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Effects of Soil Modification Materials on the Quality of Sandy Soil in Mine Dumps

Luying Shao [1], Shichao Chen [1,2,*], Qing Zhang [1], Juan Li [1] and Zhi Jia [3]

[1] College of Desert Control, Inner Mongolia Agricultural University, Hohhot 010018, China; shaoluying0703@163.com (L.S.)
[2] Key Laboratory of Sand Physics and Sand Control Engineering of Inner Mongolia Autonomous Region, Hohhot 010018, China
[3] Ordos Wulan Coal (Group) Co., Ltd., Ordos 017000, China
* Correspondence: chenshichao2005@126.com

Abstract: Large-scale coal mine dumps are formed during the mining process of coal resources. These coal mine dumps comprise impoverished soil, posing significant challenges for vegetation restoration. To address this problem, soil microbial (EM) agents and fly ash have effectively improved soil quality. However, the effects of different application ratios on the quality of sandy soil in coal mine dumps are still unclear. This study aims to explore the applicable ratio for sandy soil in coal mine dumps. This study employed a field-based potted experiment design. A two-factor complete factorial experimental setup was utilized, with four levels of EM microbial agent to sandy soil weight ratio (0 g/kg, 0.1 g/kg, 0.2 g/kg, and 0.3 g/kg) and four levels of fly ash to sandy soil weight ratio (0 g/kg, 25 g/kg, 50 g/kg, and 75 g/kg), and the mixing of EM microbial agents and fly ash with the sandy soil was carried out at different ratios. Subsequently, the study examined the impacts of various dosages on the physicochemical properties of soil within the mine spoil heap, and a soil quality index was derived to quantify these effects. The application of EM microbial and fly ash resulted in significant improvements in the physicochemical properties of the soil compared to the control group. Notably, the combined application of EM microbial agent and fly ash exhibited superior effects on soil physicochemical properties compared to the individual applications of EM microbial agent or fly ash. Specifically, when the EM microbial agent concentration was 0.2 g/kg and the fly ash content was 75 g/kg, the enhancement in soil quality was most pronounced, with a soil quality index of 0.78. Mantel analysis revealed that the growth index and photosynthetic index of *Corethrodendron fruticosum* were primarily driven by soil total nitrogen and organic carbon. The research results can provide guidance and technical support for soil improvement in mining areas.

Keywords: open-cast coal mine dump; microbial (EM) agents; fly ash; soil quality; *Corethrodendron fruticosum*

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1. Introduction

Coal resources constitute a pivotal material foundation for the progression and sustenance of human society [1]. Open-pit mining operations result in the creation of extensive spoil heaps, which directly induce land degradation and pose severe ecological repercussions [2]. Specifically, these activities disrupt soil structure, invert soil horizons, and alter soil microbial communities. Consequently, coal mine spoil dumps have problems such as poor soil quality, defective soil structure, severe soil erosion, and difficulty in vegetation restoration [3]. Addressing the aforementioned challenges, the primary strategies for land

reclamation in mining dumps encompass chemical and biological interventions, specifically the incorporation of soil conditioners and the restoration of vegetation. However, vegetation rehabilitation is a protracted process, with incomplete recovery to pre-destruction levels observed even after several years [3]. In recent years, Chinese researchers have developed soil conditioners capable of rapidly enhancing soil fertility in mining dumps [4]. Yet, variations in the application dosage during this process exert distinct influences on soil fertility and plant growth dynamics. Consequently, the investigation of optimal application rates of soil conditioners in coal mine dumps represents a pivotal research focus.

Addressing the challenge of soil enhancement in coal mine dumps, Yan et al. (2017) employed mineral soil conditioners to augment the adsorption capacity of clay minerals for metal ions [5]. Chen et al. (2024) utilized biochar and sepiolite to mitigate metal migration in leaching processes and enhance the physical and chemical soil attributes [6]. Alfonso et al. (2016) demonstrated that the application of compost sludge can effectively elevate the availability of soil nutrients [7]. The acquisition of mineral soil conditioners, meerschaum, and composted sewage sludge requires a long and complex process. Currently, soil enhancement strategies encompass not only the aforementioned materials but also microbial (EM) agents, which are globally recognized for their intricate composition, robust structure, high efficacy, and environmental benignity. These EM microbial agents are capable of fostering plant growth and augmenting soil microbial activity [8,9]. Fly ash, serving as a physical modifier, exhibits a heterogeneous particle surface adorned with numerous pores and cracks. Upon exposure to water, it undergoes disintegration into finer particles, which subsequently leads to a reduction in soil mass, an augmentation in soil pore volume, and an elevation in soil moisture content. Consequently, this process enhances the soil's capacity for water retention and fertilizer retention [10]. Cui's report mentioned that the application of fly ash significantly increased soil pH by 0.23–0.86 units and significantly reduced the contents of exchangeable Pb and Cu. In addition, fly ash application increased aboveground and root biomass [11]. This also confirms the feasibility of fly ash in soil improvement. Nguyen's report mentioned that fly ash significantly improved the growth indicators and yield of radish plants when mixed with clay and sandy soil, respectively [12]. Barišić et al. (2019) showed that the application of fly ash can change the soil structure and make it loose and porous, thus improving the water retention performance of the soil [13]. Du et al. (2020) found that the addition of fly ash could reduce the density of gangue substrate and improve the fertility of potting substrate through potting tests [14]. Li et al. (2024) demonstrated that the addition of EM microbial agents resulted in increased aboveground biomass, soil organic carbon, total nitrogen, available phosphorus, and microbial biomass, while simultaneously decreasing soil electrical conductivity [15]. Wang Tao et al. (2020) further revealed that the incorporation of EM microbial agents could enhance the nutrient content of arsenic-contaminated sandstone soil, elevate soil enzyme activity, and foster the growth of vegetation [16]. Deng et al. (2018) showed that application of EM microbial agents can increase soil organic matter, TN, TP, and AN content. It can be seen that fly ash and EM microbial agents have certain potential for soil and vegetation restoration [17]. However, more studies have focused on the effects of a single application of fly ash or EM on soil physical and chemical properties and plant growth. There is a lack of research on the effects and appropriate dosage of mixed application of two amendments on soil improvement in open-pit mine dumps. Mixed application of EM microbial agents and fly ash at different application rates will produce different complementary effects [18].

Fly ash is a waste material produced by power plants, and using it as a soil conditioner not only solves the problem of large quantities of fly ash being piled up, but also greatly improves the efficient use of fly ash resources, reduces environmental pollution, and promotes the improvement of the strength of agricultural land [19]. The application of

EM microbial agents can enhance the microbial activity in the soil, thereby improving the turnover of soil nutrients. Soil microbial communities are a key factor in determining soil texture because microorganisms are more dynamic and sensitive than soil physical and chemical properties [20]. *Corethrodendron fruticosum* is an excellent sand-fixing plant with a well-developed and deep root system, which helps to fix the soil and reduce soil erosion, and has broad application prospects in energy utilization. Therefore, this study carried outmixed EM microbial agents and fly ash with different dosage and sandy soil at the Manlaiyang open-pit mine dump in Ordos City, northern China. The specific objectives of this study are (1) to explore the effects of different application rates on soil quality in the coal mine dump and (2) to clarify the factors affecting the growth of *C. fruticosum*. We seek suitable application combinations of EM microbial agents and fly ash to provide a theoretical basis and technical support for ecological construction and land reclamation in mining areas.

2. Materials and Methods

2.1. Study Area

Considering the limitations of indoor pot experiments, this study adopted the field pot experiment method to avoid the contingency in the experiment. The potted experiment was conducted from May to September 2023 at the Nalinmanlailiang coalmine dump in Inner Mongolia, northern China. The coalmine spoil dump is located in the northeast of the Maowusu Desert. It has a typical temperate continental climate, with an average altitude of 1100 m, an average annual temperature of 7.2 °C in the past two decades, annual rainfall of 360–420 mm, a frost-free period of 130–140 d, and an annual evaporation of 2000 mm. It is windy and sandy all year round. The area has severe aeolian activity and serious wind erosion all year round. It is urgent to carry out afforestation to suppress wind and sand activities. The surface soil of the mine dump is mainly sandy soil, with a thickness of about 1 m, low soil nutrient content and poor soil. Therefore, this study conducted soil improvement experiments to address key ecological issues.

2.2. Experimental Design

The experiment was a field-based potted experiment, and the experimental soil was taken from the soil layer at a depth of 0–20 cm in the coalmine spoil dump. We conducted five-point sampling and mixed determination of the basic physical and chemical properties of the experimental soil. Table 1 shows the physical and chemical properties of the tested soils. Considering the production cost and transportation cost of soil improvement materials, we chose EM microbial agent and fly ash here. The main ingredients of EM microbial agent are yeast, enterococcus faecalis, bacillus, and complex amino acids (organic matter content $\geq$ 45.0%, effective viable bacteria count $\geq$ 500 million/g), and the recommended application level is 0.2 g/kg. Fly ash was taken from coalmine power stations, and coal-fired power generation is an effective way of energy integration. It was mainly composed of silicon, aluminum, calcium, and other elements, and also contained a small amount of carbon. The planting container was a PVC flowerpot, 24 cm high and 23 cm in diameter. The *Corethrodendron fruticosum* was purchased from the *Corethrodendron fruticosum* seedling base in northern China. The basic properties of fly ash are shown in Table 2.

Based on the recommended application rate of 0.1 g/kg for the EM microbial agent, coupled with the preliminary test procedures established by our research team, an incremental increase of 0.1 g/kg appeared suitable for conducting the study. However, considering practical local production experiences and consulting the research conducted [21], the fly ash application increment was finally adjusted to 25 g/kg for research. The EM microbial agent was set at four levels of 0 g/kg, 0.1 g/kg, 0.2 g/kg, and 0.3 g/kg of the weight ratio

of the in soil, which were recorded as E0, E1, E2, and E3, respectively. The application rate of fly ash was set at four levels of 0 g/kg, 25 g/kg, 50 g/kg, and 75 g/kg of the weight ratio of the original soil, which were noted as F0, F1, F2, and F3, respectively. The experiment consisted of 16 treatments with 5 replications in 80 pots.

Table 1. Physical and chemical properties of the tested soil.

Index	Norm	
Soil physical properties	Soil bulk density (SBD) (g/cm^3)	1.71
	Soil water content (SWC) (%)	4.36
	Total porosity (POR) (%)	35.46
Soil chemical properties	pH	8.72
	organic matter (SOM) (g/kg)	1.25
	available phosphorus (AP) (mg/kg)	1.16
	available potassium (AK) (mg/kg)	33.4
	alkaline hydrolysis nitrogen (AN) (mg/kg)	3.15
	total phosphorus (TP) (g/kg)	0.94
	total potassium (TK) (g/kg)	39.2
	total nitrogen (TN) (g/kg)	0.16

Table 2. Mechanical composition and chemical properties of fly ash.

Term	Index	Percentage
Mechanical composition	Clay (%)	9.2
	Silt (%)	49.8
	Sand (%)	41.0
Chemical composition	SiO_2 (%)	54.2
	Al_2O_3 (%)	28.5
	CaO (%)	4.88
	Fe_2O_3 (%)	8.4
	Other	4.02

Based on a comprehensive two-factor experimental design, the EM microbial agent and fly ash were thoroughly mixed with 10 kg of sand sourced from the coal mine dump to create planting substrates with varying proportions. To prevent overflow during pot irrigation, the potting medium was filled to 3 cm from the upper edge of the pot. The treatment without the application of the amendment was used as the control (CK). The specific application design is shown in Table 3. In May 2023, uniform one-year-old *C. fruticosum* seedlings with homogeneous growth traits were transplanted into individual pots (one seedling per pot). Standardized cultivation practices were implemented to ensure optimal growth conditions. Irrigation was administered at five-day intervals, calibrated to the maximum field water-holding capacity of the control group (CK), while all other environmental and maintenance parameters were maintained uniformly throughout the experimental period.

Table 3. Table of two-factor complete experimental design.

Group	Treatment	EM Microbial Agent (g/kg)	Fly Ash (g/kg)
control	CK	E0 (0 g/kg)	F0 (0 g/kg)
A	T1	E0 (0 g/kg)	F1 (25 g/kg)
	T2	E0 (0 g/kg)	F2 (50 g/kg)
	T3	E0 (0 g/kg)	F3 (75 g/kg)
B	T4	E1 (0.1 g/kg)	F0 (0 g/kg)
	T5	E2 (0.2 g/kg)	F0 (0 g/kg)
	T6	E3 (0.3 g/kg)	F0 (0 g/kg)

Table 3. *Cont.*

Group	Treatment	EM Microbial Agent (g/kg)	Fly Ash (g/kg)
C	T7	E1 (0.1 g/kg)	F1 (25 g/kg)
	T8	E1 (0.1 g/kg)	F2 (50 g/kg)
	T9	E1 (0.1 g/kg)	F3 (75 g/kg)
D	T10	E2 (0.2 g/kg)	F1 (25 g/kg)
	T11	E2 (0.2 g/kg)	F2(50 g/kg)
	T12	E2 (0.2 g/kg)	F3 (75 g/kg)
E	T13	E3 (0.3 g/kg)	F1 (25 g/kg)
	T14	E3 (0.3 g/kg)	F2 (50 g/kg)
	T15	E3 (0.3 g/kg)	F3 (75 g/kg)

2.3. Soil Sample Collection and Indicator Determination

The plant height and base stem were measured on the 30th and 90th days after the *C. fruticosum* were planted, and the growth of plant height and base stem was calculated. On the 70th day, the photosynthetic index of plants was measured between 9:00 and 11:00 on a sunny day. Soil samples were collected in October 2023. The soil sample collection was divided into two parts. One part was sampled with a ring knife on the surface of the soil in each pot for analysis of soil bulk density (SBD), porosity (POR), and soil water content (SWC); the other part was put into a valve bag and taken back to the laboratory for drying in the shade and removal of impurities. The collected soil samples were manually sieved at 2 mm and 0.15 mm to determine the soil pH, organic matter (SOM), alkaline hydrolysis nitrogen (AN), available phosphorus (AP), available potassium (AK), total nitrogen (TN), total phosphorus (TP), and total potassium (TK). The SBD, POR, and SWC were calculated by the drying method and weighing after drying for 12 h. The pH was measured using a pH meter with a water-soil ratio of 2.5 to 1. The SOM was determined by a potassium dichromate oxidation–external heating method. TN was determined by the Kjeldahl method. The TP was determined by NaOH melting-molybdenum antimony colorimetry. The TK was determined by NaOH melting-flame photometry. The AN was determined by the alkaline diffusion method. The AP was determined by $NaHCO_3$ extraction–molybdenum antimony colorimetry. The AK was determined by NH_4OAc extraction–flame photometry. Plant height and basal stem were measured using a tape measure and a vernier caliper, respectively. Chlorophyll (CHL) was measured by chlorophyll meter. The net photosynthetic rate (Pn), stomatal conductivity (GS), transpiration rate (Tr), and intercellular CO_2 concentration (Ci) were measured using a GFS-3000 photosynthetic instrument.

2.4. Evaluation of Soil Quality

In this study, we employed a method to establish a minimum data set (MDS) for evaluating soil quality in potting substrates following the application of soil conditioners. Initially, principal component analysis (PCA) was utilized to rank soil physicochemical property indicators for dimensionality reduction and grouping. Factors with eigenvalues of principal components ≥ 1 were extracted. Indicators with loading values > 0.5 were grouped together; if an indicator exhibited a loading value > 0.5 across different principal components, it was categorized into a group exhibiting lower correlation with other indicators. Subsequently, the Norm value and weight of each indicator were calculated, and indicators within the top 10% of Norm values were retained to establish the MDS. The

weight of an indicator indicated its relative contribution to soil quality evaluation. The Norm value was computed using the following formula:

$$N_{ik} = \sqrt{\sum_{i=1}^{k} \left(U_{ik}^2 M_k\right)} \quad (1)$$

where N_{ik} is the combined loading of the ith indicator on the first k principal components with eigenvalues > 1; U_{ik} is the loading of the ith indicator on the kth principal component; and M_k is the eigenvalue of the kth principal component.

The type of function to which the indicator belongs is determined based on the positive or negative correlation between the soil evaluation indicator and the soil function, and the degree of affiliation is calculated.

The formula for the ascending distribution function is as follows:

$$Q(X_i) = \left(X_{ij} - X_{imin}\right) / \left(X_{imax} - X_{imin}\right) \quad (2)$$

The descending distribution function is formulated as follows:

$$Q(X_i) = \left(X_{imax} - X_{ij}\right) / \left(X_{imax} - X_{imin}\right) \quad (3)$$

where $Q(X_i)$ is the affiliation value of each soil indicator; X_{ij} is the value of each indicator for soil; and X_{imax} and X_{imin} refer to the maximum and minimum values in the ith soil indicator, respectively.

Finally, the calculation of the soil quality index was carried out, and the soil quality classes were classified. The formula for calculating soil quality is as follows:

$$SQI = \sum_{i=1}^{n} K_i \times C_i \quad (4)$$

where n is the number of indicators; K_i is the weight of the ith evaluation indicator; and C_i is the affiliation value of the ith evaluation indicator.

2.5. Data Processing and Analysis

SPSS 22.0 software was utilized to perform one-way ANOVA (one-way analysis of variance) and principal component analysis of data. Redundancy analysis was performed using Canoco 5.0. Mantel analysis and graphing were performed using R based on the Vegan package, and the principle was to use the Bray–Curtis calculation method to calculate the distance matrix for different types of data; then, the correlation between the two matrices was calculated [22]. Mapping was performed using Origin 2022 software.

3. Results

3.1. Changes in Soil Physical Properties Under Different Treatments

The results of variance analysis showed that EM microbial agent and fly ash significantly affected soil bulk density, total porosity, and soil water content (Tables 4 and 5) ($p < 0.001$). When compared to the control (CK) treatments, single applications of either fly ash or the EM microbial agent significantly decreased soil bulk density, increased total porosity, and enhanced soil moisture content ($p < 0.05$). Notably, within each treatment group, the application of fly ash alone (group A) exhibited a more pronounced impact on these soil properties than the application of the EM microbial agent alone (group B). Specifically, the T3 and T6 reduced soil bulk density by 8.77% and 1.75%, respectively, relative to CK, while total porosity increased by 19.71% and 13.89%, and soil water content rose by 143% and 46.44%, respectively. As shown in Table 4, the interaction between fly

ash and EM microbial agent has a significant impact on soil bulk density, total porosity, and moisture content compared to the application of fly ash or EM microbial agent alone (groups A and B) ($p < 0.05$). In groups C, D, and E, with the increase of fly ash, soil bulk density gradually decreased, soil total porosity continued to increase, and soil water content gradually increased. Among them, the soil water content and total porosity of T9 were significantly increased by 168% and 22.61% compared with CK, and the bulk density was significantly reduced by 8.83% compared with CK. The soil water content and total porosity of T12 were significantly increased by 261% and 29.35% compared to CK, and the bulk density was significantly reduced by 13.45% compared to CK. T12 has a better effect on improving soil bulk density, total porosity, and water content.

Table 4. Effect of different treatments on soil physical properties.

Group	Treatments	SBD (g/cm^3)	POR (%)	SWC (%)
Control	CK	1.71 ± 0.03 ab	34.15 ± 1.27 fg	4.36 ± 0.59 j
A	T1	1.66 ± 0.02 bcd	36.00 ± 0.80 def	5.59 ± 1.19 ij
	T2	1.62 ± 0.02 cd	37.62 ± 0.73 b	8.61 ± 1.58 fg
	T3	1.56 ± 0.05 f	39.95 ± 1.73 abcd	10.60 ± 1.09 de
B	T4	1.72 ± 0.02 a	33.79 ± 0.96 g	5.19 ± 1.01 ij
	T5	1.71 ± 0.05 ab	36.97 ± 0.98 de	6.37 ± 0.68 hi
	T6	1.68 ± 0.02 abc	37.58 ± 0.61 cdef	6.37 ± 0.68 hi
C	T7	1.64 ± 0.03 cd	40.02 ± 0.76 b	6.54 ± 0.49 hi
	T8	1.62 ± 0.02 cd	34.15 ± 2.11 fg	9.39 ± 1.73 efg
	T9	1.56 ± 0.02 f	36.90 ± 1.10 de	11.71 ± 1.32 cd
D	T10	1.64 ± 0.03 cd	39.60 ± 2.14 bc	8.73 ± 0.73 efg
	T11	1.57 ± 0.06 ef	42.91 ± 1.63 a	13.82 ± 1.67 b
	T12	1.48 ± 0.04 g	35.49 ± 0.87 efg	15.72 ± 2.17 a
E	T13	1.62 ± 0.04 de	37.83 ± 1.38 cd	7.63 ± 1.48 gh
	T14	1.55 ± 0.04 f	40.46 ± 1.70 b	9.90 ± 1.96 def
	T15	1.50 ± 0.07 g	42.47 ± 2.66 a	12.83 ± 2.23 bc

Note: A: single application of fly ash; B: single application of EM microbial agents; C, D, E: mixed application of fly ash and EM microbial agents. Different letters in the figure indicate significant differences between different treatments ($p < 0.05$).

Table 5. F-values of the effects of EM microbial agents, fly ash, and their interactions on the physico-chemical properties of the soil in the discharge site.

	SBD	POR	SWC	pH	SOM	AN
A	80.521 ***	80.717 ***	105.554 ***	181.975 ***	5.070 **	40.933 ***
B	9.649 ***	9.948 ***	27.978 ***	5.520 **	7.898 ***	13.678 ***
A × B	1.422 *	1.122 *	1.730	8.232 ***	1.936 *	11.112 ***
	AP	**AK**	**TN**	**TP**	**TK**	
A	96.416 ***	154.668 ***	1.965	4.891 **	2.995 *	
B	92.493 ***	437.879 ***	31.201 ***	19.081 ***	20.186 ***	
A × B	28.175 ***	18.169 ***	5.878 ***	6.720 ***	17.750 ***	

Note: A: single application of fly ash; B: single application of EM microbial agents; A × B: mixed application of fly ash and EM microbial agents. *** represents $p < 0.001$, ** represents $p < 0.01$, * represents $p < 0.05$; SBD: bulk density; POR: porosity; SWC: soil water content; SOM: organic matter; AN: alkaline hydrolysis nitrogen; AP: available phosphorus; AK: available potassium; TN: total nitrogen; TP: total phosphorus; TK: total potassium.

3.2. Changes in Soil Chemical Properties Under Different Treatments

The results of variance analysis showed that EM bacterial agent and fly ash and their interaction had a significant impact on soil pH, AN, AP, and AK ($p < 0.05$) (Tables 4 and 6). The single application of fly ash alone can improve the SOM, AP, AK, and AN more than

the single application of the EM microbial agent. Comparing other treatments, it was found that the mixed application of fly ash and EM microbial agent significantly increased the contents of the SOM, AP, AK, and AN compared with CK, and significantly reduced the pH. As shown in Table 6, different treatments in C, D, and E showed different influence trends on SOM and available nutrients. Specifically, the T7 was significantly higher than the T8 and T9 in group C, and the T12 was significantly higher than T10 and T11 in group D. T13 was significantly higher than T14 and T15 in group E. The study showed that the effects of the SOM and available nutrients did not increase with the addition of EM microbial agents and fly ash. Among them, the T12 showed the best effect on improving the SOM, AK, AP, and AN. Under T12, SOM, AK, AP, and AN were significantly increased by 194%, 75.45%, 331%, and 402%, respectively compared with CK ($p < 0.05$). Generally speaking, a neutral soil with a pH of 6.5–7.5 is most suitable for the survival of soil microorganisms and the growth and development of plants, and too acidic or too alkaline is detrimental to the transformation and supply of nutrients in the soil. The improvement in soil pH by T12 was superior among the different treatments in this study and favored the growth and development of vegetation.

Table 6. Effect of different treatments on soil available nutrients.

Group	Treatments	pH	SOM (g/kg)	AN (mg/kg)	AP (mg/kg)	AK (mg/kg)
Control	CK	8.72 ± 0.06 a	1.25 ± 0.28 c	3.15 ± 1.75 g	1.16 ± 0.26 k	33.40 ± 1.82 i
A	T1	7.97 ± 0.08 cd	1.31 ± 0.32 c	4.83 ± 1.30 fg	1.71 ± 0.26 hij	38.40 ± 4.56 fghi
	T2	7.77 ± 0.04 efg	1.95 ± 0.13 bc	9.31 ± 1.28 cd	2.06 ± 0.34 gh	45.20 ± 3.11 bcde
	T3	7.61 ± 0.20 gh	1.52 ± 0.21 c	8.68 ± 1.99 de	1.90 ± 0.46 h	40.80 ± 2.68 efgh
B	T4	8.60 ± 0.12 a	1.42 ± 0.49 c	3.92 ± 1.30 fg	1.09 ± 0.26 k	35.40 ± 2.70 hi
	T5	8.31 ± 0.08 b	1.65 ± 0.19 c	4.90 ± 1.58 fg	1.36 ± 0.20 jk	36.80 ± 4.92 ghi
	T6	8.12 ± 0.13 c	1.52 ± 0.89 c	4.76 ± 1.67 fg	1.42 ± 0.36 ijk	36.60 ± 1.67 ghi
C	T7	7.90 ± 0.07 de	2.12 ± 0.32 bc	12.46 ± 0.88 b	2.61 ± 0.31 ef	50.80 ± 3.90 b
	T8	7.70 ± 0.03 g	1.91 ± 0.74 c	7.84 ± 0.84 de	1.86 ± 0.44 hi	42.00 ± 6.24 defg
	T9	7.67 ± 0.09 g	1.79 ± 0.13 c	6.72 ± 1.69 def	1.43 ± 0.33 ijk	39.80 ± 2.95 efgh
D	T10	7.99 ± 0.10 cd	2.16 ± 1.74 bc	6.37 ± 1.06 ef	2.38 ± 0.38 fg	41.60 ± 3.78 defgh
	T11	7.73 ± 0.06 fg	3.04 ± 1.01 ab	12.95 ± 2.25 b	3.57 ± 0.27 bc	49.20 ± 7.33 bc
	T12	7.51 ± 0.10 h	3.66 ± 0.17 a	15.82 ± 0.63 a	5.02 ± 0.20 a	58.60 ± 4.04 a
E	T13	7.94 ± 0.08 d	2.37 ± 1.32 bc	13.58 ± 3.62 ab	3.85 ± 0.45 b	47.40 ± 6.50 bcd
	T14	7.89 ± 0.12 def	2.00 ± 0.97 bc	9.45 ± 2.50 cd	2.96 ± 0.46 de	39.20 ± 3.83 efghi
	T15	7.62 ± 0.29 gh	2.20 ± 0.58 bc	11.62 ± 4.53 bc	3.30 ± 0.25 cd	44.20 ± 3.35 cdef

Note: A: single application of fly ash; B: single application of EM microbial agents; C, D, E: mixed application of fly ash and EM microbial agents. Different letters in the figure indicate significant differences between different treatments ($p < 0.05$).

As shown in Tables 4 and 7, EM microbial agents and fly ash and their interaction significantly affected soil TP, TN, and TK. The use of EM microbial agents alone (i.e., T2 and T3) and fly ash alone (i.e., T4 and T5) significantly increased TP and TK compared with CK. Among them, the soil TN, TP, and TK were significantly higher in the T5 than in the other treatments ($p < 0.05$), and the soil TN, TP, and TK were increased by 400%, 87%, and 28.75%, respectively, relative to the CK. Compared to a single application of EM microbial agents and fly ash, the mixed application of EM microbial agents and fly ash showed better improvement in soil total nitrogen. In group D, the soil total nitrogen content was highest in T12, which was significantly increased by 378% compared with CK., the soil total nitrogen content was highest in T13 in group E, which was significantly increased by 378% compared with CK.

Table 7. Effect of different treatments on soil total nutrients.

Group	Treatment	TN (g/kg)	TP (g/kg)	TP (g/kg)
Control	CK	0.16 ± 0.02 e	0.94 ± 0.71 def	39.20 ± 1.50 gh
A	T1	0.16 ± 0.06 e	0.76 ± 0.31 ef	35.67 ± 3.04 i
	T2	0.39 ± 0.02 cd	1.25 ± 0.20 bcd	41.47 ± 1.49 efg
	T3	0.48 ± 0.02 bcd	1.36 ± 0.31 abc	45.80 ± 1.13 bcd
B	T4	0.38 ± 0.09 cd	1.53 ± 0.22 ab	41.53 ± 1.69 efg
	T5	0.80 ± 0.07 a	1.76 ± 0.16 a	50.47 ± 1.71 a
	T6	0.40 ± 0.20 cd	0.61 ± 0.15 ef	37.40 ± 2.45 hi
C	T7	0.51 ± 0.04 bcd	1.36 ± 0.54 abc	45.53 ± 4.35 bcd
	T8	0.46 ± 0.07 bcd	1.52 ± 0.30 ab	44.27 ± 3.14 cde
	T9	0.36 ± 0.05 d	1.04 ± 0.43 cde	43.80 ± 0.85 cdef
D	T10	0.63 ± 0.08 ab	0.63 ± 0.17 ef	47.40 ± 2.18 b
	T11	0.58 ± 0.23 bc	0.66 ± 0.11 ef	41.00 ± 0.65 fg
	T12	0.77 ± 0.11 a	0.74 ± 0.04 ef	42.93 ± 2.08 def
E	T13	0.77 ± 0.11 a	0.78 ± 0.09 ef	46.00 ± 1.96 bc
	T14	0.46 ± 0.32 bcd	0.71 ± 0.23 ef	42.27 ± 1.93 ef
	T15	0.50 ± 0.19 bcd	0.59 ± 0.10 f	41.93 ± 0.22 efg

Note: A: single application of fly ash; B: single application of EM microbial agents; C, D, E: mixed application of fly ash and EM microbial agents. Different letters in the figure indicate significant differences between different treatments ($p < 0.05$).

3.3. Comprehensive Evaluation of Soil Quality of Different Potting Substrates

After ranking the 11 indicators, principal component analysis was performed. The results are shown in Table 8. The eigenvalues of the first two principal components are ≥1, and the cumulative variance contribution rate reaches 80.334%, which meets the requirements of information extraction. The results yielded an approximate chi-square value of 210.123, with 55 degrees of freedom. The KMO index was 0.592 > 0, and the significance level was less than 0.001. These findings suggest that principal component analysis is appropriate for the selected soil physicochemical indicators. According to the method of minimum dataset construction, the indicators of the minimum dataset for soil quality evaluation of potting substrates were determined as the AN, TP, and TK. Then determine the type of membership function to which each indicator belongs, calculate its membership value and weight, and draw a membership radar chart for each indicator. As shown in Figure 1, the AN, TP, and TK were the limiting and critical factors for evaluating soil quality in this study.

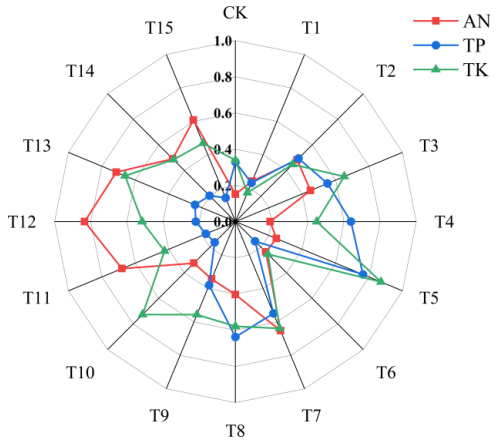

Figure 1. Radar plot of soil index affiliation for different ratios of potting substrates. Note: AN: alkaline hydrolysis nitrogen; TP: total phosphorus; TK: total potassium. CK, T1, T2, T3, T4, T5, T6, T7,

T8, T9, T10, T11, T12, T13, T14, and T15 represent different dosages of EM microbial agent and fly ash, which are E0F0, E0F1, E0F2, E0F3, E1F0, E2F0, E3F0, E1F1, E1F2, E1F3, E2F1, E2F2, E2F3, E3F1, E3F2, and E3F3, respectively. From the above method of calculating the soil quality index, it can be concluded that the range of the soil quality index under different combinations of the two amendment materials is 0.156 to 0.753. As shown in Figure 2, both fly ash and EM microbial agent had a significant effect on the soil quality index ($p < 0.001$), and the interaction between the two had a significant effect on soil quality ($p < 0.001$). Among them, T12 had the best effect on improving the soil quality of sandy soil, with a soil quality index of 0.753, followed by T11 and T15. T12, T11, and T15 increased by 382%, 262%, and 255%, respectively, compared to CK. According to the soil quality index classification standard, CK belonged to Class V. The addition of reclamation materials has led to a gradual improvement in soil quality from Class V to Class II level. It can be seen that the application of the two soil reclamation materials has a significant effect on soil quality and can achieve the purpose of improving the soil in the mining area.

Table 8. Load matrix for principal component subject original analysis and Norm value calculation.

Norm	PC1	PC2	Clusters	Norm Value	Common Factor Variance	Weights
Alkaline nitrogen	0.923	0.091	1	2.431	0.925	0.347
Quick-acting phosphorus	0.921	−0.019	1	2.423		
Organic matter	0.918	0.083	1	2.417		
Water content	0.899	−0.131	1	2.372		
Bulk weight	−0.887	0.251	1	2.359		
Potassium	0.881	0.125	1	2.324		
Porosity	0.863	−0.172	1	2.282		
pH	−0.821	0.124	1	2.166		
Total nitrogen	0.612	0.684	1	1.868		
Phosphorus	−0.403	0.698	2	1.435	0.865	0.324
Potassium	0.223	0.899	2	1.377	0.877	0.329
Eigenvalue	6.918	1.919			2.667	1.000
Variance contribution rate/%	62.892	17.441				
Cumulative variance contribution/%	62.892	80.334				

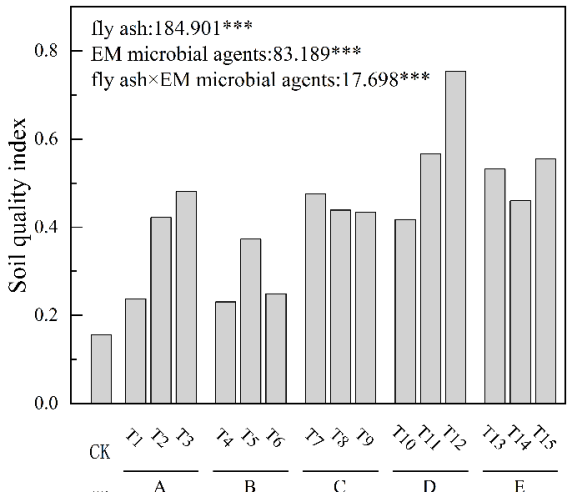

Figure 2. Soil quality index of different application combinations. Note: A: single application of fly ash; B: single application of microbial agents; C, D, E: mixed application of fly ash and EM microbial agent, *** represents $p < 0.001$.

3.4. Analysis of the Relationship Between Soil Physicochemical Properties and Photosynthetic Indexes of C. fruticosum Growth

A notable correlation between the two sets of variables is evident from Figure 3. Redundancy analysis (RDA) revealed that RDA1 and RDA2 accounted for 84.84% and 10.26% of the variance, respectively, collectively explaining 95.1% of the total variance. This indicates that soil physicochemical properties effectively capture the response of vegetation growth and photosynthetic indices. Among them, plant growth and photosynthetic indexes were positively correlated with TK, TN, SBD, SWC, AK, and AN, while negative correlations were observed with pH and TP. The small angle between changes in plant height and basal stems and soil physicochemical properties indicates a strong correlation between plant height, basal stems, and soil physicochemical properties.

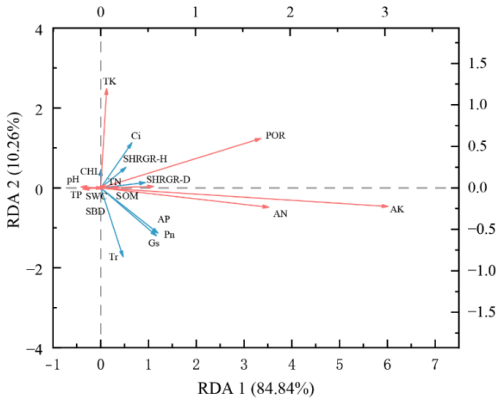

Figure 3. Redundancy analysis of soil physicochemical properties and growth and development indicators of *C. fruticosum*.

The relationship between soil physicochemical properties and photosynthetic indexes of *C. fruticosum* was further explored based on Mantel analysis. As shown in Figure 4, the lower triangle shows the correlation between the growth indicators and photosynthetic indicators of *C. fruticosum* and soil physicochemical properties, and the upper triangle shows the correlation between soil physical and chemical properties. As shown in Figure 4, the growth indexes of *C. fruticosum* were significantly affected by TN, and the photosynthetic indexes of *C. fruticosum* leaves were significantly affected by organic matter.

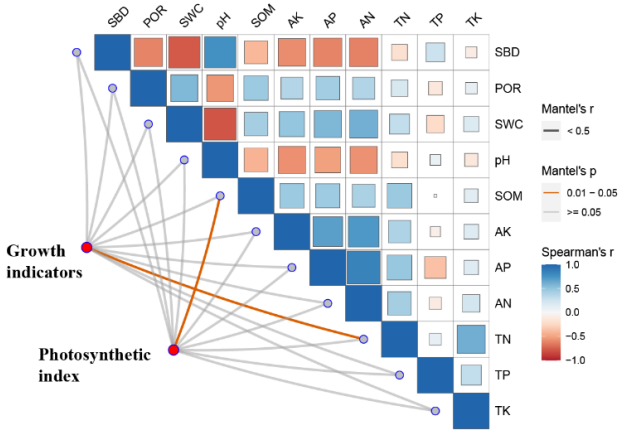

Figure 4. Mantel analysis of growth, photosynthetic indexes, and soil physicochemical properties of *C. fruticosum*. Note: Pn: net photosynthetic rate; GS: stomatal conductance; Tr: transpiration rate; Ci: intercellular carbon dioxide concentration; CHL: chlorophyll; SHRGR-H: plant height growth rate; SHRGR-H: basal stem growth rate; SBD: bulk density; POR: porosity; SWC: soil water content; SOM: organic matter; AN: alkaline hydrolysis nitrogen; AP: available phosphorus; AK: available potassium; TN: total nitrogen; TP: total phosphorus; TK: total potassium.

4. Discussion

This study used a field pot experiment, which has also been shown to be feasible in related studies [18]. Field pot experiments have certain controllability and repeatability, making the research results more accurate and reliable. Compared with field experiments, they require less space and resources. Pot experiments can be carried out in a smaller space, making them easier to manage and operate. In this study, the mechanical composition of sandy soil is mainly dominated by sand particles, and its internal pores are large, with serious soil erosion, making it difficult to maintain sufficient water supply for plant growth and development [23]. Numerous studies have shown that fly ash as a soil amendment can significantly improve soil physical properties, reduce soil bulk density, and increase total soil porosity and water content [24]. The same results were obtained in this study. In addition, EM microbial agents have a good promotion effect on the growth of plants [25]. The application of microbial agents can promote the circulation of effective substances in the soil and improve soil structure, thereby improving soil fertility [26]. This study revealed that the combined addition of EM microbial agents and fly ash significantly decreased soil bulk density while increasing total porosity and water content. Fly ash is mainly composed of fine vitreous particles, of which the clay-silt component content exceeds 59%, which can effectively fill the pores of sandy soil and slow down water and soil erosion [27]. With the addition of EM microbial agents, microorganisms multiply in large quantities and produce secretions and metabolites that favor the formation of soil aggregate structure, leading to an increase in soil porosity and a decrease in bulk density [28]. Fly ash contains a large amount of elements such as phosphorus and potassium, which are necessary for plant growth, but its organic matter content is low [5]. Therefore, while fly ash improves the physical properties, it needs to be combined with the application of EM microbial agents to improve soil fertility. EM microbial agents contain a large number of beneficial bacteria, which can enable the rapid multiplication of beneficial bacteria in the soil to solve problems such as soil sloughing and thus increase the organic matter content of the soil [29]. In this study, it was found that the addition of fly ash and EM microbial agents could significantly reduce the pH value of potting substrate and increase soil organic matter and available and total nutrients, which was basically in line with the findings of Guan et al. (2024) and Xiong et al. (2019) [29,30]. There are various reasons for the decrease in substrate pH, which may be related to the hydration of reactive SiO_2 and Al_2O3 in fly ash [31]. In addition, the fly ash in this study contains mineral nutrients such as calcium and iron. The microorganisms in the EM microbial agent can activate these nutrients by secreting substances such as organic acids. Therefore, the mixed application of the two can decrease the pH in the soil. The application of EM microbial agents provides the microorganisms in the soil with a food source, which plays the roles of phosphorus solubilization, potassium solubilization, and nitrogen fixation by decomposing the effective nutrients in the soil, promoting the release of trace elements in the soil, and enhancing the nutrient cycling process in the soil, so that the soil exhibits an activation reaction, which enhances the organic matter, available and total nutrients in the soil [32]. Establishing a scientific and reasonable soil evaluation index system is the key to soil quality evaluation, in which the establishment of the minimum data set (MDS) is a more widely used evaluation index screening method [33]. The selected indicators for soil quality evaluation were different in different studies. Liu ZY et al. (2024) selected the indicators of alkaline dissolved nitrogen, total phosphorus, and available potassium to construct MDS [34]. Hu Wei et al. (2024) selected the indicators of soil total phosphorus and total potassium to construct MDS [35]. In this study, 11 indicators of soil physical and chemical properties were selected to form a full dataset for soil quality evaluation, from which three indicators, including alkaline dissolved nitrogen, total phosphorus, and total potassium, were screened by the

PCA method and combined with the Norm value to establish MDS. The similarity of our selected MDS indicators to those reported in previous studies suggests the robustness and representativeness of the MDS evaluation index system established in this research. Through the calculation of soil quality, the soil quality index is roughly consistent with the distribution of soil physical and chemical properties.

The purpose of amending the soil is to promote plant growth by increasing the fertility of the soil. Chen L et al. (2001) found that the addition of fly ash to soil can significantly promote alfalfa growth [36]. Redundancy analysis of soil physical and chemical indexes with growth and photosynthetic indexes of *C. fruticosum* revealed a close link between growth and photosynthetic indexes of *C. fruticosum* and changes in soil nutrients due to the addition of amending materials. This is mainly due to the fact that soil nutrients directly affect leaf photosynthesis through their effects on plant chlorophyll content, enzyme activities, and the structure of photosynthetic organs, thus affecting plant growth and development [37]. The application of fly ash led to a decrease in soil bulk density and an increase in total porosity and water content, conditions that were conducive to the growth of *C. fruticosum* roots and enhanced nutrient uptake. With the application of EM microbial agents, the microorganisms therein can realize the decomposition or transformation of organic materials through the biodegradation process, providing nutrients to plants. When combined, these treatments synergistically promoted nutrient absorption by the plant, resulting in more vigorous growth [38].

5. Conclusions

The application of EM microbial agents and fly ash alone or in combination can improve the soil quality of the coal mine dump. The application of fly ash alone effectively improved the soil texture, available nutrients, and pH compared with the EM microbial agent. The mixed application of EM microbial agent and fly ash significantly improved the soil quality compared with the single application and the control. Therefore, fly ash should be used in conjunction with EM microbial agents to improve soil fertility while improving physical properties.

The application of EM microbial agents and fly ash improves soil nutrients and soil water retention. Mantel analysis and redundancy analysis found that there is a close relationship between the growth and photosynthetic indicators of *C. fruticosum* and the changes in soil nutrients. The addition of amendments caused changes in soil nutrients that affected the growth of *C. fruticosum*. Soil organic matter drives the changes in the photosynthetic rate of plant leaves, and the total nitrogen content in the soil affects the growth of *C. fruticosum*. This study will provide new insights into soil quality improvement and vegetation restoration in mining dumps. The appropriate application combination of EM microbial agents and fly ash will provide a theoretical basis and technical support for ecological construction and land reclamation in mining areas.

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