Environmental Science and Pollution Research (2024) 31:19725–19737
https://doi.org/10.1007/s11356-024-32295-0

RESEARCH ARTICLE

Effects of different ecological restoration methods on the soil physicochemical properties and vegetation community characteristics of the Baotou light rare earth tailings pond in Inner Mongolia, China

Tianyu Chen[1,2] · Ning Qu[2] · Jinxiao Wang[2] · Yaochen Liu[2] · Jiao Feng[2] · Shilei Zhang[2] · Chunying Xu[2] · Zhiquan Cao[2] · Jun Pan[1] · Chunlin Li[2]

Received: 5 July 2023 / Accepted: 28 January 2024 / Published online: 16 February 2024

Abstract

This study investigated the soil physicochemical properties and vegetation community characteristics of the Baotou light rare earth tailings pond after 10 years of aggregate spray seeding ecological restoration (S1) and ordinary soil spray seeding ecological restoration (S2), and the naturally restored dam slope area without human intervention (S3). The results showed that the vegetation community of S1 was dominated by *Caragana korshinskii Kom*, and its importance and abundance values were 0.40 and 38.4, respectively, while the vegetation communities of S2 and S3 mainly comprised herbaceous plants. Additionally, the vegetation biomass of S1 was significantly higher than that of S2 and S3 by 215.20% and 1345.76%, respectively, and the vegetation diversity index of S1 was the highest among the three treatment groups. The soil porosity (SP), water content (W), electrical conductivity (EC), and available K were significantly improved in S1, while soil bulk density (BD) was significantly reduced compared with that of S2 and S3. In addition, redundancy analysis revealed that SP, EC, W, and K positively correlate with the biomass, Shannon, Pielou, Simpson, and Marglef indices. Principal component analysis further showed that the comprehensive score of S1 (0.983) was higher than that of S2 (−0.261) and S3 (−0.648). Collectively, these findings indicate that appropriate ecological restoration can improve soil structure and vegetation community characteristics, thereby accelerating vegetation restoration, ultimately increasing the stability of the ecosystem.

Keywords Ecological restoration · Plant population and community dynamics · Vegetation diversity · Plant–soil interactions · Tailings pond · Spray seeding

Abbreviations

SOM	Soil organic matter
TN	Total nitrogen
TP	Total phosphorus
TK	Total potassium
SP	Soil porosity
EC	Electrical conductivity
IV	Important value
W	Soil water content
BD	Soil bulk density
N	Available nitrogen
P	Available phosphorus
K	Available potassium
UBio	Aboveground biomass
Bio	Total biomass

Introduction

Although the rapid development of the mining industry has promoted global economic development, it has also caused considerable damage to the ecological environment (Dutta et al. 2016; Prosdocimi et al. 2016; Vaezi et al. 2017), particularly to soil environment (Lee et al. 2001; Pourret et al. 2016). Despite increasing efforts toward the environmental management of mines and ecological restoration have increased (Neldner and Ngugi 2017; Ahirwal and Maiti 2018), tailings ponds continue to present environmental and

Responsible Editor: Kitae Baek

✉ Jun Pan
1245215648@qq.com

[1] College of Environmental and Municipal Engineering, Shenyang Jianzhu University, Shenyang 110168, People's Republic of China

[2] Greesum Ecologi Co., Ltd., Qingdao 266100, People's Republic of China

ecological safety issues, such as desertification, soil erosion, biomass and diversity loss, and surface soil and groundwater contamination with heavy metals (Chen 2010; Dutta et al. 2016; Prosdocimi et al. 2016; Tang et al. 2000; Vaezi et al. 2017). As a large mining nation with an annual tailings production of more than 600 million tons, China has more than 15,000 tailings ponds comprising more than 20 billion tons (Wang 2019). Hence, an urgent need exists for improved ecological restoration of tailings ponds.

The Baotou light rare earth tailings pond serves as the primary reservoir for storing mining and smelting wastes from the China Baotou Steel Group (Xiao et al. 2012; Liu et al. 2019). However, the dam body was dammed with tailings fines, while the inner and outer surfaces of the dam body were covered with mineral fines without implementing dust suppression measures. In addition, the overall particle size of tailing fines is relatively small, and the proportion of particles with particle sizes less than 0.5 mm is 96.24% (Pan 2010). Under the arid, rainless, and windy climatic conditions, it is easy to cause dust pollution (Nordstrom 2011; Nordstrom et al. 2015; Ivarez et al. 2022) (Supplementary Fig. 1), while the mineral fines adhere to the surface of plants. Moreover, the surface temperature of mineral fines can reach 50 °C under sunlight exposure, increasing the risk of plants becoming burnt or dying. Additionally, the bare mineral fines lack the nutrients required for plant growth (Shen et al. 2014; Wang et al. 2018) and contains many harmful heavy metals, including Cd, Pb, and Zn (concentrations exceeding 85.71%, 57.14%, and 50.00% of the soil specification limits, respectively) (Li et al. 2019). The heavy metal elements in the mineral fines also become suspended in the air or seep into groundwater with surface runoff after settlement, leading to high heavy metal content in the air and groundwater. This poses a risk to humans health, and individuals living near tailings ponds are susceptible to osteoporosis, hemiplegia and cancer (Chen 2007). Hence, adopting advanced ecological restoration methods is the key to controlling the ecological and environmental pollution caused by the Baotou light rare earth tailings pond.

Spray seeding is an important means in the field of ecological restoration, which make use of the self-recovery ability of the ecosystem, and is supplemented by artificial measures to gradually restore the original function and structure of the damaged ecosystem, thus being able to self-maintain positive succession and ecological balance. Up to now, the spray seeding methods that have been widely used mainly include soil spraying, vegetated concrete spray seeding, hydraulic spray seeding, and aggregate spray-seeding (Li et al. 2018; Wang et al. 2023). However, the effects of different spraying methods on soil and vegetation diversity of tailings pond are rarely reported, especially the long-term studies on different ecological restoration methods at the same site.

Therefore, in the current study, we assessed the effects of particle spraying, soil spraying, and natural restoration without artificial intervention on the soil's physical and chemical properties and vegetation community characteristics of the Baotou light rare earth tailings pond. Moreover, we calculated the comprehensive recovery score to provide a scientific basis for tailings management and ecological restoration.

Materials and methods

Overview of the study area

The Baotou light rare earth tailings pond is located at the confluence of the front of the alluvial-diluvial fan of the Hadmen Gully and the Kundurun River in Baotou City, Inner Mongolia Autonomous Region, China (109°41′E, 40°38′N) (Fig. 1). The local climate is characterized by long winters and short summers. The lowest average temperature in January is – 12.3 °C, and the average temperature in summer is 22.8 °C. The average annual precipitation is 308.9 mm, primarily concentrated from July to September, and the annual evaporation is 3242 mm (~ 10.5 times the precipitation).

The tailings pond is located in the transition zone between the temperate steppe and desert; the zonal wild plants surrounding the pond primarily include Compositae, Gramineae, Leguminous, and Chenopodiaceae, with a few shrubs. Before ecological restoration, the slope of the tailings pond had very little vegetation cover, including a few plants, such as *Caragana korshinskii* Kom., *Hippophae rhamnoides* L., *Ziziphus jujuba* Mill., *Ulmus pumila* L., and *Populus* L.

Ecological restoration overview in the study area

In this study, three different ecological restoration methods were performed in three sites, as follows.

The S1 site was located on the east side of the Baotou light rare earth tailings pond, with a slope length of 52.1 m and a slope of 23.6°. The vegetation restoration method "aggregate spray-seeding" was used, and the soil preparation was carried out using relevant proprietary equipment from Greesum Ecologi Co., Ltd. First, clay, organic material, plant fiber, and stabilizer were added to the spray seeding machine at a volume ratio of 4:2:4:0.01, and then added fertilizer, plant seeds, and an appropriate amount of water were added and stirred evenly for 6–12 min. The plant seeds included *Lespedeza daurica* (Laxm.) Schindl., *Amorpha fruticosa* Linn., *Hippophae rhamnoides* Linn., *C. korshinskii.*, *Caragana microphylla* Lam., *Nitraria sibirica* Pall., and *Haloxylon ammodendron*, and the amount of

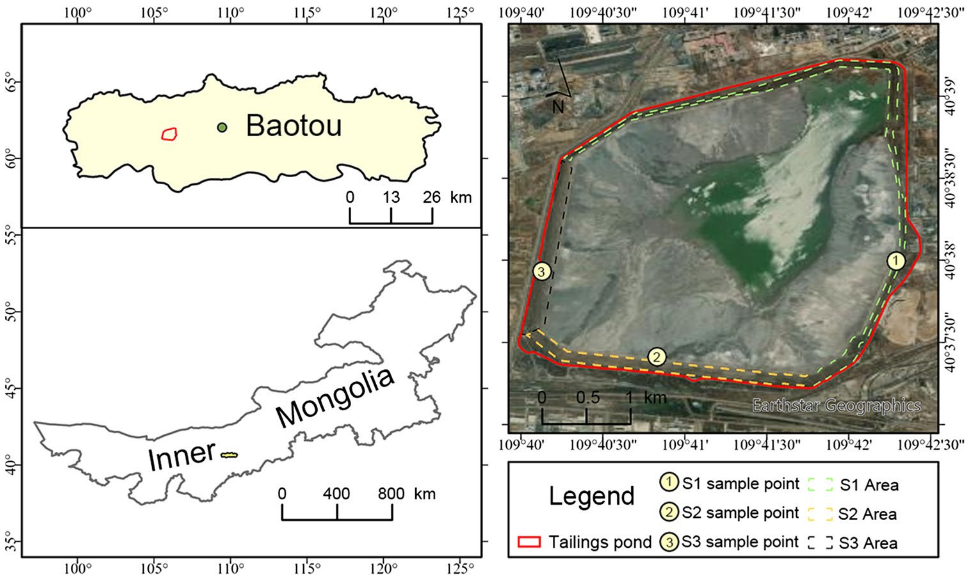

Fig. 1 Overview of the research area of the Baotou light rare earth tailings pond

spray plant seeds used was ≥ 30 g·m^{-2}. The fertilizer was a mixture of nitrogen, phosphorus, and potassium (N: P_2O_5: K_2O content ratio of 15%:15%:15%), and the amount of fertilizer used was ≥ 10 g·m^{-2}. Meanwhile, an appropriate amount of water was injected into another container of the spray seeding machine (15–30 °C), to which polisoil (polyacrylamide) was added and stirred evenly for 10–15 min. The two materials were mixed thoroughly with the nozzle to allow the pellet reaction to occurs. When the sprayed substrate covered the surface, the water and soil separated, and excess water was expelled. The thickness of the soil matrix sprayed was 5–7 cm.

The S2 site was located on the southern side of the Baotou light rare earth tailings pond, with a slope length of 99.2 m, sloping toward the south, and a slope of 18.5°. Using the "ordinary soil spraying" vegetation restoration method from Baotou Iron and Steel Group Greening Co., LTD., the clay, organic material, plant fiber, fertilizer, and seeds were mixed in the S1 treatment ratio and sprayed on the surface of the tailings dam after stirring. The seed configuration, seed dosage, and fertilizer addition amount were the same as those of S1. The difference between S2 and S1 is that S2 does not react with the stabilizer and polisoil when sprayed.

S3 was located on the west side of the Baotou light rare earth tailings pond, with a slope length of 95.3 m, sloping toward the west, and a slope of 14.6°. This was a naturally restored area without manual intervention and served as the control site. The S3 treatment differs from S1 and S2 as it is a natural recovery method that does not require human intervention.

Survey sample site setting and sample collection

The Baotou Steel rare earth tailings pond was repaired in July 2011. One month after ecological restoration (August 2011), four quadrates were randomly selected and marked in each ecological restoration area, and soil samples were collected using the five-point sampling method and brought back to the laboratory for analysis. The results are shown in Supplementary Table 1. One year after ecological restoration (July 2012), five 2 m × 2 m shrub sampling points were selected from the four quadrates marked in each ecological restoration area using the five-point sampling method, and 1 m × 1 m herb sampling points were randomly selected from each 2 m × 2 m shrub sampling point to calculate the plant emergence rate. The results are shown in Supplementary Table 2. After 10 years of ecological restoration (September 2021), soil and plant samples were collected from each sample sites. The type and number of vegetation species, length, width, height, and coverage of each plant in each quadrat were measured. The stones on the soil surface were removed, and using the ring knife collected samples, soil BD was determined, soil W was determined using the drying method (Gradwell 1972), and SP was calculated using soil BD and specific gravity. All the plant samples in the set sample site were weighed and brought back to the laboratory for air drying, and the vegetation biomass was measured using the quadrat harvest-dry weight method.

Measured parameters

After drying and sieving the soil samples, the physicochemical properties were analyzed. Total N (TN) was determined using the Kjeldahl method (NKY6120) (Bremner and Mulvaney 1982), pH and electrical conductivity (EC) were determined using the potentiometric method (PHBJ-261L) (Tavakoli et al. 2018), and soil organic matter (SOM) was determined using the potassium dichromate hydration heating method (DXY-2H) (Nelson and Sommers 1982). Total K (TK) was determined via flame atomic spectrophotometry (UV-9000S) (Bao 2000), total P (TP) was determined via $(NH4)_2M_0O_4$ spectrophotometry (Olsen and Sommers 1982), N was determined using the alkaline diffusion method (Stanford 1982), P was extracted using 0.5 $mol{\cdot}L^{-1}$ $NaHCO_3$ and quantified through spectrophotometry (UV-9000S) (Homer and Pratt 1962), and K was determined using CH_3COONH_4-flame atomic absorption spectrophotometry (UV-9000S) (Bower et al. 1952).

The importance value index represents the status and role of plant species in the community; the dominant species exhibit control over the community structure and formation of the community environment (Yin et al. 2022). The importance values were calculated using Eq. (1):

$$\text{Importance value(IV)} = \left(\text{relative cover} + \text{relative multiple degrees} + \text{relative frequency}\right)/3 \tag{1}$$

Plant communities in the Baotou light rare earth tailings pond were dominated by herbs and shrubs. Relative coverage, relative abundance, and relative frequency were selected as evaluation indices to calculate the importance values (Han et al. 2020) using Eqs. (2)-(5):

Margalef richness index Dm (Margalef 1958):

$$D_m = \frac{(S-1)}{lnN}, \tag{2}$$

Simpson advantage index D (Greenberg 1956):

$$D = 1 - \sum \frac{n_i\left(n_i - 1\right)}{N(N-1)}, \tag{3}$$

Shannon–Wiener diversity index H (Magurran 1988):

$$H = -\sum\nolimits_{i=1}^{s} P_i l_n P_i, \tag{4}$$

Pielou uniformity index J (Pielou 1975):

$$J = \frac{H}{lnN}, \tag{5}$$

where S is the number of species, N is the sum of the individuals of all species, ni is the number of individuals in the ith species, P is the proportion of individuals in the ith species, and H is the Shannon–Wiener diversity index.

The remote sensing image was generated using the global land cover data from the Sentinel-1 and Sentinel-2 Earth observation satellites of the European Aeronautics Agency (ESA) at a resolution of 10 m, taken in 2020. Land use data can be divided into 11 categories, namely, forest land, shrubs, grasslands, cultivated land, buildings, deserts, snow, ice, water bodies, wetlands, mangroves, moss, and lichens. After verification, the data accuracy reached 74.4%. Data statistical analysis and visualization were performed using the PIE Engine Explore Tool of the PIE Engine Studio platform (https://engine.piesat.cn/engine-studio/).

Statistical analysis

Data processing, statistical analysis, and sorting were performed using Microsoft Excel 2010. The vegetation characteristics and the soil physicochemical properties were analyzed using one-way analysis of variance (ANOVA) and significance tests, performed using the SPSS Statistics 23 (IBM, Armonk, NY, USA). Bar graphs were generated using the Origin 2023 (OriginLab, Northampton, MA, USA). Redundancy analysis (RDA) analysis was performed using the R language (version 3.6.3) and the "vegan" package (version 2.5–7).

Results

Vegetation biomass and diversity

The two ecological restoration methods in S1 and S2 significantly increased the ground vegetation biomass (Fig. 2) after 10 years of ecological restoration and, thus, increased the total biomass (Bio) of the restoration area. The aboveground biomass (UBio) of S1 was significantly higher than that of S2 and S3 by 202.96% and 1338.51%, respectively, and the aboveground biomass was significantly higher by 260.13% and 1378.66%, respectively. The biomass of S1 reached 158.42 $kg{\cdot}m^{-2}$, which was significantly higher than that of S2 and S3 by 215.20% and 1345.76%, respectively.

The Simpson and Shannon–Wiener indices of all three sites showed the same change trend in all quadrats; the overall performance was S1 > S3 > S2 (Fig. 3). The Margalef index was in the order S1 > S2 > S3, with S1 exhibiting significantly higher values than did S2 and S3 ($p < 0.05$). Notably, the Simpson, Shannon–Wiener, and Pielou indices of S2 were all lower than those of S3. Therefore, according to

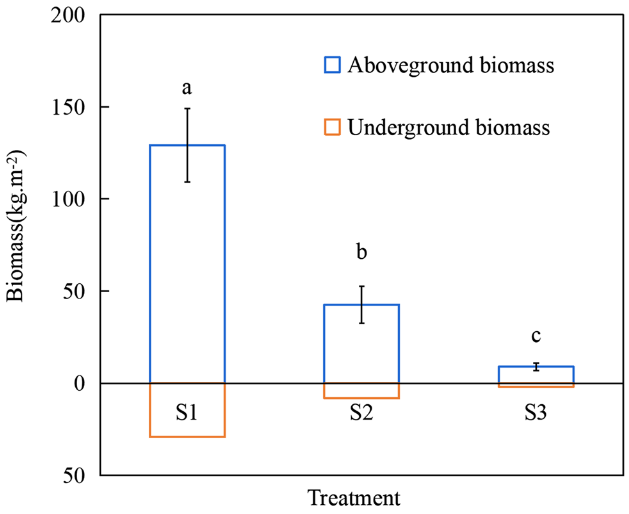

Fig. 2 Vegetation biomass under different ecological restoration methods of tailings ponds. S1: aggregate spray-seeding, S2: ordinary guest soil spraying, S3: naturally restored dam body slope area without manual intervention. Different lowercase letters indicate significant differences in aboveground plant biomass under different ecological restoration treatments ($p < 0.05$)

these indices, the S2 community formed through ecological restoration was the least stable.

Vegetation communities

Significant differences were observed in the plant community composition among S1, S2, and S3 (Table 1; Table 2; Fig. 4). The two species with the highest shrub importance value in S1 were *Caragana korshinskii Kom* (0.40) and *Caragana microphylla Lam* (0.25), and their corresponding species abundances were 38 and 35, respectively. In S2, although the importance values of *C. korshinskii* and *C. microphylla* were 0.34 and 0.43, respectively, their abundances were only 3 and 4, respectively. The frequency of *C. korshinskii* and *C. microphylla* reached 1.0 and 0.8, respectively, in S1 and decreased to 0.4 and 0.8, respectively, in S2, while no shrubs were found in S3. In terms of herbs, *Setaria viridis (L.) P. Beauv* had the highest importance value in S1 and S3, reaching 0.32 and 0.49, respectively, while *Artemisia argyi H. Lév. and Vaniot* had an evident advantage in S2, with its importance value reaching 0.43. In general, the different ecological restoration methods resulted in different vegetation community structures; particularly, S1 was covered by a large amount of *C. korshinskii* and *C. microphylla*, whereas S2 was covered by tall herbs, including *Artemisia argyi*, and S3 was only covered by *Setaria viridis (L.) P. Beauv* and *Salsola collina Pall*.

Soil physical and chemical properties

The result showed that W, SP, EC, SOM, and K content exhibited a significant gradient: S1 > S2 > S3. The BD and P of S1 were significantly reduced compared to those of S3, and there were no differences in pH, TK, or N (Table 3). Compared with those in S2 and S3, the SP in S1 increased significantly by 11.03% and 13.07%, respectively, and W increased significantly by 54.67% and 114.97% ($p < 0.05$), respectively. The EC of S1 was significantly higher by 35.93% and 119.58% than that of S2 and S3, respectively, while the BD of S1 was significantly lower by 6.38% and 9.93% than that of S2 and S3, respectively. In terms of soil chemistry, the SOM of S1 was significantly increased by 5.19% and 11.51% compared to that of S2 and S3, respectively, and K increased by 22.39% and 16.46%, respectively. In addition, there was no significant difference in TN between S1 and S3, and they were significantly lower than S2. Thus, the physicochemical properties of the soil after aggregate spray-seeding ecological restoration are optimal for plant growth.

Fig. 3 Differences in vegetation diversity under different ecological restoration treatments of tailings ponds. S1: aggregate spray-seeding, S2: ordinary guest soil spraying, S3: naturally restored dam body slope area without manual intervention. Different lowercase letters indicate significant differences in vegetation diversity under different ecological restoration methods ($p < 0.05$)

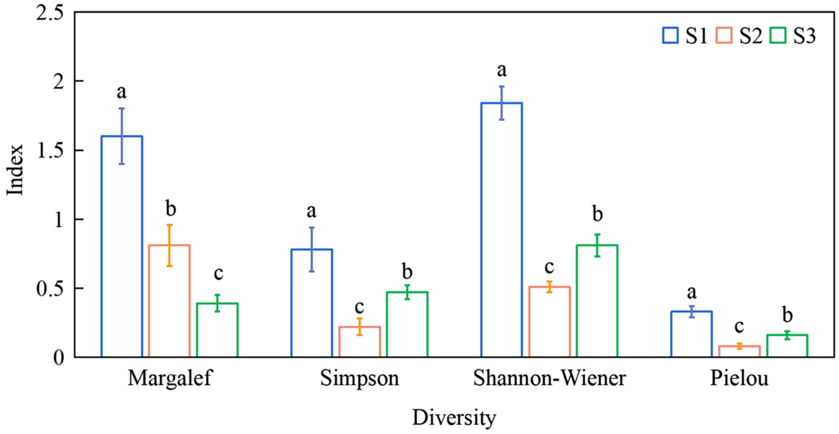

Table 1 Vegetation characteristics under different ecological restoration methods of tailings ponds

Classification	Species	Abundance			Frequency			Cover degree		
		S1	S2	S3	S1	S2	S3	S1	S2	S3
Shrub	Caragana korshinskii Kom	38.4 ± 9.2a	3.0 ± 2.0b	-	1.0 ± 0a	0.4 ± 0.2b	-	0.43 ± 0.05a	0.43 ± 0.03a	-
	Caragana microphylla Lam	35.0 ± 6.0a	4.0 ± 1.7b	-	0.8 ± 0.2a	0.8 ± 0.2a	-	0.1 ± 0.03a	0.1 ± 0.02a	-
	Corethrodendron scoparium Fisch. et Basiner	7	-	-	0.4	-	-	0.04	-	-
	Lespedeza daurica (Laxm.) Schindl	8	-	-	0.6	-	-	0.18	-	-
	Tamarix chinensis Lour	5	-	-	0.2	-	-	0.02	-	-
Herb	Artemisia caruifolia Buch-Ham. ex Roxb	12.0 ± 3.6a	16.0 ± 4.0a	-	0.4 ± 0.2a	0.4 ± 0.2a	-	0.03 ± 0.02a	0.03 ± 0.01a	-
	Artemisia argyi H. Lév. & Vaniot	9.0 ± 2.6b	432.0 ± 45.5a	-	0.6 ± 0.2a	1.0 ± 0a	-	0.03 ± 0.02a	0.03 ± 0.02a	-
	Solanum nigrum L	11.0 ± 2.0a	5.0 ± 1.0b	-	0.4 ± 0.2b	0.8 ± 0.2a	-	0.04 ± 0.01a	0.02 ± 0b	-
	Setaria viridis (L.) P. Beauv	108.4 ± 12.6a	30.2 ± 4.1b	-	1.0 ± 0a	0.4 ± 0.2b	-	0.02 ± 0.01a	0.02 ± 0a	-
	Asparagus cochinchinensis (Lour.) Merr	42	-	-	0.4	-	-	0.02	-	-
	Salsola collina Pall	-	-	36	-	-	1	-	-	0.02
	Setaria viridis (L.) P. Beauv	-	-	121	-	-	1	-	-	0.02
	Cuscuta chinensis Lam	-	-	18	-	-	0.6	-	-	0.01

S1: aggregate spray-seeding, S2: ordinary guest soil spraying, S3: naturally restored dam body slope area without manual intervention. Different letters indicate difference between different ecological restoration methods according to Duncan method ($p < 0.05$)

Correlation between soil physicochemical properties and vegetation diversity index

The contribution of the first RDA axis accounted for 85.49%, that of the second axis accounted for 14.02%, and the cumulative variance contribution of the first two axes accounted for 99.51% (Fig. 5). Factors such as BD, W, N, and K were distributed along the first axis, whereas TN, TK, TP, and P were distributed along the second axis. The first two axes of the RDA reflected the comprehensive influence of multiple environmental factors. The first axis of the RDA primarily reflected changes in plant community diversity along the gradient of soil physical indices. The second-order axis of the RDA generally reflected changes in the plant community distribution pattern in the soil nutrient gradient.

Redundancy analysis showed that SP and W were positively correlated with aboveground biomass and total vegetation biomass, as well as the Shannon, Pielou, and Simpson indices, whereas BD was negatively correlated with the aboveground biomass, total vegetation biomass, Shannon, Pielou, and Simpson indices. Moreover, BD, W, and SP were the main factors affecting plant community characteristics. SOM, N, and K were positively correlated with plant biomass and diversity, whereas P was negatively correlated with the aboveground biomass, total vegetation biomass and Margalef indices, and TP was positively correlated with the aboveground biomass, total vegetation biomass, and Margalef indices. In addition, TN and TK were not significantly correlated with vegetation biomass.

Comprehensive scores of the ecological restoration methods

The principal component analysis revealed that among the first three principal components (Table 4), F1, F2, and F3 explained 56.95%, 25.36%, and 6.90% of the total variation, respectively, accounting for 89.21% of the variation. Combined with the coefficient score matrix of the two principal components, the extracted principal components were calculated to obtain the comprehensive score, F (Eq. (6)):

$$F = (56.95\% \times F1 + 25.36\% \times F2 + 6.90\% \times F3)/100\% \tag{6}$$

The comprehensive scores of the principal component analysis for the different ecological restorations were ranked S1 > S2 > S3. Moreover, S1 (0.983) had the highest scores for soil physicochemical properties and plant community diversity and the best restoration effect, followed by S2 (− 0.261). The F value of S3 was the lowest.

Table 2 Plant species importance values under different ecological restoration methods of tailings ponds

Sample plot	Classification	Species	Relative abundance	Relative frequency	Relative	Importance value
S1	Shrub	Caragana korshinskii Kom	0.41	0.33	0.47	0.40
		Caragana microphylla Lam	0.38	0.27	0.11	0.25
		Corethrodendron scoparium Fisch. et Basiner	0.08	0.13	0.04	0.08
		Lespedeza daurica (Laxm.) Schindl	0.09	0.20	0.20	0.16
		Tamarix chinensis Lour	0.05	0.07	0.02	0.05
	Herb	*Artemisia caruifolia* Buch-Ham. ex Roxb	0.07	0.14	0.03	0.08
		Artemisia argyi H. Lév. & Vaniot	0.05	0.21	0.03	0.10
		Solanum nigrum L	0.06	0.14	0.04	0.08
		Setaria viridis (L.) P. Beauv	0.59	0.36	0.02	0.32
		Asparagus cochinchinensis (Lour.) Merr	0.23	0.14	0.02	0.13
S2	Shrub	Caragana korshinskii Kom	0.43	0.33	0.27	0.34
		Caragana microphylla Lam	0.57	0.67	0.06	0.43
	Herb	*Artemisia caruifolia* Buch-Ham. ex Roxb	0.03	0.15	0.02	0.07
		Artemisia argyi H. Lév. & Vaniot	0.89	0.38	0.02	0.43
		Setaria viridis (L.) P. Beauv	0.06	0.15	0.01	0.08
		Solanum nigrum L	0.01	0.31	0.01	0.11
S3	Herb	Salsola collina Pall	0.21	0.38	0.40	0.33
		Setaria viridis (L.) P. Beauv	0.69	0.38	0.40	0.49
		Cuscuta chinensis Lam	0.10	0.23	0.20	0.18

S1: aggregate spray-seeding, S2: ordinary guest soil spraying, S3: naturally restored dam body slope area without manual intervention

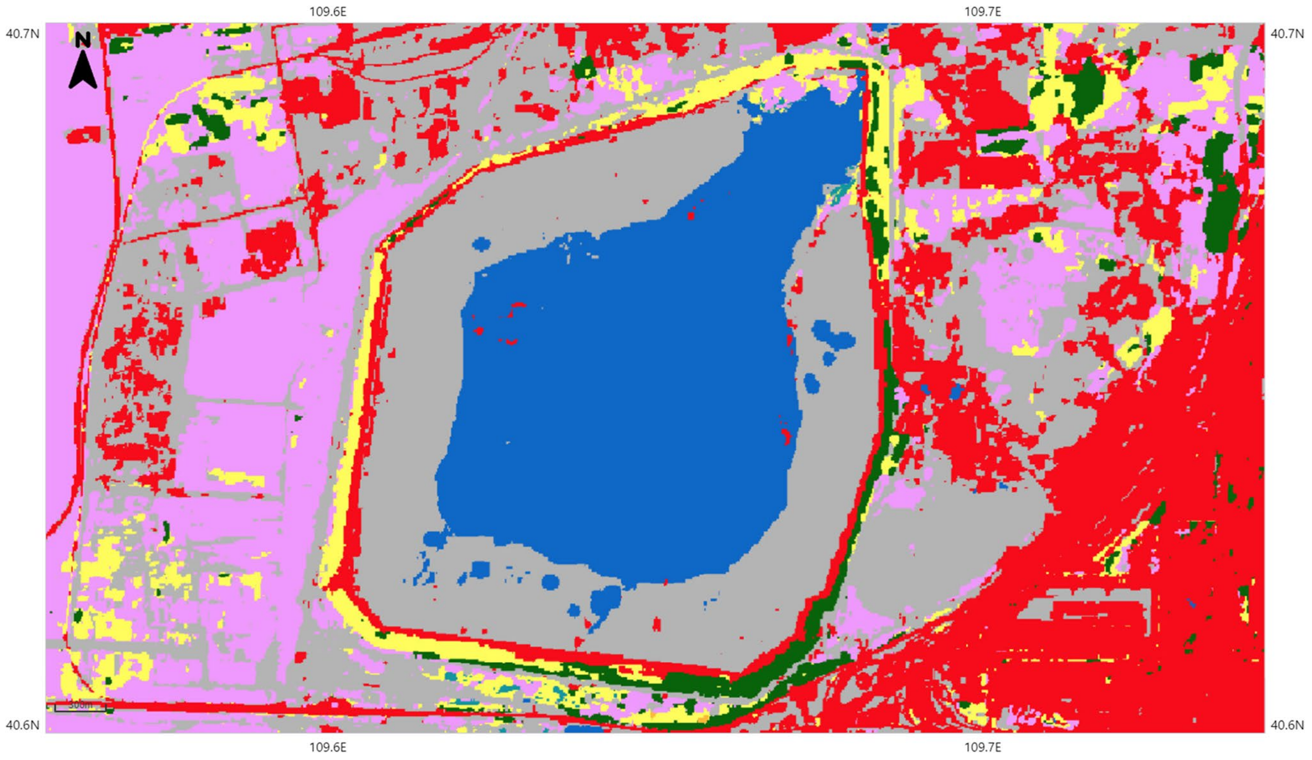

Fig. 4 Remote sensing of vegetation. In the 2020 remote sensing map, green represents woody plants, yellow represents herbs, red represents buildings or roads, gray represents desert (mineral fines), and blue represents water body

Table 3 Physical and chemical properties of soil under different ecological restoration methods of tailings ponds

Index	S1	S2	S3
W (%)	7.61 ± 0.42 a	4.92 ± 0.65 b	3.54 ± 0.33 c
BD ($g \cdot kg^{-1}$)	1.41 ± 0.05 b	1.50 ± 0.05 a	1.55 ± 0.04 a
SP (%)	46.79 ± 0.02 a	43.39 ± 0.03 b	41.38 ± 0.01 c
EC (μs/cm)	460.3 ± 71.34 a	338.63 ± 32.22 b	209.63 ± 90.91 c
SOM ($g \cdot kg^{-1}$)	23.73 ± 0.20 a	22.56 ± 0.48 b	21.28 ± 0.54 c
TN ($g \cdot kg^{-1}$)	0.30 ± 0.03 b	0.40 ± 0.08 a	0.28 ± 0.04 b
TP ($g \cdot kg^{-1}$)	0.68 ± 0.04 a	0.70 ± 0.04 a	0.58 ± 0.04 b
TK ($g \cdot kg^{-1}$)	3.02 ± 0.18 a	4.61 ± 1.70 a	3.14 ± 0.27 a
N ($g \cdot kg^{-1}$)	14.29 ± 0.07 a	14.25 ± 0.02 a	14.25 ± 0.02 a
P ($g \cdot kg^{-1}$)	85.05 ± 7.64 b	85.50 ± 3.34 b	109.70 ± 12.01 a
K ($g \cdot kg^{-1}$)	73.36 ± 3.39 a	59.94 ± 3.86 b	62.99 ± 2.50 c
pH	7.62 ± 0.11a	7.43 ± 0.09 a	7.67 ± 0.14 a

S1: aggregate spray-seeding, S2: ordinary soil spraying, S3: naturally restored dam body slope area without manual intervention, *W* water content, *BD* soil bulk density, *SP* soil porosity, *EC* soil electric conductivity, *SOM* soil organic matter, *TN* total nitrogen, *TP* total phosphorus, *TK* total potassium, *N* available nitrogen, *P*: available phosphorus, *K* available potassium

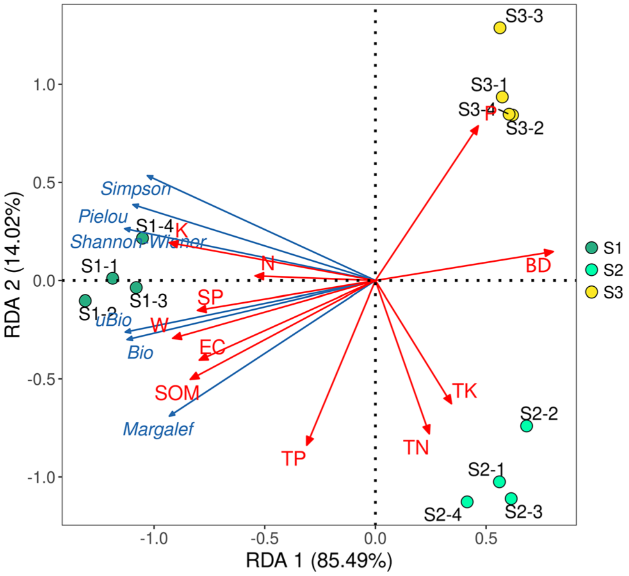

Fig. 5 Analysis of plant diversity and redundancy of environmental factors in the ecological restoration of tailings ponds. S1: aggregate spray-seeding, S2: ordinary guest soil spraying, S3: naturally restored dam body slope area without manual intervention, W, water content; BD, soil bulk density; SP, soil porosity; EC, soil electric conductivity; TN, total nitrogen; TP, total phosphorus; TK, total potassium; N, available nitrogen; P, available phosphorus; K, available potassium; SOM, soil organic matter; UBio, aboveground biomass; Bio, total biomass

Discussion

Vegetation biomass and diversity

As an important component of the ecosystem, the plant community is the primary target for the ecological restoration of tailings ponds (Shan et al. 2019). In the present study, the aboveground and underground biomasses of the restored site were significantly increased by the two ecological restoration methods compared with that of the naturally restored dam slope area after 10 years (Fig. 2). Moreover, the S1 exhibited the highest plant biomasses and diversity indices (Figs. 2 and 3), and a superior restoration effect. Indeed, the aggregate spray-seeding method used to treat the S1 site significantly improved the diversity of the vegetation community and resulted in high community stability. This may be due to the artificial soil formed as a result of the spraying method, covering the surface of the mineral fines. Artificial soil provides appropriate soil physical properties for plant growth (Supplementary Table 1), effectively prevents the toxic effects of mineral fines heavy metals, alleviates wind erosion, increases the survival rate of plants (Ceccon et al. 2003; Davidson et al. 2004), and significantly increases the biomass and diversity of vegetation. Indeed, the physical and chemical properties of soil substrates markedly influence the succession of plant communities during ecological restoration (Stuble et al. 2017; Powers and Marín-Spiotta 2017). The woody plants primarily included *C. korshinskii*, which prolifically propagated in S1 to become the dominant species after 10 years of ecological restoration, generating a large biomass. In contrast, the S2 site contained a few woody plants and many herbs, while S3 was devoid of woody plants, resulting in relatively low biomass in S2 and S3. This result was also confirmed by the 2020 remote sensing data (Fig. 4). Collectively, these findings indicate that different ecological restoration methods have unique effects on vegetation biomass and diversity, which impacts the direction of the plant ecological succession (Supplementary Fig. 2).

Vegetation community characteristics

After 10 years, S1 and S2 formed different community structures under the same seed bank conditions. This indicates that ecological restoration measures have important effects on the formation of plant community structures in tailings ponds as the artificial soil covers the surface of mineral fines, blocking the toxic effect of heavy metals on plant seeds. Artificial soil adhesion and erosion resistance occurring due to spraying can effectively prevent soil erosion, retain more seeds and nutrients (Huang et al. 2018; Ai et al. 2021), provide better site conditions for plant growth, and form different plant communities (Siddique et al. 2010; Campanharo et al. 2020).

Table 4 Comprehensive scores of the main components in different ecological restoration areas of the Baotou Steel tailings pond

	F1	F2	F3	F
S1	0.623	0.237	0.123	0.983
S2	−0.251	0.063	−0.074	−0.261
S3	−0.302	−0.280	−0.066	−0.648

S1: aggregate spray-seeding, S2: ordinary soil spraying, S3: naturally restored dam body slope area without manual intervention

Although the seed and fertilizer conditions of the spray sowing method were the same between S1 and S2, the soil adhesion, erosion resistance, fertilizer, and water retention ability were relatively poor without the agglomeration reaction in S2. This resulted in a low survival rate of woody plants such as *C. korshinskii* in the early restoration period (Supplementary Table 2). Instead, the living space and resources of woody plants, such as *C. korshinskii*, were occupied by many herbaceous plants, thus forming a vegetation community dominated by herbaceous plants.

The unsprayed plants *Tamarix*, *Artemisia caruifolia*, and *Artemisia argyi* are the main native plants at the Baotou light rare earth tailings pond (Gioria et al. 2012; Gioria and Pyšek 2015). However, the seeds do not germinate due to the deficiency in nutrients (e.g., N, P, K) and high metal concentrations of tailing fines (Li et al. 2019). Under the influence of natural factors, human factors, and animal migration, external seeds may be brought into tailings ponds (Tropek et al. 2010). Following ecological restoration, the soil environment was improved, allowing *Tamarix*, *Artemisia caruifolia*, *Artemisia argyi*, and *Setaria viridis* seeds to germinate, and significantly increasing the plant diversity index of the tailings pond. A community structure dominated by woody plants was formed under treatment with aggregate spray-seeding, which altered the vegetation community structure in the restoration area and accelerated the succession process of the vegetation community.

Soil physicochemical properties

Soil physicochemical properties are important environmental factors that impact plant growth (Estrada et al. 2019; Van et al. 2018). In the present study, the S1 treatment significantly increased the survival rate of seeds (Supplementary Table 2), thus increasing the aboveground and underground biomasses (Fig. 2). The roots of underground vegetation have strong penetrability and water absorption ability, and they can also promote the formation of water-stable aggregates and improve soil porosity, resulting in increased W (Deng et al. 2008), which is consistent with the results of this study. Large underground vegetation biomass increased W and SP and decreased BD in S1. In S2 and S3, the ordinary guest soil without aggregate reaction and exposed mineral fines was easily lost following wind and rainfall. Consequently, the water storage and fertilizer retention ability of soils in S2 and S3 were poor, and the plant biomass was low. Thus, the physical properties of these soil were relatively poor.

The SOM in the S1 site was significantly higher than that in the S2 and S3 sites, potentially due to a large amount of aboveground litter and belowground secretions of woody plants, such as *C. korshinskii*, that were returned to the soil over the 10-year ecological restoration period. This would have significantly increased the organic matter content under the aggregate spray-seeding method. Moreover, the K content in S1 was significantly higher than that in S2 and S3. K provides nutrients to crops in the form of ions in the soil, and its high mobility leads to K leaching loss being the main reason for soil K loss, particularly in soils with heavy precipitation and poor soil and water conservation (Lehmann and Schroth 2003). Compared with those in S1, there were fewer woody plants in S2 and no woody plants in S3. Therefore, sparse woody plants and a few herbaceous plants cannot achieve effective soil K retention through roots, and their resistance to rain erosion is limited, resulting in high K leaching loss caused by rain. Meanwhile, the large number of *Caragana* roots in the S1 site likely provided strong water and soil conservation ability. In particular, from the perspective of the root structure of *Caragana*, a large number of epidermal cells protrude outward to form root hairs. Plant root hairs can significantly reduce soil erosion when the root density is sufficiently high (Baets et al. 2020). Therefore, in future ecological restoration work, plant root microstructure can also be used for plant seed screening to facilitate an increase in soil and water conservation capacity.

The TN content in S1 did not significantly improve compared to that of S3 and was significantly lower than that of S2. This may have been due to *Caragana korshinskii Kom* and *Caragana microphylla Lam* being the dominant species in S1, which produce a large amount of litter and root secretions to provide sufficient nutritional conditions for the spore division of the eutrophic bacterium *Bacillus*. The proliferation of *Bacillus* accelerates the mineralization and release of N and enables the nitrogen in the soil to be absorbed and utilized by plants, thus reducing the TN content in S1 and increasing the vegetation biomass; a high abundance of *Bacillus* and its secretions in the plant's roots accelerated the mineralization and release of N, resulting in most soil N being absorbed and utilized by plants, generating a large amount of plant aboveground biomass (Fig. 2; Supplementary Fig. 3) (Campanharo et al. 2020; Chen et al. 2023). Conversely, S2 comprised the same organic material as that of S1; however, the S2 site primarily contained herbaceous plants with less conversion and utilization of N in the soil, resulting in a relatively high TN content.

In conclusion, different ecological restoration methods lead to different vegetation community structures due to different initial substrates. Subsequently, the vegetation community structure leads to significant differences in the physical and chemical properties of soil.

Correlation between soil physicochemical properties and vegetation community characteristics

Soil properties have important effects on plant community characteristics (Chodak and Niklińska 2010). In the present study, redundancy analysis showed that SP and W were positively correlated with aboveground and total biomass, Shannon, Pielou, and Simpson indices, whereas BD was negatively correlated with the Shannon, Pielou, and Simpson indices, indicating that BD, W, and SP were the main soil factors affecting plant community characteristics. This finding agrees with that of Vidal-Macua et al. (2020), who concluded that the restoration succession of vegetation was driven primarily by soil texture, soil erosion, and climatic conditions. In the ecological restoration area of tailings ponds, the aggregate soil provides better site conditions for plant growth, thereby promoting plant growth and increasing plant biomass and diversity. In turn, a large number of woody plants, including *Caragana*, exhibited a decrease in BD and an increase in SP and W content, effectively improving soil physical properties.

SOM is the material basis of soil fertility and can provide various nutrient elements to promote plant growth and development. In return, litter and root exudates formed by plants enter the soil and increase the SOM content (Kweon et al. 2013). Accordingly, in the present study, SOM content was positively correlated with plant biomass and diversity. In addition, N, P, and K are essential nutrients required for plant growth and are directly absorbed and utilized by plants as alkali-hydrolyzed N, available P, and available K, respectively (Marage and Gégout 2009; Ueda et al. 2017). Therefore, N and K contents were positively correlated with plant biomass and diversity, whereas TN and TK contents were not, which signifies that they were not directly absorbed or utilized by plants (Wu et al. 2016). Typically, soil restoration is the top priority of tailings pond ecological restoration. Indeed, good soil physical and chemical properties directly impact plant biomass, diversity, and community structure and, thus, improve the quality of ecological restoration.

Comprehensive score of different ecological restoration methods

Vegetation community diversity, soil physicochemical properties, and correlation analyses under different tailings pond ecological restoration methods do not systematically reflect the differences between the plant community structure and soil properties in the tailings pond restoration area (Tian et al. 2021). Thus, principal component analysis was used to comprehensively evaluate the tested indices to screen the ecological restoration methods with the best recovery effects and provide a theoretical basis for the ecological restoration of tailings ponds. S1 (0.983) had the highest score for soil physicochemical properties and plant community diversity as well as the best restoration effect, followed by S2 (−0.261) (Table 4). Although the restoration effect was significantly lower than that of S1, it was higher than that of S3. The *F* value of S3 was the lowest, indicating that the naturally restored area will require a longer recovery time, whereas appropriate artificial intervention can accelerate the formation of the plant community (Campanharo et al. 2020). Appropriate vegetation restoration techniques can be applied by rebuilding soil and seed banks on mineral fines, in order that (i) the slow primary succession transitions to rapid secondary succession; (ii) the biomass, plant community diversity, and soil structure of tailings ponds are improved; and (iii) the ecological benefit is increased.

Conclusions

Appropriate and reasonable artificial intervention measures can accelerate the formation of plant community structure and improve the soil structure, vegetation community diversity, and ecological benefit of the restored land. Under harsh site conditions, different methods of ecological restoration result in the generation of unique vegetation community structures, which affect the succession direction of the vegetation community. Redundancy analysis showed that the main driving factors affecting this result were W, SP, K, and SOM; appropriate artificial intervention can drive these environmental factors, accelerate the speed of vegetation recovery, and increase the diversity and stability of vegetation communities. After 10 years of ecological restoration, compared with ordinary soil spraying and natural restoration without manual intervention, the aggregate spray-seeding method with agglomeration significantly increased SP, W, SOM, and K; decreased BD; and formed a woody vegetation community dominated by *Caragana korshinskii Kom*. Thus, increasing the vegetation biomass and diversity of the restoration area. Meanwhile, the principal component analysis revealed that the aggregate spray-seeding method had the highest comprehensive score and evident restoration effect among the ecological restoration methods in this study.

This study provides a scientific reference for the ecological restoration of tailings ponds. However, certain limitations were noted. In particular, given that are no continuous research studies on the characteristics of plant communities over many years under different ecological restoration methods, future studies should include the influence of restoration on plant community structure across successive years.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-024-32295-0.

Author contribution Tianyu Chen and Chunlin Li: designing the experiment. Tianyu Chen and Jun Pan: performing research — analyzing data, and writing the first draft. Ning Qu and Jinxiao Wang: data curation, writing review and editing. Jiao Feng and Shilei Zhang: writing review and editing. Chunying Xu and Zhiquan Cao: given suggestions for data processing. Chunlin Li: conceptualization, supervision, funding acquisition.

Funding This work was supported by the National key research and development program (no. 2017YFD0504900) and the Qingdao People's Livelihood Science and Technology Project (no. 17–3-3–72-nsh).

Data availability The data will be made available upon request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Consent for publication was obtained from all participants.

Conflict of interest The authors declare no competing interests.

References

Ahirwal J, Maiti SK (2018) Development of technosol properties and recovery of carbon stock after 16 years of revegetation on coal mine degraded lands, India. CATENA 166:114–123. https://doi.org/10.1016/j.catena.2018.03.026

Ai X, Wang L, Xu D, Rong J, Ai S, Liu S, Li C, Ai Y (2021) Stability of artificial soil aggregates for cut slope restoration: a case study from the subalpine zone of southwest China. Soil and Tillage Research 209:104934. https://doi.org/10.1016/j.still.2021.104934

Baets SD, Denbigh TDG, Smyth KM, Eldridge BM, Weldon L, Higgins B, Matyjaszkiewicz A, Meersmans J, Larson ER, Chenchiah IV, Liverpool TB, Quine TA, Grierson CS (2020) Micro-scale interactions between arabidopsis root hairs and soil particles influence soil erosion. Commun Biol 3:1–11. https://doi.org/10.1038/s42003-020-0886-4

Bao SD (2000) Analysis of soil agrochemistry. China Agriculture Press, Beijing (in Chinese)

Bower CA, Reitemeier RF, Fireman M (1952) Exchangeable cation analysis of saline and alkali soils. Soil Sci 73:251–261. https://doi.org/10.1097/00010694-195204000-00001

Bremner JM, Mulvaney CS (1982) Nitrogen-total. Methods of soil analysis. Part 2. Chemical and Microbiological Properties, pp 595–624

Campanharo TF, Martins SV, Villa PM, Kruschewsky GC, Dias AA, Nabeta FH (2020) Effects of forest restoration techniques on community diversity and aboveground biomass on area affected by mining tailings in Mariana, Southeastern Brazil. Res Ecol 002:22–30

Ceccon E, Huante P, Campo J (2003) Effects of nitrogen and phosphorus fertilization on the survival and recruitment of seedlings of dominant tree species in two abandoned tropical dry forests in Yucatán, Mexico. For Ecol Manage 182:387–402. https://doi.org/10.1016/s0378-1127(03)00085-9

Chen T, Qu N, Wang J, Liu Y, Feng J, Zhang S, Xu C, Cao Z, Pan J, Li C (2023) Effects of different ecological restoration methods on the soil bacterial community structure of a light rare earth tailings pond. Plant and Soil 1–17. https://doi.org/10.1007/s11104-023-06295-x

Chen Z (2010) Thinking of China rare earth industry and technology development. Si Chuan Rare Earth 4:2–7 (in Chinese)

Chen Z (2007) Environmental behavior of rare earths, biological toxic effect and potential harm of agricultural application of rare earths. See: Chinese Society of Rare Earths. Proceedings of the 12th National Rare Earth Element Analytical Chemistry Academic Report and Symposium (1)[C]. Beijing:Chinese Society of Rare Earths,2007.227–229 (in Chinese)

Chodak M, Niklińska M (2010) The effect of different tree species on the chemical and microbial properties of reclaimed mine soils. Biol Fertil Soils 46:555–566. https://doi.org/10.1007/s00374-010-0462-z

Davidson EA, Reis de Carvalho CJ, Vieira ICG, Figueiredo RO, Moutinho P, Yoko Ishida F, Santos MTRO, Guerrero JB, Kalif K, Tuma-Sabá R (2004) Nitrogen and phosphorus limitation of biomass growth in in a tropical secondary forest. Ecol Appl 14:150–163. https://doi.org/10.1890/01-6006

Deng F, Kang Y, Yan Y, Wang D, Lv X, Sun P (2008) The study on ecological restoration of mining tailing pond in xiaoshuijing gold mine in Yunnan province. Ecol Econ 01:120–123

Dutta T, Kim KH, Uchimiya M, Kwon EE, Jeon BH, Deep A, Yun ST (2016) Global demand for rare earth resources and strategies for green mining. Environ Res 150:182–190. https://doi.org/10.1016/j.envres.2016.05.052

Estrada VS, Bailón M, Hall JS, Schnitzer SA, Turner BL, Caughlin TT, Van Breugel M (2019) Edaphic factors and initial conditions influence successional trajectories of early regenerating tropical dry forests. J Ecol 108:160–174. https://doi.org/10.1111/1365-2745.13263

Gioria M, Pyšek P, Moravcová L (2012) Soil seed banks in plant invasions: promoting species invasiveness and long-term impact on plant community dynamics. Preslia 84:327–350. https://doi.org/10.1105/tpc.112.099994

Gioria M, Pyšek P (2015) The legacy of plant invasions: changes in the soil seed bank of invaded plant communities. Biol Sci 66:40–53. https://doi.org/10.1093/biosci/biv165

Gradwell MW (1972) Methods for physical analysis of soils. New Zealand Soil Bureau Scientific Report No. 10C, DSIR, Wellington

Greenberg JH (1956) The measurement of linguistic diversity. Language 32:109–115

Han Y, Yang Y-M, Guo Z-L, Qu R-F (2020) Distribution of natural plant communities and the characteristics of their soil environments in xiaojinggou of Daqing mountains. J Arid Land Res Environ 34:115–121 (in Chinese). https://doi.org/10.13448/j.cnki.jalre.2020.337

Huang L, Zhang P, Hu Y, Zhao Y (2018) Soil water deficit and vegetation restoration in the refuse dumps of the heidaigou open-pit coal mine, Inner Mongolia, China. Sci Cold Arid Reg 8:22–35

Homer CD, Pratt PF (1962) Methods of analysis for soils, plants and waters. University of California, Agricultural Sci Press, Berkeley, pp 309. https://doi.org/10.1097/00010694-196201000-00015

Ivarez-Rogel J, Penalver-Alcala A, Gonzalez-Alcaraz MN (2022) Spontaneous vegetation colonizing abandoned metal(loid) mine tailings consistently modulates climatic, chemical and biological soil conditions throughout seasons. Sci Total Environ 831:10. https://doi.org/10.1016/j.scitotenv.2022.155945

Kweon G, Lund E, Maxton C (2013) Soil organic matter and cation-exchange capacity sensing with on-the-go electrical conductivity and optical sensors. Geoderma 199:80–89. https://doi.org/10.1016/j.geoderma.2012.11.001

Lee CG, Chon HT, Jung MC (2001) Heavy metal contamination in the vicinity of the daduk Au-Ag-Pb-Zn mine in Korea. Appl Geochem 16:1377–1386. https://doi.org/10.1016/s0883-2927(01)00038-5

Lehmann J, Schroth G (2003) Nutrient leaching. In: Schroth G, Sinclair EL (eds) Trees, crops, and soil fertility: concepts and research methods. CAB International, Wallingford, UK, pp 151–166

Li R, Zhang W, Yang S, Zhu M, Kan S, Chen J, Ai X, Ai Y (2018) Topographic aspect affects the vegetation restoration and artificial soil quality of rock-cut slopes restored by external-soil spray seeding. Sci Rep 8:12109. https://doi.org/10.1038/s41598-018-30651-y

Li C, Xu J, Chen S, Cao Z (2019) Risk assessment of heavy metal pollution in tailings reservoir soil of Baotou Iron and Steel company. World Nonferrous Metals 09:185–186 (in Chinese)

Liu K, Liu R, Liu Y (2019) A tailings pond identification method based on spatial combination of objects. IEEE J. Selected Topics. Appl Earth Observ Remote Sensing. pp 1–11. https://doi.org/10.1109/jstars.2019.2904297

Magurran AE (1988) Why diversity? Ecological diversity and its measurement. Springer Nether-lands, Dordrecht, pp 1–5

Marage D, Gégout JC (2009) Importance of soil nutrients in the distribution of forest communities on a large geographical scale. Glob Ecol Biogeogr 18:88–97. https://doi.org/10.1111/j.1466-8238.2008.00428.x

Margalef R (1958) Information theory in ecology. Int J Gen Syst 3:36–71

Neldner VJ, Ngugi MR (2017) Establishment of woody species across 26 years of revegetation on a Queensland coal mine. Eco Manag Restor 18:75–78. https://doi.org/10.1111/emr.12243

Nelson DW, Sommers LE (1982) Total carbon, organic carbon and organic matter. In: Page AL, Miller RH, Keeney DR (eds) Methods of soil analysis, Part 2. American Society of Agronomy, Madison, pp 539–579

Nordstrom DK (2011) Hydrogeochemical processes governing the origin, transport and fate of major and trace elements from mine wastes and mineralized rock to surface waters. Appl Geochem 26:1777–1791. https://doi.org/10.1016/j.apgeochem.2011.06.002

Nordstrom DK, Blowes DW, Ptacek CJ (2015) Hydrogeochemistry and microbiology of mine drainage: an update. Appl Geochem 57:3–16. https://doi.org/10.1016/j.apgeochem.2015.02.008

Olsen SR, Sommers LE (1982) Phosphorus: phosphorus soluble in sodium bicarbonate. In: Page AL, Miller RH, Keeney DR (ed) Methods of soil analysis, Part 2, Chemical and Microbiological Properties, 2nd ed. Am Soc Agron, Madison, WI, pp 421–422

Pan S (2010) A research on the stability of Baogang tailings dam. China university of Geosciences, Beijing (in Chinese)

Pielou EC (1975) Ecological diversity. Wiley, New York

Pourret O, Lange B, Bonhoure J, Colinet G, Decrée S, Mahy G, Séleck M, Shutcha M, Faucon MP (2016) Assessment of soil metal distribution and environmental impact of mining in Katanga (Democratic Republic of Congo). Appl Geochem 64:43–55. https://doi.org/10.1016/j.apgeochem.2015.07.012

Powers JS, Marín-Spiotta E (2017) Ecosystem processes and biogeochemical cycles in secondary tropical forest succession. Ann Rev Ecol Evol Syst 48:497–519. https://doi.org/10.1146/annurev-ecolsys-110316-022944

Prosdocimi M, Jordán A, Tarolli P, Keesstra S, Novara A, Cerdà A (2016) The immediate effectiveness of barley straw mulch in reducing soil erodibility and surface runoff generation in Mediterranean vineyards. Sci Total Environ 547:323–330. https://doi.org/10.1016/j.scitotenv.2015.12.076

Shan D, Xing E-D, Rong H, Liu Y-P, Liang Z-Q (2019) Ecological restoration of different vegetation collocations of coal mine dump in typical steppe. Chi J Ecol 38:336–342 (in Chinese). https://doi.org/10.13292/j.1000-4890.201902.019

Shen Z-J, Wang Y-P, Sun Q-Y, Wang W (2014) Effect of vegetation succession on organic carbon, carbon of humus acids and dissolved organic carbon in soils of copper mine tailings sites. Pedosphere 24:271–279. https://doi.org/10.1016/s1002-0160(14)60013-8

Siddique I, Vieira ICG, Schmidt S, Lamb D, Carvalho CJR, Figueiredo RO, Davidson EA (2010) Nitrogen and phosphorus additions negatively affect tree species diversity in tropical forest regrowth trajectories. Ecol 91:2121–2131. https://doi.org/10.1890/09-0636.1

Stanford G (1982) Nitrogen in agricultural soils. in: Stevenson FJ (ed) Am Soc Agron, Madison, Wisconsin, pp 651–688

Stuble KL, Fick SE, Young TP (2017) Every restoration is unique: testing year effects and site effects as drivers of initial restoration trajectories. J Appl Ecol 54:1051–1057. https://doi.org/10.1111/1365-2664.12861

Tang X, Li M, Yang D (2000) Landslide and its prevention of in situ leaching of ionadsorption rare earth minerals. Metal Mine 7:6–8 (in Chinese)

Tian Y-F, Liu D-Z, Chu H-J, Shi P-J, Ma W (2021) Soil physicochemical properties and vegetation community characteristic in a gold mine at ungulates wildlife nature reserve in Kalamaili mountain. Bulletin of Soil and Water Consesrvation 41:107–114 (in Chinese). https://doi.org/10.13961/j.cnki.stbctb.2021.05.015

Tavakoli M, Kooch Y, Akbarinia M (2018) The effect of degraded and reclaimed forest areas on carbon dioxide gas emissions and soil carbon mineralization in west of Mazandaran. International conferences of climate change and dendrochronology in Caspian ecosystems, Sari, Iran

Tropek R, Kadlec T, Karesova P, Spitzer L, Kocarek P, Malenovsky I, Banar P, Tuf IH, Hejda M, Konvicka M (2010) Spontaneous succession in limestone quarries as an effective restoration tool for endangered arthropods and plants. J Appl Ecol 47:139–147. https://doi.org/10.1111/j.1365-2664.2009.01746.x

Ueda Y, Konishi M, Yanagisawa S (2017) Molecular basis of the nitrogen response in plants. Soil Sci Plant Nutrition 63:329–341. https://doi.org/10.1080/00380768.2017.1360128

Vaezi AR, Ahmadi M, Cerdà A (2017) Contribution of raindrop impact to the change of soil physical properties and water erosion under semi-arid rainfalls. Sci Total Environ 583:382–392. https://doi.org/10.1016/j.scitotenv.2017.01.078

Van Breugel M, Craven D, Lai HR, Baillon M, Turner BL, Hall JS (2018) Soil nutrients and dispersal limitation shape compositional variation in secondary tropical forests across multiple scales. J Ecol 107:566–581. https://doi.org/10.1111/1365-2745.13126

Vidal-macua JJ, Manuel J, Vicente E, Moreno-de M (2020) Assessing vegetation recovery in reclaimed opencast mines of the Teruel coal field (Spain) using landsat time series and boosted regression trees. Sci Total Environ 717:137250. https://doi.org/10.1016/j.scitotenv.2020.137250

Wang Q-J (2019) The report of mineral resources saving & comprehensive utilization in China 2019. Geology Press. Beijing (in Chinese)

Wang Y, Shen Z, Zhang Z (2018) Phosphorus speciation and nutrient stoichiometry in the soil-plant system during primary ecological restoration of copper mine tailings. Pedosphere 28:530–541. https://doi.org/10.1016/s1002-0160(18)60031-1

Wang X, Li XG, Luo TY (2023) Application of high-order aggregate spray seeding technology in ecological restoration and treatment of exposed rock slope. China Mining Magazine 32:100–106. https://doi.org/10.12075/j.issn.1004-4051.2023.04.002

Wu X, Wu F, Zhou X, Fu X, Tao Y, Xu W, Pan K, Liu S (2016) Effects of inter-cropping with potato onion on the growth of tomato and rhizosphere alkaline phosphatase genes diversity. Front Plant Sci 7:846. https://doi.org/10.3389/fpls.2016.00846

Xiao R, Shen W, Fu Z, Shi Y, Xiong W, Cao F (2012) The application of remote sensing in the environmental risk monitoring of tailings pond: a case study in Zhangjiakou area of China. Proc Spie 8538:963–964. https://doi.org/10.1117/12.964380

Yin G-M, Ji C, Liu S-B, Yang F-L, Zhang Y, Mu Z-J, Zhao Y-W, Ma C-M, Lu P-F, Zhang J, Liu Y-L (2022) Responses of vegetation community characteristics and species diversity to different ecological restoration measures in Mu Us desertified grassland. Anim. Husb. Feed Sci 43:68–75 (in Chinese). https://doi.org/10.12160/j.issn.1672-5190.2022.01.011