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Heavy metal pollution and risk assessment of tailings in one low-grade copper sulfide mine

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Analyzing the pollution level and ecological risk of heavy metals in tailings is a necessary step for conducting revegetation after a tailings pond's closure. Herein, we determined the heavy metal pollution status and ecological risk in one low-grade copper sulfide tailings pond using chemical and mineralogical analysis, chemical extraction, and ecological risk assessment. The results showed that the low-grade copper sulfide tailings displayed a low pollution status and exhibited a very low ecological risk. Among six heavy metals (Cu, Pb, Zn, As, Cr, and Cd), only Cu (53.7 mg/kg) slightly exceeded its standard value limit (50 mg/kg), and was the main pollutant in the tailings. Due to its high toxicity, As had the maximum contribution to the potential ecological risk in the tailings. Pb, Zn, Cr, and Cd in the tailings were practically of no pollution, and at low or none potential ecological risk. In order to conduct revegetation in the tailings pond, more attention should be paid to the acidity change of tailings and its impact on the chemical activity and bioavailability of Cu and As. This research provides a theoretical basis for heavy metals risk control and revegetation in the low-grade copper sulfide tailings pond.

KEYWORDS

mine tailings, heavy metal, chemical fraction, pollution level, ecological risk assessmemt

1 Introduction

Mineral resources provide an important material foundation for society development and national security (Wu et al., 2021). However, the mining processes generate a large amount of tailings, which is about 2–12 times of the metal extracted from the ore (Jiang et al., 2021). At present, over 10 billion tons of mine tailings are produced globally each year (Xie and van Zyl, 2020). Billions of tons of tailings are increasingly accumulated in tailings ponds and are inevitably exposed to the environment for a long-term period. These tailings usually contain various kinds of heavy metals such as Pb, As, Cr, Cd, Mn, Zn, and Cu, which are commonly associated with the metal ore and would be released into the surrounding farmland soil, groundwater system and nearby rivers by directly penetrating, surface runoff and/or groundwater recharge (Barcelos et al., 2020). Therefore, heavy metal contents in the environment near tailings ponds might continue to increase, leading to severe environmental pollution (Khoeurn et al., 2019; Wang et al., 2019; Kan et al., 2021; Luo et al., 2021; Qi et al., 2022a).

Previous studies have demonstrated the great impacts of tailings on environmental quality and the ecological landscape (Nie et al., 2022). For example, affected by Hg mining deposits, the average contents of Hg and Ni in agricultural soil in Gongguan of Shaanxi province exceeded the national secondary standard value by 3.9, and 4.0 times, respectively (Zhu et al., 2018). Affected by artisanal gold mining, the mean concentrations of Hg and Cd in six villages in Tongguan (east of Shaanxi Province of China) were respectively 3.9 and 5.1 times of their maximum allowable concentrations for agricultural soils (Xiao et al., 2017). The translocation and accumulation of heavy metals in tailings may not only threaten the regional ecological security (Dubey et al., 2018; Ismail et al., 2019), but also affect the human health through food chain *via* causing some chronic diseases, metabolism disorders, deformities, and cancers (Al osman et al., 2019; Sanaei et al., 2021). For instance, Wang et al. found that Cu, Cr, Pb, Cd, and As in vegetables and crops near four typical mining and smelting zones in central China were 6.7%, 6.7%, 66.7%, 80.0%, and 26.7% higher than the national standards, respectively (Wang et al., 2021b).

It is worth noting that only the total contents of heavy metals are not enough for assessing the ecological risk of tailings (Moore et al., 2014; Jiang et al., 2021). The toxicity, bioavailability, mobility, or potential risks of heavy metals should also depend on their chemical fractions (Zhao et al., 2021). Heavy metals' chemical fractions in tailings can be determined by various extractants with different leaching strength (Cheng et al., 2018; Gitari et al., 2018; Roebbert et al., 2018; Wu et al., 2018). Among the various extraction protocols, the modified BCR sequential extraction is one of the most widely used method and applied in various environmental components such as soil, sediment, sewage sludge, and mining waste (Matong et al., 2016; Li et al., 2018; Wang et al., 2021a; Gao et al., 2021; Liu et al., 2022). By using this technique, the bioavailability of As, Cr, Cd, Mn, Pb, and Zn were also successfully estimated from environmental matrices (Barcelos et al., 2020). In addition, in the farmland soils around several typical mining areas, Zhao et al. (2021) analyzed the association relationship between multiple heavy metals and Fe fractions.

For characterizing the ecological risk of contaminants to the environment, various risk assessment methods have been developed in many studies under multiple matrices (Wu et al., 2018; Buch et al., 2021; Dash et al., 2021; Masri et al., 2021; Demirak et al., 2022; Zhang et al., 2022). Among these methods, risk assessment code (*RAC*), geo-accumulation index (I_{geo}), and potential ecological risk index (*RI*) have been widely used based on the total content and chemical fraction of heavy metals. For example, Cheng et al. reported a moderate soil Cd contamination around a coal mining area of Huaibei coalfield by applying *RAC*, I_{geo} and *RI* (Cheng et al., 2018). Using the improved I_{geo} and *RI*, Luo et al. (2021) found that Sb and As exhibited a serious risk and Cr, Cd, Cu, Pb, and Zn posed a low risk in Qinglong antimony mine tailings. In addition, the Nemerow integrated pollution index (P_N) is also frequently applied to assess the pollution level of multiple heavy metals (Zhang et al., 2018; Chai et al., 2021).

Currently, one low-grade copper sulfide mine tailings pond has to face the problem of ecological restoration after its closure. In addition to copper, this low-grade copper sulfide ore consists of a large number of minerals, which contain potentially toxic elements, such as As, Pb, Zn, Mn, Cr, and Cd. In the process of copper mining, these coexisting heavy metals are discarded and enter the mine tailings pond. Heavy metals play a significant impact on the quality of the soil, and can be enriched in organisms (Xing et al., 2022). In order to successfully achieve ecological restoration of the tailings pond, investigating the pollution levels in the tailings and assessing the potential ecological risks has become an urgent problem.

Therefore, the objectives of this study are as follows: 1) performing the chemical and mineralogical analysis of the low-grade copper sulfide mine tailings; 2) determining the concentrations and chemical fraction of various heavy metals (Cu, Pb, Zn, As, Cr, and Cd); 3) investigating the pollution degree and ecological risk of these metals. This research is expected to provide a comprehensive information on heavy metals in the low-grade copper sulfide mine tailings and lay a basis for the tailings' pollution control and vegetation reconstruction.

2 Materials and methods

2.1 The tailings sample and reagents

About 5.0 t tailings slurry were sampled from the total outlet of the transfer pump of the low-grade copper sulfide mine tailings pond. The water content of tailings slurry was about 40%. The collected tailings were air-dried, evenly mixed, grinding and sieved by a 10-mesh nylon mesh screen.

All reagents used in this study were analytically pure and were directly used. Only hydrochloric acid (purity 37%), nitric acid (purity 65%), and perchloric acid (purity 70%) were purchased from Xilong Scientific Co., Ltd. (Chengdu, China), and other reagents, including standard metal solutions (1000 mg/L) were purchased from Macklin Biochemical Technology Co., Ltd. (Shanghai, China). All the solutions were prepared in deionized water.

2.2 Chemical and mineralogical analysis

Analysis of physicochemical properties is necessary to characterize the tailings sample. The pH was measured using a pH meter (PHS-3C, Ramag, China) at a 2.5:1 water-to-tailings ratio. The cation exchange capacity was estimated at pH equal to seven by ammonium acetate exchange method (Belay et al., 2022). The mineral phase of the tailings was determined by X-ray diffraction spectroscopy (X'Per Powder, PANalytical, Netherlands) scanning from 10° to 80° at a scan speed of 1°/min. The chemical composition of the tailings was determined by X-ray fluorescence spectroscopy (S8 TIGER, Bruker, Germany). The particle size analysis of the tailings was performed with a laser particle size analyzer (BT-9300H(T), China) with a detection limit of 0.01 μm.

2.3 Tailings digestion and chemical fraction

2.3.1 Tailings digestion

The total contents of various heavy metals in the tailings were analyzed by aqua regia and $HClO_4$ digestion method

TABLE 1 The degrees of contamination and ecological risk.

Degree	Speciation index	Total content indices			
	RAC	I_{geo}	P_N	E_r^i	RI
None	≤1%	≤0	$P_N < 0.7$	–	–
Alert level	–	–	$0.7 < P_N < 1.0$	–	–
Low	1%–10%	0–1	$1.0 < P_N < 2.0$	<40	<150
Moderate	10%–30%	1–2	$2.0 < P_N < 3.0$	40–80	150–300
Considerable	–	2–3	–	80–160	–
High	30%–50%	3–4	$P_N > 3.0$	160–320	300–600
Very high	>50%	4–5	–	>320	≥600
Extremely Serious	–	>5	–	–	–

(Ying et al., 2022). 30 ml of acid solutions (15 ml HCl and 5 ml HNO_3 + 10 ml $HClO_4$) was added to 0.5 g tailings, and then heated to 200°C. Digested solutions were diluted by 1% HNO_3 aquation into 100 ml volumetric flasks. All glassware was immersed in 20% nitric acid solution to at least 24 h before usage.

2.3.2 Chemical fractions of heavy metals

Chemical fractions of heavy metals in the low-grade copper sulfide tailings were determined by the modified BCR sequential extraction (Zhao et al., 2021; Demirak et al., 2022). This method separates the chemical fractions of heavy metals into four forms: weak acid soluble fraction, reducible fraction, oxidizable fraction and residual fraction (Jayarathne et al., 2018). Weak acid soluble fraction (F1): added 20 ml of 0.11 M CH_3COOH solution to one 50 ml tube containing 0.5 g of tailings, continuously shaken for 16 h at 25°C. Reducible fraction (F2): added 20 ml of 0.5 M $NH_2OH{\cdot}HCl$ solution (adjusted to pH = 1.5 with HCl) to the former tube and shook for 16 h at 25°C. Oxidizable fraction (F3): added 3 ml of 30% H_2O_2 solution, shook intermittently for 1 h at 25°C, and then continued to digest for another 1 h at 85°C until the volume in the tube dropped to 2–3 ml. Repeated the above steps until the volume was reduced to 1 ml. Finally, put 20 ml of 1.0 M CH_3COONH_4 solution into the cooled tube and shook for 16 h. Residual fraction (F4): used aqua regia and $HClO_4$ to extract the residual heavy metals.

Centrifuged all the above suspensions at 1500 r/min for 10 min, and then filtered by 0.45 μm membrane. The dissolved heavy metals were determined by a flame atomic absorption spectrophotometer (Shimadzu AA-7000F, Japan), while As was measured by atomic fluorescence spectrophotometer (AFS-9800, Beijing KeChuang HaiGuang Instrument Co., Ltd, China), and reported on a dry weight basis (mg/kg).

The accuracy of the modified BCR sequential extraction method was verified by comparing the sum of four chemical fractions with the total contents obtain from direct tailings digestion. The recovery of the sequential extraction method was calculated according to Eq. 1 (Demirak et al., 2022):

$$\text{Recovery rate} = (C_{\text{F1}} + C_{\text{F2}} + C_{\text{F3}} + C_{\text{F4}}) \big/ C_{\text{total digestion}} \times 100\% \quad (1)$$

where $C_{\text{total digestion}}$ is the total concentration of heavy metal; C_{F1}, C_{F2}, C_{F3}, and C_{F4} are the contents of F1, F2, F3 and F4 forms of heavy metals in the low-grade copper sulfide tailings.

2.4 Pollution status and ecological risk of heavy metals

The risk assessment code (RAC), geo-accumulation index (I_{geo}), Nemerow integrated pollution index (P_N), and potential ecological risk index (RI), were performed to comprehensively evaluate the pollution status and ecological risk of various heavy metals in the low-grade copper sulfide tailings. The degrees of RAC, I_{geo}, P_N and RI are shown in Table 1 (Demirak et al., 2022). The details of the above-mentioned methods are described as follows.

2.4.1 Risk assessment code (*RAC*)

Chemical fractions of heavy metals largely affect their harm to the environment (Moore et al., 2014). In particular, the weak acid soluble fraction of metals is weakly bound to the minerals in soil, they would easily enter aqueous solution and affect the organisms. Therefore, the RAC is defined as the percentage of the weak acid soluble fraction within the total metal concentration (Nemati et al., 2011; Demirak et al., 2022).

$$RAC = \left(C_{\text{F1}} \big/ C_{\text{total digestion}} \right) \times 100\% \quad (2)$$

where C_{F1} is the weak acid soluble fraction concentration of certain heavy metal; $C_{\text{total digestion}}$ is the total concentration of certain heavy metal. RAC is one of the most important environmental risk assessment methods for soils and sediments.

2.4.2 Geo-accumulation index (I_{geo})

The geo-accumulation index (I_{geo}), known as the Muller Index, is widely used to characterize the sediment pollution level by comparing current heavy metals contents with pre-industrial values (Dash et al., 2021; Su et al., 2022). Unlike of other methods, I_{geo} takes into account the impact of the geochemical background values on the heavy metals' pollution status. Since the low-grade copper sulfide mine locates in Fujian Province, China, the geochemical background values in the

Fujian province were used here. The calculation formula is as follows (Ma et al., 2016):

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5B_n} \right) \tag{3}$$

where C_n is the total digestion concentration of metal n in the soil, B_n is the geochemical background value of heavy metal n. The factor 1.5 is a conversion coefficient to eliminate variations in background value that might be caused by differences in rocks.

2.4.3 The Nemerow integrated pollution index (P_N)

The Nemerow integrated pollution index (P_N), proposed by American scholar Nemerow, is widely employed to assess the comprehensive pollution status of various heavy metals (Wang et al., 2022). P_N is calculated by the average value and the maximum value of single factor pollution index. The calculation formula are expressed as follows (Chai et al., 2021):

$$P_i = \frac{C_i}{S_i} \tag{4}$$

$$P_N = \sqrt{\frac{(\bar{P}_i)^2 + (P_{imax})^2}{2}} \tag{5}$$

where P_i is the single factor pollution index of heavy metal i; C_i is the total concentration of heavy metal i; S_i is the evaluation standard of heavy metal i, taking the national soil pollution risk screening value (GB 15618-2018, denoted as "standard" below) as the reference standard. P_N is the Nemerow integrated pollution index, $\bar{P}_i$ represents the average value of all P_i, P_{imax} shows the maximum value of all P_i.

2.4.4 Potential ecological risk index (*RI*)

The potential ecological risk index (*RI*), proposed by Hakanson, is widely used to assess the soil environmental ecological risk caused by heavy metals. This method not only considers the influence of concentration and toxicological characteristics of heavy metals in a specific environment, but also eliminates the difference caused by the background value of heavy metals. The calculation formula are as follows (Qi et al., 2022b):

$$RI = \sum E_r^i \tag{6}$$

$$E_r^i = T_r^i \times C_f^i \tag{7}$$

$$C_f^i = C_s^i / C_n^i \tag{8}$$

where *RI* is the potential ecological risk index; E_r^i is the individual coefficient of potential ecological risk of heavy metal i; T_r^i is the toxicity response coefficient of heavy metal i; C_f^i is the single factor pollution index of heavy metal i; C_s^i is the total concentration of heavy metal i in the surface soil; C_n^i is the reference standard of heavy metal i. The toxicity response coefficient T_r^i of heavy metals are: Cu = Pb = 5, Zn = 1, As = 10, Cr = 2, and Cd = 30 (Jiang et al., 2021).

3 Results and discussion

3.1 Physicochemical properties of tailings

The physicochemical characteristics of tailings affect the accumulation and mobility of the heavy metals in tailings. The low-grade copper sulfide mine tailings was found to be acidic with a pH of 4.5. Cation exchange capacity was determined to be 13.1 cmol/kg. The d_{10}, d_{50}, and d_{90} values of the tailings particle sizes were 1.61, 16.18, and 72.4 μm, respectively. According to the particle size distribution results, it can be seen that the permeability of the tailings is very poor.

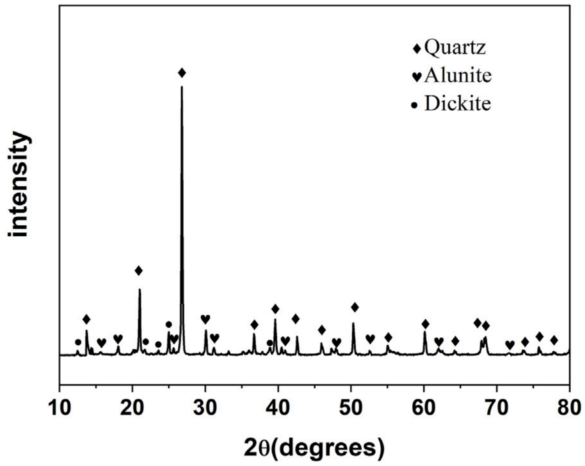

FIGURE 1
The XRD patterns of the low-grade copper sulfide tailings.

The XRD test (Figure 1) indicated that the tailings in the low-grade copper sulfide mine was composed by quartz, alunite, dickite, pyrite, and sericite. The results obtained by XRF (Table 2) showed that heavy metal elements in the tailings included Cu, Pb, Ba, As, Mn, Cr, Zn, Ni, and so on. Considering the content and the toxicity of various heavy metals, Cu, Pb, Zn, As, Cr, and Cd were chosen to be analyzed by tailings digestion and the modified BCR protocol.

3.2 Contents and chemical fractions of heavy metals in the low-grade copper sulfide tailings

3.2.1 Contents of heavy metals

Heavy metal concentrations, as shown in Table 3, were investigated to reveal the pollution status in the low-grade copper sulfide tailings pond. In comparison to the national soil pollution risk screening value limit (GB 15618-2018), only the Cu content (53.7 mg/kg) in tailings slightly exceeded the standard limit (50 mg/kg). The As content (33.9 mg/kg) in tailings was close to the standard limit (40 mg/kg), so more attention should be paid to it. The contents of Pb and Zn were significantly less than their relevant standard limits. The Cr and Cd contents in tailings were not detected. Based on the above analysis, Cu was considered to be the main pollutant in the tailings.

3.2.2 Chemical fractions of heavy metals

Chemical fractions of heavy metals in the tailings were carried out to characterize their chemical activity and bioavailability as well as their risks to the environment. As shown in Table 3, recovery rates of all heavy metals were 93.2%–98.3%, suggesting that the sums of

TABLE 2 Chemical compositions of the low-grade copper sulfide tailings by XRF analysis (wt%).

Element	Si	Al	S	K	Fe	Ca	Ti	Na	Cu	Pb	P	Mg
Result	29.9	5.35	4.05	1.88	1.50	0.217	0.132	0.109	0.0768	0.0454	0.0350	0.0341
Element	Ba	Sr	Zr	As	Mn	Cl	Cr	Zn	Nb	Ga	Ni	Rb
Result	0.0338	0.0295	0.0107	0.0078	0.0074	0.00695	0.00541	0.00326	0.00310	0.00296	0.00143	0.00142

TABLE 3 Contents of six heavy metals in the tailings obtained by digestion and BCR, background values in Fujian Province and national soil pollution risk screening value (mg/kg).

Element	Content	BCR	Recovery (%)	Background value	Standard (GB15618-2018) pH $\leq$ 5.5
Cu	53.7	52.9	98.5	21.6	50
Pb	4.09	3.81	93.2	34.9	70
Zn	13.0	12.3	94.6	82.7	200
As	33.9	32.4	95.6	5.78	40
Cr	–	–	–	41.3	150
Cd	–	–	–	0.054	0.3

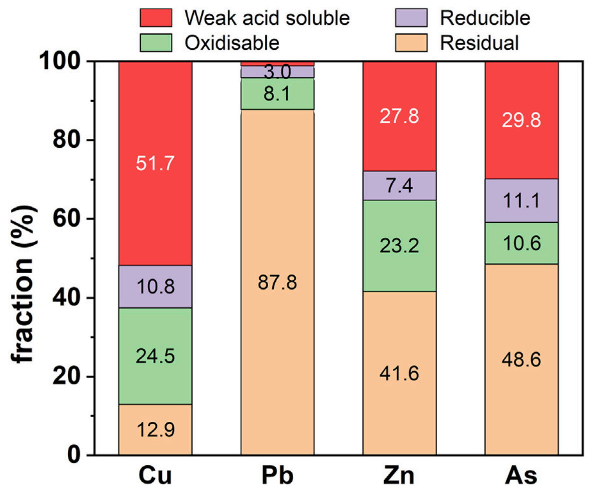

FIGURE 2
Heavy metals chemical fractions in the low-grade copper sulfide tailings using the modified BCR sequential extraction.

four chemical fractions were consistent with the total contents. Therefore, the modified BCR sequential extraction was reliable and repeatable. The chemical fractions of heavy metals were depicted in Figure 2. Various chemical fractions of Cr and Cd were not detected; thus, they were not provided here.

Cu. As shown in Figure 2, Cu was distributed in all four chemical fractions, and the considerable proportion (51.7%) of total Cu existed in the weak acid soluble fraction. This part of Cu existed in the form of ion-exchange and carbonate binding, and was loosely combined with soil matrices. Once the environmental conditions change, such as the pH, Cu in the weak acid soluble fraction would easily release into the environment. Therefore, among four kinds of chemical fractions, the weak acid soluble metal fraction is the most unstable, toxic, and bioavailable component (Matong et al., 2016; Demirak et al., 2022). The portion (24.5%) of oxidizable fraction was also noticeable. In oxidizable fraction, Cu combined with various organics and sulfide to form highly stable organic-copper compounds (Ma et al., 2016). About 12.9% and 10.8% of Cu had been found in residual and reducible fractions, respectively.

Pb. A proportion of 87.8% of Pb existed in the residual fraction, which was hard to release into pore-waters through dissociation due to its combination with aluminosilicate minerals (Burachevskaya et al., 2019; Ying et al., 2022). Only 8.1%, 3.0%, and 1.1% of Pb were found in oxidizable, reducible, and weak acid soluble fraction, respectively. Therefore, it is believed that Pb has weak chemical activity and bioavailability in the low-grade copper sulfide tailings.

Zn and As. Zn and As were very similar in chemical fractions, and mainly existed in the residual fraction with the proportions of 41.6% and 48.6%. This part of Zn and As were difficult to re-enter into the environment. In addition, there were about 30% of Zn and As in the weak acid soluble fraction, which were labile and easy to release under acidic conditions. 23.2% of Zn and 10.6% of As were observed in the oxidizable fraction. The reducible fractions of Zn and As were 7.4% and 11.1%, indicating that only small amounts of Zn and As were bound with Fe and Mn (oxyhydr) oxides.

3.3 Heavy metal pollution and ecological risk assessment

3.3.1 Risk assessment code (*RAC*)

Based on the chemical fraction results obtained by the modified BCR sequential extraction, the potential risks to the environment were estimated using the *RAC* method. Only the weak acid soluble fraction was considered here due to its easy entry into the environment. As displayed in Table 4, Cu posed

TABLE 4 The degrees of contamination and ecological risk of heavy metals in the low-grade copper sulfide tailings.

Element	*RAC* (%)		I_{geo}		P_N		Potential ecological risk			
							E_r^i		*RI*	
Cu	51.7	Very high	0.728	Low	1.13	Low	5.4	Low	14.2	Low risk
Pb	1.1	Low	−3.68	None			0.29	Low		
Zn	27.8	Medium	−3.25	None			0.065	Low		
As	29.8	Medium	1.97	Moderate			8.5	Low		
Cr	–	None	−∞	None			0	None		
Cd	–	None	−∞	None			0	None		

very high risk to the environment, while Zn and As posed the medium risks, and Pb posed the low risk, Cr and Cd posed no risk. Meanwhile, only Cu content in tailings slightly exceeded the national soil pollution risk screening value limit (GB 15618-2018), As content was close to the standard, other four heavy metals were much lower than their standard limit. Therefore, considering the *RAC* values and concentrations of heavy metals in the tailings, special attention should be paid to the environmental/ecological impacts caused by Cu. It is suggested that several amendments to the tailings may be required to passivate Cu (i.e., reducing the weak acid soluble fraction) before establishing revegetation in the low-grade copper sulfide tailings pond. Furthermore, in the process of revegetation, Cu enrich plants should not be selected unless they could be properly treated.

3.3.2 Geo-accumulation index (I_{geo})

For the purpose of determining heavy metals contamination levels in the tailings, the geo-accumulation index I_{geo} values of six heavy metals were calculated, as shown in Table 4. The level of I_{geo} from high to low was As > Cu > Zn ≈ Pb ≈ Cr ≈ Cd. Only the I_{geo} value of As exceeded 1, indicating that As fell into the "moderately polluted" level. The I_{geo} value of Cu was less than 1, indicating that Cu belonged to "unpolluted to moderately polluted". Furthermore, the I_{geo} values of Zn, Pb, Cr, and Cd were below 0, suggesting that these four kinds of heavy metals were practically of "no pollution". In this study, the I_{geo} values were calculated according to the soil background value in the Fujian province. However, while the low-grade copper sulfide mine is rich in copper element, it may also contain some other heavy metals, such as As, Pb and Zn. Therefore, the background values of heavy metals in the low-grade copper sulfide mine may be different from the soil background values in the Fujian province. It is speculated that the main reason why the As content in the tailings (33.9 mg/kg) is higher than its background value (5.78 mg/kg) is due to natural contribution rather than anthropogenic activities. The pollution status of Cu and As reflected by the high I_{geo} values only indicated the impact of heavy metals to ecological environment.

3.3.3 The Nemerow integrated pollution index (P_N)

The Nemerow integrated pollution index (P_N) was applied to assess the comprehensive pollution levels of heavy metals in the tailings. This index highlights the impacts of high concentrations of pollutants on soil environment quality. As shown in Table 4, the P_N obtained by six heavy metals was equal to 1.13, suggesting that the tailings sample showed low pollution to the environment. The P_{imax} value was determined by the content of Cu, indicating that Cu was the main contributor to heavy metals pollution of the tailings.

3.3.4 Potential ecological risk index (*RI*)

The potential ecological risk index (*RI*) was applied based on the national soil pollution risk screening value (GB 15618-2018) to assess the ecological risk. This method can reflect the comprehensive impacts of multiple pollutants. As illustrated in Table 4, the individual coefficient of potential ecological risk E_r^i values in decreasing order were As > Cu > Pb > Zn > Cr ≈ Cd. According to E_r^i values of six heavy metals, As and Cu were the main sources of potential ecological risk of the low-grade copper sulfide tailings. Although single factor pollution index C_f^i of Cu was larger than that of As, due to the higher toxicity of As, As had a higher E_r^i, indicating that As posed a higher potential ecological risk than Cu. Even so, all E_r^i values of six heavy metals were far below 40, as well as *RI* value (14.2) was far less than 150, indicating that there was a very low potential ecological risk in the low-grade copper sulfide tailings. The results of *RI* were basically the same as those of the P_N index.

4 Conclusion

Chemical and mineralogical analysis, chemical extraction, and ecological risk assessment were employed to evaluate the pollution level and ecological risk in the low-grade copper sulfide tailings pond. According to the results of P_N and *RI*, the low-grade copper sulfide tailings displayed a low pollution status and exhibited a very low ecological risk.

Among the six heavy metals (Cu, Pb, Zn, As, Cr, Cd) contained in the tailings, only Cu content exceeded the standard limit. Furthermore, the *RAC* of Cu was high than 50%. Cu was the main pollutant in the low-grade copper sulfide tailings. Although the content of As was below its standard limit, its high toxicity led to the largest potential ecological risk in the tailings. Based on the I_{geo} and E_r^i values, Pb, Zn, Cr, and Cd in the tailings were practically of no pollution, and exhibited low or none potential ecological risk.

It is urgent to pay more attention to the acidity change of tailings and its impact on the chemical activity and bioavailability of Cu and

As for conducting revegetation in the low-grade copper sulfide tailings pond.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

PZ: Conceptualization, methodology, formal analysis, data curation, writing-original draft, visualization, supervision, funding acquisition. JC: Writing-review and editing. TL: Writing-review and editing. QW: Conceptualization, resources, project administration. ZW: Validation, resources. SL: Investigation, resources, data curation.

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Conflict of interest

PZ, JC, QW, and ZW were employed by the company Zijin Mining Group Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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