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

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Abstract

The restoration of mining soils is crucial for vegetation establishment and environmental rehabilitation. This study aimed to investigate variations in soil nutrient content, microbial abundance, and biomass under different gradients of substrate amendments in mining soils to identify effective restoration measures. Soil samples were collected from the Bayan Obo mining region in the Inner Mongolia Autonomous Region, China. The 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 the abundances of bacteria, fungi, and actinomycetes were assessed in soils planted with Agropyron cristatum L. Gaertn., Elymus dahuricus Turcz., and Medicago sativa L. under applications of artificial zeolite (AZ) and microbial fertilizer (MF) at T0 (0 g/kg), T1 (5 g/kg), T2 (10 g/kg), and T3 (20 g/kg). Redundancy analysis (RDA) and the technique for order preference by similarity to ideal solution (TOPSIS) were employed to identify the primary factors controlling biomass variation. Results demonstrated that chemical indices and microbial content in restored soils were substantially greater than those in the control. The application of AZ significantly increased SOM, AN, and AP by 20.27%, 23.61%, and 40.43%, respectively. AZ significantly enhanced bacterial, fungal, and actinomycete abundances by 0.63-fold, 3.12-fold, and 1.93-fold relative to the control, respectively. RDA indicated that AN, MBC/MBN ratio, and SOM were the dominant predictors of biomass in samples with AZ application, explaining 87.6% of the variance in biomass. SOM, MBC/MBN ratio, and AK were the dominant predictors with MF application, explaining 82.9% of the variance in biomass. TOPSIS analysis indicated that T2 was the optimal dosage, and that all three plant species could be utilized for the remediation of mining soils. The application of AZ and MF at T2 concentration in mining soils planted with M. sativa was identified as the most appropriate restoration measure.

Full Text

Preamble

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

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Abstract: Restoration of mining soils is critical for vegetation establishment and environmental rehabilitation. This study investigated variations in soil nutrient contents, microbial abundance, and biomass under different amendment gradients in mining soils to identify effective restoration 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 abundances of bacteria, fungi, and actinomycetes were assessed in soils planted with *Agropyron cristatum* L. Gaertn., *Elymus dahuricus* Turcz., and *Medicago sativa* L. under artificial zeolite (AZ) and microbial fertilizer (MF) applications at T0 (0 g/kg), T1 (5 g/kg), T2 (10 g/kg), and T3 (20 g/kg). Redundancy analysis (RDA) and the technique for order preference by similarity to ideal solution (TOPSIS) were employed to identify the primary factors controlling biomass variation. Results demonstrated that chemical indices and microbial contents in restored soils were substantially greater than those in control soils. AZ application significantly increased SOM, AN, and AP by 20.27%, 23.61%, and 40.43%, respectively. AZ also significantly enhanced bacteria, fungi, and actinomycetes abundances by 0.63, 3.12, and 1.93 times compared to the control, respectively. RDA indicated that AN, MBC/MBN ratio, and SOM were the dominant predictors of biomass across AZ-treated samples, explaining 87.6% of biomass variance. With MF application, SOM, MBC/MBN ratio, and AK were the dominant predictors, explaining 82.9% of biomass variance. TOPSIS analysis identified T2 as the optimal dosage, and all three plant species proved suitable for mining soil restoration. The combination of AZ and MF application at T2 concentration in soils planted with *M. sativa* emerged as the most appropriate restoration measure.

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

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1 Introduction

Intensive mining activities have profoundly impacted vegetation growth and soil conditions. Metal mining generates vast quantities of waste materials, ranging from waste rock to fine tailings [?, ?]. Tailings and mine waste from metalliferous mining contain potentially toxic concentrations of trace elements and are susceptible to wind erosion [?, ?], resulting in contamination of surrounding ecosystems and food chains that ultimately endangers human health [?, ?]. Moreover, toxic and oligotrophic tailings hinder plant restoration [?, ?]. Mine wastes pose significant long-term environmental risks without careful rehabilitation [?, ?]. Previous studies have demonstrated that depleted nutrients can be restored through appropriate soil management and reclamation strategies [?, ?]. Although the extent of pollution varies across different mine types and areas, the foundations of reclamation are homologous and can be divided into in situ and ex situ techniques [?, ?]. The most common approaches involve applying geomembranes and clean covers for chemical treatment of surface substrates, aiming to neutralize pH and immobilize metals. Soil amendment is also regarded as a suitable approach to improve soil physical-chemical properties and substantially shorten reclamation time [?, ?].

Recently, increasing research has focused on amendment applications, which have proven effective for rapidly improving soil nutrient content and microbial activity [?, ?]. Both organic and inorganic amendments are effective for soil improvement. Amendments facilitate establishment of site-specific vegetation, stabilize soil, control pollution, and remove threats [?, ?]. Due to potentially toxic elements near mining areas, numerous additives have been applied to immobilize pollutants, including compost, lime, coal fly ash, manure, phosphate fertilizers, biochar, clay minerals, and silica [?, ?, ?, ?, ?]. Ideal outcomes are often achieved through combined organic and inorganic amendments. These amendments, used as immobilizing agents, can simultaneously increase soil nutrients and water retention capacity, improve soil structure, enhance soil quality, and increase vegetation coverage [?, ?].

Organic soil additives are known to not only supplement deficient soil organic carbon (SOC) and nutrients but also replenish exogenous beneficial microorganisms [?, ?]. They stimulate biological activity and alter soil energy dynamics, ultimately improving the soil' s nutrient retention capacity. By contrast, inorganic soil amendments provide nutrition by increasing soil pH and modifying soil structure [?, ?]. Increased pH results in abundant negative charges on soil particle surfaces, which strongly attract metal cations to immobilize toxic metals [?, ?]. Previous studies have primarily focused on the fixation and degradation of toxic elements, but the improvement of nutrients requires further investigation.

Artificial zeolite (AZ), a typical inorganic substance, was initially used as a solidification agent for heavy metals, though its applications have become increasingly extensive [?, ?]. AZ emerged to meet production and application output and efficiency needs [?, ?]. However, its capacity to promote nutrient content remains to be studied. Microbial fertilizer (MF) is an organic carbon fertilizer that uses ground coal and dust powder as a carrier and is compounded by multiple microbial strains. Occasionally, MF has been shown to cause pollution and damage soil, but it can also improve the soil micro-environment and anti-corrosion capacity [?, ?]. The mycorrhizal network of microorganisms 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, which has an extremely positive effect on mining soil improvement [?, ?]. MF undoubtedly possesses wide application potential in mining areas.

Previous studies have demonstrated that additive effectiveness strongly relates to both environmental and soil factors [?, ?]. In arid mining areas with degraded soil structure, low water content, and excessive heavy metal concentrations, AZ and MF applications have been utilized in industrial fields. However, the use of these amendments for mining reclamation has not been widespread due to limited understanding of their benefits, availability at reclamation sites, application techniques, and apprehension about field application results. This study established different potted experiments to explore the effects of amendments on mining soils. Two amendments and three vegetation types were used to specifically address: (1) variations in mining soil properties when applying different rates and types of additives; (2) correlations between soil properties in restored mining soils; and (3) suitable amendment types, concentrations, and vegetation combinations for arid mining areas.

2.1 Study Area

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

The Bayan Obo mining region covers an area of 328 km^2 and represents a rare polymetallic symbiotic deposit measuring 18 km long, 3 km wide, and 200 m high. More than 160 mineral types and 70 elements have been identified in the deposit. In recent years, over-exploitation has resulted in serious environmental damage.

2.2.1 Soils

Composite soil samples from 0–15 cm depth were collected using a 5-cm diameter auger. In each sampling plot, soil samples were collected at three locations after removing surface litter. At each location, five sub-samples were obtained within a 10 m × 10 m area to create a composite sample. Samples were sealed in plastic bags and transported to the laboratory, where stones were removed and soils were sieved through a 2-mm mesh for property measurement. Soils were air-dried at 25°C. More than 95% of soils in the mining region are chestnut soils, with the remainder being brown soils. The basic chemical properties before the 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, and bacteria, fungi, and actinomycetes contents of 0.07\$$\times 10^{\{6\},0.04\times 10}$\{5\}, and0.07×10^\{6\}\$ CFU (colony forming unit)/g, respectively.

2.2.2 Amendments

AZ possesses a high pore structure and excellent cost-performance ratio, with superior air permeability and water absorption capacity. Thus, AZ functions as both a water-retaining material and soil conditioner. AZ has been increasingly used in agriculture, particularly in heavy metal-enriched areas, due to its excellent adsorption and buffering effects. The AZ used in this study was produced by Chubu Electric Power Co., Inc., Nagoya, Japan, from rice husk ash and contained SiO_2 (43.86%), Al_2O_3 (30.76%), Na_2O (17.9%), and trace amounts of calcium (Ca), iron (Fe), magnesium (Mg), fluorine (F), and other elements.

AZ is a non-toxic, pollution-free fertilizer with a specific surface area of 20.36 m^2/g and pore diameters of approximately 10.67–11.96 nm. It features a three-dimensional framework structure connected by silicon (aluminum) oxygen tetrahedrons, with strong lattice openness and cavities of various sizes.

MF provides highly efficient and long-lasting soil fertility by directly increasing nutrient elements and improving soil fertility. Microorganisms in MF accelerate humification in mining areas, further increasing soil SOM and nutrients, particularly absorbable phosphorus. The MF used in this study was produced by Shanxi Green Promise Yongbao Rotten Fertilizer Co., Ltd., China, from coal humic acids. The composition included natural mineral nutrition-wheat rice powder (74 m), natural zeolite powder (74 m), and biological xanthohumate potassium (30%), with weathered coal (74–149 m) comprising the remaining 70%. MF primarily consisted of humic acids, nitrogen (N), phosphorus (P), potassium (K), and trace elements including P, manganese (Mn), and zinc (Zn). Over 40% was SOM, along with 20% humic acids and 15% trace elements. The effective viable count of compound probiotics exceeded 500 million/g, with main organisms being *Azotobacter*, *Rhizobium*, *Bacillus amylolyticus*, and *Bacillus subtilis*.

2.2.3 Plant Species

Three herbaceous species were selected: *Agropyron cristatum* L. Gaertn., *Elymus dahuricus* Turcz., and *Medicago sativa* L. All possess well-developed root systems and are suitable for soil improvement under poor conditions, making them appropriate test species. The seeding rate for each species was 20 g per pot. Preliminary surveys confirmed natural distribution of all three plants in mining areas. *A. cristatum* and *E. dahuricus* are gramineous plants with exceptional cold and drought resistance. *M. sativa* is a leguminous plant that can coexist with *Rhizobium*, playing a synergistic role with MF in this study.

2.3 Experimental Design

Potted plants were used in this study, conducted in the nursery of Beijing Forestry University, Beijing, China. AZ and MF were applied as additives at four dosages: T0 (0 g/kg), T1 (5 g/kg), T2 (10 g/kg), and T3 (20 g/kg). The non-amended control was designated T0 (0 g/kg). Each treatment was replicated three times, yielding 72 potted plants across the three species. Test pots were standardized with an outer diameter of 0.2 m. After filling pots with original soil from the Bayan Obo mining area, amendments were mixed with surface soil (0–10 cm depth). Seeds were sown in the amended soil and covered with a thin layer of raw soil. During growth, plants were watered twice weekly for the first 8 weeks and once weekly thereafter, with 1000 mL per pot per watering. Plants were established in mid-June and harvested in mid-September. After 120 days of growth, soil nutrients and both aboveground and belowground plant biomass were measured.

2.4.1 Sample Analysis

After plant removal, 0–10 cm soil in each pot was mixed thoroughly before sampling using the quartering method. Collected soils were placed in self-sealing bags and returned to the laboratory. Each soil sample was divided into two portions: one fresh sample was stored in cold storage for immediate microbial enumeration, while the other was air-dried for nutrient determination. Plants were uprooted, thoroughly washed with pure water, cleaned, and stored in paper bags for biomass measurement after drying. All indices were determined in triplicate.

Chemical properties were measured using routine methods: SOM content by potassium dichromate ($K_2Cr_2O_7$) oxidation, AN by alkaline hydrolysis diffusion, AP extracted with 0.5 mol/L $NaHCO_3$ solution and measured by colorimetric molybdenum blue method, and AK extracted with 1 mol/L NH_4OAc and measured by flame photometry [?, ?]. Microbial biomass carbon and nitrogen were measured by fumigation-extraction [?, ?, ?]. Microbial populations (bacteria, fungi, and actinomycetes) were assessed following [?, ?].

2.4.2 Data Analysis by TOPSIS

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a multi-criteria decision-making method that calculates proximity to ideal goals. It is widely used for comprehensive assessment of vegetation characteristics and soil nutrients. The application steps are as follows [?, ?]:

Step 1: Create a decision matrix represented as:

$$[X_{cd}]$$

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

Step 2: Normalize the matrix values. Normalized values for each element are calculated as:

For positive indicators:

$$X'_{ij} = \frac{X_{ij}}{X_{ij}^{\max}}$$

For negative indicators:

$$X'_{ij} = \frac{X_{ij}^{\min}}{X_{ij}}$$

where X'_{ij} is the normalized value, X_{ij} is the original value, $X_{ij}^{\max}$ is the maximum original value, and $X_{ij}^{\min}$ is the minimum original value. The normalized matrix is:

$$[X'_{cd}]$$

where X'_{cd} represents normalized indicators. Weighted normalized values r_{ij} are calculated as:

$$r_{ij} = w_i \times X'_{ij}$$

where w_i is the indicator weight, determined using the entropy weight method in this study.

Step 3: Determine the ideal solution A^+ (combination of optimal values) and negative-ideal solution A^- (combination of worst values):

For positive indicators:

$$A^+ = \max(r_{ij}), \quad A^- = \min(r_{ij})$$

For negative indicators:

$$A^+ = \min(r_{ij}), \quad A^- = \max(r_{ij})$$

where r_j^+ is the maximum value and r_j^- is the minimum value.

Step 4: Calculate Euclidean distances from each alternative to A^+ and A^-:

$$D_j^+ = \sqrt{\sum_{i=1}^{d}(r_{ij} - r_i^+)^2}$$

$$D_j^- = \sqrt{\sum_{i=1}^{d}(r_{ij} - r_i^-)^2}$$

where D_j^+ is the distance to the ideal solution and D_j^- is the distance to the negative-ideal solution.

Step 5: Calculate the proximity coefficient C_j:

$$C_j = \frac{D_j^-}{D_j^+ + D_j^-}$$

A higher C_j value indicates better performance (closer to the ideal solution). For comprehensive improvement, higher D_j^- and lower D_j^+ values yield higher C_j values, indicating better restoration effects.

3.1 Changes in Plant Growth and Soil Properties

Amendment treatments significantly influenced SOM, biomass, AN, AP, and AK in mining soils ($P<0.05$; Fig. 1 [Figure 1: see original paper]). For *M. sativa*, no significant SOM differences were observed across AZ treatments, though AZ application increased SOM content from T0 to T2 by 10.61%-20.27%. With MF amendment, SOM in *M. sativa* soils ranged from 9.60% to 28.65%, showing differential responses to additive changes. Both AZ and MF amendments significantly increased biomass (Fig. 1b). For *E. dahuricus*, the same additive amount produced large biomass differences, with a 5.4 g/pot difference between amendments at T3. Other species (*A. cristatum* and *M. sativa*) showed smaller differences. Soil AN contents under T1 and T2 with *E. dahuricus* were 10.28% and 16.67% higher than T0, respectively. Similar results occurred in *A. cristatum*, where available nutrients increased significantly in AZ treatments compared to T0 ($P<0.05$).

MF application significantly increased AN, AP, and AK in mining soils planted with all three species compared to no amendment (T0). Under T1 and T2, AZ amendment yielded higher AP than T0 in *A. cristatum* and *M. sativa* soils, with highly significant differences among treatments. Conversely, AP in *E. dahuricus* soils showed an opposite trend under the same treatments, ranging from 33.4 to 39.8 mg/kg. Interestingly, in *M. sativa* soils, AP under T0 did not differ significantly from T1 with MF but differed significantly from T2 and T3. Maximum AP occurred under T1 (38.72 mg/kg). AK contents with MF in *A. cristatum* soils exceeded control values, though no significant differences existed among T0–T3 treatments. AK peaked at 87.3 mg/kg under T2. When both amendments were applied across the three plant species, MF produced relatively stable nutrient variation, while AZ caused more rapid changes.

According to the National Standard for Classification of Soil Nutrient Content, AN content in pre-improvement mining soils was low. Post-treatment concentrations reached high levels, with some measurements achieving upper-medium classification, demonstrating that amendments improved nutrient content. Similar results were observed for AP, SOM, and AN. Amendments improved AK content, though the magnitude of change was smaller than for SOM and AN.

3.2 Effects of Amendments on Microbial Properties

Both AZ and MF applications significantly increased soil microbial biomass (C/N) and microbial populations, including bacteria, fungi, and actinomycetes (Table 1). The largest increases in microbial biomass and bacterial populations occurred under T2 or T3 treatments. All treatments in *A. cristatum* soils did not significantly affect MBC/MBN ratio, though AZ amendment caused continuous microbial increases. MBC/MBN ratios ranged from 0.67-14.00 with AZ and 4.31-18.16 with MF. With AZ application, MBC/MBN ratios under T1, T2, and T3 in *A. cristatum* soils did not differ significantly from T0. Actinomycetes increased by 19.3% and 22.8% in *A. cristatum* soils with AZ and MF, respectively. No significant differences existed among the four MF treatments in *E. dahuricus* and *M. sativa* soils. *A. cristatum* soils contained more actinomycetes than other plant soils, with no difference between AZ and MF. For example, with AZ application, actinomycetes in *A. cristatum* soil were 1.35 and 1.80 times higher than in *E. dahuricus* and *M. sativa* soils, respectively.

Bacterial contents ranged from 1.02×10^{6} to 1.94×10^{6} CFU/g with AZ and MF applications. Most AZ treatments showed no significant differences compared to other treatments, while MF application increased bacterial content variation. Bacterial responses varied among plant species. *E. dahuricus* was highly sensitive to amendment application, showing minimal change at low concentrations but significant increases at high concentrations. Similar patterns occurred in *M. sativa.* Fungi catalyze turnover of complex organic resources and promote SOM degradation. Fungal communities showed complex trends with increasing AZ and MF. In *E. dahuricus* soils with MF, fungi (2.15×10^{5} CFU/g) were significantly lower under T3 than T0 (2.17×10^{5} CFU/g).

With AZ, fungi increased under T1 and T2 but decreased under T3.

3.3 Relationship Between Nutrients and Microorganisms

Redundancy analysis (RDA) was performed to determine which factors correlated with aboveground and belowground biomass (Fig. 2 [Figure 2: see original paper]). With AZ application, AN, MBC/MBN ratio, and SOM were the three main predictors of biomass across samples, explaining 87.6% of total variance (Fig. 2a). 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 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 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, with similar results for AP. Except for actinomycetes and MBC/MBN ratio, all other nutrients negatively influenced AP (Fig. 2b; Table 3).

3.4 Comprehensive Performance Under Different Treatments by TOPSIS

For TOPSIS analysis, higher indicator contents provide more nutrients for vegetation growth and promote soil microbial activity, effectively improving soil conditions in abandoned mining areas. All 12 indicators calculated through the entropy weight method ranged from 0.036 to 0.210. Fungi received relatively high weight, followed by AN. Weights for aboveground, belowground, and total biomass were equivalent (Fig. 3 [Figure 3: see original paper]). Ranking results showed significant variation among amendment types, dosages, and host vegetation. Vegetation selection played an essential role in restoration effectiveness, with mining soils planted with *M. sativa* showing greater improvement than those planted with *E. dahuricus* and *A. cristatum*, although all species remediated mining soils to some extent (Fig. 4 [Figure 4: see original paper]).

A Nightingale rose plot was created based on normalized C_j values (Fig. 5 [Figure 5: see original paper]). Points farther from the center indicate higher rankings, representing better comprehensive properties of the additive-vegetation combination and greater potential for improving abandoned mining soils. The top five treatments were: (1) AZ with *M. sativa* under T2 (AZ-ML-T2; C_j=0.0583), (2) MF with *M. sativa* under T2 (MF-ML-T2; C_j=0.0553), (3) AZ with *M. sativa* under T3 (AZ-ML-T3; C_j=0.0512), (4) AZ with *E. dahuricus* under T3 (AZ-ET-T3; C_j=0.0508), and (5) AZ with *E. dahuricus* under T2 (AZ-ET-T2; C_j=0.0505).

4.1 Effect of Soil Amendments on Biomass

Zeolites in soil store nutrients such as NH_4^+ and K^+ in their three-dimensional structural channels, reducing ion leaching and increasing nutrient availability to plants while accelerating shoot and root growth and increasing total biomass [?, ?]. Similar conclusions have been demonstrated for maize and oat growth in various polluted soils, including gold mine-contaminated, smelter factory-contaminated, and farmland-contaminated soils [?, ?, ?]. Zeolite application mitigates salinity stress and other adverse impacts in arid mining areas, enhances soil water holding capacity, and improves Ca and Mg uptake [?, ?]. As a gramineous forage, *E. dahuricus* develops a robust root system with strong water retention capacity [?, ?], enabling adaptation to low water content limitations in arid areas.

Soil removal and storage after mining decrease SOM content [?, ?]. Increasing SOM is fundamental for ecosystem restoration as it improves soil structure, enhances nutrient cycling and retention, and promotes biological activity [?, ?]. Pot experiment results showed that SOM values were significantly affected by amendment concentration, with lowest values under T0 treatment. SOM increased with amendment application, particularly when using MF as an additive. Amendment effects on SOM status in plants have been previously demonstrated [?, ?].

Soil pH varies with SOM and positively correlates with soil acid buffering capacity while negatively correlating with basic cation leaching from acid mining soils (Ca, Mg, and K) [?, ?]. Humic substances have high molecular weight distributions and multiple functional groups that can decrease acidity in contaminated soils. Abundant SOM, suitable pH, adequate humic substances, and other nutrients collectively increase the soil nutrient pool responsible for plant growth and production [?, ?, ?]. Total plant biomass increased with MF application for these reasons. Similar conclusions have been reported, showing that fertilizer application produces obvious increases in plant growth in mine tailings [?, ?, ?, ?].

4.2.1 Effect of AZ on Chemical Characteristics

Soils from abandoned mining areas exhibit extremely poor nutrient content. This study demonstrated that available soil nutrients markedly improved with AZ and MF application compared to no amendment. Due to additive efficacy, SOM content and nutrient retention increased in treated surface mining soils [?, ?]. Furthermore, SOM decomposition aided by additives promoted release of soil micronutrients [?, ?].

Zeolite can immobilize metals while simultaneously enhancing soil properties [?, ?]. More than half of zeolite structure comprises silicon oxide, particularly SiO_2 (reaching 40%). Silicon increases activity of H^+-ATPase pumps on plant cell plasma membranes, regulating nutrient uptake and increasing membrane stability [?, ?]. In soil, zeolite particles adhere to root surfaces and improve SOM solubilization and nutrient availability [?, ?].

Available soil nutrients, including AK, are held on clay particle and SOM surfaces. After plant uptake, AK becomes enriched in modified mining soils through nutrient cycling. AZ amendment increases AK in topsoil, with effects far exceeding those of K fertilizer application [?, ?]. K from zeolite is a key component of AK content, with exchangeable K far exceeding that adsorbed and stored in zeolite channels. Interestingly, existing K in zeolite does not hinder its capacity to adsorb excess K [?, ?]. When soil nutrients decline, K adsorbed by zeolite is easily released for plant uptake [?, ?]. This process provides continuous nutrient supply during vegetation growth and improves nutrient cycling. While insufficient nutrient supply rarely causes yield reduction over short periods, it can limit production over extended periods [?, ?]. Earlier studies confirmed that zeolite retains N and reduces ammonia loss to the atmosphere [?, ?]. This contrasts with the present study, which found a decreasing AN trend in *M. sativa* soils and no significant AN differences among the four treatments. One possible explanation is that AZ amendment promoted soil microbial community activity and enhanced denitrification gene expression [?, ?].

Pot experiments may not have fully captured complete nutrient cycling effects due to the short experimental duration. Additive application generally has significant effects on soil AP concentration regardless of plant type or amendment rate [?, ?], consistent with present findings.

4.2.2 Effect of MF on Chemical Characteristics

Increased soil available nutrients (AN, AP, and AK) primarily resulted from MF application acting as a nutrient-building amendment. Increased nutrient availability also partly stemmed from reduced soil acidity. The microbial community is indirectly reshaped during this process [?, ?, ?, ?]. MF contains numerous microbial strains that promote mass reproduction of microbial communities. Beneficial microbes such as N-, K-, and P-fixing bacteria accelerate transformation of available nutrients and provide nutrients for plants. MF also enriches functional microbial species involved in carbon fixation, N metabolism (nitrification and denitrification), and P acquisition [?, ?]. These organisms increase nutrient conversion, further elevating available nutrients.

MF can increase N content in shallow soil layers through slow AN release from soil additives and reduced nitrate-N conversion [?, ?]. In this study, legumes increased nutrient content in mining soils more effectively than other plants, consistent with previous findings [?, ?]. This occurs because increased pH alters microbial activity and intensifies several N metabolism pathways [?, ?], increasing soil N loss.

High MF content also inhibited soil nutrient increases because excessively high concentrations enhance soil water interactions and reduce air permeability, inhibiting nutrient cycling. Additionally, increased soil microbial content raises water consumption, reducing available water content and slowing nutrient cycles due to low intermediary concentrations.

4.3.1 Interactive Dynamics Under AZ Amendment

The Bayan Obo mining area in Inner Mongolia represents a typical Chinese arid region where water scarcity restricts vegetation growth. AZ application alleviates this problem primarily through its framework structure. Molecules link together like shelves, forming numerous cavities that increase porosity and reduce bulk density (Fig. 6 [Figure 6: see original paper]). These pores also retain water, enhancing saturated hydraulic conductivity—a primary indicator of soil physical characteristics and water storage capacity [?, ?]. AZ also significantly affects nutrient availability [?, ?].

Previous studies have demonstrated that zeolite improves soil moisture by retaining water and supporting plant growth [?, ?, ?]. Zeolites in mining soils increase chlorophyll content and photosynthesis rate by preventing leaching of elements such as N and improving water retention [?, ?, ?]. Due to adsorption capacity and porous nature, zeolite improves water and fertilizer use efficiency simultaneously. It can buffer acidic soil pH, releasing initially inaccessible nutrients to plants and microbes. Nutrients such as K and silicon are released after AZ amendment, alleviating negative nutrient balances. Increased nutrients enhance vegetation growth [?, ?], consequently improving productivity for mining soil restoration [?, ?].

Zeolite can slightly increase soil organic carbon (SOC) content through soil interactions, increasing available carbon and energy sources and promoting microbial activity [?, ?]. Although zeolite adds little organic carbon directly [?, ?], it prevents SOC decline and maintains soil structure [?, ?]. When AZ is combined with other fertilizers, it helps retain fertilizing effects and stabilizes carbon through organic-mineral compound formation [?, ?]. However, previous studies demonstrated that organic additives better increased microbial biomass and activity compared to mineral fertilization such as AZ [?, ?, ?].

4.3.2 Interactive Dynamics Under MF Amendment

Mining disturbance substantially alters soil microbial distribution and influences soil function and quality [?, ?, ?]. Soil microorganisms are limited in most mining areas. As shown in Figure 6b, MF application inoculates mining soils with large microbial populations. Microbial population fluctuations regulate enzyme activity and community structure, which are crucial contributors to the entire carbon cycle (decomposition, transformation, and stabilization) [?, ?, ?]. Decomposed carbon from MF is utilized by microorganisms for energy [?, ?]. Microbes respond rapidly to environmental variations and ensure smooth operation of soil ecosystems [?, ?]. Soil microbes promote plant growth directly and indirectly by altering soil nutrients. *Bacillus polymyxa*, for example, is a rhizosphere bacterium that promotes plant growth [?, ?]. Plant biomass increased regularly with increasing MF-derived nutrients because MF facilitated growth of advantageous microbes while suppressing pathogenic microorganisms such as the pathogenic fungi *Basidiomycota* and *Ascomycota* [**?**, **?**].

SOM is another pivotal MF component that greatly influences soil microbes and N cycling. The MBC/MBN ratio also influences SOM decomposition and microbial activity intensity [**?**, **?**]. All soil nutrients affect and restrict each other, collectively interacting with plants to form a complete system. *M. sativa* and other N-fixing species have excellent N uptake abilities and can serve as carbon additives [**?**, **?**]. During decomposition, enhanced N also increases carbon storage in mining soils, primarily controlled by extracellular enzymes [**?**, **?**, **?**].

Environmental factors also vastly influence nutrient conversion [**?**, **?**]. Other studies have shown that soil microbiomes regulate revegetation in arid mining areas together with soil physical-chemical properties [**?**, **?**]. In turn, vegetation restoration increases soil nutrient accumulation, leading to improved nutrient status [**?**, **?**].

4.4 Implications

Among tested plants, *M. sativa* exhibited the greatest growth when treated with AZ or MF (Fig. 5 [Figure 5: see original paper]). *M. sativa* was selected for its high protein content, feed value, and strong soil consolidation ability [**?**, **?**]. As an N-fixing species, it reduces N fertilization requirements. Based on this study' s results, it is a superior choice for mining soil restoration. *E. dahuricus* can alleviate drought stress through water retention by its robust root system, addressing a common limiting factor in Inner Mongolian mining areas. In such regions, vegetation type greatly impacts remediation success. It is important to note that long-term mining ecological rehabilitation may not be achieved through amendment strategies alone in arid areas. This study combined RDA and TOPSIS to comprehensively evaluate sandy soil nutrient content, providing a theoretical basis for amendment application and promotion in abandoned mining soils. This approach overcomes the one-sidedness of single evaluation models that can be easily influenced by multiple indicators and is applicable to other soil nutrient quality assessments. This study focused on separate application of two additives; further research is needed to understand effects of mixed amendment applications and mixed vegetation on soil restoration in mining areas.

5 Conclusions

Both amendment strategies generally enhanced soil properties, but amendment types impacted soil quality distinctly. AZ improved soil quality by increasing porosity and water retention, while MF improved quality by providing nutrition and enriching microbial communities. Pot experiments demonstrated that AZ and MF application enhanced soil nutrition and vegetation biomass by 3.15% to 91.16% in arid mining soils. Amendments in abandoned coal mining soils clearly influenced nutrient content and plant growth. AN, MBC/MBN ratio, and SOM were the three main predictors of biomass in AZ-amended soils, while SOM, MBC/MBN ratio, and AK were the main predictors in MF-amended soils. Applying AZ at 10 g/kg concentration in *M. sativa*-planted mining soils was the optimal treatment strategy for nutrient improvement, followed by applying MF at 10 g/kg concentration in *M. sativa*-planted soils. These two methods can serve as foundations for enhanced remediation efficacy. However, detailed mechanisms of productivity enhancement and nutrient improvement may differ between inorganic and organic amendments. Further study and validation of microbial functional genes are critical for understanding amendment effects on microbial communities and productivity increases 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.

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