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Ecological Restoration of Coalmine-Degraded Lands: Influence of Plant Species and Revegetation on Soil Development

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Abstract: This study investigated soil development resulting from revegetation in a coal mining area in northern Henan, China. The effectiveness of six distinct revegetation methods for reclaiming mine-degraded lands was assessed. These methods employed various species such as *Ulmus pumila*, *Amorpha fruticosa*, *Robinia pseudoacacia*, *Jerusalem artichoke*, and Sea buckthorn. Over a three-year reclamation period, soil development was analyzed to identify the most suitable plant species. Soil samples were collected from different depths, encompassing the topsoil (0–20 cm) and subsoil (20–40 cm) for each method and a control group. Principal component analysis was employed to evaluate the impacts of the revegetation methods on soil development. The findings show that revegetation significantly impacted soil properties, lowering pH, electric conductivity, and density while increasing moisture, organic carbon, nitrogen, phosphorus, and potassium. The effects were more pronounced in the topsoil. Among the six revegetation methods, a mixed plantation of Sea buckthorn and *Amorpha fruticosa* was the most effective, delivering the highest organic carbon in the topsoil at 3.23% and the subsoil at 1.32%. This study offers insights into successful mine reclamation and the advancement of green and climate-smart mining practices.

Keywords: green mining; mine reclamation; mine rehabilitation; natural restoration; coal mining

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1. Introduction

Mining is historically the backbone of China's national economy, providing essential resources for various industries. However, it also results in ecological disturbances and land degradation, posing significant environmental challenges such as air and water pollution, soil erosion, habitat destruction, and the release of harmful chemicals into the environment [1,2]. According to the statistics of the Ministry of Land and Resources of China, mining has impacted up to 3.87×10^4 km^2 of land area, 5.38×10^4 km^2 of groundwater aquifer, and the total waste disposal has increased to 4×10^{10} tons. The annual wastewater discharge is approximately 4.7×10^9 m^3, and the mining-affected land area continues to increase by 330–470 km^2 per year in China. Mining has also destroyed 1.06×10^4 km^2 of forest area and 2.63×10^4 km^2 of grassland area in China.

Coal, accounting for approximately 60% of China's total energy consumption, is a major focus of mining activities. The environmental impacts of coal production, particularly in semi-arid and ecologically fragile areas like northwestern China, are substantial. For instance, the transformation of surface topography, the destruction of surface vegetation, water and soil loss, ground fissures, groundwater/surface water loss/shortage and pollution, cropland destruction, ecosystem degradation, etc. The top layer of soil is a delicate and intricate ecosystem. It is not usually saved beforehand and is damaged during coal mining. Mining reduces soil water content, cohesion, and organic matter [3].

The abandoned coal mining areas are usually infertile and have poor moisture, air, and temperature conditions, low content of organic matter, and a poor preservation capacity of soil moisture, and are therefore vulnerable to drought [4,5]. To address adverse impacts and enhance the optimization of mineral resource development, China has achieved notable progress in advancing green mining techniques. These techniques prioritize the sustainable extraction of resources while mitigating the effects on the ecosystem and surrounding communities. The key green mining techniques encompass various approaches, such as backfilling mining, where mined-out areas are refilled with waste materials. Additionally, strip mining is employed, involving the removal of layers of soil and rock to access coal seams near the surface. One notable innovation is the practice of coal and coalbed methane co-extraction. Simultaneously extracting coal and coalbed methane and utilizing methane as an alternative energy source reduces greenhouse gas emissions, increasing overall mining efficiency. Furthermore, implementing a technical system of underground reservoirs has proven beneficial. This system effectively manages underground water within the coalmine, preventing water seepage, controlling water flow, and mitigating potential water-related hazards [6].

The reclamation of mine-degraded land is a crucial aspect of green mining [7]. In this context, ecological restoration is an effective approach to realizing this goal [8–10]. Ecological restoration aims to bring back the site characteristics such as land stability, vegetation, soil fertility, biodiversity, hydrological cycle, and overall land productivity. To this end, vegetation establishment and soil amendment are viable means. The former involves planting trees, shrubs, and grasses to improve soil cover, reduce erosion, and provide food and habitat for wildlife. The latter entails adding organic matter, nutrients, and other amendments to the soil to improve its fertility and structure. Land restoration becomes feasible by establishing a diverse pioneer plant community that evolves into a natural ecological system and utilizing biological elements to enrich soil nutrients in abandoned lands. Revegetation with suitable landscape plants offers significant benefits [11,12]. Notably, it mitigates geological hazards, such as cave-ins, landslides, and debris flows. Moreover, this process contributes to water and soil conservation by cleaning up the water and soil in the mining area, absorbing various toxic elements. Additionally, it plays a vital role in air purification by absorbing dust and sulfur dioxide. Lastly, the green coverage of the mining area enhances and revitalizes the overall environmental aesthetics, transforming the mine site into a visually appealing and sustainable landscape. Certain landscape plants, such as Sea buckthorn, *Ulmus pumila*, *Amorpha fruticosa*, *Robinia pseudoacacia*, *Dittrichia viscosa,* and others, can afforest the abandoned mining areas by increasing soil organic matter nutrients and improving soil chemical and physical properties, allowing recovery of surface soil. Generally, the plant species should have the ability to grow in dry and infertile soil conditions and develop vegetation cover in a short time. Additionally, the plants ought to withstand soil and water erosion, mitigate nutrient loss and water runoff, and enhance the bio-physicochemical properties of the soil. This includes improving microbial biomass and organic matter status, among other relevant factors [13,14]. Previous research into using specific plant species for land reclamation and soil development has produced encouraging results. For instance, Ren et al. [15] demonstrated that revegetation can enhance soil nutrients in an abandoned quarry with weak soil, with *Pinus sylvestris* var. *Mongolia* showing better performance than *Pinus densiflora* var. *ussuriensis* for this purpose. Yan [16] investigated the influences of revegetation on the soil properties in the abandoned open-cast mine area in Northeastern China. Sea buckthorn emerged as the most suitable choice among the various plant species considered due to its positive impact on the soil. Jun et al. [17] observed that 18-year vegetation restoration promoted the formation of water-stable soil aggregates in an open-cast coalmine dump in the loess area. It was found that a high soil organic matter content and a high soil clay content were beneficial to forming water-stable soil aggregates. Similarly, Zhou et al. [18] reported that revegetation increased soil organic carbon and improved aggregate structure and water stability in red soil in Yingtan, China. In the west-northern Loess Plateau of China, Zhao et al. [19]

highlighted the positive impact of Sea buckthorn (*Hippophae rhamnoides* ssp. *sinensis*) on soil aggregation and microbiological development in the reclamation of open-cast mine spoils. Sasmaz et al. [20] suggested that *Carduus nutans*, *Cynoglossum officinale*, *Isatis, Phlomis* sp., *Silene compacta*, and *Verbascum thapsus* could be useful for remediation or phytoremediation of soils polluted by thallium (Tl) in the mining areas. Arshi [14] emphasized the importance of nitrogen-fixing bacteria and arbuscular mycorrhizal for plant growth in coalmine overburden dumps. For the reclamation of coalmine-degraded land in the Dhanbad district of Jharkhand, Eastern India, Mukhopadhyay et al. [21] suggested *Cassia siamea* and *Dalbergia sissoo* as suitable tree species for tropical climate. Fu et al. [22] discovered that the concentration of soil organic carbon is the main driver for the change in both the physical structure and chemical properties of reclaimed mine soil in Inner Mongolia, China. Notably, different plants showcase varying accumulation rates of organic carbon, while the application of organic amendments further enhances soil development. Torroba-Balmori et al. [23] proposed the use of native colonizer shrubs (*Genista florida* and *Cytisus scoparius*) as nurse plants to enhance *Quercus petraea* and *Quercus pyrenaica* reintroduction in reclaimed open-cast coalmines in Northern Spain.

The preceding research provides insight into restoring mine-degraded lands and aids land reclamation planning. However, due to the dry and semi-arid environment in the mining regions, screening plant species for potential application in the reclamation of mine-degraded land continues to be a challenge. The present research fills this knowledge gap by evaluating the effect of vegetation restoration on soil development of coalmine-degraded land and screening plant species appropriate for reclamation in the mining area. In order to achieve the intended goal, six distinct revegetation methods are established for the reclamation of coalmine-degraded land and waste piles in the designated coalmine area. The first method entails the utilization of *Ulmus pumila* for revegetation. The second method combines *Ulmus pumila* with *Amorpha fruticosa* and *Robinia pseudoacacia*. The third method incorporates a vegetation scheme of *Ulmus pumila*, *Robinia pseudoacacia*, and *Jerusalem artichoke*. The fourth method focuses exclusively on *Jerusalem artichoke*. The fifth method combines Sea buckthorn with *Amorpha fruticosa*, while the last method involves a synergistic combination of *Ulmus pumila* and *Amorpha fruticosa*. Soil physicochemical analyses were conducted, and multivariate statistics were performed to investigate the impact of plant species on soil in reclaimed coalmine-degraded land. The engineering case for this research was the Hebi No. 10 Mine located in the northern Henan mining region of China. This site has been part of China's Pilot Mine Reclamation Project since 2014. This research provides insights into effective ecological remediation for mine-degraded lands.

2. Materials and Methods

2.1. Study Area

The northern region of Henan province, China is characterized by a warm and arid climate with distinct seasonal changes. Spring is dry and windy, while summer is hot and rainy. Autumn brings long sunny days, and winter is cold with occasional snowfall. The annual average evaporation stands at 2328.3 mm, while the annual average precipitation is 556.8 mm, indicating a relatively dry environment. The maximum depth of frozen soil reaches 35 cm. The predominant soil type in this vicinity is sandy loam, complemented by coniferous forest vegetation.

The specific study site selected for this research is located in the southern region of the Henan coal mining area. The mine was established at the end of 1994, started trial production in October 2000, and underwent inspection in February 2002 for full operation. It specializes in the extraction of anthracite coal and bituminous coal using an underground longwall mining method. The targeted coal seam originates from the Permian Shanxi Formation. The dip angle of the coal seam is 31.5° to 45°, with an average of 35°. The average thickness of the coal seam measures 7.09 m. The location of the study area is shown in Figure 1. The pilot revegetation project was initiated in 2014, and substantial growth in the planted vegetation has been observed over the subsequent years.

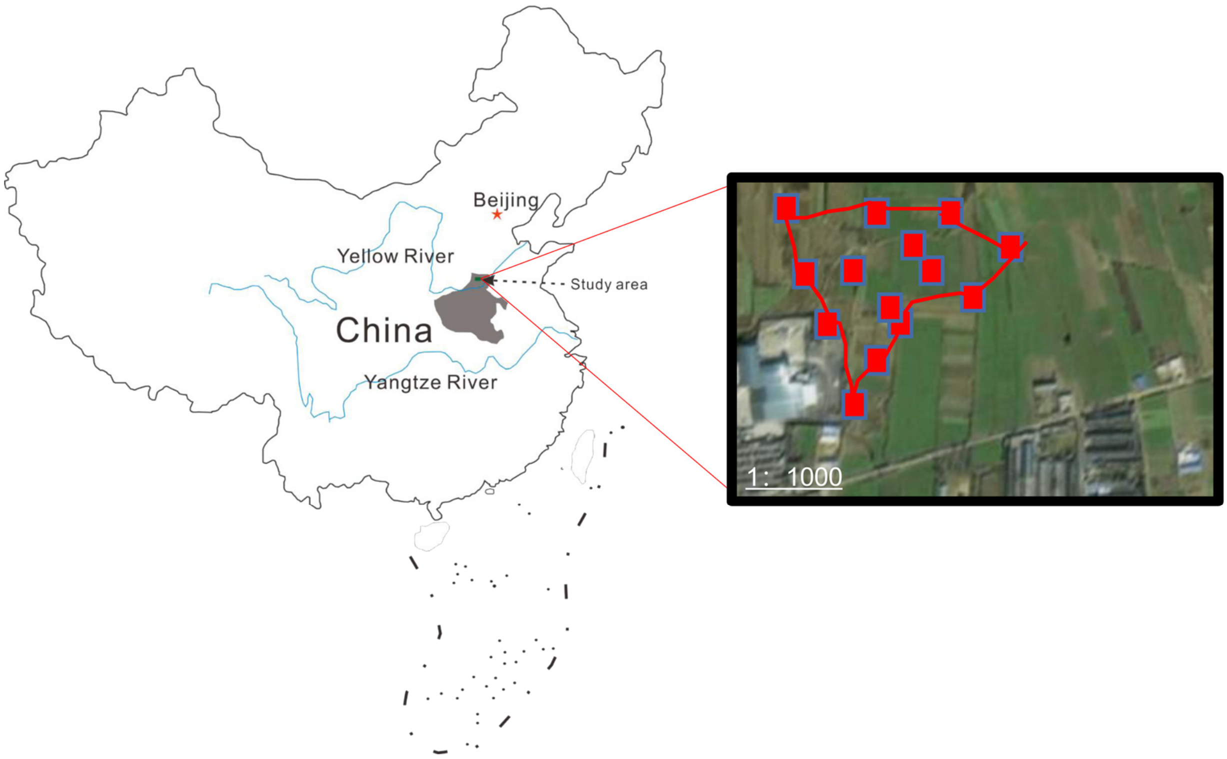

Figure 1. Location of the study area.

2.2. Revegetation Method in the Study Area

Six different revegetation methods were applied across six plots, each covering an area of approximately 200 to 300 m^2. For the sake of comparison, bare land with similar characteristics to the other six experimental groups was the control group (Table 1).

Table 1. Overview of revegetation methods.

Method	Revegetation Type	Altitude (m)	Slope (°)	Vegetation Coverage (%)	Slope Exposition
1	*Ulmus pumila*	143	34	90	Adret
2	*Ulmus pumila* + *Amorpha fruticosa* + *Robinia pseudoacacia*	204	0	90	
3	*Ulmus pumila* + *Amorpha fruticosa* + *Robinia pseudoacacia* + *Jerusalem artichoke*	212	0	92	
4	*Jerusalem artichoke*	215	0	93	
5	Sea buckthorn + *Amorpha fruticosa*	238	0	94	
6	*Ulmus pumila* + *Amorpha fruticosa*	186	35	91	
7 (Control group)	Bare land	201	0	0	

2.3. Soil Sampling and Analysis

Soil sampling was carried out following the established industry standard in China, namely LY/T 1210-1999, titled "Field Sampling and Preparation of Forest Soil Samples" [24].

The subsequent soil analysis was performed according to another industry standard, LY/T 1275-1999, titled "Forest Soil Analysis Methods" [25].

In this study, a total of seven groups of samples were collected and tested, comprising six revegetation methods and one control group. The selection of these groups was based on the different reclamation techniques employed. Three soil samples were collected for each group, and for the analysis, the average value of each group was utilized. Soil samples were collected from depths of 0–20 cm (topsoil) and 20–40 cm (subsoil). The physical parameters measured include soil moisture content, bulk density, and total porosity. The measured chemical parameters were soil pH, electrical conductivity, organic carbon, and contents of nitrogen, phosphorus, and potassium. The determination methods are briefly described below [26].

Soil moisture content was determined using an oven-drying method. The sample was first placed in an aluminum box and weighed. The box was put into an incubator for 12 h at 105 °C and weighed again after cooling to 25 °C. The box was dried for additional 2 h and weighed again until the weight of the box remained constant.

The bulk density of soil was determined using the cutting ring method. The soil sample was collected with a metal ring inserted into the soil. The weight of the sample was determined after drying. Soil bulk density was computed using Equation (1).

$$\rho = (M_2 - M_1)/V, \tag{1}$$

where M_1 is the mass of the empty cutting ring, g; M_2 is the combined mass of the cutting ring and dry soil, g; V is the volume of the cutting ring, cm^3.

Soil porosity was determined from bulk density measurements with an assumed particle density of 2.65 Mg/m^3 [27]. Equation (2) was used to calculate soil porosity.

$$\beta = \left(1 - \frac{\rho}{2.65}\right) \times 100\%. \tag{2}$$

Soil pH was determined using a potentiometric method when the water–soil ratio was 2.5:1. We placed 20 g of air-dried soil into the beaker, added 25 mL of distilled water, and stirred vigorously. After standing for half an hour, the glass electrode was inserted into the suspension. Next, the beaker was shaken slightly to ensure even distribution of the liquid pH. Finally, the readings were recorded till the measurements became stable. Each sample was measured repeatedly five times and adopted the average value.

Electrical conductivity was determined by a conductivity meter where the water-soil ratio was 5:1. We placed 20 g of sample soil into a beaker flask of 250 mL, put 100 mL of distilled water into it, and took the filtering liquid out after vigorous stirring conditions. Then, the electrical conductivity of the liquid was measured through the conductivity meter at room temperature.

The determination of organic carbon followed the H_2SO_4 and $K_2Cr_2O_7$ volumetric oxidation method. A 0.3 g sample was placed into a test tube. Subsequently, 5 mL of 0.8 mol/L $K_2Cr_2O_7$ solution and 5 mL of concentrated H_2SO_4 were added sequentially. The mixture was then heated to 180 °C, and the organic carbon in the solution was quantified using a blank titration procedure.

Nitrogen content was determined by the alkaline hydrolysis diffusion method. Phosphorous content was measured by Sodium Bicarbonate, in which phosphorous was extracted by a cation exchange resin membrane. Potassium content was tested by flame photometry.

2.4. Statistical Analysis

To establish the correlation between the soil physicochemical properties and identify the most suitable plant species for reclamation, multivariate statistics were performed using the statistical software, SPSS v19. Principal component analysis (PCA) was conducted. The purpose of PCA was to identify the most influential factors among the soil physicochemical properties and to rank the different revegetation methods based on their effectiveness in soil development. The multitude of measured soil properties presents challenges in directly interpreting the relationships and relative contributions of each property to the overall improvement in soil quality. PCA can help summarize the variable interrelationships and provide a concise representation of the data in the form of a few principal components. Subsequently, these components were utilized to rank the revegetation methods, facilitating the identification of the most successful approaches for improving soil properties. By transforming the original variables into a few new variables called principal components, PCA reduces the dimensionality of the original data set, which greatly aids in the ranking and sorting of the data [28].

To rank the revegetation methods, we proposed a composite principal component (CPC) score index, denoted as F, which is defined as follows:

$$F = \frac{\lambda_1}{\lambda_1 + \lambda_2 + \lambda_3} F_1 + \frac{\lambda_2}{\lambda_1 + \lambda_2 + \lambda_3} F_2 + \frac{\lambda_3}{\lambda_1 + \lambda_2 + \lambda_3} F_3, \tag{3}$$

where F_1, F_2, F_3 are the three principal component scores and λ_1, λ_2, λ_3 are the corresponding eigenvalues of these principal components.

3. Results

3.1. Soil Analysis Results

The test results indicating the impact of plant growth on the physicochemical properties of soil in coalmine-degraded land are presented in Tables 2 and 3 and Figure 2. It can be seen that the revegetation process decreases soil pH, conductivity, and bulk density while also resulting in increased moisture content, organic carbon, nitrogen, phosphorus, and potassium levels. Notably, the physicochemical properties of the topsoil exhibit substantial responsiveness to revegetation efforts. It is worth noting that the extent to which revegetation fosters soil development diminishes with increasing soil depth.

Table 2. Physical properties of soil samples from different depths.

Method	Moisture (%)	Moisture Ratio *	Bulk Density (g cm^{-3})	Bulk Density Ratio *	Porosity (%)	Porosity Ratio *
			(**a**) topsoil (0–20 cm)			
1	10.51	5.53	1.12	0.84	57.22	0.95
2	10.14	5.34	1.03	0.77	60.51	1.00
3	8.2	4.32	1.04	0.78	61.61	1.02
4	11.1	5.84	1.31	0.98	50.52	0.83
5	11.93	6.28	1.04	0.78	62.32	1.03
6	10.15	5.34	1.22	0.91	54.43	0.90
7	1.9	1	1.34	1	60.55	1
			(**b**) subsoil (20–40 cm)			
1	11.39	2.57	1.02	0.77	62.37	1.23
2	10.95	2.47	1.21	0.92	54.49	1.08
3	10.23	2.30	1.03	0.78	60.52	1.20
4	12.6	2.84	1.12	0.85	57.22	1.13
5	14.14	3.18	1.06	0.80	60.51	1.20
6	11.61	2.61	1.01	0.77	61.63	1.22
7	4.44	1	1.32	1	50.56	1

* Ratio refers to the ratio of parameter *i* to no. 7 parameter (control group), *i* is 1,2,3,4,5,6.

Table 3. Chemical properties of soil samples.

Method	Soil Layer Depth (cm)	pH	pH Ratio	Conductivity (/μS·cm^{-1})	Conductivity Ratio	Organic Carbon (%)	Organic Carbon (Ratio)	Available Nitrogen (mg·kg^{-1})	Available Nitrogen Ratio	Available Phosphorus (mg·kg^{-1})	Available Phosphorus Ratio	Available Potassium (mg·kg^{-1})	Available Potassium Ratio
(**a**) topsoil													
1	0~20cm	6.98	0.91	113.16	14.79	1.12	1.81	28.31	1.70	1.5	1.63	434.79	3.91
2	0~20cm	6.42	0.84	75.11	9.82	2.12	3.42	45.95	2.76	2.01	2.18	187.12	1.68
3	0~20cm	6.38	0.83	91.05	11.90	1.86	3.00	47.12	2.83	3.72	4.04	624.02	5.62
4	0~20cm	6.16	0.81	130.28	17.03	0.95	1.53	24.31	1.46	1.02	1.11	606.41	5.46
5	0~20cm	7.23	0.95	112.87	14.75	3.23	5.21	54.3	3.26	2.19	2.38	123.79	1.11
6	0~20cm	6.78	0.89	125	16.34	1.51	2.44	40.34	2.42	3.72	4.04	438.65	3.95
7	0~20cm	7.65	1.00	630.28	82.39	0.62	1.00	16.64	1.00	0.92	1.00	111.1	1.00
(**b**) subsoil													
1	20~40	7.33	0.89	130.25	0.15	0.66	2.87	14.93	1.44	1.23	1.64	260.01	4.73
2	20~40	7.58	0.92	91.19	0.11	0.84	3.65	39.99	3.85	1.53	2.04	105.81	1.93
3	20~40	6.60	0.80	115.60	0.13	1.15	5.00	25.02	2.41	2.42	3.23	579.02	10.54
4	20~40	6.67	0.81	256.51	0.30	0.56	2.43	13.16	1.27	0.86	1.15	472.33	8.59
5	20~40	6.53	0.79	139.73	0.16	1.32	5.74	33.74	3.24	1.33	1.77	68.96	1.25
6	20~40	6.67	0.81	184.95	0.21	0.78	3.39	27.94	2.69	3.08	4.11	187.84	3.42
7	20~40	8.25	1.00	862.74	1.00	0.23	1.00	10.40	1.00	0.75	1.00	54.96	1.00

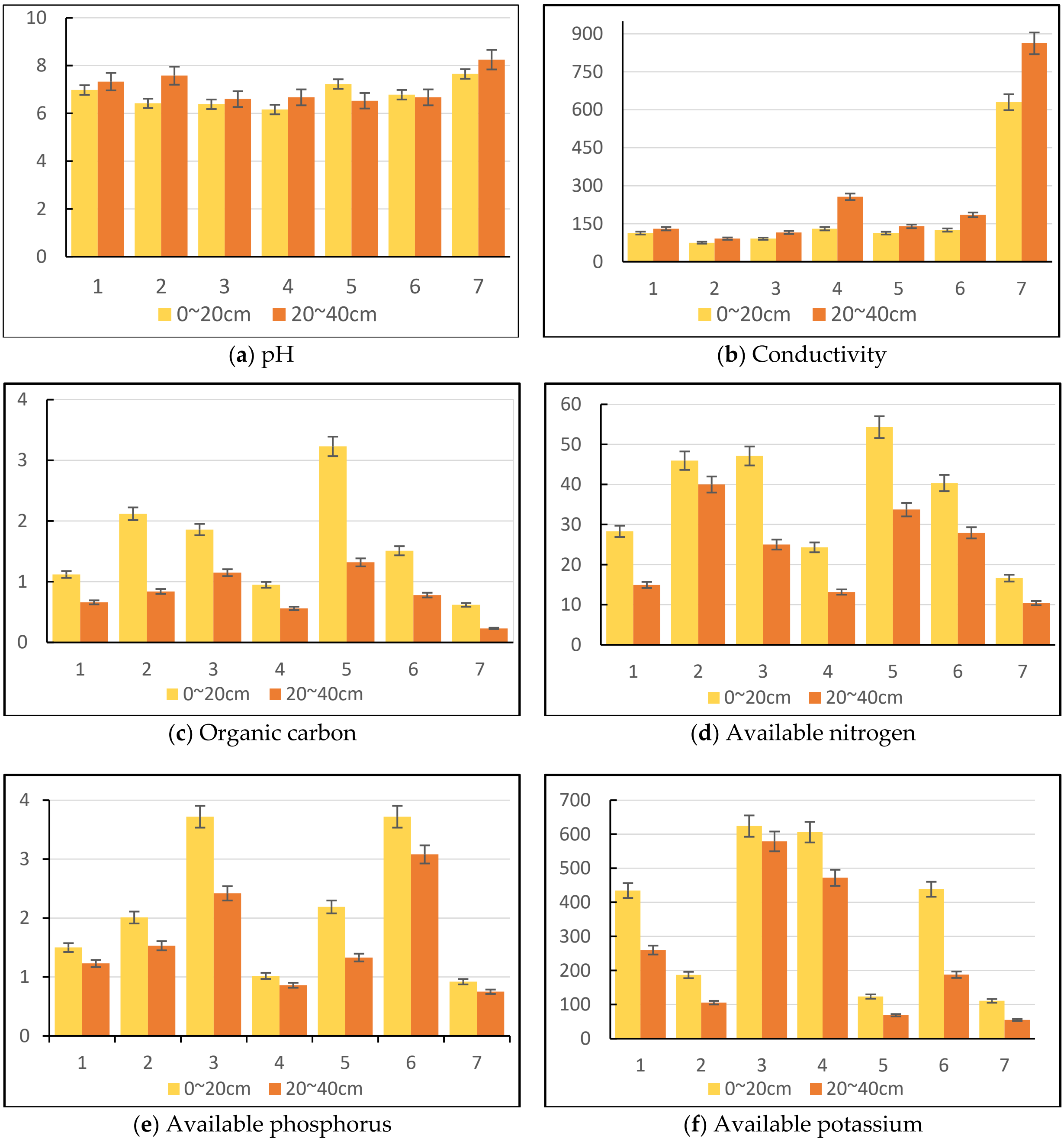

Figure 2. Physicochemical analysis of soil samples.

The pH level signifies the acidity or alkalinity of the soil. It is evident that the application of six distinct revegetation methods exerts a discernible influence on soil pH. A neutral pH is seven, so values below seven indicate acidic soil, and values above seven indicate alkaline soil. The control group has the highest pH values in both the topsoil and subsoil, indicating that the soil is alkaline. This is likely due to the presence of carbonate rocks in the soil. The six revegetation methods demonstrate the potential to mitigate soil alkalinity. Notably, Method 1 emerges as the most effective in the topsoil, while Method 2 proves more impactful in the subsoil. This reduction in alkalinity is attributed to the interactions between vegetation and soil constituents.

Soil electrical conductivity, a measure of chemical characteristics influenced by salinity, is vital for assessing plant growth conditions. Elevated salt concentrations elevate electrical conductivity, and values surpassing 500 $\mu S \cdot cm^{-1}$ indicate inadequate conditions for plant growth. The findings indicate that all six revegetation methods can potentially decrease electrical conductivity, with Method 2 being the most effective in the topsoil and Method 1 being the most effective in the subsoil. Remarkably, the reduction in electrical conductivity due to revegetation methods is nearly 80%, demonstrating their substantial impact on improving soil conditions for plant growth. The comparatively lower electrical conductivity values highlight the suitability of revegetation for promoting healthy plant growth by mitigating the adverse effects of excessive salt levels on water uptake and nutrient availability.

The organic carbon in soil is an important parameter determining soil fertility. This component not only aids in soil aeration, but also represents a primary source of crucial elements such as nitrogen, phosphorus, and potassium. In addition, it significantly contributes to overall soil fertility. According to the findings, different revegetation methods can increase the organic carbon in the soil of coalmine-degraded lands. Notably, organic carbon is relatively higher in the topsoil than the subsoil across different revegetation methods. Method 5 stands out as the most effective strategy for augmenting organic carbon, while Method 4 exhibits the lowest value. This variance can be attributed to the specific characteristics of each revegetation method, such as plant species selection and their influence on organic carbon.

The analysis extends to the essential nutrients, including available nitrogen, available phosphorus, and available potassium. These nutrients are pivotal for plant development and growth. The results from Table 3 highlight the influence of various revegetation methods on the availability of these nutrients. For instance, Method 2 exhibits a noteworthy increase in available nitrogen and available phosphorus content in both topsoil and subsoil layers. This enhancement in nutrient availability can be attributed to the interactions between the revegetation methods and soil microbial communities, which facilitate nutrient cycling and release. Such findings underline the potential of these methods to contribute to improved soil nutrient availability, fostering enhanced plant growth and ecosystem sustainability.

3.2. Multivariate Statistical Results

The correlation patterns among the nine variables, as presented in Table 4, provide valuable insights into the relationships among the various soil physicochemical properties explored in this study. A strong positive correlation of 0.883 suggests that higher organic carbon is associated with increased nitrogen availability. Organic matter serves as a source of nitrogen through decomposition processes, leading to a positive relationship between these variables. The correlation coefficient 0.635 suggests a moderate positive correlation between available nitrogen and phosphorus. Both nutrients are essential for plant growth, and their availability might be influenced by similar soil conditions, leading to this positive relationship.

Table 4. Correlation matrix of the soil physicochemical properties.

Correlation Coefficient	Moisture	Density	Porosity	pH	Conductivity	Organic Carbon	Available Nitrogen	Available Phosphorus	Available Potassium
Moisture	1.000								
Density	−0.622	1.000							
Porosity	0.180	−0.772	1.000						
pH	−0.575	0.453	−0.214	1.000					
Conductivity	−0.784	0.648	−0.356	0.719	1.000				
Organic Carbon	0.300	−0.463	0.428	−0.333	−0.516	1.000			
Available Nitrogen	0.321	−0.400	0.301	−0.353	−0.614	0.883	1.000		

Table 4. *Cont.*

Correlation Coefficient	Moisture	Density	Porosity	pH	Conductivity	Organic Carbon	Available Nitrogen	Available Phosphorus	Available Potassium
Available Phosphorus	0.150	−0.439	0.324	−0.420	−0.471	0.480	0.635	1.000	
Available Potassium	0.171	−0.098	−0.117	−0.639	−0.417	0.019	0.000	0.349	1.000

The correlation coefficients between conductivity and density as well as between conductivity and pH in the provided correlation matrix are 0.648 and 0.719, respectively. As soil density increases, conductivity tends to rise, a connection attributed to factors such as reduced pore spaces in compacted soils that hinder water movement and favor salt accumulation. Similarly, the positive correlation between conductivity and pH underscores that higher pH levels correspond to elevated conductivity. This linkage arises due to pH's influence on ion mobility and solubility, with alkaline conditions enhancing the release of ions into the soil solution. These correlations collectively signify the complex interplay between soil physical properties, ion concentration, and pH levels. The results highlight negative correlations between conductivity and moisture content, organic carbon, and available nitrogen. In simpler terms, these three factors tend to decrease when conductivity increases. This negative relationship suggests that higher levels of conductivity in the soil are associated with lower moisture content, reduced organic carbon, and decreased nitrogen availability. This connection might arise from the fact that elevated conductivity is often linked to the presence of salts and ions in the soil, which can limit the movement of water and nutrients. As a result, soils with higher conductivity may experience drier conditions, lower organic carbon, and reduced nitrogen availability.

Based on single-factor analysis, PCA can effectively deliver a comprehensive evaluation result and provide the best suitable revegetation method. PCA delivered three principal components (PCs) and the loadings of nine variables on the three. The results in Table 5 reveal how the nine variables are associated with PCs. Each variable's loading on the PCs provides insights into their contribution to the underlying patterns in the dataset. PC1, with an eigenvalue of 4.442, accounts for 49.353% of the total variance explained. This component primarily reflects the inverse relationships between variables like moisture and density (−0.797), indicating that density tends to decrease as moisture increases. Additionally, variables like pH (−0.737) and conductivity (−0.896) are negatively associated with PC1, suggesting that higher pH and lower conductivity correspond to this component. PC2 captures 18.011% of the total variance and is influenced by positive relationships, such as between pH (0.531) and conductivity (0.229). This implies that higher pH and conductivity coincide with PC2. Similarly, organic carbon (0.421) and available nitrogen (0.362) are positively connected to PC2. PC3 contributes to 13.151% of the total variance. Variables like available phosphorus (0.475) and moisture (−0.456) are prominent contributors to this component, suggesting that higher available phosphorus and lower moisture levels align with PC3. These findings are crucial for understanding the main drivers of variability in the dataset, aiding in the interpretation of underlying soil properties and their interactions.

Table 5. Loadings of nine variables on principal components (PCs).

Variable	PC1	PC2	PC3
Moisture	0.682	−0.255	−0.456
Density	−0.797	−0.196	0.459
Porosity	0.561	0.498	−0.385
pH	−0.737	0.531	0.007

Table 5. *Cont.*

Variable	PC1	PC2	PC3
Conductivity	−0.896	0.229	0.107
Organic Carbon	0.731	0.421	0.336
Available Nitrogen	0.753	0.362	0.454
Available Phosphorus	0.673	0.054	0.475
Available Potassium	0.355	−0.790	0.245
Eigenvalue	4.442	1.621	1.184
Variance explained, %	49.353	18.011	13.151
Total variance explained, %	49.353	67.365	80.515

Table 6 presents a comprehensive evaluation of the impact of different methods. According to the results, the overall properties of topsoil are better than those of subsoil. With the increasing depth of soil, soil fertility gradually decreases. Among the examined revegetation methods, Method 5, Method 3, Method 2, and Method 6 exhibit a notable capacity to effectively enhance soil development. On the other hand, the effectiveness of the remaining two methods, Method 1 and Method 4, is comparatively lower. These findings underscore the crucial role of revegetation methods in influencing soil quality, with certain methods showcasing higher efficacy in promoting improved soil conditions compared to others.

Table 6. Comprehensive evaluation of the effect of principal component analysis.

Method	Score				Rank
	1st PC	2nd PC	3rd PC	CPC	
1	0.05079	−0.50098	−0.18101	−0.1105	9
	−0.08494	0.16104	−1.80928	−0.31156	10
2	0.86509	0.71528	0.11280	0.708702	3
	−0.32826	0.35718	0.17342	−0.09299	8
3	1.16573	−0.14424	1.33229	0.899898	2
	0.53086	−0.70880	−0.27077	0.122616	7
4	−0.27767	−2.18588	0.67790	−0.54845	11
	−0.27104	−1.22627	−1.21682	−0.6392	12
5	1.06954	1.88041	0.45563	1.150656	1
	0.46117	0.37507	−1.25746	0.161195	6
6	0.40900	−0.50377	1.74985	0.423825	4
	0.48800	0.24721	−0.73497	0.234381	5
7	−1.67544	1.00265	0.44889	−0.72938	13
	−2.40284	0.53111	0.51956	−1.26919	14

4. Discussion

Mine reclamation is a pivotal pillar within the realm of green and climate-smart mining practices, acting as a countermeasure to the detrimental environmental consequences of mineral resource extraction. Ecological damage and land disturbance are key concerns, making reclamation a vital post-mining step, necessitating thorough investigation. Reclamation, in this context, refers to the restoration of mined lands [29]. This process extends beyond restoring the land to its original state and aims to transform it for alternative uses. The success of mine reclamation hinges on various factors, such as mining methods, soil composition, local climate, hydrology, and the choice of plant species for revegetation [21,30].

This study investigated the impact of six distinct revegetation methods on soil development in coalmine-degraded lands, aiming to identify suitable plant species for effective mine reclamation. The investigation revealed significant enhancements in the physicochemical properties of soil resulting from these revegetation efforts. According to the findings, the initial alkaline soil conditions, indicated by the control group's higher pH values due to carbonate rock presence, were mitigated by applying the six methods. Method 1 exhibited remarkable efficacy in addressing soil alkalinity in the topsoil, while Method 2 showed pronounced results in the subsoil. Similarly, the revegetation methods notably reduced electrical conductivity values by approximately 80%, with Method 2 being most effective in the topsoil and Method 1 in the subsoil. This substantial reduction underscores the potential of revegetation in fostering optimal soil conditions for robust plant growth. Concerning organic carbon, Method 5 stood out as the most effective strategy. The variation in organic carbon across methods can be attributed to factors such as plant species selection and their influence on organic carbon accumulation. Furthermore, Method 2 demonstrated a significant increase in available nitrogen and available phosphorus in both topsoil and subsoil layers, signifying improved nutrient availability for plant growth. Among the methods evaluated, Method 5, Method 3, Method 2, and Method 6 displayed notable prowess in enhancing soil development, while Method 1 and Method 4 showed relatively lower effectiveness. In particular, the mixed plantation of Sea buckthorn and *Amorpha fruticosa* was the most effective approach. This method exhibited notable organic carbon in both the topsoil (3.23%) and subsoil (1.32%). The findings indicate positive effects on soil quality, resulting in lower pH, electrical conductivity, and bulk density. These improvements contribute to a conducive environment for ecosystem restoration. Moreover, increased levels of moisture content, organic carbon, nitrogen, phosphorus, and potassium were observed, collectively enhancing soil fertility and ecosystem health. The significance of revegetation in enhancing soil quality aligns with prior research highlighting its role in facilitating the return of native fauna, creating favorable conditions for vegetation rooting, and enhancing soil development [31]. Considering the region's arid climate and water scarcity, successful revegetation in degraded lands necessitates drought-resistant, fast-growing, and cost-effective plant species [32,33]. The chosen nitrogen-fixing species, Sea buckthorn and *Amorpha fruticosa* [34,35], adapt to the local arid climate and limited water resources. These choices offer pragmatic solutions for mine reclamation. The mixed plantation of these species leverages various mechanisms such as nitrogen fixation, phosphorus uptake, and mulching to improve soil quality. Beyond their functional benefits, these shrubs support local wildlife by providing food and shelter for birds, bees, and other insects. Being fast-growing and hardy, these species are well-adapted to a range of conditions, further promoting soil development in coalmine-degraded lands when coupled with technological inputs for enhanced soil fertility.

Correlation analysis provides insights into the relationships governing different soil parameters. For instance, a positive correlation between organic carbon and available nitrogen underscores the role of organic carbon in nutrient availability. The negative correlation between soil conductivity and moisture content highlights the significance of maintaining soil salinity for optimal vegetation growth. Plants contribute to soil structure by increasing organic carbon and forming root networks that bind soil particles, reducing erosion and enhancing water infiltration. Additionally, plants release nutrients into the soil through their roots and leaves, further enhancing soil fertility. Moreover, plants provide shade, moderating soil temperature and minimizing evaporation, fostering an environment conducive to microorganisms crucial for soil development. Despite positive outcomes, challenges exist for soil development in mine-degraded lands, including nutrient deficiency and disruptions in water regimes. Therefore, hydroseeding can reduce surface erosion [36], which should be explored in future studies. A notable outcome of this study is the differential impact of revegetation on topsoil and subsoil. A notable finding of this study is the differential impact of revegetation on topsoil and subsoil, with a more pronounced effect observed in the topsoil. This emphasizes the importance of considering depth-specific effects when evaluating the efficacy of vegetation in promoting soil development. However, other factors such as mine waste type, local climate, land slope, and water availability should also be considered when designing a revegetation plan for mine-degraded lands. The choice of plant species should be tailored to the specific conditions of the site, and the plan should be implemented promptly, as prolonged bare soil can hinder reclamation efforts.

The research findings present valuable insights into the potential for successful mine reclamation and soil improvement, contributing to green and climate-smart mining advancement. However, certain limitations exist within this study. Notably, heavy metal concentrations in soil were not investigated. This aspect holds ecological significance, as elevated heavy metal levels in soil, water, and, subsequently, the food chain pose substantial risks to both local ecosystems and human health. In light of this, special attention must be given to two particular plant species: *Amorpha fruticosa*, known for its value to bees, and Sea buckthorn, a vital resource for food and medicinal products. Additionally, the interaction between irrigation water and soil on abandoned land necessitates exploration, given its influence on soil properties and ecological restoration efforts. Addressing these limitations and conducting comprehensive research is key to enhancing the effectiveness and sustainability of reclamation endeavors. While this study provides broader trends and potential correlations, it does not extensively delve into the evolving impact of revegetation over time, nor does it explore the underlying metabolic and material circulation processes. Future research should aim to fill these gaps by conducting long-term empirical studies that thoroughly examine specific metabolic processes, material circulation patterns, and the adaptability of various plant species within coalmine-degraded lands. Furthermore, extending the scope to consider the enduring impacts of revegetation techniques on biodiversity, ecosystem services, and overall landscape restoration in mine-degraded regions is highly recommended.

5. Conclusions

In the pursuit of green and climate-smart mining practices, effective mine reclamation remains a significant challenge. This research studied the impact of revegetation restoration on soil development in a coal mining area in northern Henan, China. Six distinct revegetation methods were implemented to analyze their impacts on the physicochemical properties of soil in mine-degraded lands. According to the findings, remarkable improvements were observed in various soil attributes. The mixed plantation strategy involving Sea buckthorn and *Amorpha fruticosa* was the most efficacious approach. This approach increased organic carbon in both the topsoil (3.23%) and subsoil (1.32%). While the quality of topsoil at depths of 0–20 cm improved, the efficacy of soil improvement decreased with increasing depth, specifically beyond 20 cm in the soil profile. The mixed plantation of sea buckthorn and *Amorpha fruticosa*, both nitrogen-fixing species, stands out as a solution tailored to the arid climate and limited water resources prevalent in the region. Their resilience and rapid growth potential align cohesively with the demands of mine reclamation in the area. Moreover, their ability to support local wildlife adds to their functional significance.

In conclusion, the study indicates that revegetation is an effective way to improve the physicochemical properties of soil in mine-degraded lands. However, careful consideration must be given to the choice of plant species and soil depth when formulating a revegetation strategy. This research contributes to our understanding of mine reclamation and soil improvement. It is a stepping stone to further exploration to fully harness the potential of revegetation restoration, particularly the long-term impacts of revegetation on soil properties and ecosystem services.

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