm	32.86700° N, 116.6357° E	
G7	DJ	Parting Gangue	Grayish-black with small grayish-white areas	Mudstone, containing minor fine sandstone	Relatively fragmented, particle size ranging from 0.2 to 3 cm	32.86700° N, 116.6357° E	
G8	ZJ	Excavation Gangue	Grayish-black	Mudstone and siltstone	Relatively intact	32.7443° N, 116.5206° E	
G9	XQ	Excavation Gangue	Grayish-black containing minor grayish-white	Mudstone, containing minor fine sandstone	Relatively fragmented, particle size ranging from 0.2 to 8 cm	32.7716° N, 116.3918° E	
G10	PE	Excavation Gangue	Grayish-black containing minor grayish-white	Mudstone, containing minor fine sandstone	Relatively fragmented, particle size ranging from 0.2 to 10 cm	32.8134° N, 116.8990° E	

2.2. Sample Processing and Analysis

After pretreatment, including crushing and grinding, the samples were analyzed experimentally. The mineral composition of coal gangue was determined by X-ray diffraction

(XRD, Xpert Power, Bruker, Karlsruhe, Germany). Chemical composition was analyzed using wavelength-dispersive X-ray fluorescence spectrometry (XRF, Axios mAX, Panalytical, Almelo, The Netherlands). Heavy metals and REEs in coal gangue were analyzed using atomic fluorescence spectrometry (AFS, BAF-3000, Baode Instruments, Beijing, China) and inductively coupled plasma mass spectrometry (ICP-MS, iCAP-Qc, Thermo Scientific, Waltham, MA, USA). Excel 2021, Origin Pro 2026, ArcGIS Pro 3.0.2, and other software were used for data processing and statistical analysis. To investigate associations between the sources and distributions of heavy metals and the major chemical components of coal gangue, bivariate correlation analysis was performed using Pearson's correlation coefficient, and a correlation heatmap was generated in Origin. Statistical significance was set at $p < 0.05$.

2.3. Evaluation Methods

To address the multidimensional environmental risks posed by heavy metal pollution in coal gangue, this study selected three evaluation methods. First, the geoaccumulation index method incorporates regional background values and a correction for geological variability, allowing the enrichment of a single heavy metal caused by human activities to be objectively reflected and providing a basic basis for identifying pollution sources and accumulation levels [35]. Second, the potential ecological risk index method integrates the toxicity response coefficient of each heavy metal on the basis of concentration, thereby comprehensively evaluating the potential ecological hazards of combined heavy metal pollution and overcoming the limitation of single enrichment indices that ignore toxicity differences [36]. Third, the adverse biological toxicity effect assessment method, based on biological-effects databases, uses probable effect concentrations (PECs) and threshold effect concentrations (TECs) as references to directly link pollutant concentrations with biological toxicity effects and predict the likelihood that mixed heavy metals will pose actual hazards to soil or aquatic organisms [37]. Together, these three methods form a progressive evaluation framework that fully considers the complexity of pollution characteristics during the long-term migration of coal gangue, providing scientific and reliable methodological support for comprehensive assessment and risk management of heavy metal pollution in the study area.

The calculation formulas and parameters for the ecological risk assessment of coal gangue are presented in Table 2. In the table, C_i represents the measured concentration of a pollutant (mg/kg); B_i is the regional background value of heavy metal element i (mg/kg); K is the correction factor, set at 1.5; and T_r^i is the toxicity response coefficient of heavy metal element i . The values for As, Cd, Cu, Cr, Hg, Ni, Pb, and Zn are 10, 30, 5, 2, 40, 5, 5, and 1, respectively. Unlike heavy metals, the ecotoxicity of REEs has rarely been studied. Based on the principle that toxicity is determined by elemental abundance and release effects, Chen et al. [38] proposed toxicity coefficients for REEs as follows: La (1), Ce (1), Pr (5), Nd (2), Sm (5), Eu (10), Gd (5), Tb (10), Dy (5), Ho (10), Er (5), Tm (10), Yb (5), Lu (20), and Y (2). RI is the comprehensive potential ecological risk index; E_r^i is the potential ecological risk index for heavy metal element i ; Q is the mean probable effect concentration quotient; CPE_i is the probable effect concentration of heavy metal i ; and n is the number of heavy metals. The CTE (CPE) values for Cd, As, Hg, Cr, Ni, Cu, Zn, and Pb are 0.99 (4.98), 9.79 (33), 0.18 (1.06), 43.4 (111), 22.7 (48.6), 31.6 (149), 121 (459), and 35.8 (128), respectively. The pollution levels for heavy metal ecological risk assessment are classified as shown in Table 3.

Table 2. Methods for the ecological risk assessment of coal gangue.

Methods for Ecological Risk Assessment	Formula
I_{geo}	$I_{geo} = \log_2 \left(\frac{C_i}{KB_i} \right)$
RI	$RI = \sum_{i=1}^n E_r^i = \sum_{i=1}^n \left(T_r^i \times \frac{C_i}{B_i} \right)$
$mPEC-Q$	$Q = \sum_{i=1}^n \left(\frac{C_i}{CPE_i} \right) / n$

Table 3. Classification of pollution levels for ecological risk assessment of heavy metals.

Methods for Ecological Risk	Classification Criteria	Classification
I_{geo}	≤ 0	Pollution-free
	$0 < I_{geo} \leq 1$	Light to moderate pollution
	$1 < I_{geo} \leq 2$	Moderate pollution
	$2 < I_{geo} \leq 3$	Moderate to heavy pollution
	$3 < I_{geo} \leq 4$	Severe pollution
	$4 < I_{geo} \leq 5$	Severe to very severe pollution
	$5 < I_{geo} \leq 10$	Extremely severe pollution
E_r	$E_r < 40$	Low risk
	$40 \leq E_r < 80$	Medium risk
	$80 \leq E_r < 160$	Medium to high risk
	$160 \leq E_r < 320$	High risk
	$320 \leq E_r$	Extremely high risk
RI	$RI < 150$	Minor
	$150 \leq RI < 300$	Intermediate
	$300 \leq RI < 600$	Strong
	$RI \geq 600$	Very strong
$mPEC-Q$	$mPEC-Q \leq 0.1$	$PTP \leq 14\%$
	$0.1 < mPEC-Q \leq 1.0$	$15\% \leq PTP \leq 14\%$
	$1.0 < mPEC-Q \leq 5.0$	$33\% \leq PTP \leq 58\%$
	$5.0 < mPEC-Q$	$75 \leq PTP \leq 81\%$

3. Results and Discussion

3.1. Mineral Composition Characteristics

As shown in Figures 2 and 3, the main minerals in coal gangue from the study area are quartz and clay minerals, followed by siderite, plagioclase, potassium feldspar, and calcite, with occasional dolomite and pyrite. Quartz contents in all samples range from 35.5% to 75.1%, with the highest content in sample G5 (75.1%), followed by sample G4 (70.4%), and the lowest in sample G10 (35.5%). The total clay mineral content (TCCM) ranges from 18.6% to 60.8%: samples G10 and G2 have the highest contents, at 60.8% and 56.9%, respectively, sample G8 has 48.4%, and sample G4 has the lowest content, at only 18.6%. As the third most abundant component, siderite ranges from 0 to 14.0%; sample G3 has the highest content (14.0%), sample G9 has 7.2%, and siderite is not detected in sample G5.

Overall, samples G10 and G2 are dominated by clay minerals and have high mudstone contents, indicating relatively pure mudstone. Compared with gangue from other mines in the area, these samples are more prone to disintegration under external factors such as weathering and rainfall, thereby releasing pollutant components into the surrounding soil and groundwater environments. In samples G5, G4, G1, and G6, quartz accounts for more than 50%, a proportion higher than that in gangue from the other mines. This indicates that such coal gangue can better maintain its morphology under weathering, rainfall, and other

external factors [39]; however, the specific release patterns of its pollutant components under the action of water require further investigation and validation.

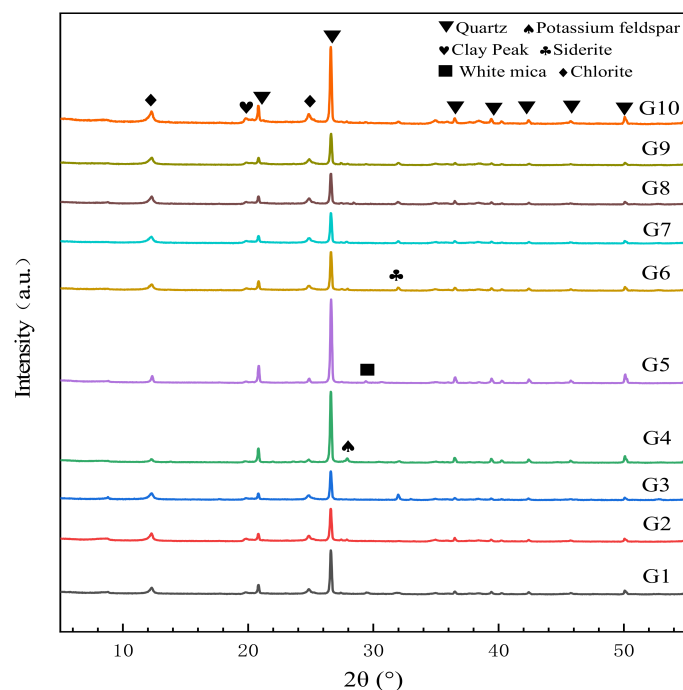


Figure 2. XRD diffraction pattern of coal gangue.

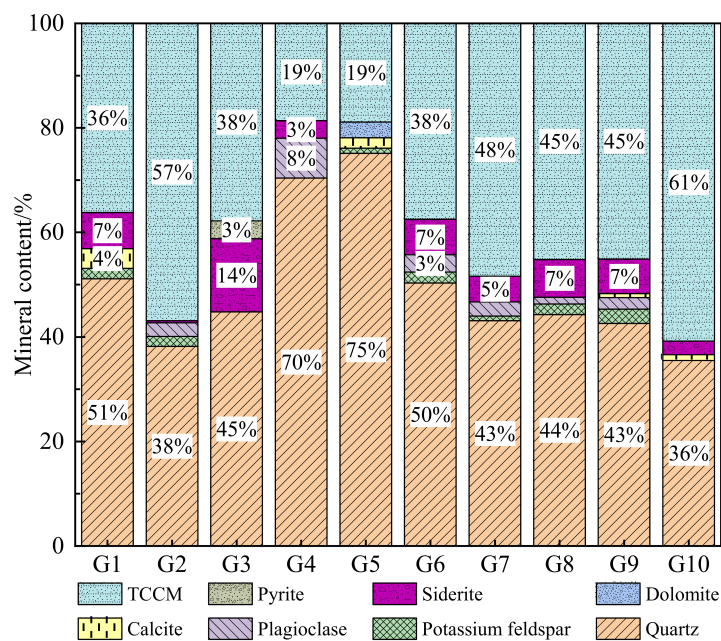


Figure 3. Analysis of the mineral composition of coal gangue.

3.2. Chemical Characteristics Analysis

3.2.1. Chemical Composition

As shown in Table 4, coal gangue is mainly composed of SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , MgO , and other oxides. The SiO_2 content ranges from 59.57% to 77.76%, with an average of 66.17%; Al_2O_3 ranges from 12.75% to 25.03%, with an average of 20.60%; Fe_2O_3 ranges from 1.97% to 11.16%, with an average of 5.59%; CaO ranges from 0.14% to 2.48%, with an average of 0.87%; MgO ranges from 0.56% to 1.02%, with an average of 0.69%; K_2O ranges from 1.29% to 2.06%, with an average of 1.66%; Na_2O ranges from 0.18% to 1.21%, with an

average of 0.59%; TiO_2 ranges from 0.41% to 1.20%, with an average of 0.88%; MnO_2 ranges from 0 to 0.15%, with an average of 0.06%; and P_2O_5 ranges from 0.04% to 0.15%, with an average of 0.07%. In coal gangue, SiO_2 and Al_2O_3 mainly originate from kaolinite and quartz. Together, they account for more than 86% on average, indicating that coal gangue in the Huainan mining area is dominated by aluminosilicate minerals. The $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratio is below 0.5, suggesting that the coal gangue is mainly composed of quartz and kaolinite. Based on XRF analysis, the coal gangue has a typical high-silica and medium-alumina chemical composition, and its rock type can be classified as clayey quartzite gangue.

Table 4. XRF analysis of the main chemical constituents of coal gangue/%.

Coal Gangue	Chemical Composition									
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	TiO_2	MnO_2	P_2O_5
G1	65.34	20.75	5.66	2.32	1.02	1.96	0.37	0.95	0.09	0.15
G2	63.31	24.5	2.43	0.14	0.72	2.06	0.69	0.93	0	0.05
G3	59.57	23.32	11.16	0.18	0.74	1.71	0.39	1	0.1	0.08
G4	75.29	13.49	3.95	0.59	0.67	1.54	1.21	0.55	0.02	0.05
G5	77.76	12.75	1.97	1.56	0.56	1.55	0.18	0.41	0.02	0.04
G6	66.28	21.35	5.56	0.23	0.61	1.43	0.54	0.94	0.06	0.06
G7	65.34	23.79	3.31	0.56	0.58	1.56	0.51	0.96	0.04	0.06
G8	61.55	25.03	7.18	0.23	0.56	1.29	0.43	1.2	0.04	0.04
G9	62.02	24.86	5.69	0.45	0.66	1.45	0.52	1.02	0.07	0.07
G10	65.25	16.14	9.01	2.48	0.81	2.01	1.03	0.80	0.15	0.13
Minimum value	59.57	12.75	1.97	0.14	0.56	1.29	0.18	0.41	0.00	0.04
Maximum value	77.76	25.03	11.16	2.48	1.02	2.06	1.21	1.20	0.15	0.15
Average	66.17	20.60	5.59	0.87	0.69	1.66	0.59	0.88	0.06	0.07

3.2.2. Heavy Metal Mass Concentrations

As shown in Table 5, the concentrations of heavy metals in coal gangue differ markedly and vary over a wide range. The Cd concentration ranges from 0.04 to 0.16 mg/kg, with an average of 0.09 mg/kg, which is nearly equivalent to the soil background value and far below the soil environmental quality risk-screening value. The Hg concentration ranges from 0.012 to 0.199 mg/kg, with an average of 0.085 mg/kg. The As concentration ranges from 0 to 11.5 mg/kg, with an average of 2.14 mg/kg; only sample G1 has an As content close to the soil background value of China. The Pb concentration ranges from 10.2 to 33.7 mg/kg, with an average of 25.7 mg/kg. The Cr concentration ranges from 27.4 to 88.8 mg/kg, with an average of 61.5 mg/kg. The Cu concentration ranges from 5.7 to 28.1 mg/kg, with an average of 21.72 mg/kg, slightly higher than the soil background value of Anhui Province but lower than that of China and far below the risk-screening value. The Ni concentration ranges from 7.76 to 30.7 mg/kg, with an average of 21.1 mg/kg. The Zn concentration ranges from 39.2 to 78.3 mg/kg, with an average of 56.2 mg/kg. Overall, the concentrations of all heavy metals in coal gangue from the Huainan mining area do not exceed the risk-screening values for agricultural land soil pollution, indicating no heavy metal enrichment beyond the risk control standards.

Table 5. Heavy metal content in coal gangue/(mg/kg).

Coal Gangue	Heavy Metal Elements							
	Cd	Hg	As	Pb	Cr	Cu	Ni	Zn
G1	0.16	0.046	11.5	33.7	58.4	28.1	28.1	78.3
G2	0.10	0.062	0	30.1	68.2	26.3	14.0	53.5
G3	0.11	0.199	5.46	27.1	73.7	23.3	30.7	76.7
G4	0.06	0.112	1.09	18.7	37.7	10.9	13.00	56.0

Table 5. Cont.

Coal Gangue	Heavy Metal Elements							
	Cd	Hg	As	Pb	Cr	Cu	Ni	Zn
G5	0.04	0.012	0.686	10.2	27.4	5.7	7.76	39.2
G6	0.10	0.055	0.41	30.3	62.6	24.0	19.2	49.1
G7	0.13	0.146	0.88	29.4	64.7	27.0	19.9	57.1
G8	0.04	0.043	0	22.7	88.8	21.4	30.4	42.5
G9	0.08	0.039	0.436	28.4	63.3	22.7	24.4	58.6
G10	0.08	0.138	0.957	26.6	70.1	27.8	23.5	51.1
Minimum value	0.04	0.012	0	10.2	27.4	5.7	7.76	39.2
Maximum value	0.16	0.199	11.5	33.7	88.8	28.1	30.7	78.3
Average value	0.09	0.085	2.14	25.7	61.5	21.72	21.1	56.2
Background value [40]	0.097	0.033	9.0	26.6	66.5	20.4	29.8	62.0
Chinese soil background values [41]	0.097	0.065	11.20	26.0	61.0	22.6	26.9	74.2
Risk value [40]	0.6	1.0	20	170	250	100	190	300

3.2.3. Characteristics of Rare Earth Element Mass Concentrations

As shown in Table 6, the concentrations of different REEs in coal gangue differ markedly, and each REE shows a distinct range of variation among the coal gangue samples. Among the light REEs, La ranges from 32.3 to 70.8 mg/kg, with an average of 50.47 mg/kg; Ce ranges from 59.7 to 139 mg/kg, with an average of 97.59 mg/kg; Pr ranges from 6.7 to 15.3 mg/kg, with an average of 11.056 mg/kg; Nd ranges from 24.2 to 58.7 mg/kg, with an average of 41.58 mg/kg; Sm ranges from 3.82 to 10.4 mg/kg, with an average of 7.21 mg/kg; and Eu ranges from 0.78 to 2.08 mg/kg, with an average of 1.477 mg/kg. Among the heavy REEs, Gd ranges from 3.78 to 8.98 mg/kg, with an average of 6.359 mg/kg; Tb ranges from 0.6 to 1.41 mg/kg, with an average of 1.005 mg/kg; Dy ranges from 3.44 to 8.39 mg/kg, with an average of 5.926 mg/kg; Ho ranges from 0.77 to 1.77 mg/kg, with an average of 1.257 mg/kg; Er ranges from 2.33 to 5.03 mg/kg, with an average of 3.617 mg/kg; Tm ranges from 0.37 to 0.8 mg/kg, with an average of 0.579 mg/kg; Yb ranges from 2.38 to 5.41 mg/kg, with an average of 3.805 mg/kg; Lu ranges from 0.37 to 0.82 mg/kg, with an average of 0.587 mg/kg; and Y ranges from 20.4 to 49.3 mg/kg, with an average of 34.13 mg/kg.

Table 6. Rare earth element content in coal gangue/(mg/kg).

Coal Gangue	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y
G1	54.5	107	12.4	49.3	9.53	2.08	8.17	1.33	8.07	1.72	4.85	0.76	4.99	0.77	46.0
G2	56.6	106	11.9	44.1	7.24	1.44	6.47	1.06	6.56	1.41	4.09	0.66	4.29	0.66	37.8
G3	44.1	90.0	10.1	37.1	6.36	1.23	5.65	0.87	5.07	1.09	3.23	0.52	3.43	0.54	30.0
G4	40.1	78.4	8.79	33.0	5.46	1.39	4.92	0.74	3.98	0.81	2.34	0.37	2.38	0.37	21.0
G5	42.7	79.5	9.17	33.1	5.13	1.10	4.59	0.69	3.74	0.79	2.34	0.38	2.44	0.37	20.4
G6	47.9	92.5	10.5	39.0	6.81	1.34	6.09	0.99	6.01	1.29	3.71	0.60	4.02	0.62	35.0
G7	32.3	59.7	6.70	24.2	3.82	0.78	3.78	0.60	3.44	0.77	2.33	0.39	2.51	0.41	23.2
G8	70.8	139	15.3	58.7	10.4	1.96	8.98	1.41	8.39	1.77	5.03	0.80	5.41	0.82	49.3
G9	65.2	126	14.3	54.5	9.57	1.87	8.24	1.29	7.55	1.56	4.34	0.68	4.42	0.68	42.5
G10	50.5	97.8	11.4	42.8	7.78	1.58	6.70	1.07	6.45	1.36	3.91	0.63	4.16	0.63	36.1
Minimum value	32.3	59.7	6.7	24.2	3.82	0.78	3.78	0.6	3.44	0.77	2.33	0.37	2.38	0.37	20.4
Maximum value	70.8	139	15.3	58.7	10.4	2.08	8.98	1.41	8.39	1.77	5.03	0.8	5.41	0.82	49.3
Average value	50.47	97.59	11.056	41.58	7.21	1.477	6.359	1.005	5.926	1.257	3.617	0.579	3.805	0.587	34.13
Background value	36.3	67.3	7.97	26.5	4.73	0.98	4.38	0.65	3.85	0.82	2.4	0.31	2.01	0.31	23.4

Compared with the REE background values of the A-horizon soil in Anhui Province, the average concentrations of all REEs in coal gangue from this region are higher than the background values. Among the samples, G8 shows the highest concentrations of most REEs, whereas the total REE concentrations in samples G7, G4, and G5 are relatively lower. Overall, light REEs account for a much higher proportion than heavy REEs, and Ce, La, and Nd are the three REEs with the highest concentrations in coal gangue.

3.3. Analysis of the Differential Characteristics of Coal Gangue

As shown in the correlation analysis of heavy metal elements and major chemical components in coal gangue (Figure 4), SiO₂ is significantly negatively correlated ($p < 0.05$, the same below) with Al₂O₃, TiO₂, Pb, Cr, Cu, and Ni, with Pearson correlation coefficients of -0.883 , -0.993 , -0.750 , -0.921 , -0.819 , and -0.817 , respectively. In contrast, Al₂O₃ is significantly positively correlated with TiO₂, Pb, Cr, and Cu, with Pearson coefficients of 0.926 , 0.690 , 0.796 , and 0.684 , respectively. Fe₂O₃ is significantly positively correlated with MnO₂ and Ni, with Pearson coefficients of 0.802 and 0.806 . MgO is significantly positively correlated with K₂O, P₂O₅, Cd, As, and Zn, with Pearson coefficients of 0.751 , 0.906 , 0.654 , 0.831 , and 0.737 , respectively. TiO₂ is significantly positively correlated with Pb, Cr, Cu, and Ni, with Pearson coefficients of 0.724 , 0.926 , 0.765 , and 0.813 , respectively. P₂O₅ is significantly positively correlated with CaO, K₂O, MnO₂, and As, with Pearson coefficients of 0.762 , 0.635 , 0.799 , and 0.736 , respectively. Significant positive correlations also occur among the heavy metals Cd, As, Pb, Cu, and Zn, including Cd-As (0.694), Cd-Pb (0.811), Cd-Cu (0.706), Cd-Zn (0.785), As-Zn (0.827), and Pb-Cu (0.937), as well as Cr-Cu (0.757), Cr-Ni (0.791), and Cu-Ni (0.633). These results indicate that the heavy metals in coal gangue may share common sources or similar distribution mechanisms.

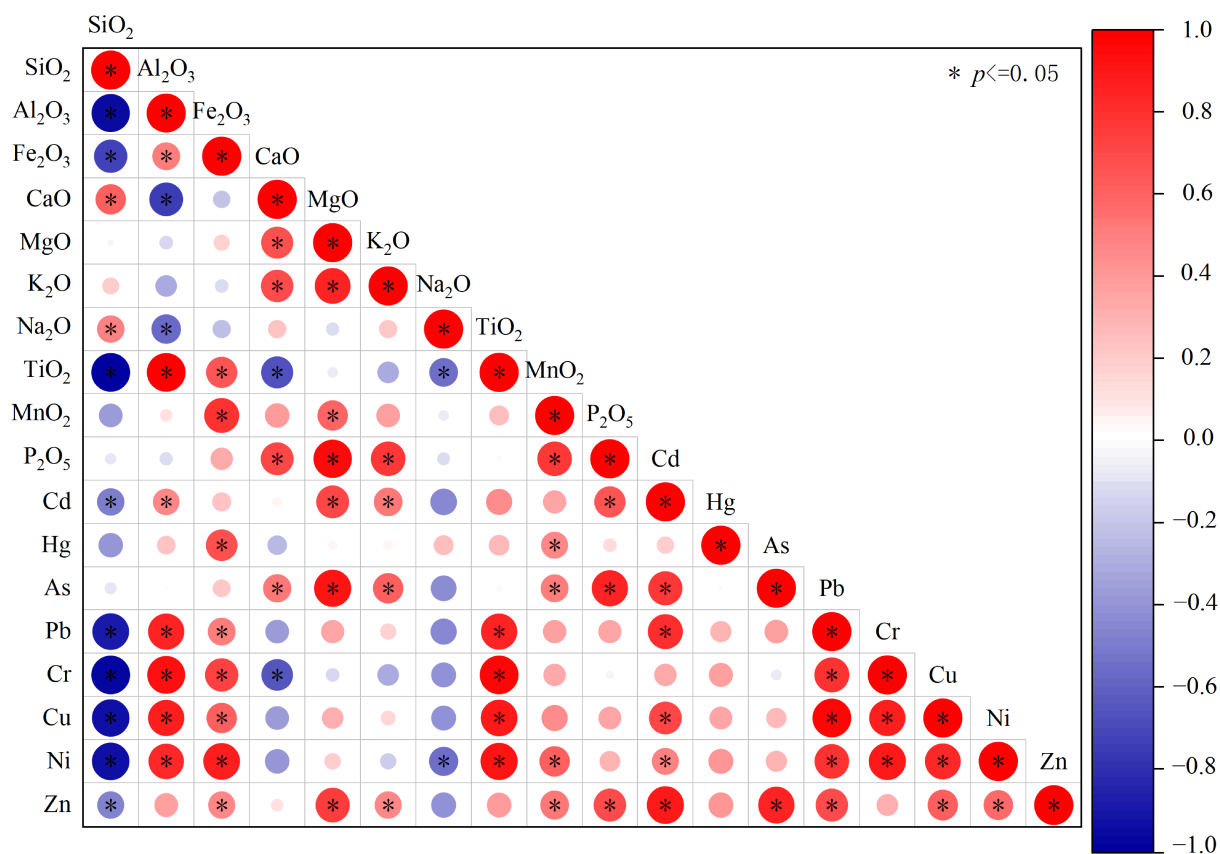


Figure 4. Correlation analysis of heavy metal elements and major chemical constituents in coal gangue.

Based on the correlation analysis of heavy metal elements and major chemical components in coal gangue, the differential characteristics of coal gangue are mainly reflected in the high heterogeneity of its chemical composition and the complex association patterns among elements [42,43]. As the dominant component, SiO₂ shows significant negative correlations with Al₂O₃, TiO₂, and various heavy metals, indicating that areas with high silicon contents are often accompanied by decreases in Al, Ti, and heavy metal elements.

This suggests that silicate mineral phases occur independently of other element-enriched phases, forming a pattern of compositional differentiation. In contrast, the strong positive correlations of Al_2O_3 with TiO_2 , Pb, Cr, and Cu indicate that the synergistic enrichment of aluminum oxides with Ti and heavy metals may result from adsorption or co-precipitation of heavy metals in aluminosilicate minerals, reflecting the differential distribution of specific mineral phases in coal gangue. The positive correlations of Fe_2O_3 with MnO_2 and Ni further verify the occurrence characteristics of Fe-Mn mineral phases in coal gangue. In addition, the significant positive correlations of MgO with K_2O , P_2O_5 , Cd, As, and Zn indicate the affinity and synergy of Mg-based minerals for K, P, and heavy metals such as Cd, As, and Zn. The widespread positive correlations among Cd, As, Pb, Cu, Zn, Cr, and Ni suggest that these elements may co-occur due to sulfides or organic matter residues in coal gangue, whereas the positive correlations of P_2O_5 with As and MnO_2 point to the synergistic behavior of P and Mn under specific environmental conditions.

Overall, the differential characteristics of coal gangue are manifested in the coexistence and mutual exclusion of multiple element groups: the Si-dominated phase is separated from other element phases; Al, Ti, and heavy metals are closely associated; and the Fe-Mn, Mg-K-P, and heavy metal groups each form internal positive correlation networks. These findings reveal the separation mechanism between the silicate phase and the heavy metal phase in coal gangue [44], providing a new perspective for source control of pollution in mining areas and for targeting the migration and transformation of pollutant elements.

3.4. Evaluation Results and Analysis

3.4.1. Geoaccumulation Index Method

The geoaccumulation index is classified into seven grades according to its magnitude, with the classification shown in Table 3. The pollution levels of heavy metals in coal gangue from different mining sources are shown in Figure 5. The geoaccumulation indices of As, Pb, Cr, Cu, Ni, and Zn are all below 1, indicating no pollution. Cd in coal gangue from the GQ, ZJD, and DJ mines is in the unpolluted to moderately polluted state, whereas Cd in coal gangue from the other sources is classified as unpolluted. Hg in GB coal gangue is classified as unpolluted. In coal gangue from the ZJD and DJ mines, the geoaccumulation indices of Hg are greater than 2, corresponding to moderate to heavy pollution. For coal gangue samples G1, G2, G4, G6, G8, G9, and G10, the geoaccumulation indices of Hg range from 1 to 2, corresponding to unpolluted to moderately polluted levels.

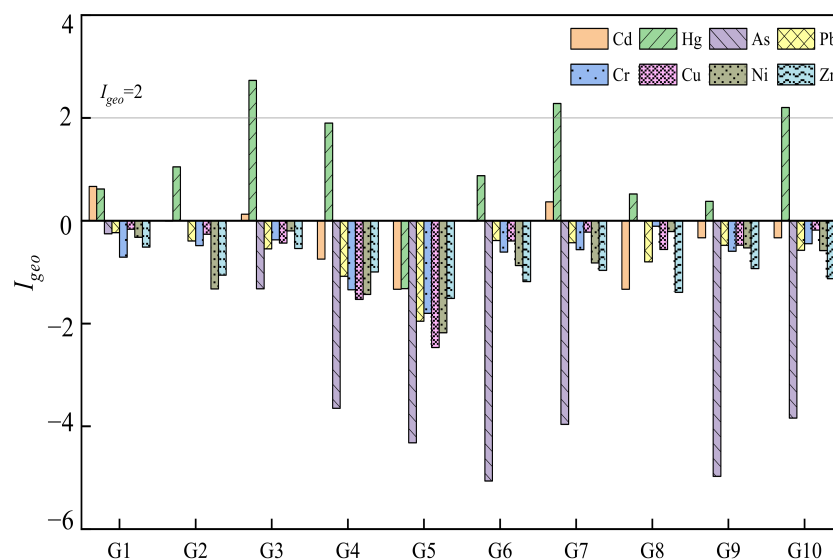


Figure 5. Geoaccumulation indices of heavy metals in coal gangue.

3.4.2. Potential Ecological Risk and Adverse Biological Toxicity Assessments

The E_r values of coal gangue from each mining area, calculated using the Hakanson potential ecological risk index method, are shown in Table 7. The E_r ranges for Cd, Hg, As, Pb, Cr, Cu, Ni, and Zn are 12.37–49.48, 14.55–241.21, 0–12.78, 1.92–6.33, 0.82–2.67, 1.4–6.89, 1.3–5.15, and 0.63–1.26, respectively. The E_r values for As, Pb, Cr, Cu, Ni, and Zn in coal gangue from the study area are all below 40, indicating that the ecological risks of these six heavy metals are at a low level. The highest E_r values for Hg and Cd are 241.21 and 49.48, respectively, suggesting that these two heavy metals pose moderate to high risk levels. As shown in Table 8, the overall potential ecological risk of REEs in coal gangue from the Huainan mining area is low. However, the E_r value of Lu in the XQ mining area is slightly higher, at 52.90, corresponding to a moderate to high risk level.

Table 7. Results of the ecological risk assessment of heavy metals in coal gangue from the Huainan mining area.

E_r^i	Cd	Hg	As	Pb	Cr	Cu	Ni	Zn
G1	49.48	55.76	12.78	6.33	1.76	6.89	4.71	1.26
G2	30.93	75.15	0.00	5.66	2.05	6.45	2.35	0.86
G3	34.02	241.21	6.07	5.09	2.22	5.71	5.15	1.24
G4	18.56	135.76	1.21	3.52	1.13	2.67	2.18	0.90
G5	12.37	14.55	0.76	1.92	0.82	1.40	1.30	0.63
G6	30.93	66.67	0.46	5.70	1.88	5.88	3.22	0.79
G7	40.21	176.97	0.98	5.53	1.95	6.62	3.34	0.92
G8	12.37	52.12	0.00	4.27	2.67	5.25	5.10	0.69
G9	24.74	47.27	0.48	5.34	1.90	5.56	4.09	0.95
G10	24.74	167.27	1.06	5.00	2.11	6.81	3.94	0.82
Minimum value	12.37	14.55	0	1.92	0.82	1.4	1.3	0.63
Maximum value	49.48	241.21	12.78	6.33	2.67	6.89	5.15	1.26
Average value	27.84	103.27	2.38	4.83	1.85	5.32	3.54	0.91

Table 8. Results of the ecological risk assessment of REEs in coal gangue from the Huainan mining area.

E_r^i	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y
G1	1.50	1.59	7.78	3.72	10.08	21.22	9.33	20.45	10.48	20.99	10.10	24.62	12.41	49.94	3.93
G2	1.56	1.58	7.47	3.33	7.66	14.71	7.38	16.34	8.52	17.21	8.52	21.27	10.67	42.45	3.23
G3	1.22	1.34	6.34	2.80	6.73	12.54	6.45	13.42	6.59	13.30	6.73	16.74	8.52	34.57	2.56
G4	1.10	1.17	5.51	2.49	5.77	14.21	5.62	11.41	5.17	9.88	4.87	12.04	5.93	24.11	1.80
G5	1.18	1.18	5.76	2.50	5.43	11.19	5.24	10.55	4.85	9.61	4.87	12.27	6.06	23.73	1.75
G6	1.32	1.37	6.61	2.94	7.20	13.71	6.95	15.24	7.80	15.70	7.74	19.46	9.99	39.90	2.99
G7	1.39	1.45	7.14	3.23	8.23	16.13	7.65	16.43	8.37	16.52	8.14	20.31	10.34	40.86	3.09
G8	0.89	0.89	4.20	1.83	4.03	7.96	4.31	9.23	4.47	9.39	4.86	12.44	6.26	26.16	1.98
G9	1.95	2.06	9.60	4.43	10.97	20.00	10.25	21.69	10.90	21.59	10.48	25.81	13.46	52.90	4.21
G10	1.80	1.88	8.96	4.11	10.12	19.10	9.40	19.79	9.80	18.97	9.04	22.04	10.99	44.17	3.63
Minimum value	0.89	0.89	4.2	1.83	4.03	7.96	4.31	9.23	4.47	9.39	4.86	12.04	5.93	23.73	1.75
Maximum value	1.95	2.06	9.6	4.43	10.97	21.22	10.25	21.69	10.9	21.59	10.48	25.81	13.46	52.9	4.21
Average value	1.39	1.45	6.94	3.14	7.62	15.08	7.26	15.46	7.69	15.32	7.54	18.70	9.46	37.88	2.92

Using ArcGIS Pro, interpolation analysis was conducted for the total potential ecological risk index (RI) corresponding to each mining area. For different coal gangue samples from the same mining area, the maximum RI value was used in the analysis to better characterize the potential ecological risk of heavy metals in coal gangue from the Huainan mining area. As shown in Figure 6a, heavy metal RI values in the Huainan mining area range from 33.75 to 300.71. Coal gangue from the ZJD mining area falls within the strong pollution category, that from the DJ and PE mining areas falls within the moderate pollution category, and that from the remaining mines falls within the slight pollution category. The spatial distribution of heavy metal RI values is strongly influenced by Hg and Cd, showing

an east-high, west-low pattern. The RI values for REEs in the Huainan mining area range from 98.9 to 220.3. Coal gangue from the GQ, PS, ZJ, XQ, and PE mines is at a moderate risk level, whereas coal gangue from the remaining mines is at a slight pollution level. The spatial distribution of REE RI values is strongly influenced by Lu, showing a pattern of higher values in the east and west and lower values in the central region. In summary, priority should be given to establishing a monitoring network for Hg and Cd, as well as Lu among REEs, in the eastern ZJD mining area.

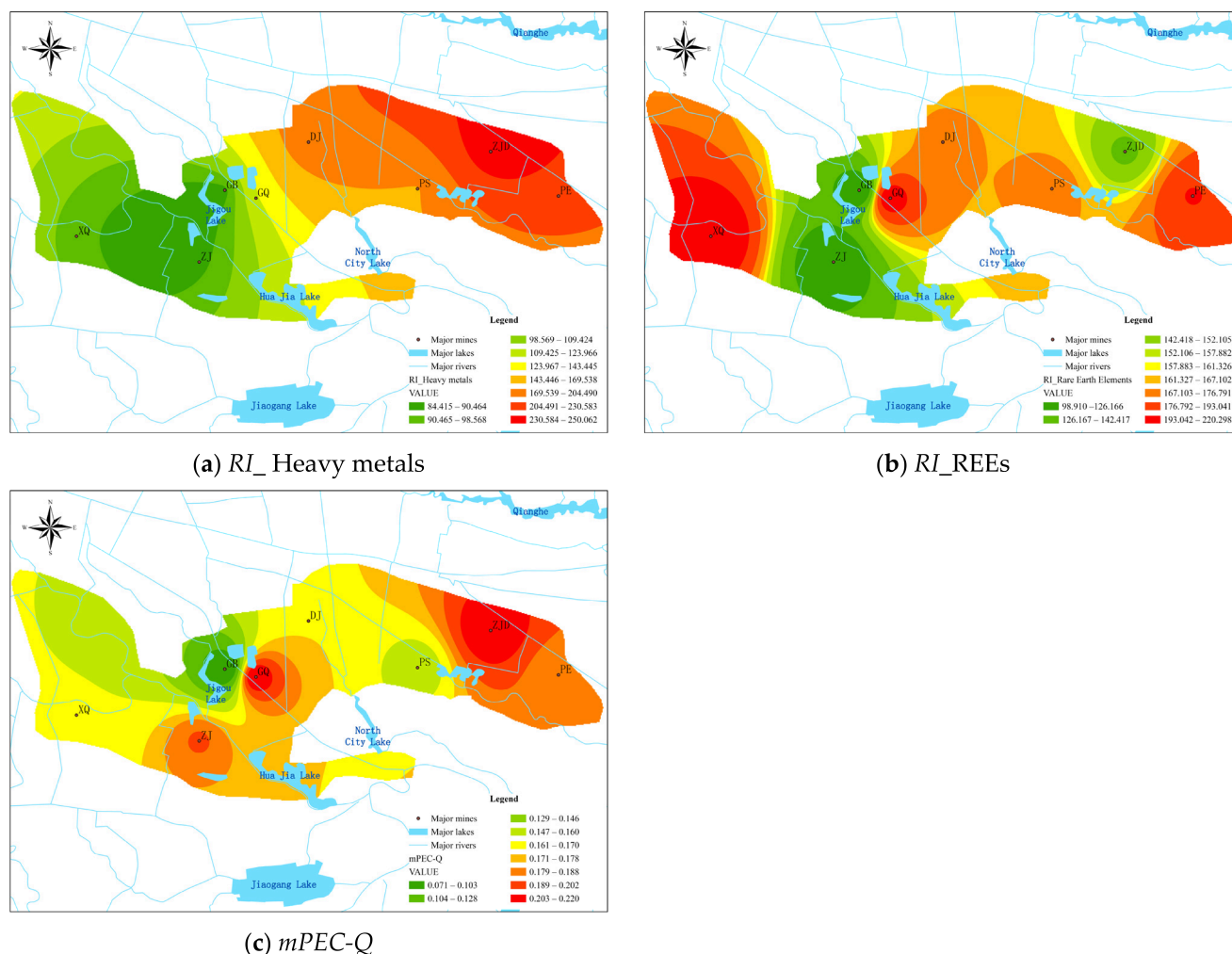


Figure 6. Potential risk index (RI) and mean probable effect concentration quotient ($mPEC-Q$) for heavy metals in the study area.

As shown in Figure 6c, the $mPEC-Q$ values of heavy metals in coal gangue from the study area range from 0.07 to 0.22. According to the classification criteria for biological toxicity, the probability of adverse biological toxicity effects in the study area ranges from 14% to 15%, indicating a low level of toxic risk associated with coal gangue. As shown in Figure 7, the variation trend of $mPEC-Q$ values is generally consistent with that of RI values, with both concentrated mainly in the ZJD and PE mining areas in the eastern part of the study area. Therefore, the ecological disposal of coal gangue in these two mining areas requires particular attention. Based on the ratios of heavy metal concentrations to the corresponding threshold effect concentrations (TECs) and probable effect concentrations (PECs) shown in Figure 7, the likelihood of adverse biological toxicity effects for the heavy metals follows the order Cr, Ni, Pb, Cu, Hg, Zn, As, and Cd. This order differs from the assessment results obtained using the geoaccumulation index (I_{geo}) and the potential

ecological risk index (RI), indirectly reflecting the limitations and uncertainties of applying a single evaluation method to ecological risk assessment.

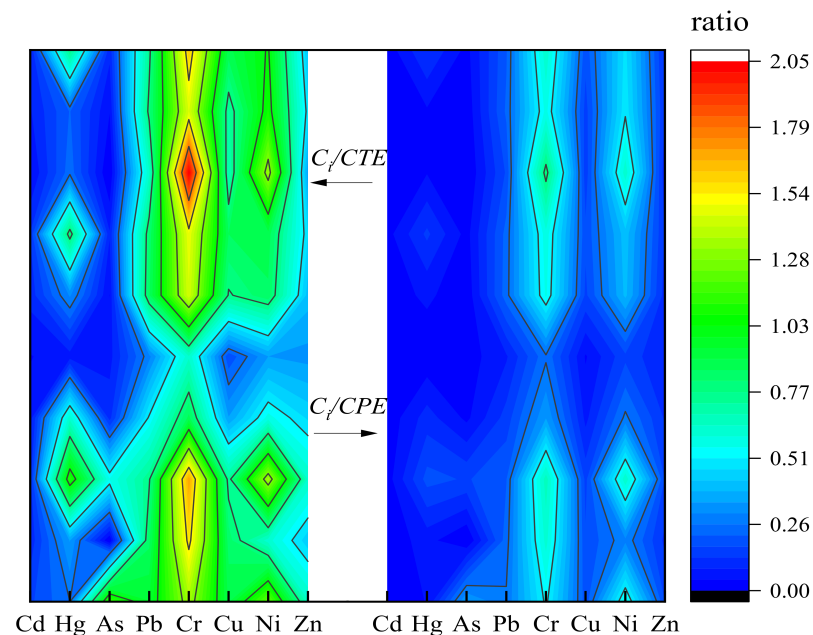


Figure 7. Heavy metal mass concentrations and their corresponding TEC and PEC ratios.

In summary, as a mining area with a long exploitation history and large coal gangue output, the Huainan mining area requires focused attention on heavy metal pollution in the ecological disposal of coal gangue. Based on the ecological risk assessment results for the study area, classified control and management of coal gangue in the Huainan mining area are recommended. Continuous monitoring of Hg and Cd in coal gangue from the ZJD and PE mines should be strengthened, and *mPEC-Q* biotoxicity data should be incorporated to provide a theoretical basis for ecological disposal of coal gangue in the Huainan mining area. This approach can also be extended to coal bases nationwide, supporting the construction of “zero-waste cities” and the carbon neutrality strategy, promoting the coordinated optimization of resource development and ecological security, and underpinning the green, high-quality development of resource-depleted cities.

4. Conclusions

- (1) Coal gangue in the Huainan mining area is classified as high-silica, medium-alumina clayey quartzite, with SiO_2 and Al_2O_3 together accounting for more than 86%. Although the concentrations of all heavy metals are below the risk screening values for soil contamination of agricultural land, the concentrations of Hg, Cd, and most rare earth elements (REEs) exceed the soil background values of Anhui Province. The potential ecological risk exhibits notable spatial heterogeneity. The comprehensive heavy metal risk index (RI) ranges from 33.75 to 300.71, with the highest risk identified in the eastern ZJD mining area ($\text{RI} > 300$, indicating a severe pollution level); Hg and Cd are the principal drivers. The comprehensive risk index for REEs ranges from 98.9 to 220.3, with Lu serving as the key influencing element. An assessment of predicted toxicity probability (PTP) indicates a low biotoxicity risk of 14–15% across the mining area, with the intensity of toxic effects following this sequence: $\text{Cr} > \text{Ni} > \text{Pb} > \text{Cu} > \text{Hg} > \text{Zn} > \text{As} > \text{Cd}$. This finding differs from the results of the conventional geoaccumulation index assessment.

- (2) This study is the first to systematically incorporate rare earth elements into the risk assessment framework for coal gangue in mining areas with high water tables in East China. It reveals elemental fractionation mechanisms involving silicate-phase separation and adsorption-driven enrichment by aluminosilicate and Fe–Mn phases, providing new insights into the source–sink relationships of contaminants in coal gangue. The study further demonstrates the spatially heterogeneous distribution of environmental risks associated with coal gangue in the Huainan mining area, underscoring the necessity of implementing risk-based, differentiated management strategies for coal gangue.
- (3) It is recommended that a “classification, zoning, and grading” management strategy be adopted for coal gangue in the Huainan mining area. Priority monitoring and remediation should be directed toward high-risk mining areas such as ZJD and PE in the eastern region, with particular emphasis on long-term monitoring of Hg, Cd, and Lu. In decision-making regarding ecological disposal and resource utilization, biotoxicity data such as mPEC-Q should be integrated with conventional risk indices to enable a more comprehensive assessment of environmental and health risks. This approach will provide a precise, science-based foundation for the “zero-waste” transition and green, high-quality development of Huainan and similar resource-depleted cities.

Although this study systematically covered eight major mines in the Huainan mining area, the ten coal gangue samples collected remain limited relative to the enormous historical stockpiles and pronounced spatial heterogeneity of the mining area. This may impose certain constraints on the precision with which the risk distribution is characterized. Future research should therefore expand the sampling density, include samples spanning different stockpiling durations and degrees of weathering, and incorporate data from toxicity leaching tests on coal gangue to simulate the long-term release of contaminants under dynamic conditions such as weathering and leaching, thereby enabling a more precise characterization of the spatiotemporal evolution of risk. In addition, when the multidimensional assessment framework constructed in this study is extended to other coal-mining areas, particular attention must be paid to the use of locally appropriate background values, the calibration of key parameters (e.g., toxicity coefficients), and careful consideration of local geological and climatic conditions (e.g., groundwater migration risks in mining areas with high water tables). In practical engineering applications, further challenges will arise, including the high cost of establishing high-frequency monitoring networks, the interdisciplinary challenge of integrating risk classification results with specific remediation technologies, and non-technical barriers such as the need for policy support involving coordination among enterprises and environmental protection and planning authorities.

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Data Availability Statement: The data presented in this study are available on request from the corresponding authors.

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