J Arid Land (2023) 15(9): 1067–1083
https://doi.org/10.1007/s40333-023-0028-1

Science Press Springer-Verlag

Combination of artificial zeolite and microbial fertilizer to improve mining soils in an arid area of Inner Mongolia, China

LI Wenye[1], ZHANG Jianfeng[2], SONG Shuangshuang[3], LIANG Yao[4], SUN Baoping[1*], WU Yi[5], MAO Xiao[6], LIN Yachao[1]

[1] School of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China;
[2] China ENFI Engineering Co., Ltd., Beijing 100038, China;
[3] PIESAT Information Technology Co., Ltd., Beijing 100195, China;
[4] Key Laboratory of Deep-Earth Dynamics of Ministry of Natural Resources, Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China;
[5] Shanxi Dadi Minji Ecological Environment Co., Ltd., Beijing Branch, Beijing 100083, China;
[6] Bureau of Agriculture and Rural Affairs, Wangcheng District, Changsha 410211, China

Abstract: Restoration of mining soils is important to the vegetation and environment. This study aimed to explore the variations in soil nutrient contents, microbial abundance, and biomass under different gradients of substrate amendments in mining soils to select effective measures. Soil samples were collected from the Bayan Obo mining region in Inner Mongolia Autonomous Region, China. Contents of soil organic matter (SOM), available nitrogen (AN), available phosphorus (AP), available potassium (AK), microbial biomass carbon/microbial biomass nitrogen (MBC/MBN) ratio, biomass, and bacteria, fungi, and actinomycetes abundance were assessed in *Agropyron cristatum* L. Gaertn., *Elymus dahuricus* Turcz., and *Medicago sativa* L. soils with artificial zeolite (AZ) and microbial fertilizer (MF) applied at T0 (0 g/kg), T1 (5 g/kg), T2 (10 g/kg), and T3 (20 g/kg). Redundancy analysis (RDA) and technique for order preference by similarity to ideal solution (TOPSIS) were used to identify the main factors controlling the variation of biomass. Results showed that chemical indices and microbial content of restored soils were far greater than those of control. The application of AZ significantly increases SOM, AN, and AP by 20.27%, 23.61%, and 40.43%, respectively. AZ significantly increased bacteria, fungi, and actinomycetes abundance by 0.63, 3.12, and 1.93 times of control, respectively. RDA indicated that AN, MBC/MBN ratio, and SOM were dominant predictors for biomass across samples with AZ application, explaining 87.6% of the biomass variance. SOM, MBC/MBN ratio, and AK were dominant predictors with MF application, explaining 82.9% of the biomass variance. TOPSIS indicated that T2 was the best dosage and the three plant species could all be used to repair mining soils. AZ and MF application at T2 concentration in the mining soils with *M. sativa* was found to be the most appropriate measure.

Keywords: amendment; arid area; mining soils; restoration; soil nutrition

Citation: LI Wenye, ZHANG Jianfeng, SONG Shuangshuang, LIANG Yao, SUN Baoping, WU Yi, MAO Xiao, LIN Yachao. 2023. Combination of artificial zeolite and microbial fertilizer to improve mining soils in an arid area of Inner Mongolia, China. Journal of Arid Land, 15(9): 1067–1083. https://doi.org/10.1007/s40333-023-0028-1

1 Introduction

Frequent mining activities have greatly affected vegetation growth and soil conditions. Metal

*Corresponding author: SUN Baoping (E-mail: sunbp@163.com)
Received 2023-06-02; revised 2023-08-20; accepted 2023-08-26

mining produces large quantities of waste material, ranging from waste rock to fine tailings (Franks et al., 2011). Tailings and mine waste from metalliferous mining contain potentially toxic concentrations of trace elements, and they are susceptible to wind erosion (Suppes and Heuss-Aßbichler, 2021), resulting in contamination of surrounding ecosystems and food chains, finally endangering the humans' health (Wong, 2003). Moreover, toxic and oligotrophic tailings hinder plant restoration (Li and Huang, 2015). Mine wastes pose significant and long-term environmental risks without careful rehabilitation (Ledin and Pedersen, 1996). Previous studies found that depleted nutrients can be restored through appropriate soil management and reclamation strategies (Shrestha and Lal, 2010). Though the pollution extent varies across different mine types and areas, foundations of reclamation are homologous, and can be divided into *in situ* and *ex situ* techniques (Wang et al., 2015). The most common approaches are applying geomembranes and clean covers for chemical treatment of surface substrates, aiming to neutralize pH and immobilize metals. Amendments of soils is also regarded as a suitable approach to improve soil physical-chemical properties and largely shorten reclamation time (Wang et al., 2020a).

Recently, more studies focus on performing amendments. It has been proved as an effective way to improve soil nutrient content and microbial activity rapidly (Wang et al., 2020a). Organic and inorganic amendments are both effective for soil improvement. Amendments are conducive to establishing site-specific vegetation, stabilizing soil, controlling pollution, as well as removing threats (Wong, 2003). Due to potentially toxic elements near mining areas, plentiful additives have been applied to immobilize pollutants, such as compost, lime, coal fly ash, manure, phosphate fertilizers, biochar, clay minerals, and silica (Wu et al., 2016; Zhao et al., 2016; Palansooriya et al., 2020; Wang et al., 2020b). Actually, ideal outcomes are represented by organic and inorganic amendments. The amendments, used as immobilized agents, can also increase soil nutrients and water retention capacity, develop soil structure, enhance soil quality institute, and vegetation coverage (Celestina et al., 2019).

Organic soil additives are known to not only add deficient soil organic carbon (SOC) and nutrients but also replenish exogenous beneficial microorganisms (Hoang et al., 2021). They stimulate biological activity and vary soil energy, ultimately improve soil's ability to hold nutrients. By contrast, inorganic soil amendments bring nutrition through increasing soil pH and varying soil structure (Urra et al., 2020). Increasing pH results in abundant negative charges presenting on the surface of soil particles, which strongly attract metal cation to immobilize toxic metals (Zhao et al., 2022). In previous studies, the focus has been on the fixation and degradation of toxic elements, but the improvement of nutrients still needs to be discussed.

Artificial zeolite (AZ), a typical inorganic substance, was initially used as a solidification agent for heavy metals, though its application has become increasingly extensive (Rahimi et al., 2021). AZ emerged to meet the production and application output and efficiency needs (Li et al., 2022). However, whether it can promote the nutrient content still needs to be studied. Microbial fertilizer (MF) is an organic carbon fertilizer. Taking ground coal and dust powder as the carrier, it is a type of fertilizer compounded by multiple strains. Occasionally, MF has been shown to cause pollution and damage the soil, but it can also improve soil micro-environment and anti-corrosion ability (Urra et al., 2020). The mycorrhizal network of microorganisms in the soil promoted by MF can extend throughout the soil like a rope, gradually forming a large network that contributes to the formation and stability of soil aggregates; this has an extremely positive effect on the improvement of mining soils (Aparna et al., 2014). MF undoubtedly has a wide application potential in mining areas.

Previous study demonstrated that the effectiveness of additives strongly relates to both environmental and soil factors (Wu et al., 2021). In arid mining areas with broken soil structure, low water content, and excessive heavy metal content, the application of AZ and MF has been utilized in industry fields. Use of the above amendments for mining reclamation has not been widespread due to a lack of understanding their benefits, their availability at reclamation sites, application techniques, and apprehension about the results of field application. In this study, different potted experiments were set up to explore the effects of amendments on mining soils. Two amendments and three types of vegetation were used in this study. We specifically aim to explain the following questions: (1) variations in mining soils properties when adding varying rates and types of additives; (2) correlation between soil properties in restored mining soils; and (3) suitable amendment type, concentration, and combination of selected vegetation for use in arid mining areas.

2 Materials and methods

2.1 Study area

Bayan Obo mining region (41°39′–41°53′N, 109°47′–110°04′E) belongs to Inner Mongolia Autonomous Region, China. It is located 150 km north of Baotou City. The region belongs to inland dry climate zone, with an annual average temperature of 7.2°C, an annual average wind speed of 1.2 m/s, total annual precipitation of 421.8 mm, and 2882.2 h of sunshine.

Bayan Obo mining region covers an area of 328 km^2. It is a rare polymetallic symbiotic deposit with a range of 18 km long, 3 km wide, and 200 m high. More than 160 types of minerals and 70 types of elements have been found in the deposit. In recent years, over exploitation has result in serious damage to the environment.

2.2 Materials

2.2.1 Soils

Composite soil samples from 0 to 15 cm depth were collected using a 5-cm diameter auger. In each sampling plot, soil samples were collected at three sampling locations after stripping the litter. In each sampling location, five sub-samples were obtained at a range of 10 m×10 m to make a composite soil sample. The composite soil samples were sealed in plastic bags and transported to laboratory. Tiny stones were removed and samples were sieved the through a 2-mm mesh for measuring soil properties. Soil samples were air-dried under 25°C. More than 95% of the soil in the mining region is chestnut soil, and the rest is brown soil. The basic chemical properties of soil samples before experiment were pH 8.59, available nitrogen (AN) 30.95 mg/kg, available phosphorus (AP) 3.37 mg/kg, available potassium (AK) 41 mg/kg, soil organic matter (SOM) 9.12 g/kg, bacteria, fungi, and actinomycetes contents were 0.07×10^6, 0.04×10^5, and 0.07×10^6 CFU (colony forming unit)/g, respectively.

2.2.2 Amendments

AZ has high pore structure and cost:performance ratio, with excellent air permeability and water absorption ability. Thus, AZ is used as a water-retaining material and soil conditioner. AZ has been increasingly used in agriculture, especially in heavy metal-enriched areas, as a result of its excellent adsorption and buffer effect. AZ used in this test is produced by Chubu Electric Power Co., Inc., Nagoya, Japan from rice husk ash. It contained SiO_2 (43.86%), Al_2O_3 (30.76%), Na_2O (17.9%), and trace calcium (Ca), ferrum (Fe), magnesium (Mg), fluorum (F), and other elements. AZ is a non-toxic and pollution-free fertilizer. Specific surface area of AZ is 20.36 m^2/g, with pore diameter around 10.67–11.96 nm. It has a three-dimensional frame structure connected by silicon (aluminum) oxygen tetrahedrons. The lattice has strong openness and has cavities and channels of different sizes.

MF is highly efficient and long-lasting fertility in soils. MF can directly increase the nutrient elements and improve soil fertility. Microorganisms in MF accelerate humification in mining areas and further increase soil SOM and nutrients, especially absorbable phosphorus. MF used in this study was produced by Shanxi Green Promise Yongbao Rotten Fertilizer Co., Ltd., China from coal humic acids. Natural mineral nutrition–wheat rice powder (74 μm), natural zeolite powder (74 μm), and biological xanthohumate potassium–accounted for 30%, while weathered coal (74–149 μm) accounted for 70%. MF mainly consisted of humic acids, nitrogen (N), phosporous (P), potassium (K), and trace element like P, manganese (Mn), and zinc (Zn). Over 40% was made up of SOM, along with 20% humic acids, and 15% trace elements. The effective viable number of compound probiotics in this fertilizer was more than 500 million/g, with the main organisms being *Azotobacter*, *Rhizobium*, *Bacillus amylolyticus*, and *Bacillus subtilis*.

2.2.3 Plant species

Three types of herbaceous plants were selected in this study: *Agropyron cristatum* L. Gaertn., *Elymus dahuricus* Turcz., and *Medicago sativa* L.. They all had developed roots and are suitable for soil improvement in poor conditions, so they were chosen as test species. The quantitative sowing amount of each herb in each pot was 20 g. In the early survey, natural distribution in mining areas was found for all three plants. *A. cristatum* and *E. dahuricus* are gramineous plants, which are extremely cold and drought resistant. *M. sativa* is a leguminous plant that can coexist with *Rhizobium*, and play a synergistic role with MF in this study.

2.3 Experimental design

Potted plants were used in this study. The experiment was operated in the nursery of Beijing Forestry University, Beijing, China. AZ and MF were used as additives. Each amendment was set up using four dosages: T0 (0 g/kg), T1 (5 g/kg), T2 (10 g/kg), and T3 (20 g/kg). The non-amended group was labeled as T0 (0 g/kg). Each dosage was set up in triplicate. There were 72 potted plants of three types of plants. Specifications of the test pots were unified at an outer diameter of 0.2 m. After filling the basin with original soil from the Bayan Obo mining area, we mixed the amendment with surface soil at 0–10 cm depth. Seeds were sowed in the mixed soil, covered with a thin layer of raw soil. During plant growth, plants were watered twice a week in the first 8 weeks and once a week in the later period. The volume of water per pot was 1000 mL at each watering. Plants were planted in mid-June and harvested in mid-September. After 120 d of plant growth, nutrients in the soil and both aboveground and underground plant biomass were measured.

2.4 Soil analysis

2.4.1 Sample analysis

After taking out the plants from pot, we mixed 0–10 cm soil in the pot evenly, then took samples by quartering method, put the collected soil into a self-sealing bag and return it to the laboratory. The collected soil sample was divided into two parts. One part of fresh soil sample was stored in cold storage, and the number of microorganisms was measured immediately. The other part was dried naturally and then nutrients were determined. Plants were uprooted from pot and thoroughly washed by pure water, cleaned, and stored in paper bags. Measurement of the biomass was performed after drying. The determination of all indices was repeated for three times.

Chemical properties were determined by routine methods, the details are as follows: soil organic matter (SOM) content was measured by the method of potassium dichromate ($K_2Cr_2O_7$) oxidation, and AN content was measured by the method of alkaline hydrolysis diffusion. AP was extracted with 0.5 mol/L $NaHCO_3$ solution before being assayed. Finally, the colorimetric molybdenum blue method is used for obtaining AP content. The content of AK was extracted with 1 mol/L NH_4OAc and measured by flame photometry (Bao, 2000). We measured microbial biomass carbon and N using the method of fumigation-extraction (Brookes et al., 1985; Vance et al., 1987). We assessed microbial population (bacteria, fungi, and actinomycetes) based on Guo et al. (2012).

2.4.2 Data analysis by TOPSIS

Technique for order preference by similarity to ideal solution (TOPSIS) is a method based on a limited number of evaluation criteria that calculate the degree of proximity to ideal goals. It is widely used in assessing the comprehensive ranking of vegetation characteristics and soil nutrients. The steps to apply the TOPSIS method are listed as follows (Behzadian et al., 2012):

Step 1: create a matrix and its representation is expressed as:

$$X_{cd}=\begin{bmatrix} X_{11} & \cdots & X_{1d} \\ \vdots & \ddots & \vdots \\ X_{c1} & \cdots & X_{cd} \end{bmatrix}, \tag{1}$$

where X_{cd} is the matrix composed by alternatives and metrics; c is the number of alternative group, and d is the number of indicators.

Step 2: normalize the values in matrix X_{cd}. Normalized values of each element in matrix X_{cd} can be calculated as follows.

Positive indicators:

$$X'_{ij} = \frac{X_{ij} - \min\{X_{ij}\}}{\max\{X_{ij}\} - \min\{X_{ij}\}}, \tag{2}$$

and negative indicators:

$$X'_{ij} = \frac{\max\{X_{ij}\} - X_{ij}}{\max\{X_{ij}\} - \min\{X_{ij}\}}, \tag{3}$$

where X'_{ij} is the normalized positive index; X_{ij} is the tested value; $\max\{X_{ij}\}$ is the maximum of original number; and $\min\{X_{ij}\}$ is the minimum of original number. Normalization matrix constructed is expressed as:

$$X'_{cd} = \begin{bmatrix} X'_{11} & \cdots & X'_{1d} \\ \vdots & \ddots & \vdots \\ X'_{c1} & \cdots & X'_{cd} \end{bmatrix}, \tag{4}$$

where X'_{cd} is the normalized indicator.

Weighted value of normalized indicator r_{ij} is calculated using the following formula:

$$r_{ij} = w_i X'_{cd}, \tag{5}$$

where w_i is the weight of the indicator. This study uses the entropy weight method to calculate the weight value.

Step 3: ideal value A^+ is the combination of the ideal values (optimal values) of all indicators, while ideal negative value A^- is the combination of the worst values of all parameters. Ideal value A^+ and negative ideal value A^- are calculated using the following formulas:

$$A^+ = \{r_1^+, r_2^+, \cdots, r_d^+\}, \tag{6}$$

$$A^- = \{r_1^-, r_2^-, \cdots, r_d^-\}, \tag{7}$$

$$r_j^+ = \begin{Bmatrix} \max_j\{r_{ij}\}, \text{when } i \text{ is a positive indicator} \\ \min_j\{r_{ij}\}, \text{when } i \text{ is a negative indicator} \end{Bmatrix}, \tag{8}$$

$$r_j^- = \begin{Bmatrix} \max_j\{r_{ij}\}, \text{when } i \text{ is a negative indicator} \\ \min_j\{r_{ij}\}, \text{when } i \text{ is a positive indicator} \end{Bmatrix}, \tag{9}$$

where A^+ and A^- are positive ideal value and negative ideal value, respectively; r_j^+ is the maximum; and r_j^- is the minimum.

Step 4: Euclidean distances from r_{ij} to the ideal value A^+ and negative ideal value A^- are calculated using formulas 10 and 11, respectively:

$$D_j^+ = \sqrt{\sum_{j=1}^{n}\left(r_j^+ - r_{ij}\right)^2}, j = 1, 2, \cdots, n, \tag{10}$$

$$D_j^- = \sqrt{\sum_{j=1}^{n}\left(r_{ij} - r_j^-\right)^2}, j = 1, 2, \cdots, n, \tag{11}$$

where D_j^+ is the distance between the evaluation object and maximum; and D_j^- is the distance between the evaluation object and minimum.

Step 5: proximity coefficient is calculated using Equation 12. The larger the proximity coefficient, the closer the profile is to the ideal profile:

$$C_j = \frac{D_j^-}{D_j^+ + D_j^-}, \tag{12}$$

where C_j is the normalized score.

In terms of comprehensive improvement effect, a higher D_j^- value and lower D_j^+ value lead to a higher C_j value, indicating a better restoration effect, and vice versa.

3 Results

3.1 Changes in plant growth and soil properties

In pot experiment, treatments with additives significantly influenced SOM, biomass, AN, AP, and AK in mining soils (P<0.05; Fig. 1). For *M. sativa*, no significant changes in SOM were found with different AZ amendments though the application of AZ significantly increased SOM content from T0 to T2 by 10.61%–20.27%. For MF amendment, SOM in *M. sativa* soils varied from 9.60% to 28.65%. SOM in *M. sativa* had different responses to changes in additives. As shown in Figure 1b, AZ and MF amendments both significantly increased biomass. For *E. dahuricus*, the same amount of additive resulted in a large difference in biomass, in T3, *E. dahuricus* biomass difference with different amendments reached 5.4 g/pot. The other plants, *A. cristatum* and *M. sativa*, had lower differences when compared with *E. dahuricus*. In addition, soil AN contents of T1 and T2 treatments with *E. dahuricus* were 10.28% and 16.67% higher, than that of T0 treatment. Similar results were observed in *A. cristatum*, where available nutrients increased significantly in AZ treatment compared with T0 treatment (P<0.05).

Compared with no amendments (T0), the application of MF significantly increased AN, AP, and AK in mining soils planted with *A. cristatum, E. dahuricus*, and *M. sativa*. Under T1 and T2 treatments, both dosages with AZ amendment resulted in higher AP than those of T0 treatment in *A. cristatum* and *M. sativa* soils, with great significant differences among these treatments. In contrast, AP in *E. dahuricus* soils had an opposite trend under the same treatment, varying from 33.4 to 39.8 mg/kg. Interestingly, in *M. sativa* soils, AP under T0 treatment did not differ significantly from that under T1 treatment with MF, but differed significantly compared with that under T2 and T3 treatments. The maximum AP was found under T1 treatment (38.72 mg/kg). AK contents treated with MF in *A. cristatum* soils were greater than those of control treatment, but no significant difference was found among T0–T3 treatments. AK reached its maximum (87.3 mg/kg) under T2 treatment. When two amendments were applied to three types of plant soils, the variation of soil nutrients with MF is relatively stable, but change rate with AZ is relatively fast.

According to the National Standard for Classification of Soil Nutrient Content, AN content in the mining soils before improvement was low. After treatment, the content reached a high concentration, and some measurements even reached the upper medium, which proves that the application of amendments improved nutrient content to some extent. Similar results were found in AP, SOM, and AN. The application of additive improved AK content, but its variation extent was not as large as those of SOM and AN.

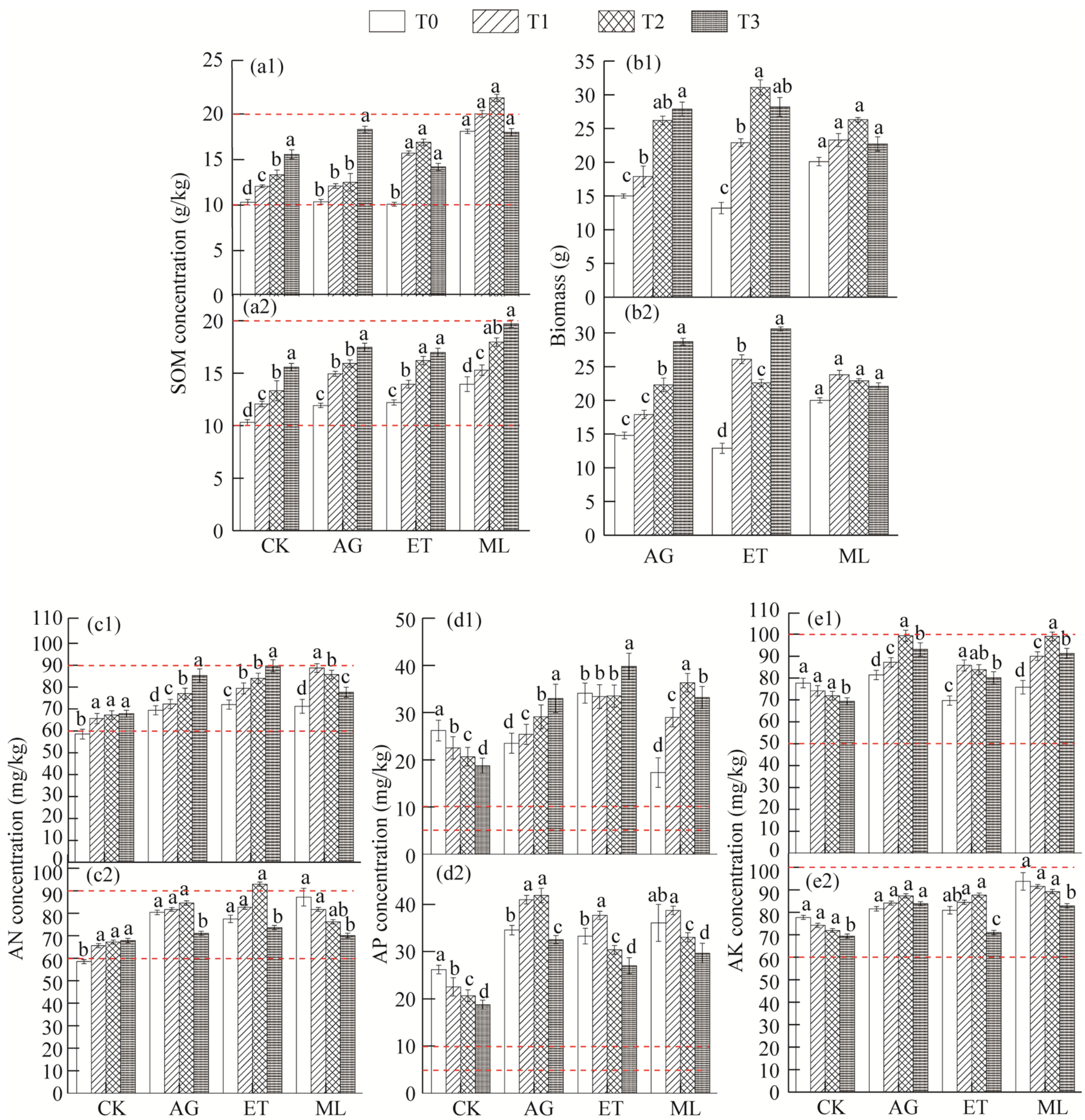

Fig. 1 Soil nutrients and biomass of different plants with the application of artificial zeolite (AZ, a1–e1) and microbial fertilizer (MF, a2–e2). CK, control; AG, *Agropyron cristatum* L. Gaertn.; ET, *Elymus dahuricus* Turcz.; ML, *Medicago sativa* L.; SOM, soil organic matter; AN, available nitrogen; AP, available phosphorous; AK, available potassium; T0, 0 g/kg; T1, 5 g/kg; T2, 10 g/kg; T3, 20 g/kg. Different lowercase letters within the same treatment indicate significant difference among different amended concentrations of AZ and MF. The red dotted line represents nutrient classification. Bars are standard errors.

3.2 Effects of amendments on microbial properties

As shown in Table 1, both AZ and MF application significantly increased soil microbial biomass (C/N) and microorganism, including bacteria, fungi, and actinomycetes. The largest increases in soil microbial biomass and bacterial population were observed under T2 or T3 treatment. All treatments in *A. cristatum* soils did not significantly affect MBC/MBN ratio, although AZ amendment led to a continuous increase in microorganism. When AZ and MF were applied, MBC/MBN ratio changed within the range of 0.67–14.00 and 4.31–18.16, respectively. Similarly, when applying AZ, MBC/MBN ratios under T1, T2, and T3 treatments in *A. cristatum* soils were not significantly different in comparison to T0 treatment. In *A. cristatum* soils, actinomycetes increased by 19.3% and 22.8%, respectively when AZ and MF were applied. When MF was added to soils with *E. dahuricus* and *M. sativa*, there were no significant differences among four treatments. There were more actinomycetes in *A. cristatum* soils than those of other plants, with no difference between AZ and MF, for example, when AZ was applied, actinomycetes in *A. cristatum* soil were 1.35 and 1.80 times higher than those in *E. dahuricus* and *M. sativa* soils, respectively.

Table 1 Microbial content and microbial biomass carbon/microbial biomass nitrogen (MBC/MBN) ratio with the application of artificial zeolite (AZ) and microbial fertilizer (MF)

Plant	Treatment	Concentration (g/kg)	AZ				MF			
			Bacteria ($\times10^6$ CFU/g)	Fungi ($\times10^5$ CFU/g)	Actinomycetes ($\times10^6$ CFU/g)	MBC/MBN	Bacteria ($\times10^6$ CFU/g)	Fungi ($\times10^5$ CFU/g)	Actinomycetes ($\times10^6$ CFU/g)	MBC/MBN
AG	T0	0	1.07 ± 0.38^{b}	2.95 ± 0.05^{b}	3.06 ± 0.04^{c}	3.69 ± 0.47^{a}	1.02 ± 0.05^{b}	2.19 ± 0.25^{b}	3.02 ± 0.61^{a}	18.16 ± 0.58^{a}
	T1	5	1.14 ± 0.05^{c}	2.81 ± 0.07^{b}	3.25 ± 0.09^{d}	5.50 ± 0.91^{a}	1.03 ± 0.12^{b}	2.14 ± 0.36^{cd}	3.80 ± 0.32^{b}	7.41 ± 0.09^{b}
	T2	10	1.17 ± 0.04^{c}	3.23 ± 0.08^{a}	3.20 ± 0.14^{a}	7.87 ± 5.14^{a}	1.08 ± 0.08^{a}	2.16 ± 0.86^{c}	3.66 ± 0.15^{c}	6.25 ± 0.73^{c}
	T3	20	1.44 ± 0.03^{a}	3.37 ± 0.17^{a}	3.65 ± 030^{b}	2.72 ± 0.56^{a}	1.07 ± 0.26^{a}	2.22 ± 0.35^{a}	3.71 ± 0.02^{b}	6.97 ± 1.04^{b}
ET	T0	0	1.03 ± 0.02^{a}	0.78 ± 0.08^{a}	1.82 ± 0.13^{a}	0.67 ± 0.14^{b}	0.83 ± 0.31^{d}	2.17 ± 1.06^{c}	1.80 ± 0.57^{c}	16.46 ± 0.47^{a}
	T1	5	1.22 ± 0.04^{b}	1.68 ± 0.32^{b}	2.18 ± 3.91^{b}	8.71 ± 2.14^{a}	1.14 ± 0.25^{b}	2.22 ± 0.65^{b}	1.93 ± 0.26^{b}	6.63 ± 0.69^{b}
	T2	10	1.41 ± 0.49^{b}	3.12 ± 1.49^{b}	2.10 ± 1.60^{ab}	8.58 ± 4.33^{a}	0.93 ± 0.17^{c}	2.24 ± 0.43^{a}	1.62 ± 0.05^{d}	6.54 ± 0.35^{b}
	T3	20	1.48 ± 0.14^{b}	2.43 ± 0.64^{b}	2.70 ± 1.35^{ab}	14.02 ± 5.72^{a}	1.46 ± 0.05^{a}	2.15 ± 0.26^{d}	1.45 ± 0.41^{a}	6.44 ± 0.83^{b}
ML	T0	0	1.19 ± 0.53^{ab}	2.00 ± 0.13^{b}	1.05 ± 0.05^{c}	1.92 ± 0.28^{b}	1.17 ± 1.02^{b}	2.17 ± 0.52^{d}	1.03 ± 1.05^{d}	10.51 ± 0.27^{a}
	T1	5	1.20 ± 0.20^{b}	2.05 ± 1.29^{b}	1.77 ± 4.32^{bc}	2.44 ± 0.23^{ab}	1.09 ± 1.73^{c}	2.40 ± 1.31^{c}	1.23 ± 0.71^{c}	4.31 ± 1.08^{c}
	T2	10	1.28 ± 0.74^{b}	4.58 ± 1.58^{a}	2.07 ± 3.74^{a}	1.83 ± 0.15^{b}	0.84 ± 1.51^{d}	2.95 ± 1.27^{a}	1.27 ± 0.32^{b}	5.28 ± 0.24^{b}
	T3	20	1.94 ± 0.42^{a}	4.35 ± 1.43^{ab}	2.03 ± 5.68^{ab}	6.68 ± 4.68^{a}	1.51 ± 0.89^{a}	2.52 ± 0.51^{b}	1.47 ± 0.98^{a}	6.00 ± 0.71^{b}

Note: CFU, colony forming unit; AG, *Agropyron cristatum* L. Gaertn.; ET, *Elymus dahuricus* Turcz.; ML, *Medicago sativa* L.. Different lowercase letters within the same plant species indicate significant differences among different treatments at $P<0.05$ level. Mean±SE.

Bacterial contents varied from 1.02×10^6 to 1.94×10^6 CFU/g with the application of AZ and BF. With AZ application, most treatments had no significant differences when compared with other treatments, and the variation of bacterial content increased with MF application. The changes of bacteria in the soil varied with different plants. *E. dahuricus* began to be very sensitive to the application of amendment. Soil changed little when low concentrations of amendment were applied, but this change increased significantly when a high concentration was applied. Similar results were seen in *M. sativa*. Fungi catalyze complex organic resources' turnover and promote degradation of SOM. Fungal community showed a complex trend with the increase of AZ and MF. In *E. dahuricus* soils with MF application, fungi (2.15×10^5 CFU/g) were significantly lower under T3 treatment than under T0 treatment (2.17×10^5 CFU/g). With AZ application, fungi increased under T1 and T2 treatments, but decreased under T3 treatment.

3.3 Relationship between nutrients and microorganisms

To explain the effects of amendments and soil nutrients on biomass, we performed redundancy analysis (RDA) to determine which factors correlated with aboveground and underground biomass (Fig. 2). When AZ was used, AN, MBC/MBN ratio, and SOM were the three main predictors for biomass across samples, explaining 87.6% of the total variance (Fig. 2a). Furthermore, we found that AN was positively correlated with AP, actinomycetes, and AK, but negatively correlated with microbes. MBC/MBN ratio was positively correlated with AK and SOM, but negatively correlated with microbes and fungi. SOM was positively correlated with AK, but was negatively correlated with microbes and fungi (Fig. 2a; Table 2).

With MF application, SOM, MBC/MBN ratio, and AK were the three main predictors of biomass, explaining 82.9% of the total variance. AP and actinomycetes were positively correlated with MBC/MBN ratio (P<0.05) and negatively correlated with SOM and bacterial content. Only fungal content was positively correlated with AK, similar results were found for AP. Expect for actinomycetes and MBC/MBN ratio, other nutrients all had negative influences on AP (Fig. 2b; Table 3).

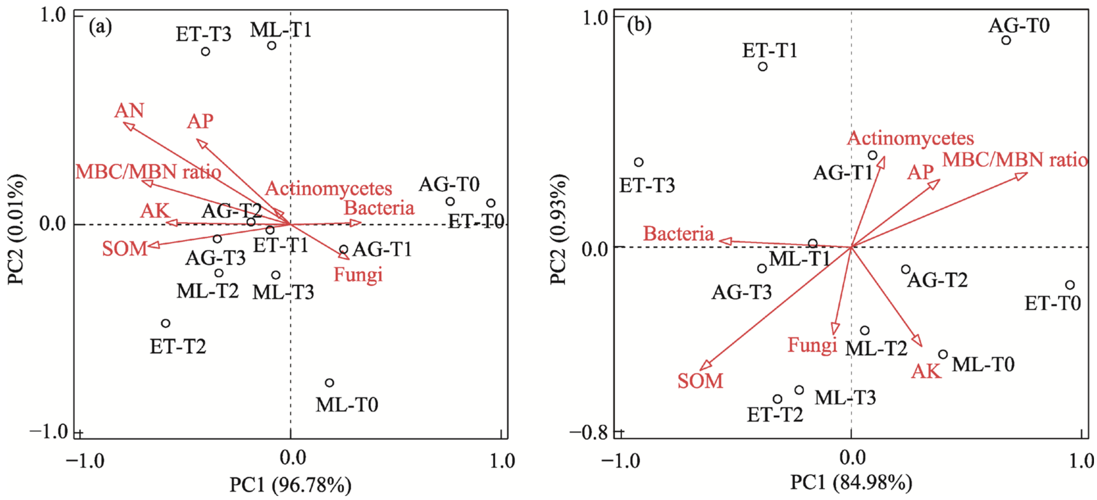

Fig. 2 Redundancy analysis (RDA) for the relationship between environmental factors (red lines) with the application of artificial zeolite (AZ; a) and microbial fertilizer (MF; b). AN, available nitrogen; AP, available phosphorous; AK, available potassium; MBC/MBN ratio, microbial biomass carbon/microbial biomass nitrogen ratio; SOM, soil organic matter; CK, control; AG, *A. cristatum*; ET, *E. dahuricus*; ML, *M. sativa*; T0, 0 g/kg; T1, 5 g/kg; T2, 10 g/kg; T3, 20 g/kg.

Table 2 Redundancy analysis (RDA) results between biomass and soil nutrient factors with the application of artificial zeolite

Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalue	0.9678	0.0116	0.0203	0.0003
Explained variation (cumulative; %)	96.78	97.94	99.97	100.00
Pseudo-canonical correlation	0.9925	0.8115	0.0000	0.0000
Explained fitted variation (cumulative; %)	98.82	100.00		

Table 3 RDA analysis results between biomass and soil nutrient factors with the application of microbial fertilizer

Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalue	0.8498	0.0093	0.1318	0.0091
Explained variation (cumulative; %)	84.98	85.91	99.09	100.00
Pseudo-canonical correlation	0.9305	0.7083	0.0000	0.0000
Explained fitted variation (cumulative; %)	98.92	100.00		

3.4 Comprehensive performance under different treatments by TOPSIS

For TOPSIS analysis, the higher the content of indicators, the more they can provide nutrients for vegetation growth or promote soil microbial activity, effectively improving soil conditions of abandoned mining areas. All 12 indicators calculated through entropy weight method ranged from 0.036 to 0.210. Fungi had a relatively high weight, followed by AN. The weights of aboveground biomass, underground biomass, and total biomass were equivalent (Fig. 3). From the ranking results, variation in the amendment type, dosage, and host vegetation resulted in significant differences. The selection of vegetation types also played an essential role in the restoration effect, and mining soils planted with *M. sativa* was more improved than those planted with *E. dahuricus* and *A. cristatum*, although all plants remediated mining soils to a certain extent (Fig. 4).

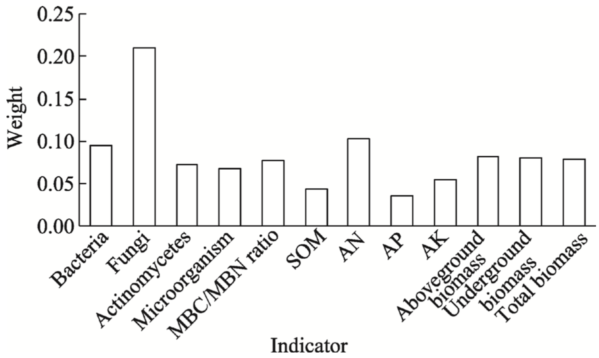

Fig. 3 Weight results of various evaluation indicators. MBC/MBN ratio, microbial biomass carbon/microbial biomass nitrogen ratio; SOM, soil organic matter; AN, available nitrogen; AP, available phosphorous; AK, available potassium.

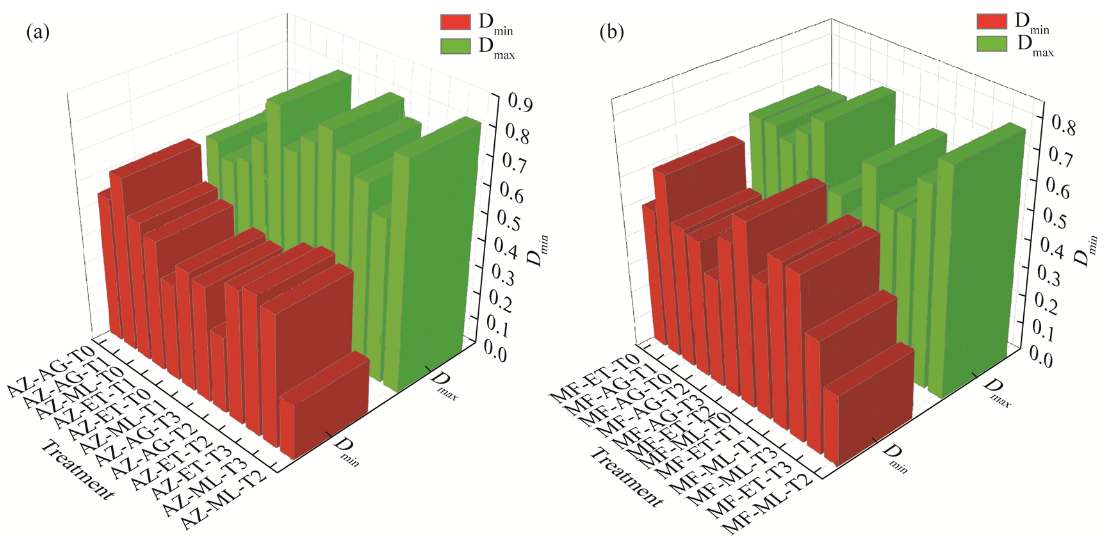

Fig. 4 Euclidean distances of artificial zeolite (AZ; a) and microbial fertilizer (MF; b). AG, *A. cristatum*; ET, *E. dahuricus*; ML, *M. sativa*; T0, 0 g/kg; T1, 5 g/kg; T2, 10 g/kg; T3, 20 g/kg. D_{min}, the minimum of distance; D_{max}, the maximum of distance.

We created a Nightingale rose plot based on the normalized C_j values (Fig. 5). The farther the point is from the central region, the higher it ranks. The higher the ranking, the better the comprehensive properties of additive and vegetation group, and the greatest potential for improving abandoned mining soils. The top five treatments were, in order, AZ with *M. sativa* under T2 treatment (AZ-ML-T2; C_j=0.0583), MF with *M. sativa* under T2 treatment (MF-ML-T2; C_j=0.0553), AZ with *M. sativa* under T3 treatment (AZ-ML-T3; C_j=0.0512), AZ with *E. dahuricus* under T3 treatment (AZ-ET-T3; C_j=0.0508), and AZ with *E. dahuricus* under T2 treatment (AZ-ET-T2; C_j=0.0505).

4 Discussion

4.1 Effect of soil amendments on biomass

Zeolites in soil store nutrients in their three-dimensional structural channels, including NH_4^+ and K^+, reducing ion leaching and increasing their availability to plants, meanwhile, shoot and root

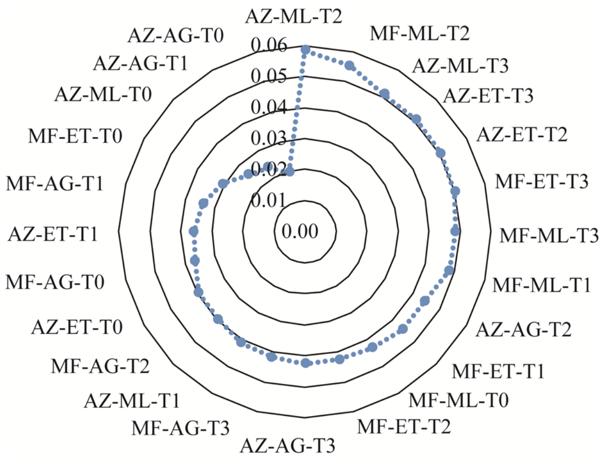

Fig. 5 Technique for order preference by similarity to ideal solution (TOPSIS) ranking result graph based on entropy weight method. AZ, artificial zeolite; MF, microbial fertilizer; AG, *A. cristatum*; ET, *E. dahuricus*; ML, *M. sativa*; T0, 0 g/kg; T1, 5 g/kg; T2, 10 g/kg; T3, 20 g/kg.

growth is accelerated and total biomass is increased (Farzad et al., 2007). Similar conclusions have been demonstrated with maize and oat growth in different polluted soils such as in gold mine-contaminated, smelter factory-contaminated, and farmland-contaminated soils (Knox et al., 2003; Lahori et al., 2020). When zeolite is applied to soils, salinity stress and other adverse impacts in arid mining areas can be mitigated, soil water holding capacity can be enhanced, and Ca and Mg uptake is improved (Rahimi et al., 2021). As a kind of Gramineae herbage, *E. dahuricus* has developed a stubborn root system and strong water retention ability (Liu et al., 2023). To some extent, it can adapt to the limitations of low water content in arid areas.

It is known that SOM content in soils decreases due to soil removal and storage after mining (Angst et al., 2018). Increasing SOM content is fundamental for ecosystem restoration as it leads to improved soil structure, enhanced nutrient cycling and retention, and improved biological activity (Gmach et al., 2019). The results of these pot experiments show that SOM values were significantly affected by fertilizer application concentration, with the lowest values observed under T0 treatment. SOM increased with amendment application concentration, especially when using MF as an additive. The effect of amendments on SOM status in plants has been demonstrated (Dębska et al., 2016).

Value of pH in soils varies with SOM, and positively correlates with soil acid buffering capacity and negatively correlates with basic cations leaching from acid mining soils such as Ca, Mg, and K (Jiang et al., 2018). In addition, humic substances have a high molecular weight distribution and contain multiple functional groups, and can decrease acidity in contaminated soils. Abundant SOM, suitable pH value, adequate humic substances, and other nutrients are jointly beneficial to increase soil nutrient pool responsible for plant growth and production (Dai et al., 2019; Liu et al., 2021). The total biomass of plants grown with MF application also increased for these reasons. Similar conclusions have been found in other studies, showing that the application of fertilizer can bring about an obvious increase in plant growth in mine tailings (Feagley et al., 1994; Ye et al., 2002; Green and Renault, 2008).

4.2 Effect of soil amendments on chemical characteristics

4.2.1 Effect of AZ on chemical characteristics

Soils from abandoned mining areas have extremely poor nutrient content. This study indicated that available soil nutrients markedly improved with the application of AZ and MF compared with no amendment. Owing to the efficacy of additive, SOM content and nutrient retention increase in treated surface mining soils (Ribeiro et al., 2021). Furthermore, the decomposition of SOM aided with additives can promote the release of soil micronutrients (Baumann et al., 2013).

Metals can be immobilized by zeolite. Additionally, immobilization is also accompanied by enhancement of soil properties (Ge et al., 2022). More than half of zeolite structure is composed of silicon oxide, especially silicon dioxide (SiO_2), reaching for 40%. Silicon increases the activity of H^+-ATPase pumps, which exist on the plasma membrane of plant cells; this regulates the uptake of nutrients and is expected to increase membrane stability (Savvas and Ntatsi, 2015). In soil, zeolite particles adhere to the surface of roots and improve SOM solubilization and nutrient availability (Trinchera et al., 2010).

Available soil nutrients, including AK, are held on the surface of clay particles and SOM. After the nutrients are absorbed by plants, AK becomes enriched in modified mining soils through nutrient cycling. AZ amendment increases AK in topsoil, and its effect is far greater than that of applying K fertilizer (Li et al., 2022). K from zeolite is a key part of AK content, and its exchangeable K is far more than that adsorbed and stored in zeolite channels. Interestingly, the existing K in zeolite does not hinder its ability to adsorb excess K (Moraetis et al., 2016). When soil nutrients decrease, K adsorbed by zeolite can be easily released into the soil for plant uptake (Li et al., 2022). This process gives the vegetation a continuous supply of nutrients during growth, which is also conducive to improved nutrient cycling in the soils. While insufficient nutrient supply seldom causes the decrease of yield during a short period, it could limit production during a long period (Hou et al., 2019). Earlier studies testified that zeolite was able to retain N and decreased the loss of ammonia to the atmosphere (Montalvo et al., 2020). This result contradicted with present study, where a decreasing AN trend was found in *M. sativa* soils. In addition, soil nutrients like AN were not significantly different among the four treatments. One possible explanation is that amendment with AZ promoted the activity of soil microbial communities and enhanced the expression of denitrification genes (Xiao et al., 2021). Pot experiments also may not have fully demonstrated the full nutrient cycling effects because of the short period of experiment. Additive application generally has significant effects on soil AP concentration regardless of plant type and amendment application rate (Nisbet et al., 1993), which was consistent with the findings of present study.

4.2.2 Effect of MF on chemical characteristics

The increase in soil available nutrients (AN, AP, and AK) primarily resulted from MF application acting as a nutrient-building soil amendment. An increase in the availability of soil nutrients after soil amendment was also partly resulted from a reduction in soil acidity. The microbial community is indirectly reshaped during this process (Xu et al., 2020; Chen et al., 2022; Zheng et al., 2023). MF contains a large number of microbial strains and promotes the mass reproduction of microbial communities. Beneficial microbes such as N, K, and P fixing bacteria accelerate the transformation of available nutrients and provide nutrients for plants. MF also leads to the enrichment of functional microbial species involved in carbon fixation, N metabolism (nitrification and denitrification), and P acquisition (Xiao et al., 2021). These organisms increase nutrient conversion in soil, thus increasing available nutrients further.

MF can increase N content in shallow soil layers through the slow release of AN from soil additives and reduced nitrate-N conversion (Liu et al., 2023). In this study, legumes increased nutrient content in mining soils much better than other plants, which was in line with the conclusion of previous study (Zheng et al., 2023). This is because increasing pH altered microbial activity and intensified several N metabolism pathways (Xiao et al., 2021), increasing soil N loss. High MF content also inhibited the increase of soil nutrients because excessively high concentrations of MF increases soil water interactions and reduces soil air permeability, inhibiting nutrient cycling interactions. On the other hand, the increase in soil microbial content leads to an increase in soil water consumption, reducing available water content. In this case, nutrient cycle has to slow due to the low concentration of intermediary.

4.3 Interactive dynamics between soil and nutrition

4.3.1 Interactive dynamics under AZ additive

Bayan Obo mining area in Inner Mongolia is a typical arid area found in China, and water scarcity restricts vegetation growth. The application of AZ to soil could alleviate this problem, mainly because of its frame structure. The molecules are linked together like a shelf and many cavities are formed, which increases porosity and reduces bulk density of soils (Fig. 6). In addition, these pores can also hold water, enhancing saturated hydraulic conductivity, a primary indicator of soil physical characteristics and a measure of soil water storage capacity (Reichert et al., 2009). AZ also significantly affects nutrient availability in the soils (Reynolds et al., 2008). Previous studies have also demonstrated that zeolite improves soil moisture by retaining water and supporting plant growth (Zahedi et al., 2009; Hazrati et al., 2017). Zeolites in mining soils increase chlorophyll content and photosynthesis rate by preventing the leaching of elements such as N and improving soil water retention (Farzad et al., 2007; Rahimi et al., 2021). Because of its adsorption capacity and porous nature, it improves water and fertilizer use efficiency simultaneously. It can buffer pH of acidic soil, releasing nutrients that were initially inaccessible to plants and microbes. Nutrients such as K and silicon, were released into the soil after amendment with AZ, alleviating the negative nutrient balance. Increased nutrients enhanced the growth of vegetation (Zhao et al., 2022), and consequently improved the productivity of plant cultivation for the restoration of mining soils (Li et al., 2022).

Zeolite could also slightly increase soil organic carbon (SOC) content through interaction with soils, increasing available carbon and energy sources, and promoting soil microbial activity (Ge et al., 2022). Although zeolite adds little organic carbon into soils (Li et al., 2009), it prevents SOC decrease and maintains soil structure (Ge et al., 2022). When AZ is used with other fertilizers, it helps retain fertilizing effects and stabilizes carbon through the formation of organic-mineral compounds (Noli and Tsamos, 2016). However, previous studies demonstrated that, compared with mineral fertilization such as AZ, organic additives better increased microbial biomass and activity (Aparna et al., 2014; Siebielec et al., 2018).

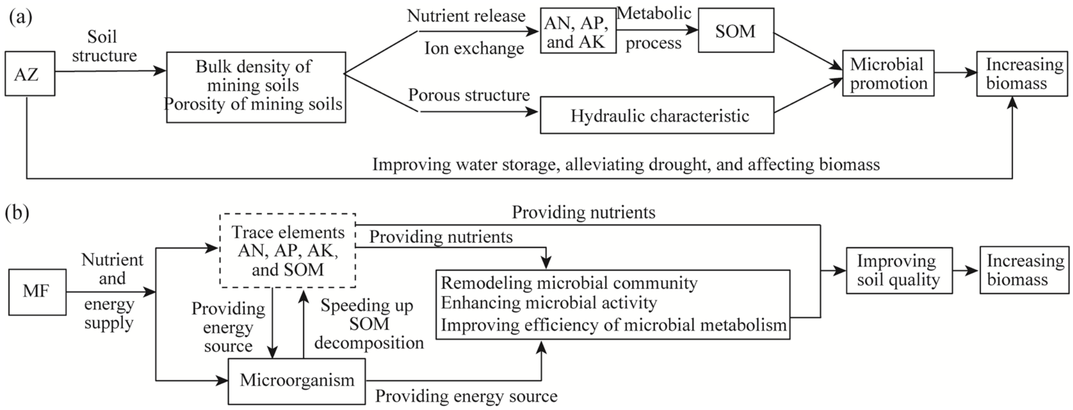

Fig. 6 Schematic diagram of improving mining soils with the application of artificial zeolite (AZ; a) and microbial fertilizer (MF; b). AN, available nitrogen; AP, available phosphorous; AK, available potassium; SOM, soil organic matter.

4.3.2 Interactive dynamics under MF additive

Mining disturbance highly alters soil microbial distribution and influences soil function and quality (Xiao et al., 2021; Chen et al., 2022). Soil microorganisms are limited in most mining areas. As shown in Figure 6b, the application of MF to mining soils inoculates the soil with a large number of microorganisms. Microbe population fluctuations regulate enzyme activity and community structure, and are crucial contributors to the entire carbon cycle (decomposition, transformation, and stabilization) (Wei et al., 2014; Raza et al., 2023). Decomposed carbon from MF is utilized by microorganisms for energy (Xie et al., 2022). They respond rapidly to environmental variations and ensure the smooth operation of soil ecosystem (Fu et al., 2017). Soil microbes promote plant growth directly and indirectly through changing soil nutrients. *Bacillus polymyxa*, as an example, is a rhizosphere bacterium that can promote plant growth (Adesemoye et al., 2010). The biomass of plants increases regularly with the increasing supply of nutrients coming from MF because it facilitated the growth of advantageous microbes while also suppressing the growth of pathogenic microorganisms such as the pathogenic fungi *Basidiomycota* and *Ascomycota* (Sun et al., 2023).

SOM is another pivotal component found in MF, which greatly influences soil microbes and N-cycling. MBC/MBN ratio also influences SOM decomposition in soils and microbial activity intensity (Marschner et al., 2008). All nutrients in the soil affect and restrict each other, and they collectively interact with plants to form a complete system. *M. sativa* and other species with N-fixing capacity have very good N uptake abilities and could be regarded as carbon additives (Moreau et al., 2019). During decomposition, enhanced N also enhances carbon storage in mining soils, which is mainly controlled by extra-cellular enzymes (Wei et al., 2014; Raza et al., 2023). Environmental factors also vastly influence nutrient conversion (Raza et al., 2023). In other studies, soil microbiomes regulated re-vegetation in arid mining areas together with soil physical-chemical properties (Xiao et al., 2021). In turn, vegetation restoration increased the accumulation of soil nutrient, leading to improved soil nutrient status (Kumari et al., 2022).

4.4 Implications

Out of the tested plants, *M. sativa* grew the most when treated with AZ or MF (Fig. 5). *M. sativa* was mainly planted due to its high protein content, high feed value, and strong soil consolidation ability (Liu et al., 2023). It is also an N-fixing species, decreasing the need for N fertilization. Based on the results of this study, it is a superior selection for restoring mining soils. *E. dahuricus* can easily alleviate drought stress because of its water retention capacity by stubborn root system, resolving the common limiting factor found in the Inner Mongolian mining areas. In areas such as this, the type of vegetation greatly impacts the success of remediation. It is important to note that the long-term success of mining ecological rehabilitation may not be achieved only through amendment strategies in arid areas. In this study, a combination of RDA and TOPSIS was used to comprehensively evaluate the nutrient content of sandy soil, providing a theoretical basis for the application and promotion of amendment strategies in abandoned mining soils. The method above overcomes the one-sidedness of a single evaluation model that can easily be influenced by multiple indicators. It is also applicable for use in other soil nutrient quality evaluations. This study mainly focused on the separate application of two additives, and further research and verification are needed to understand the effects of mixed amendment application and mixed vegetation on soil restoration in mining areas.

5 Conclusions

Soil properties were generally enhanced by both amendment strategies used in this study, but amendment type impacted soil quality in distinct ways. AZ improved soil quality by increasing porosity and water retention, while MF improved it by offering soil nutrition and enrichment of microbial community. The pot experiments carried out in present study demonstrate that AZ and MF application enhanced soil nutrition and vegetation biomass from 3.15% to 91.16% in arid mining soils. Amendments in abandoned coal mining soils clearly influenced the soil nutrient content and plant growth. AN, MBC/MBN ratio, and SOM were the three main predictors for biomass quantity in soils with AZ application, while SOM, MBC/MBN ratio, and AK were the three main predictors in soils with MF application. In this study, applying AZ at 10 g/kg concentration in mining soils where *M. sativa* was planted was the optimal treatment strategy for nutrient improvement, then, applying MF at 10 g/kg concentration in mining soils where *M. sativa* was planted was the second-best strategy. These two methods can be built upon for next steps toward increased remediation efficacy. However, detailed mechanisms of productivity enhancement and nutrition improvement may differ between inorganic and organic amendment. Further study and validation of microbial functional genes are critical to understanding amendment effects on microbial communities and increased productivity in other soil ecosystems.

Conflict of 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.

Acknowledgments

This work was supported by the Beijing Forestry University (BJFU), China. In addition, we also acknowledge other researchers and students who providing management and skills.

Author contributions

Conceptualization: SUN Baoping; Writing - original draft preparation: LI Wenye; Methodology: ZHANG Jianfeng, LIANG Yao; Data curation: SONG Shuangshuang; Formal analysis: WU Yi; Supervision: MAO Xiao, LIN Yachao.

References

Adesemoye A, Torbert H, Kloepper J. 2010. Increased plant uptake of nitrogen from ^{15}N-depleted fertilizer using plant growth-promoting rhizobacteria. Applied Soil Ecology, 46(1): 54–58.

Angst G, Mueller C W, Angst Š, et al. 2018. Fast accrual of C and N in soil organic matter fractions following post-mining reclamation across the USA. Journal of Environmental Management, 209: 216–226.

Aparna K, Pasha M, Rao D, et al. 2014. Organic amendments as ecosystem engineers: Microbial, biochemical and genomic evidence of soil health improvement in a tropical arid zone field site. Ecological Engineering, 71: 268–277.

Bao S. 2000. Soil and Agricultural Chemistry Analysis. Beijing: China Agriculture Press, 20–25. (in Chinese)

Baumann K, Sanaullah M, Chabbi A, et al. 2013. Changes in litter chemistry and soil lignin signature during decomposition and stabilisation of ^{13}C labelled wheat roots in three subsoil horizons. Soil Biology and Biochemistry, 67: 55–61.

Behzadian M, Khanmohammadi Otaghsara S, Yazdani M, et al. 2012. A state-of the-art survey of TOPSIS applications. Expert Systems with Applications, 39(17): 13051–13069.

Brookes P, Landman A, Pruden G, et al. 1985. Chloroform fumigation and the release of soil nitrogen: A rapid direct extraction method to measure microbial biomass nitrogen in soil. Soil Biology and Biochemistry, 17(6): 837–842.

Celestina C, Hunt J R, Sale P W, et al. 2019. Attribution of crop yield responses to application of organic amendments: A critical review. Soil & Tillage Research, 186: 135–145.

Chen D, Wang X, Carrión V J, et al. 2022. Acidic amelioration of soil amendments improves soil health by impacting rhizosphere microbial assemblies. Soil Biology and Biochemistry, 167: 108599, doi: 10.1016/j.soilbio.2022.108599.

Dai X, Zhou W, Liu G, et al. 2019. Soil C/N and pH together as a comprehensive indicator for evaluating the effects of organic substitution management in subtropical paddy fields after application of high-quality amendments. Geoderma, 337: 1116–1125.

Dębska B, Długosz J, Piotrowska-Długosz A, et al. 2016. The impact of a bio-fertilizer on the soil organic matter status and carbon sequestration–results from a field-scale study. Journal of Soils and Sediments, 16(10): 2335–2343.

Farzad N, Morteza K K, Saeid E, et al. 2007. The effects of natural zeolite on vegetative growth, flower and physiological characteristics of African marigold (*Tagetes erecta* L.'Queen'). Horticulture, Environment, and Biotechnology, 48(4): 241–245.

Feagley S E, Valdez M S, Hudnall W H. 1994. Papermill sludge, phosphorus, potassium, and lime effect on clover grown on a mine soil. Journal of Environmental Quality, 23(4): 759–765.

Franks D M, Boger D V, Côte C M, et al. 2011. Sustainable development principles for the disposal of mining and mineral processing wastes. Resources Policy, 36(2): 114–122.

Fu L, Penton C R, Ruan Y, et al. 2017. Inducing the rhizosphere microbiome by biofertilizer application to suppress banana Fusarium wilt disease. Soil Biology and Biochemistry, 104: 39–48.

Ge Q, Tian Q, Hou R, et al. 2022. Combing phosphorus-modified hydrochar and zeolite prepared from coal gangue for highly effective immobilization of heavy metals in coal-mining contaminated soil. Chemosphere, 291: 132835, doi: 10.1016/j.chemosphere.2021.132835.

Gmach M R, Cherubin M R, Kaiser K, et al. 2019. Processes that influence dissolved organic matter in the soil: A review. Scientia Agricola, 77(3): e20180164, doi: 10.1590/1678-992X-2018-0164.

Green S, Renault S. 2008. Influence of papermill sludge on growth of *Medicago sativa*, *Festuca rubra* and *Agropyron* *trachycaulum* in gold mine tailings: A greenhouse study. Environmental Pollution, 151(3): 524–531.

Guo H, Yao J, Cai M, et al. 2012. Effects of petroleum contamination on soil microbial numbers, metabolic activity and urease activity. Chemosphere, 87(11): 1273–1280.

Hazrati S, Tahmasebi-Sarvestani Z, Mokhtassi-Bidgoli A, et al. 2017. Effects of zeolite and water stress on growth, yield and chemical compositions of *Aloe vera* L. Agricultural Water Management, 181: 66–72.

Hoang S A, Sarkar B, Seshadri B, et al. 2021. Mitigation of petroleum-hydrocarbon-contaminated hazardous soils using organic amendments: A review. Journal of Hazardous Materials, 416: 125702, doi: 10.1016/j.jhazmat.2021.125702.

Hou W, Xue X, Li X, et al. 2019. Interactive effects of nitrogen and potassium on: Grain yield, nitrogen uptake and nitrogen use efficiency of rice in low potassium fertility soil in China. Field Crops Research, 236(12): 14–23.

Jiang J, Wang Y P, Yu M, et al. 2018. Soil organic matter is important for acid buffering and reducing aluminum leaching from acidic forest soils. Chemical Geology, 501: 86–94.

Knox A, Kaplan D, Adriano D, et al. 2003. Apatite and phillipsite as sequestering agents for metals and radionuclides. Journal of Environmental Quality, 32(2): 515–525.

Kumari S, Ahirwal J, Maiti S K. 2022. Reclamation of industrial waste dump using grass-legume mixture: An experimental approach to combat land degradation. Ecological Engineering, 174: 106443, doi: 10.1016/j.ecoleng.2021.106443.

Lahori A H, Mierzwa-Hersztek M, Demiraj E, et al. 2020. Direct and residual impacts of zeolite on the remediation of harmful elements in multiple contaminated soils using cabbage in rotation with corn. Chemosphere, 250: 126317, doi: 10.1016/j.chemosphere.2020.126317.

Ledin M, Pedersen K. 1996. The environmental impact of mine wastes–roles of microorganisms and their significance in treatment of mine wastes. Earth-Science Reviews, 41(17): 67–108.

Li H, Shi W Y, Shao H B, et al. 2009. The remediation of the lead-polluted garden soil by natural zeolite. Journal of Hazardous Materials, 169(1–3): 1106–1111.

Li X, Huang L. 2015. Toward a new paradigm for tailings phytostabilization–nature of the substrates, amendment options, and anthropogenic pedogenesis. Critical Reviews in Environmental Science Technology, 45(8): 813–839.

Li Y, Xia G, Wu Q, et al. 2022. Zeolite increases grain yield and potassium balance in paddy fields. Geoderma, 405: 115397, doi: 10.1016/j.geoderma.2021.115397.

Liu J, Jiang B, Shen J, et al. 2021. Contrasting effects of straw and straw-derived biochar applications on soil carbon accumulation and nitrogen use efficiency in double-rice cropping systems. Agriculture, Ecosystems & Environment, 311(6): 107286, doi: 10.1016/j.agee.2020.107286.

Liu Z, Lan J, Li W, et al. 2023. Reseeding improved soil and plant characteristics of degraded alfalfa (*Medicago sativa*) grassland in loess hilly plateau region, China. Ecological Engineering, 190: 106933, doi: 10.1016/j.ecoleng.2023.106933.

Marschner B, Brodowski S, Dreves A, et al. 2008. How relevant is recalcitrance for the stabilization of organic matter in soils?. Journal of Plant Nutrition and Soil Science, 171(1): 91–110.

Montalvo S, Huiliñir C, Borja R, et al. 2020. Application of zeolites for biological treatment processes of solid wastes and wastewaters–A review. Bioresource Technology, 301: 122808, doi: 10.1016/j.biortech.2020.122808.

Moraetis D, Papagiannidou S, Pratikakis A, et al. 2016. Effect of zeolite application on potassium release in sandy soils amended with municipal compost. Desalination Water Treatment, 57(28): 13273–13284.

Moreau D, Bardgett R D, Finlay R D, et al. 2019. A plant perspective on nitrogen cycling in the rhizosphere. Functional Ecology, 33(4): 540–552.

Nisbet A F, Konoplev A V, Shaw G, et al. 1993. Application of fertilisers and ameliorants to reduce soil to plant transfer of radiocaesium and radiostrontium in the medium to long term–a summary. Science of the Total Environment, 137(1): 173–182.

Noli F, Tsamos P. 2016. Concentration of heavy metals and trace elements in soils, waters and vegetables and assessment of health risk in the vicinity of a lignite-fired power plant. Science of the Total Environment, 563–564: 377–385.

Palansooriya K N, Shaheen S M, Chen S S, et al. 2020. Soil amendments for immobilization of potentially toxic elements in contaminated soils: A critical review. Environment International, 134: 105046, doi: 10.1016/j.envint.2019.105046.

Rahimi E, Nazari F, Javadi T, et al. 2021. Potassium-enriched clinoptilolite zeolite mitigates the adverse impacts of salinity stress in perennial ryegrass (*Lolium perenne* L.) by increasing silicon absorption and improving the K/Na ratio. Journal of Environmental Management, 285: 112142, doi: 10.1016/j.jenvman.2021.112142.

Raza T, Qadir M F, Khan K S, et al. 2023. Unrevealing the potential of microbes in decomposition of organic matter and release of carbon in the ecosystem. Journal of Environmental Management, 344: 118529, doi: 10.1016/j.jenvman.2023.118529.

Reichert J M, Suzuki L E A S, Reinert D J, et al. 2009. Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. Soil and Tillage Research, 102(2): 242–254.

Reynolds W D, Drury C F, Yang X M, et al. 2008. Optimal soil physical quality inferred through structural regression and parameter interactions. Geoderma, 146(3–4): 466–474.

Ribeiro S S, Schwartz G, Silva A R, et al. 2021. Soil properties under different supplementary organic fertilizers in a restoration site after kaolin mining in the Eastern Amazon. Ecological Engineering, 170(1): 106352, doi: 10.1016/j.ecoleng.2021.106352.

Savvas D, Ntatsi G. 2015. Biostimulant activity of silicon in horticulture. Scientia Horticulturae, 196: 66–81.

Shrestha R K, Lal R. 2010. Carbon and nitrogen pools in reclaimed land under forest and pasture ecosystems in Ohio, USA. Geoderma, 157(3): 196–205.

Siebielec G, Siebielec S, Lipski D. 2018. Long-term impact of sewage sludge, digestate and mineral fertilizers on plant yield and soil biological activity. Journal of Cleaner Production, 187: 372–379.

Sun T, Mao X, Ma Q, et al. 2023. Response of rice yield to organic amendments was regulated by soil chemical properties, microbial functional genes and bacterial community rather than fungal community. Applied Soil Ecology, 188: 104923. doi: 10.1016/j.apsoil.2023.104923.

Suppes R, Heuss-Aßbichler S. 2021. Resource potential of mine wastes: A conventional and sustainable perspective on a case study tailings mining project. Journal of Cleaner Production, 297(4): 126446, doi: 10.1016/j.jclepro.2021.126446.

Trinchera A, Rivera C M, Rinaldi S, et al. 2010. Granular size effect of clinoptilolite on maize seedlings growth. The Open Agriculture Journal, 4(1): 23–30.

Urra J, Mijangos I, Epelde L, et al. 2020. Impact of the application of commercial and farm-made fermented liquid organic amendments on corn yield and soil quality. Applied Soil Ecology, 153: 103643, doi: 10.1016/j.apsoil.2020.103643.

Vance E D, Brookes P C, Jenkinson D S. 1987. An extraction method for measuring soil microbial biomass C. Soil Biology and Biochemistry, 19(6): 703–707.

Wang B, Chu C, Wei H, et al. 2020a. Ameliorative effects of silicon fertilizer on soil bacterial community and pakchoi (*Brassica chinensis* L.) grown on soil contaminated with multiple heavy metals. Environmental Pollution, 267(3): 115411, doi: 10.1016/j.envpol.2020.115411.

Wang L, Kwok J S H, Tsang D C W, et al. 2015. Mixture design and treatment methods for recycling contaminated sediment. Journal of Hazardous Materials, 283: 623–632.

Wang X, Li Y, Wei Y, et al. 2020b. Effects of fertilization and reclamation time on soil bacterial communities in coal mining subsidence areas. Science of the Total Environment, 739(17): 139882, doi: 10.1016/j.scitotenv.2020.139882.

Wei H, Guenet B, Vicca S, et al. 2014. High clay content accelerates the decomposition of fresh organic matter in artificial soils. Soil Biology and Biochemistry, 77: 100–108.

Wong M H. 2003. Ecological restoration of mine degraded soils, with emphasis on metal contaminated soils. Chemosphere, 50(6): 775–780.

Wu L, Zheng H, Wang X. 2021. Effects of soil amendments on fractions and stability of soil organic matter in saline-alkaline paddy. Journal of Environmental Management, 294(4): 112993, doi: 10.1016/j.jenvman.2021.112993.

Wu Y J, Zhou H, Zou Z J, et al. 2016. A three-year in-situ study on the persistence of a combined amendment (limestone+sepiolite) for remedying paddy soil polluted with heavy metals. Ecotoxicology Environmental Safety, 130: 163–170.

Xiao E, Ning Z, Xiao T, et al. 2021. Soil bacterial community functions and distribution after mining disturbance. Soil Biology and Biochemistry, 157: 108232, doi: 10.1016/j.soilbio.2021.108232.

Xie Z, Yu Z, Li Y, et al. 2022. Soil microbial metabolism on carbon and nitrogen transformation links the crop-residue contribution to soil organic carbon. Npj Biofilms and Microbiomes, 8(1): 14, doi: 10.1038/s41522-022-00277-0.

Xu R, Li B, Xiao E, et al. 2020. Uncovering microbial responses to sharp geochemical gradients in a terrace contaminated by acid mine drainage. Environmental Pollution, 261: 114226, doi: 10.1016/j.envpol.2020.114226.

Ye Z H, Shu W S, Zhang Z Q, et al. 2002. Evaluation of major constraints to revegetation of lead/zinc mine tailings using bioassay techniques. Chemosphere, 47(10): 1103–1111.

Zahedi H, Noormohammadi G, Rad A S, et al. 2009. The effects of zeolite and foliar applications of selenium on growth, yield and yield components of three canola cultivars under drought stress. World Applied Sciences Journal, 7(2): 255–262.

Zhao H, Zhang J, Wu F, et al. 2022. A 3-year field study on lead immobilisation in paddy soil by a novel active silicate amendment. Environmental Pollution, 292: 118325, doi: 10.1016/j.envpol.2021.118325.

Zhao L, Cao X, Zheng W, et al. 2016. Copyrolysis of biomass with phosphate fertilizers to improve biochar carbon retention, slow nutrient release, and stabilize heavy metals in soil. ACS Sustainable Chemistry & Engineering, 4(3): 1630–1636.

Zheng T, Zeng H, Zhang X, et al. 2023. Differential responses of soil community to reclamation with legumes versus grasses after an application of blended amendments in mining-disturbed soils. Journal of Cleaner Production, 418: 138113, doi: 10.1016/j.jclepro.2023.138113.