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Research Article

Standardized framework for assessing soil quality at antimony smelting site by considering microbial-induced resilience and heavy metal contamination

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ABSTRACT

Antimony smelting activities damage the soil and vegetation surroundings while generating economic value. However, no standardized methods are available to diagnose the extent of soil degradation at antimony smelting sites. This study developed a standardized framework for assessing soil quality by considering microbial-induced resilience and heavy metal contamination at Xikuangshan antimony smelting site. The soil resilience index (SRI) and soil contamination index (SCI) were calculated by Minimum Data Set and geo-accumulation model, respectively. After standardized by a multi-criteria quantitative procedure of modified Nemerow's pollution index (NPI), the integrated assessment of soil quality index (SQI), which is the minimum of SRI_{NPI} and SCI_{NPI} , was achieved. The results showed that Sb and As were the prominent metal(loid) pollutants, and significant correlations between SQI and SRI indicated that the poor soil quality was mainly caused by the low level of soil resilience. The primary limiting factors of SRI were Fungi in high and middle contaminated areas, and *Sclerotinia* in low contaminated area, suggesting that the weak soil resilience was caused by low specific microbial abundances. Microbial regulation and phytoremediation are greatly required to improve the soil quality at antimony smelting sites from the perspectives of pollution control and resilience improvement. This study improves our understanding of ecological effects of antimony smelting sites and provides a theoretical basis for ecological restoration and sustainable development of mining areas.

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Introduction

Antimony (Sb) is a hazardous and carcinogenic metalloid, which poses potential risks to the ecosystem and human health (Bolan et al., 2022; He et al., 2012). According to the latest report of the U.S. Geological Survey (Survey, 2023), China was the global leading antimony producer and accounted for 55 % of antimony mine production in 2022. In recent decades, the widespread use of Sb-containing products aggravates antimony mining and smelting activities. The mining and smelting of antimony have a great impact on the surrounding and downstream ecosystems inevitably, leading to changes in soil properties as the accumulation of metal(loid)s (Li et al., 2021; Zou and Ren, 2023). As more and more smelting plants are shut down, there is a growing concern about the antimony pollution left behind. However, there are no targeted evaluation systems for assessing the extent of soil degradation at abandoned antimony smelting sites. It is imperative to diagnose the extent of soil degradation there, which can provide a basis for the design and implementation of ecological restoration in mining areas.

As an integrated indicator of overall capacity, soil quality (SQ) is usually considered as soil functional capacity to maintain biological productivity, preserve environmental quality, and promote plant, animal and human health within an ecosystem boundary (Doran and Parkin, 1994). Numerous efforts have been devoted to constructing validated methods to evaluate the SQ in recent decades (Khan et al., 2021), among which, the soil comprehensive quality index (SQI) has been widely used owing to its brevity and sensitivity (Barman et al., 2021). The SQI is developed to synthesize individual soil indicators into a simplified format (Li et al., 2019). For instance, researchers established a time- and cost-effective evaluation method by using principal component analysis (PCA) to construct a Minimum Data Set (MDS) to evaluate the fertility of cultivated-layer soil (Jin et al., 2021a, 2021b). It aims to reduce data redundancy and identify the most appropriate indicators for assessing the SQI (Askari and Holden, 2014). This provides a basis for assessing the soil at antimony smelting sites, because farming has become one of the alternative land use options in the closed mining areas (Wang et al., 2021). In addition, the level of heavy metal contamination is also crucial in assessing the SQI of a smelting site. The SQI can be evaluated by geo-accumulation index (I_{geo}) (Muller, 1969; Neeraj et al., 2023), potential ecological risk index (Hakanson, 1980; Liu et al., 2023) and so on. Above all, I_{geo} is a quantitative indicator that was developed to evaluate the extent of heavy metal contamination by considering the measured and the background heavy metal content in soil (Muller, 1969; Zhong et al., 2020). However, soil fertility and soil contamination are both critical aspects affecting the SQI (Teng et al., 2014), and relying solely on soil fertility or soil contamination to calculate SQI is incomplete, although by diverse computing approaches. Due to the complex human activities and the severe heavy metal pollution, it is quite necessary to establish an integrated evaluation method to better understand the soil ecosystem health in antimony mining areas.

Recently, some researchers used soil fertility assessment and heavy metal pollution to comprehensively evaluate the

soil quality level (Li et al., 2020). However, the evaluation is usually proposed by involving two independent evaluation systems with respective methodologies. Effective methods on the same scale should be considered when assessing soil quality from different perspectives to eliminate the impact of differences in mathematical modelling (Zhang et al., 2023a). Nemerow's pollution index (NPI) method has been reported to be used to assess both soil fertility (Qi et al., 2009) and soil contamination (Wang et al., 2018; Zhang et al., 2023a), as it takes into account the means and extremes of a multiple-index data set. Furthermore, the modified NPI method emphasizes the effect of the worst fertility indicator, which is more rigorous and sensitive than the weighted method (Qi et al., 2009). It is delightful to see that the NPI method has been applied to make an integrated assessment of the SQI in plastic greenhouse production systems, including both the soil fertility index and soil environmental quality index (Fan et al., 2021), suggesting that the modified NPI method can be used to assess smelting site soil by integrating multiple indicators from two perspectives on the same scale.

Soil fertility is considered to be one of the critical factors associated to soil resilience (Yang and Guo, 2018). Soil resilience, which takes microorganisms into account, is indispensable for evaluating the soil quality at antimony smelting sites comprehensively. As important biological components of soil ecosystems, microorganisms play a crucial role in driving soil biogeochemical cycles and maintaining ecological functions (Jia et al., 2022). Soil microorganisms are able to respond to environmental changes quickly because of their involvement in the carbon, nitrogen and phosphorus cycles, as well as the decomposition of organic matter (Bender et al., 2016; Breidenbach et al., 2022; Nottingham et al., 2018). In turn, the composition and diversity of the soil microbial community are extremely affected by specific environmental variables such as pH, organic carbon and heavy metals (Gao et al., 2022; Li et al., 2023). Soil microbiota has been recognized as game-changers in the restoration of degraded lands (Coban et al., 2022). Additionally, enzymatic activities (urease, sucrase, catalase, etc.) can provide valid information on soil quality and are crucial indices for assessing heavy metal-contaminated soils (Oleszczuk et al., 2014). However, most studies about soil quality assessment are only based on physical and chemical indicators because microorganisms are largely invisible to the bare eyes and it is difficult to obtain microbial indicators (Chen et al., 2022). Although there are significant correlations between soil microbial species and physicochemical parameters, it still cannot be denied that the detection of limited microbiological indicators may have led to a neglect of the actual contribution of soil microorganisms to the soil diagnostic system. The introduction of microbial indicators, such as community composition, diversity, function and enzymatic activities, may lead to a more accurate and efficient soil diagnosis system.

The Xikuangshan (XKS) Antimony Mine is the largest Sb mine in China and is famous as the world's Sb capital (Fu et al., 2010). The mining and smelting process has contaminated the soil around the mine to varying degrees, endangering the health of the surrounding populations. In this study, an integrated assessment by simultaneously assessing the soil resilience index (SRI) and soil contamination index (SCI) based on the modified NPI method was proposed to evaluate the SQI

at the XKS antimony smelting site, which provided a more comprehensive and reliable tool for evaluating soil quality of abandoned antimony smelting sites. Meantime, on the basis of the commonly used physical and chemical indicators, we introduced diverse microbiological indicators, including indicator species, community diversity indices and functional diversity indices. The main objectives of this study are: (1) to assess the soil resilience level at the XKS antimony smelting site using the modified NPI method based on the MDS model, which is obtained from the total data set (TDS) containing diverse microbial indicators; (2) to evaluate the soil contamination level represented by the content of heavy metals using the modified NPI method based on the I_{geo} ; (3) to assess soil degradation status of the antimony smelting site, and identify the microbiological indicators that significantly affect the soil quality.

1. Materials and methods

1.1. Study area

The study area is situated at the XKS antimony mine (111°25'47"–111°31'22" north and 27°43'05"–27°49'28" east), located in Lengshuijiang City, Hunan Province, China (Fig. 1). This mine covers approximately 26 km². The region has a subtropical continental monsoon climate with a mean average annual temperature of 16.7°C and an annual rainfall of 1354 mm (Guo et al., 2021). The study area is mainly covered with barren grass and shrubs with the overall vegetation coverage less than 50 %, and the ecology is fragile.

1.2. Soil sampling and analysis

A total of 96 samples including surface soils, rhizosphere soils and tailing soils were collected from an abandoned smelting site that has undergone prolonged natural recovery near Hsikwangshan Twinkling Star company to conduct a site survey. Based on antimony levels in local and previous study (He, 2007), the samples were initially divided into High (group H, ≥ 600 mg/kg), Middle (group M, $100 \leq x < 600$ mg/kg) and Low (group L, < 100 mg/kg) contamination zones. Further, 35 typical samples (refer to Fig. 1) (6 samples in group H; 15 samples in group M; 14 samples in group L) were screened to test physicochemical and biological parameters. In each spot, soils were collected by five-point sampling method, removed stones and rubbish and packed in sterile polyethylene bags. All samples were transported to the laboratory and stored at –80°C at once.

A total of 30 indicators were detected for each selected sample, including 7 basic soil property parameters, 15 soil microbial indexes and 8 heavy metal content parameters. The detection of soil pH, electrical conductivity (EC), moisture content (MC), total organic carbon (TOC) and soil particle size fractions (Peng et al., 2020) was described in Appendix A Text S1. Representative microbial parameters were selected in terms of biomass, species diversity, functional diversity, catalase activity (CAT), urease activity (URE) and sucrase activity (SUC). Bacteria, fungi and actinomycetes were cultured

for enumeration, respectively. Direct counts of viable microbial cells (DVC) were obtained by microscope (Olympus BX 41TF, Tokyo, Japan). The distinct regions (V3–V4) of 16S rRNA genes were sequenced on an Illumina HiSeq 2500 platform (E-GENE, Shenzhen, China). The alpha diversity indexes at the species and functional levels were calculated. The indexes of Shannon-S and Pielou-S were used to evaluate the species diversity and the indexes of Shannon-F and Chao1-F were used to evaluate the functional diversity. In addition, biomarkers (*Skermanella*, *Microvirga*, *Blastococcus*, *Actinoplanes*) in groups with different pollution levels were identified. The details can be found in the supplementary material. The metal(loid) content (Sb, As, Fe, Mn, Cr, Cu, Zn and Cd) content was tested by inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7700 Series, Thermo Scientific, USA).

1.3. Assessment of soil resilience level

We use MDS methods based on PCA and the NPI concept to calculate SRI. It includes four key steps: (a) indicator screening based on MDS, (b) normalization of the indicators by standard score functions, (c) indicator integration and (d) accuracy verification of SRI.

1.3.1. Indicator selection

The principal components (PCs) of the indexes were analyzed. The indicators were grouped based on the loading values of each PC (Appendix A Text S2) (Jin et al., 2021a; Li et al., 2007). However, no single PC value can represent the information of a multidimensional space, and some soil information may be lost in the process of reducing dimensionality. Norm values were adopted to solve the problem. The calculation is as follows:

$$N_{ik} = \sqrt{\sum_{i=1}^k (u_{ik}^2 \cdot \lambda_k)} \quad (1)$$

where, N_{ik} is the integrated loading of variable i in the first k PCs with eigenvalue ≥ 1 , the loading of variable i in PC_k is marked as u_{ik} , and λ_k is characteristic of the k -th PC value.

Indicators with the highest norm value and those with a norm within 10 % ranges of the highest are selected to further analyze the correlations between them (Yemefack et al., 2006). Indicators with significant correlations with the highest norm will be excluded (Wu et al., 2019). The MDS is made up of the indicators screened from each group.

1.3.2. Indicator normalization

To eliminate the differences from indicator units, linear scoring evaluation model is applied to convert indicators to assign a score between 0 and 1. According to their sensitivity of soil productivity and quality, indicators can be divided into two types (Askari and Holden, 2014; Yu et al., 2018). If the indicator value was positively correlated with soil quality within a certain range, the “more is better” scoring curve was applied as Eq. (2). On the contrary, the “less is better” was applied as Eq. (3) with a negative correlation. The pH, EC and Sand were normalized by the “less is better” scoring curve (Chen et al., 2022; Zhang et al., 2022). The two types of equations are as follows:

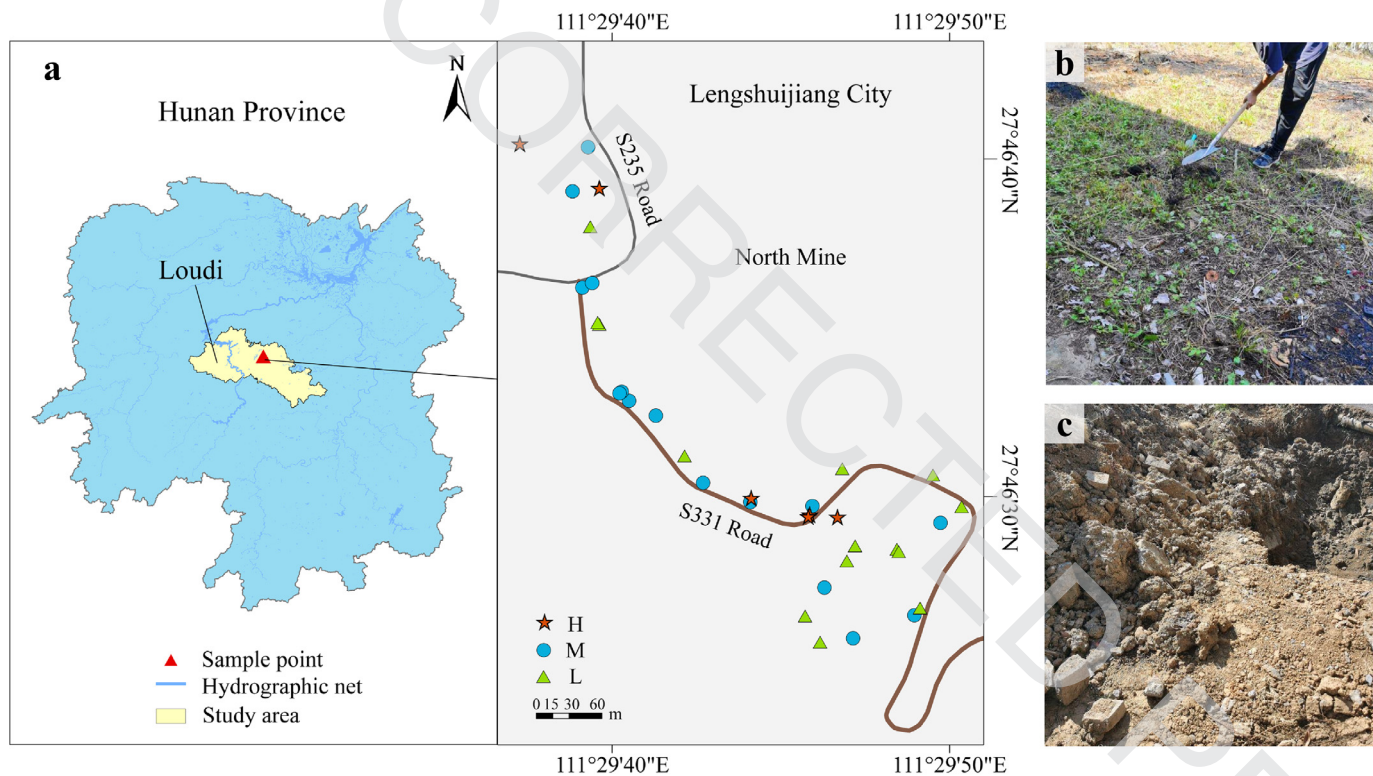


Fig. 1 – (a) Study area and sampling sites in Xikuangshan antimony mine. H, M and L mean High, Middle, and Low contamination zones, respectively. (b) The environment of sampling area: rhizosphere soils in residential area and (c) tailing soils close to the smelting site.

$$RI_i = \frac{X - L}{H - L} \quad (2)$$

$$RI_i = 1 - \frac{X - L}{H - L} \quad (3)$$

where, the resilience index (RI_i) represents the linear score. X , L and H represent the measured, the lowest and the highest value of the index, respectively.

1.3.3. Indicator integration

The traditional additive weighted method (Yuan et al., 2020) was applied to integrate MDS indicators into the soil quality assessment index. The indicator weights were commonly assigned by the common factor variance through PCA (Jin et al., 2021a). Then the weighted MDS indicator scores were summed using the following equation:

$$SRI_{TAW} = \sum_{i=1}^n W_i RI_i \quad (4)$$

where, SRI_{TAW} is the soil resilience index obtained by the traditional additive weighted method, W_i is the weight of indicator i of MDS, and RI_i is the score computed by Eqs. (2) or (3), and n is the number of evaluation indicators.

The modified NPI method was used to standardize the soil resilience index (SRI_{NPI}) by Eq. (5). To reflect the impact of the worst resilience indicator on the final result, the minimum value replaced the maximum value in the traditional NPI method (Fan et al., 2021).

$$SRI_{NPI} = \sqrt{(RI_{\min}^2 + RI_{\text{ave}}^2)/2} \quad (5)$$

where, $RI_{\min}$ and RI_{ave} are the minimum and average of RI computed by Eqs. (2) or (3).

1.3.4. Accuracy verification of SRI

$SRI_{TAW-TDS}$ (SRI_{TAW} based on the TDS) including all 22 non-heavy metal indicators were calculated by Eq. (4), and linear fitting analysis between $SRI_{TAW-MDS}$ (SRI_{TAW} based on the MDS) and $SRI_{TAW-TDS}$ was used to examine the accuracy. Since the modified NPI method was adopted to standardize SRI, we also use the linear fitting analysis between $SRI_{NPI-MDS}$ and $SRI_{TAW-MDS}$ to test the accuracy.

1.4. Assessment of soil contamination

The I_{geo} method was selected to assess soil contamination by Eq. (6):

$$I_{\text{geo}} = \log_2(C_n/1.5B_n) \quad (6)$$

where, C_n (mg/kg) and B_n (mg/kg) are the measurements and the geochemical backgrounds of heavy metal n , respectively. The correction coefficient (1.5) accounts for the natural fluctuations of the metal in soil (Loska et al., 2004). The I_{geo} has seven grades (0 to 6), which are listed in Appendix A Table S1 (Muller, 1969).

The contamination index (CI) was defined to normalize the I_{geo} to quantify the heavy metal contamination level. It was obtained by the segmentation function (Wang et al., 2018):

$$CI = \begin{cases} 1, & (I_{\text{geo}} < 0) \\ \frac{1}{I_{\text{geo}}+1}, & (I_{\text{geo}} \geq 0) \end{cases} \quad (7)$$

where, I_{geo} is the geo-accumulation index, and CI is the contamination indicator score (0–1) based on the I_{geo} values. When $I_{\text{geo}} < 0$, CI reached the highest value.

The modified NPI was also used to standardize the soil contamination index (SCI_{NPI}):

$$SCI_{NPI} = \sqrt{(CI_{\min}^2 + CI_{\text{ave}}^2)/2} \quad (8)$$

where, $CI_{\min}$ and CI_{ave} are the minimum and average of CI, respectively.

1.5. Integrated evaluation of the soil quality

We selected a multi-criteria quantitative procedure from diverse quality evaluation methods to obtain the SQI (Wang et al., 2018), which contains both soil resilience and heavy metal contamination:

$$SQI = \text{MIN}(SRI_{NPI}, SCI_{NPI}) \quad (9)$$

where, the SQI is the minimum value of SRI_{NPI} and SCI_{NPI} , ranging from 0 to 1.

1.6. Statistical analysis

Statistical analysis was conducted by SPSS. Kaiser-Meyer-Olkin (KMO) test and Bartlett's test of sphericity (BTS) were used to determine if the selected variables were sufficient for the PCA in soil resilience. Correlation among indicators and index scores were on the basis of Pearson correlation coefficients at $p < 0.05$ and $p < 0.01$. The coefficient of variance (CV) was used to indicate the sensitivity of each indicator to the variance response.

2. Results

2.1. Soil resilience level assessment

2.1.1. Soil basic properties

The values of statistical analysis of soil physicochemical and microbial indicators are presented in Table 1. The soil in this XKS smelter is weakly alkaline (62.86 % of the sampling sites have pH above 7), with high moisture content (average of 21.27 %) and low EC (0.16 dS/m). The mean value of TOC was 6.26 %. The content of clay and silt reflected sandy loam soil texture, and the sand content was 55.18 %. The variation coefficients of CAT (CV 1.98 %), Shannon-S (CV 8.02 %), Pielou-S (CV 6.39 %), Shannon-F (CV 0.28 %) and Chao1-F (CV 2.51 %) were relatively low (CV < 10 %), indicating that there were small differences for them among all sample points. While the coefficients of variation for Bacteria, Fungi, Actinomycetes, DVC and

Table 1 – Statistical characteristics of soil resilience indicators.

Indicator	Minimum	Maximum	Mean	Standard deviation	Variable coefficient (%)
pH	4.42	9.12	7.34	1.27	17.36
EC (dS/m)	0.05	0.61	0.16	0.10	64.65
MC (%)	3.98	41.63	21.27	8.64	40.61
TOC (%)	0.70	22.68	6.26	5.15	82.24
Clay (%)	1.27	14.27	9.99	3.25	32.52
Silt (%)	8.28	50.44	34.25	10.08	29.43
Sand (%)	35.55	81.75	55.18	12.01	21.76
URE (U/g)	38.54	574.98	278.09	148.46	53.39
SUC (U/g)	6.89	106.07	36.66	25.29	68.98
CAT (U/g)	89.82	97.30	95.03	1.88	1.98
Bacteria ($\times 10^5$ CFU/g)	5.33	2251.70	285.76	426.13	149.12
Fungi ($\times 10^5$ CFU/g)	0.28	430.93	74.96	102.70	137.00
Actinomycetes ($\times 10^5$ CFU/g)	14.16	2881.96	366.18	579.70	158.31
DVC ($\times 10^9$ cells/g)	10.00	933.33	228.32	236.96	103.78
Shannon-S	7.31	10.84	10.03	0.80	8.02
Pielou-S	0.66	0.94	0.89	0.06	6.39
Shannon-F	4.65	4.70	4.67	0.01	0.28
Chao1-F	163.00	182.00	170.82	4.29	2.51
Skermanella (OTUs)	1.00	203.00	34.11	39.02	114.38
Microvirga (OTUs)	3.00	158.00	51.23	37.16	72.54
Blastococcus (OTUs)	0.00	329.00	68.31	60.28	88.24
Actinoplanes (OTUs)	0.00	239.00	32.86	44.02	133.98

EC: electrical conductivity; MC: moisture content; TOC: total organic carbon; URE: urease; SUC: sucrose; CAT: catalase; DVC: direct count of viable microbial cells; Shannon-S: Shannon-Wiener index of species diversity; Pielou-S: Pielou evenness index of species diversity; Shannon-F: Shannon-Wiener index of functional diversity; Chao1-F: Chao1 index of functional diversity.

the indicator species *Skermanella* and *Actinoplanes* were relatively high ($CV > 100\%$), suggesting that the above-mentioned microbial biomass had large variations.

2.1.2. Indicator selection for MDS and normalized scores of MDS

The KMO value was greater than 0.60 with the BTS test being significant at the 0.05 level, indicating that the data could be analyzed by PCA. There were 7 PCs with eigenvalues greater than 1, and the cumulative contribution value of the first 7 PCs explained the majority of the information (80.92%), but the eigenvalue curve gradually flattened out after PC5 (Fig. 2a), and the first five PCs explained 65.23% of the variance in the total soil resilience data set, satisfying the requirements for information extraction (Zhang et al., 2022). As a result, the first five PCs were extracted for subsequent analysis. The PCA results and the grouping of soil resilience indicators were shown in Table 2, and the Pearson correlation analysis of each indicator was shown in Fig. 2b. The 22 indicators were grouped into five PCs based on their factor loadings (≥ 0.50) in each PC. For those indicators with loadings greater than 0.50 on PC6 and PC7, we included them in Group 1–5, where they had the largest loadings (Table 2).

The MDS was established based on the magnitude of norm values and correlations between indicators. The greater the norm value, the better its ability to account for overall soil quality information. In group 1, the norm value of Sand was the highest, within 10% deviations of Silt and Clay. Since the three indicators were strongly correlated (Fig. 2b), Sand was included in the MDS. In group 2, the highest norm value was observed at TOC, and except for Bacteria, the three remaining indicators had norm values within 10% of the highest.

Since TOC was significantly correlated with MC and Chao1-F, TOC and *Blastococcus* were retained in the MDS. In group 3, the correlation between Shannon-S and Pielou-S was significant, hence, the Shannon-S was selected for the MDS. In group 4, *Skermanella* had the highest norm value and correlated significantly with *Microvirga*, thus, *Skermanella* was chosen into the MDS. Similarly, CAT and Fungi in group 5 were incorporated into the MDS. Ultimately, the MDS included the following seven indicators: TOC, Sand, CAT, Fungi, Shannon-S, *Skermanella* and *Blastococcus*.

Fungi, *Skermanella*, TOC and *Blastococcus* had relatively lower RI than other indicators, whether in high, middle or low contamination zones (Fig. 3a), indicating that these four indicators were the major limiting factors for soil resilience. Additionally, the average RI of Sand in group H, M and L was 0.38, 0.49 and 0.75, respectively.

2.1.3. MDS accuracy verification and soil resilience evaluation

The common factor variance of each index in MDS and TDS was obtained by PCA, and then the weight of each indicator was evaluated (Table 3). The weights of TOC, Sand, CAT, Fungi, Shannon-S, *Skermanella* and *Blastococcus* were 0.169, 0.147, 0.127, 0.127, 0.156, 0.112 and 0.161 in the MDS, respectively. The linear scoring evaluation model (Eqs. (2) and (3)) was applied to convert the indicator scores to 0–1.

To test the accuracy of the MDS-based indicators for soil resilience assessment, $SRI_{TAW-TDS}$ was obtained by Eq. (4) based on the commonality and scoring function of each indicator. $SRI_{TAW-MDS}$ was significantly correlated with $SRI_{TAW-TDS}$ (Fig. 3b), indicating that the MDS was fully representative of the TDS for soil resilience evaluation. In addition, a significant correlation was found between the $SRI_{NPI-MDS}$ and

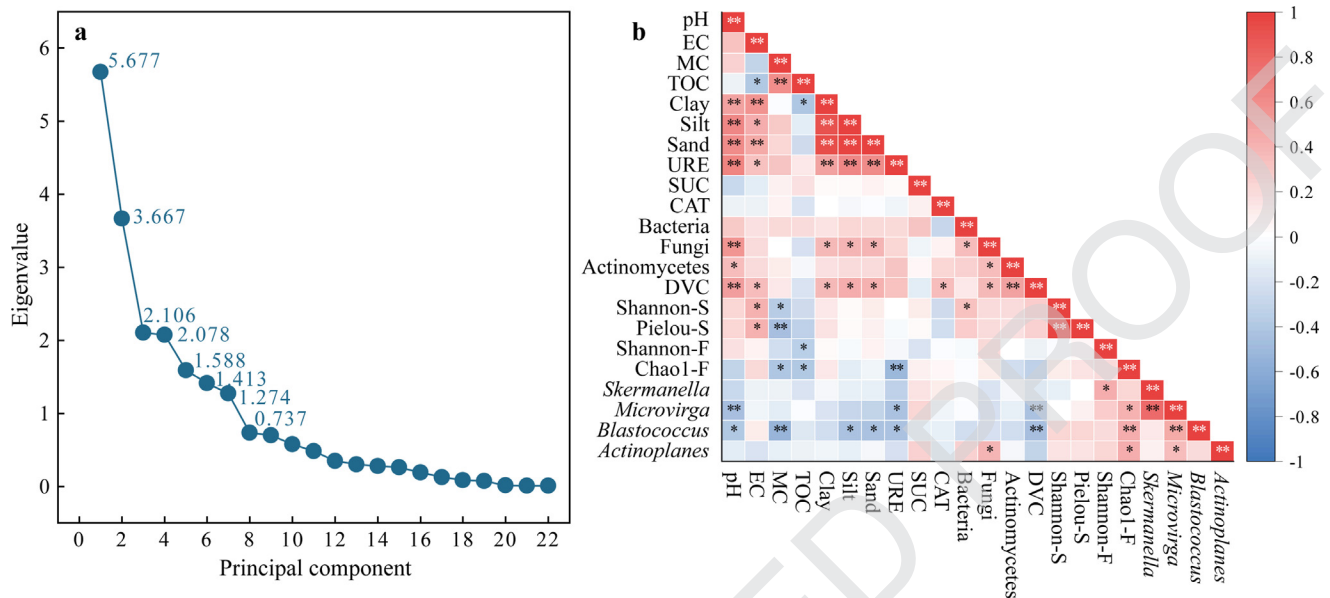


Fig. 2 – (a) Variation in eigenvalues and (b) Pearson correlation analysis of soil resilience evaluation indicators. * Indicated significant correlation at $p < 0.05$ level (two-tailed test) and ****** indicated significant correlation at $p < 0.01$ level (two-tailed test).

Table 2 – Results of the principal component analysis of each indicator*.

Indicator	PC1	PC2	PC3	PC4	PC5	PC6	PC7	Norm value	Group
Sand	0.963	0.045	0.009	−0.049	0.109	0.090	0.013	2.037	1
Silt	0.956	0.128	−0.019	−0.071	0.072	0.052	0.015	2.028	1
Clay	0.951	−0.200	0.061	−0.010	0.071	0.038	0.052	2.034	1
URE	0.639	0.450	0.068	−0.214	0.104	−0.092	−0.125	1.598	1
pH	0.589	0.330	0.227	−0.196	0.238	0.171	−0.469	1.611	1
EC	0.562	−0.317	0.489	−0.017	0.054	−0.187	−0.078	1.556	1
TOC	−0.268	0.741	−0.153	−0.126	−0.224	−0.040	0.238	1.473	2
MC	0.165	0.734	−0.399	−0.033	0.092	0.049	0.143	1.463	2
Chao1-F	−0.008	−0.711	0.009	0.204	−0.216	0.384	0.202	1.400	2
Blastococcus	−0.367	−0.522	0.248	0.183	−0.373	−0.031	−0.078	1.384	2
Shannon-S	0.038	−0.129	0.937	−0.070	0.070	0.099	0.066	1.590	3
Pielou-S	0.046	−0.194	0.920	0.028	0.071	0.082	−0.011	1.575	3
Skermanella	−0.053	−0.091	−0.066	0.938	0.057	−0.066	0.038	1.421	4
Microvirga	−0.236	−0.144	0.060	0.829	−0.209	0.097	0.196	1.419	4
DVC	0.341	0.094	0.226	−0.221	0.750	−0.124	−0.109	1.423	5
CAT	−0.074	−0.280	−0.395	0.029	0.744	−0.070	0.166	1.379	5
Actinomycetes	0.114	0.243	0.259	0.049	0.681	0.116	−0.036	1.193	5
Actinoplanes	−0.130	−0.145	0.048	0.143	−0.169	0.847	0.136	1.266	5
Fungi	0.329	−0.014	0.125	−0.177	0.331	0.722	−0.238	1.370	5
Bacteria	0.201	0.448	0.438	0.074	−0.008	0.453	0.219	1.321	2
SUC	0.039	0.129	0.071	0.209	0.046	0.170	0.813	1.133	4
Shannon-F	0.060	−0.159	−0.017	0.558	0.016	0.273	−0.605	1.227	4
Rotated eigenvalue	4.419	2.828	2.766	2.222	2.113	1.849	1.604		
Percent (%)	20.089	12.856	12.573	10.102	9.606	8.403	7.291		
Cumulative percent (%)	20.089	32.944	45.517	55.619	65.226	73.628	80.919		

* Bold letter indicated indicators had high factor loading in the first five principal components (PCs).

SRI_{TAW-MDS} in Fig. 3c, showing that the modified NPI method could reflect soil resilience quality to the same extent as the traditional method. Therefore, using the modified NPI method to construct the soil resilience index was highly reasonable.

2.2. Soil contamination level assessment

2.2.1. Soil heavy metal content

Box plots were applied to describe heavy metal content and compared them with the soil background values (Fig. 4). The

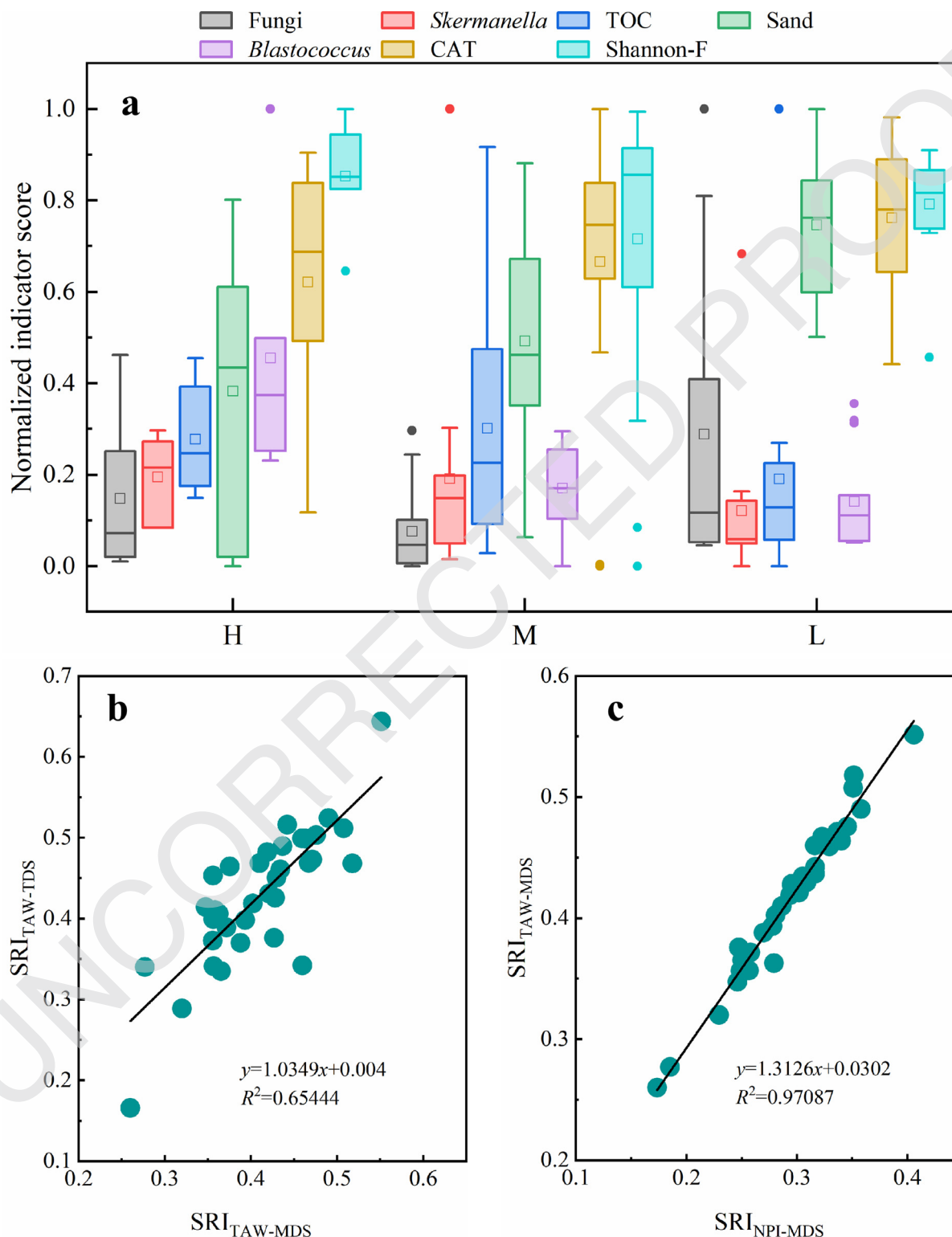
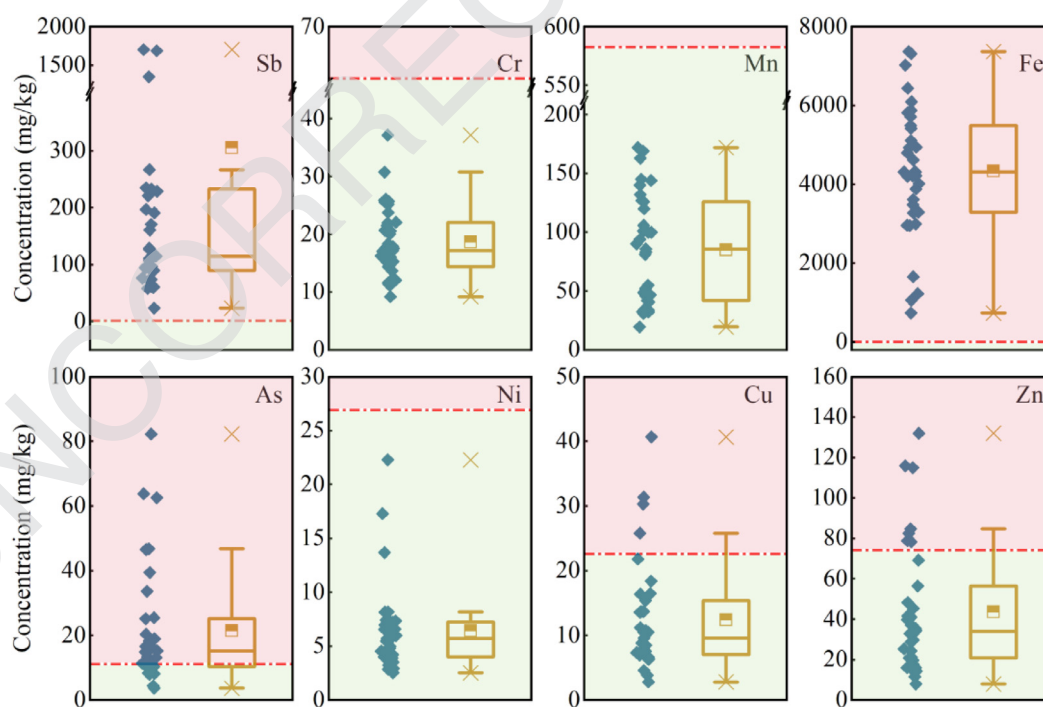


Fig. 3 – (a) Normalized soil resilience indicator scores (RI) of Fungi, *Skermanella*, total organic carbon (TOC), Sand, *Blastococcus*, catalase (CAT), and Shannon-Wiener index of functional diversity (Shannon-F), **(b)** Linear relationships between the $SRI_{TAW-MDS}$ (soil resilience index obtained by the traditional additive weighted method based on the MDS) and $SRI_{TAW-TDS}$ (soil resilience index obtained by the traditional additive weighted method based on TDS), **(c)** and linear relationships between $SRI_{NPI-MDS}$ (soil resilience index obtained by the modified NPI method based on the MDS) and $SRI_{TAW-MDS}$ (soil resilience index obtained by the traditional additive weighted method based on the MDS).

Table 3 – Common factor variances and weights of the minimum data set and total data set.

Indicator	Total data set (TDS)		Minimum data set (MDS)	
	Common factor variance	Weight	Common factor variance	Weight
pH	0.852	0.048		
EC	0.700	0.039		
MC	0.757	0.043		
TOC	0.769	0.043	0.783	0.169
Clay	0.958	0.054		
Silt	0.944	0.053		
Sand	0.952	0.053	0.682	0.147
URE	0.697	0.039		
SUC	0.759	0.043		
CAT	0.826	0.046	0.590	0.127
Bacteria	0.692	0.039		
Fungi	0.843	0.047	0.589	0.127
Actinomycetes	0.620	0.035		
DVC	0.815	0.046		
Shannon-S	0.920	0.052	0.725	0.156
Pielou-S	0.900	0.051		
Shannon-F	0.781	0.044		
Chao1-F	0.782	0.044		
Skermanella	0.904	0.051	0.521	0.112
Microvirga	0.859	0.048		
Blastococcus	0.648	0.036	0.748	0.161
Actinoplanes	0.825	0.046		

**Fig. 4 – Box-plot of heavy metal content for all soil samples in the Xikuangshan mining site (the dotted red lines represent the background values).**

content of Sb and Fe was higher than the background values
 in all samples. Meantime, the average content of As was also
 1.9 times higher than the background value, and the content

of Cu and Zn was chiefly lower than the background values. In
 addition, the content of Cr, Mn and Ni was all below the local
 background values.

2.2.2. I_{geo} of each heavy metal(loid)

I_{geo} can reflect the impact of geological factors as well as human activities on heavy metal pollution. According to the I_{geo} distribution (Fig. 5a), Sb falls in the extremely contaminated level (Appendix A Table S1) with the mean I_{geo} value being 5.19. Whereas, the I_{geo} for As, Zn, Cu, Cr, Mn and Ni is negative, indicating a low risk of contamination at the XKS antimony smelting site. As shown in Fig. 5b, the I_{geo} values of Sb in over 80 % of the samples were above grade 4, showing that the majority of the test site exceeded the heavily contaminated level. As for As, 25.7 % of these samples were above grade 1, indicating that some of the sampling sites were contaminated with As to some extent. Zn, Cu, Cr, Mn and Ni were classified into grade 0 at more than 90.0 % of the sampling sites. In summary, Sb and As were the prominent metal(loid) pollutants at the XKS antimony smelting site.

2.3. Comprehensive assessment of soil quality

The SQI obtained by the standardized framework provides a more rigorous and sensitive method for assessing soil quality at antimony smelting sites. Because low SRI or SCI will lead to low SQI, while high SQI only exists when both soil resilience is high and heavy metal pollution is low. Referring to the classification standards used in diverse soil quality assessment based on comprehensive methods (Fan et al., 2021; Wang et al., 2018), we divided the SQI into five levels equally, and the classification standard and the meanings of each grade are shown in Appendix A Table S2.

According to the comprehensive assessment framework, the SQI values ranged from 0.173 to 0.406 at the XKS antimony smelting site. The mean SQI value was 0.29, which dropped into the "Low" grade (Appendix A Table S2). Meantime, the SQI values under the "Low" grade accounted for 97.14 %, indicating that the vast majority of soil samples were of low quality. Only one of these sites exhibited a quality assessment of "Medium" with $0.4 < SQI \leq 0.6$ (Appendix A Table S2). Pearson correlation analysis between the indicators from MDS, heavy metals and soil evaluation indexes showed that the heavy metals were significantly correlated and they contributed to the SCI directly. Meantime, the indicators from MDS shaped the SQI by altering the SRI (Fig. 6a). We ranked the magnitude of the SQI of each sample and compared them with the corresponding SCI. As shown in Fig. 6b, when all the soil samples were ranked in increasing SQI values, the SCI values didn't exhibit an obvious trend. For the same points, the results obtained from the integrated assessment with the inclusion of microbial indicators differed significantly from the results of the heavy metal pollution assessment. For example, the first site is lightly contaminated with heavy metals, but the integrated assessment results with the lowest SQI indicated that the soil condition at this point is the poorest. As shown in Fig. 6c, the SRI was generally lower than the SCI, whether in group H, M and L, and the spatial distribution of the SQI was consistent with that of the SRI, indicating that the SQI at the smelting site was mainly limited by the low level of soil resilience. Furthermore, the average values of SCI increased as the pollution level decreased. However, the highest average SQI value appeared in the low contaminated area, suggesting that they had the highest soil resilience in the comprehensive assessment framework.

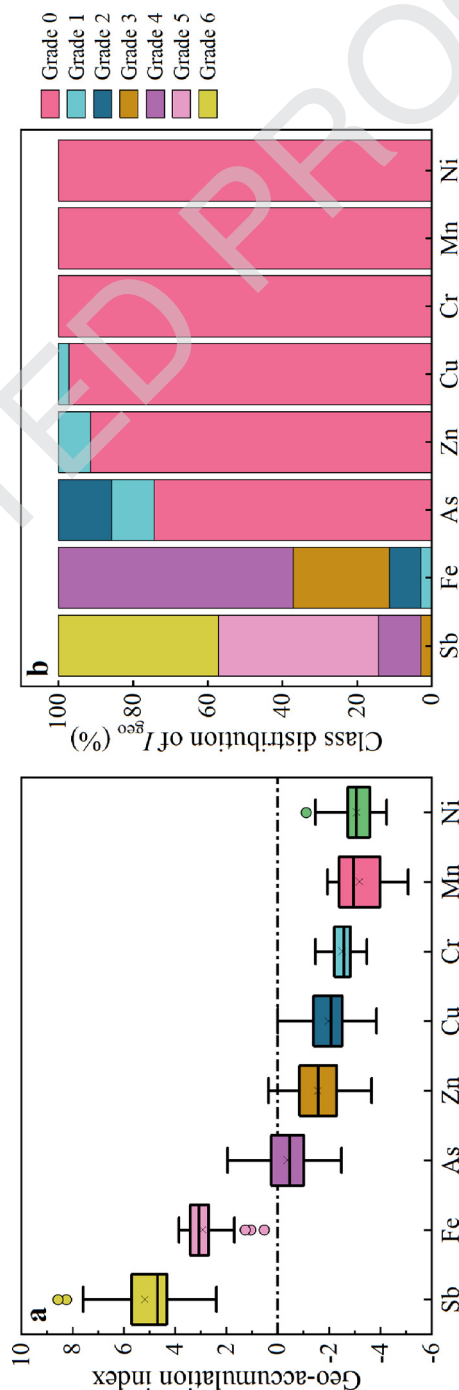


Fig. 5 – (a) The Geo-accumulation index (I_{geo}) of eight heavy metals. The 'x' inside the box-plot indicated the mean value of different heavy metals. The black line inside the box-plot indicated the median. Spots outside the box-plot were outliers. (b) The class distribution of I_{geo} for each heavy metal in soils.

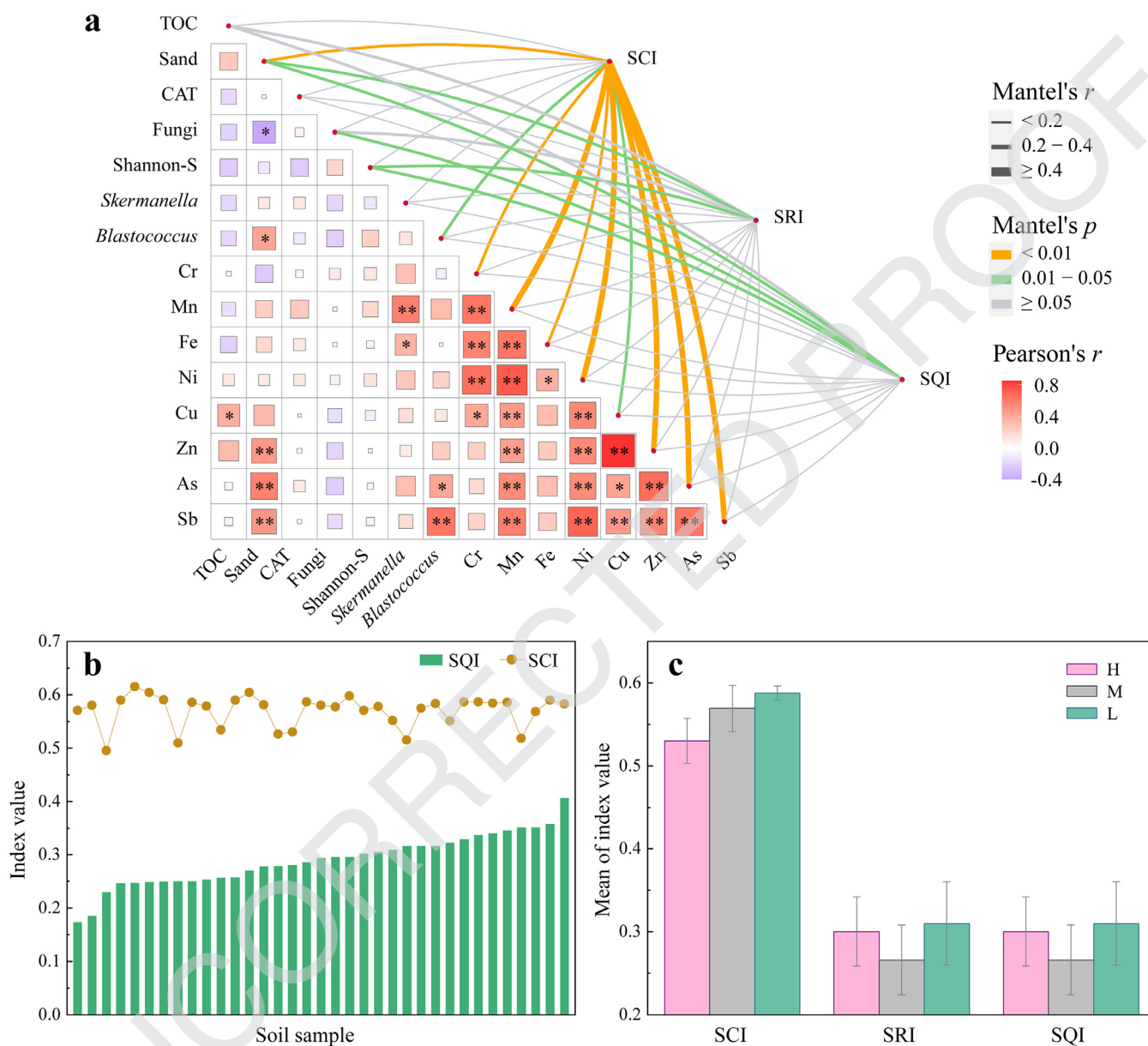


Fig. 6 – (a) Pearson correlation analysis between the indicators from MDS, heavy metals and soil evaluation indexes, * indicated a significant correlation at $p < 0.05$ level (two-tailed test) and ** indicated a significant correlation at $p < 0.01$ level (two-tailed test), (b) distribution of soil quality index (SQI) and soil contamination index (SCI) values for the 35 sampling sites, and (c) diagram of SCI, soil resilience index (SRI) and SQI in H, M and L contamination zones.

3. Discussion

3.1. Determining effects of microbial indicators on soil resilience index

The microbial community is considered to be significantly influenced by environmental factors and consequently less assessed in terms of soil quality. Particular attention was paid to the correlation between the indicators from MDS, heavy metals and soil evaluation indexes (Fig. 6a). Sand and Fungi ($r = -0.399$, $p < 0.05$) presented a strong negative correlation. High sand content suggested that the soil has high perme-

ability, which was not conducive to the accumulation of organic matter (Zhou et al., 2023). Previous research reported that fungi had a significant survival advantage over other microbial populations because they could resist high contamination by detoxifying large amounts of heavy metals (Naz et al., 2022). Nevertheless, the heavy metal pollution of the XKS smelting site still decreased the fungal abundance in the soil, which give rise to poor soil resilience. A higher coefficient of variance value of Fungi (137%, Table 1) was observed, indicating it had large variation among the sampling sites, which may be related to the fact that fungi are susceptible to the surrounding soil microenvironment (Yu et al., 2022). Taken together, Fungi had relatively lower RI compared with

other indicators (Fig. 3a), serving as one of the limiting factors on soil resilience level. *Blastococcus* was also a limiting factor of soil resilience, but it showed a strong positive correlation with Sand ($r = 0.426$, $p < 0.05$), indicating that *Blastococcus* was a more abundant species in the soil with higher sand content. It was consistent with the result that the cropland soil with similar particle size content contained higher *Blastococcus* microorganisms (Xu et al., 2021). *Blastococcus* was reported as one of the most dominant genera thriving in tailings areas, which increased with the increasing levels of heavy metals (Zeng et al., 2020). Therefore, *Blastococcus* may play essential roles in sustaining and boosting soil resilience. As a limiting factor of the SRI, *Skermanella* had strong positive correlations with Mn ($r = 0.583$, $p < 0.01$) and Fe ($r = 0.357$, $p < 0.05$), indicating that *Skermanella* acquired high resistance to Mn and Fe, which was in accordance with the previous study that the relative abundance of *Skermanella* in a constructed wetland was much higher when Fe served as functional substrate (Li et al., 2022). Moreover, a previous researcher found that *Skermanella stibiisresistens* sp. nov. was a highly antimony-resistant bacteria (Luo et al., 2012), which showed that *Skermanella* had high resistance to heavy metals. Consequently, although there are certain significant correlations between soil microbial indicators and environmental factor indicators, the specific microbial abundance plays a crucial role in the soil resilience level and cannot be ignored in soil quality assessment.

3.2. Soil quality evaluation and causal analysis of the antimony smelting site

Soil quality diagnosis has become an essential step prior to soil remediation, providing a general understanding of soil contamination levels and feasible restoration approaches. Although no attempts have been made to assess the soil degradation extent at antimony smelting sites, a series of assessments on soil fertility of cultivated soil and heavy metal contamination in mine areas, provided sufficient theoretical references for innovating the evaluation of soils at antimony smelting sites. We constructed the standardized assessing framework, based on which, the soil quality of the study area was identified to be overall low. There were significant positive correlations between most heavy metals (Fig. 6a), which was in accordance with most of the heavy metal contamination areas (Lin et al., 2019; Zeng et al., 2022). Sb was mainly correlated with Ni content ($r = 0.698$, $p < 0.01$), followed by As, Zn and Mn ($p < 0.01$). The significant positive correlation between Sb and As was mainly due to the combined antimony-arsenic pollution caused by stibnite (Sb_2S_3) smelting activities (Long et al., 2020), which contained 71.4% Sb and a trace amount of As, Cu, Fe, etc. (Qi et al., 2022).

There were three primary reasons for the low SQI value in the study area. Firstly, from the perspective of soil development history as well as the XKS mining and smelting history of more than 120 years, it mainly adopted the pyrometallurgical smelting process, during which antimony ore tended to concentrate in the dust after burning and accumulated in the soil through atmospheric. The sampling sites were near the north of the smelter and the slag yard, and Sb mainly from fumes emitted from the chimney and the dust produced during the transport of minerals and slag (Okkenhaug et al., 2011;

Tang et al., 2020). The longer the mining time, the greater the impact of heavy metal contamination of the soils in the mining area, in other words, there was not enough time for the abandoned soils to recover. Secondly, from the perspective of soil natural properties, some physicochemical and biological indicators suggested that the soil was not conducive to microbial survival. For example, the mean value of EC (0.16 dS/m, Table 1) was lower compared to other mining areas (34.85–66.20 μ S/cm) (Ma et al., 2019), which served as a reliable indicator to reflect soluble nutrients (cation or anion) in soil (Friedman, 2005). The low EC indicated that the soil at the abandoned site was nutrient-poor, structurally unstable and readily dispersed (Smith and Doran, 1997). A few samples of rhizosphere soils resulted in the mean value of TOC as high as 6.26%, which was significantly higher than that of a rare earth mining area in Jiangxi (the highest TOC there was 2.69%) (Liang et al., 2021). High TOC levels could promote the development of microorganisms (Liang et al., 2021), which corresponded to the Shannon-F having the highest RI, however, only the Shannon-F contributed most to the soil resilience level, but it was not sufficient for the overall quality of the soil. Last but not least, from the perspective of soil development status, a majority of the soils were free from regulated anthropogenic production activities and were wastelands without any plant growing. A relevant study about this antimony mining area showed that the contents of Sb in ecological restoration grassland and vegetable patch were relatively low compared to lands such as wasteland and residue-field (Tang et al., 2020), which indicated that appropriate anthropogenic disturbance was beneficial to improve soil quality at XKS antimony smelting site.

3.3. Approaches for improving the soil quality at the antimony smelting site

The soil quality evaluation by the comprehensive assessment framework showed that the poor quality of the soil at the XKS antimony smelting site was caused by its poor resilience. To improve the quality of the ambient soil, certain measures are required to be taken to improve the soil resilience level from the following perspectives.

Soil microbial communities play a critical role in soil remediation, which can accelerate the cycling of nutrients and the degradation of contaminants in soils (Zhang et al., 2023b). Fungi were one of the limiting factors on soil resilience level, which may serve as key game-changers during the self-restoration process of the contaminated soils at smelting sites. Broader metabolic competence allowed the specific fungi taxa to exhibit strong heavy metal adsorption capacity under the supplement of nutrients (Lin et al., 2019), and diverse fungi species have been used to remediate heavy metal pollutants like As (Singh et al., 2015), Zn and Fe efficiently (Vaseem et al., 2017). By induced-resistance training, fungi showed higher metal tolerance and bioaccumulation capacity, which offered a promising technological avenue in bioremediation as eco-friendly, efficient and low-cost (Liaquat et al., 2020). In addition, some fungi could also promote plant growth by increasing the phytoaccumulation, phytoextraction and phytoremediation properties of plants to achieve enhanced remediation of heavy metal contaminated soils

(Schützendübel and Polle, 2002). Therefore, introducing effective exogenous fungi species or enriching indigenous fungi by supplementing available carbon sources (Sun et al., 2016) are both feasible approaches for improving the soil quality at the antimony smelting site.

Bioremediation can also be implemented through the implementation of site-specific planting measures. It is well known that phytoremediation is one of the important tools for environmental management of heavy metal pollution. As the soils of the XKS antimony smelting site were affected by mining activities for a long time, the soils were seriously polluted by heavy metals such as Sb and As (Fig. 5a, b). Although it is not suitable to plant edible crops in a large area, ecological and economic plants with certain anti-pollution properties can be planted in this mining area, which can control the heavy metals diffuse to surrounding environmental media effectively and improve the value of land use while enhancing soil quality (Gil-Loaiza et al., 2018). Previous study showed that after seven years of restoration by different woody plant species, such as *Arundo donax* and *Cryptomeria fortunei*, the content of As and Sb in the slag reduced significantly (Sun et al., 2021). In addition, some researchers had investigated the native wild plants of the XKS antimony smelting site and found that *Imperata cylindrica* could accumulate Sb well from soils and air dust, and with a similar ability shown in *Pteridium aquilinum* var. *latiusculum* for As (Fu et al., 2019). In conclusion, it is of great significance to use phytoremediation to improve soil quality in mining areas under the premise of ensuring ecological security.

4. Conclusions

A comprehensive assessment framework considering both soil resilience and soil contamination on the same scale was constructed to reveal the trends in development of soil quality at the XKS antimony smelting site. Sb and As were the prominent metal(loid) pollutants in this mining area. Soil quality was primarily limited by the low level of soil resilience. The Fungi was the main limiting factor of soil resilience quality in high and middle contaminated areas, and *Skermanella* was the primary factor in low contaminated area. The results indicated that microorganisms may play a crucial role in soil pollution remediation. Practical and scientific ways, such as microbial regulation and phytoremediation, are greatly required to prevent further land degradation and improve the soil quality of mining sites from the perspectives of pollution control and resilience improvement. There may be some limitations in this study, such as microbiological indicators are not easily detectable and soil microorganisms can be affected by many factors, the practicality of the selected indicators also needs to be further considered in subsequent studies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jes.2023.12.031.

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