

Optimizing Soil Pore Structure in Mined Land: Integrating Arbuscular Mycorrhizal Fungi and Mixed Planting for Ecological Restoration

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Abstract

Aims

The fragile soil structure of coal mine dumps in arid and semi-arid regions presents a major obstacle to ecological restoration. Phytoremediation strategies enhancing soil porosity are critical, yet Arbuscular Mycorrhizal Fungi (AMF) inoculation efficacy in compacted soils combined with mixed planting remains unclear.

Methods

This study employed a two-factor experiment and 3D CT scanning to assess AMF inoculation and mixed planting effects on *Amorpha fruticosa* root morphology, soil pore structure, and infiltration at a northern China open-pit dump.

Results

Our results demonstrated that both AMF inoculation and mixed planting significantly improved soil porosity and root development. Notably, the combined treatment of AMF inoculation and mixed planting (A-M) yielded the most uniform distribution of connected pores within the soil cores and exhibited the highest model complexity in correlation analyses. Furthermore, A-M also maximized fractal dimension and permeability while reducing tortuosity and improving connectivity, attaining peak permeability. With respect to root morphology, both AMF and mixed planting led to substantial increases in root morphological characteristics and root density characteristics. Partial least squares path analysis revealed that the observed improvements in soil pore structure and infiltration characteristics were primarily driven by root morphological modifications induced by AMF and mixed planting treatments.

Conclusions

The synergistic application of AMF inoculation and mixed planting effectively optimized soil pore architecture and enhanced infiltration dynamics at open-pit dump sites, primarily through their stimulatory effects on plant root development. These findings provided a strong scientific foundation and practical guidance for advancing ecological restoration efforts in arid mining regions.

Introduction

Coal, as a pivotal global energy resource, has significantly bolstered energy supply through open-pit mining. However, this extraction process has also inflicted profound ecological disturbances (Feng et al., 2019). The extensive environmental degradation caused by coal mining underscores the urgent need for effective ecological restoration strategies (Chen et al., 2022; Xu and Zhang, 2021). This challenge is

particularly acute in arid and semi-arid regions, where annual precipitation is typically less than 400 mm and distributed unevenly. In such landscapes, surface coal mining generates dump soils with highly fragile structures, characterized by low porosity and poor hydraulic conductivity, which severely restrict water retention and utilization (Duncan et al., 2020; Hu et al., 2024). Consequently, the development of innovative and sustainable ecological restoration techniques has become imperative (Wu et al., 2024).

Soil pore structure is a critical determinant of water retention, gas exchange, and solute transport, influencing a multitude of physical, chemical, and biological soil processes (Fatichi et al., 2020; Rabot et al., 2018). A well-structured pore network enhances soil moisture availability, improves nutrient retention, fosters root proliferation, and ultimately contributes to the long-term stability of restored ecosystems (Jin et al., 2017; Phalempin et al., 2022). The emergence of three-dimensional (3D) X-ray computed tomography (CT) has revolutionized the non-invasive analysis of soil pore networks across multiple scales, providing unprecedented insights into soil hydraulic dynamics, gas diffusion pathways, and root-soil interactions (Burr-Hersey et al., 2020; Du et al., 2024; Ge et al., 2023). At the microscopic scale, CT-derived representative elementary volumes (REVs) enable precise quantification of pore distribution, morphology, and connectivity (Yuan and Fan, 2022), while capturing the intricate relationship between fine soil pores and organic matter aggregates (Soto-Gómez et al., 2018; Winstone et al., 2019). At a broader scale, CT imaging facilitates the visualization of extensive pore networks and their influence on water movement within the soil profile (An et al., 2022; Du et al., 2024). Despite these advancements, research applying CT technology to assess soil structural modifications in surface coal mine dumps remains limited, necessitating further investigation into its potential for guiding ecological restoration efforts.

Phytoremediation plays a pivotal role in modifying soil pore architecture, primarily through root-driven processes (Marin et al., 2022; Zhou et al., 2021). As plant roots grow and exert mechanical pressure, they generate new pore channels, thereby enhancing soil permeability and hydraulic conductivity (Hao et al., 2020; Lucas et al., 2019). Additionally, root exudates—comprising mucilage, sugars, and amino acids—facilitate soil aggregation, reinforce structural stability, and mitigate compaction, thereby improving overall soil quality (Li et al., 2024; Traore et al., 2000; Duan et al., 2023; Li et al., 2020). Notably, these effects vary depending on plant species, as differences in root morphology and biochemical secretions lead to distinct influences on soil pore dynamics (Helliwell et al., 2019; Pulido-Moncada et al., 2022).

Arbuscular mycorrhizal fungi (AMF), a ubiquitous group of symbiotic fungi, establish mutualistic associations with the root systems of most terrestrial plants, enhancing nutrient and water uptake through the formation of specialized mycorrhizal structures (Xu et al., 2024). Extensive research has demonstrated that AMF significantly influence soil pore architecture through multiple mechanisms (Rillig and Mummey, 2006). Their extensive mycelial networks penetrate micropores, effectively widening water transport pathways, improving soil permeability, minimizing water loss, and increasing water retention capacity (Keyes et al., 2022). Furthermore, AMF secrete extracellular polysaccharides that contribute to soil aggregation, reinforce structural integrity, and improve erosion resistance, thereby reducing the risk of soil degradation (Liu and Yao, 2024; Tang et al., 2024).

In agricultural systems, mixed cropping has long been employed as a sustainable approach to optimizing soil structure and enhancing water-use efficiency by leveraging the complementary interactions between different plant species (Dai et al., 2023; Yu et al., 2022). Deep-rooted plants can penetrate compacted soil layers, break up subsurface hardpans, and create larger pore channels, significantly improving vertical water infiltration. In contrast, shallow-rooted species form dense root networks in the upper soil layers, increasing lateral pore connectivity and facilitating the movement of air and water within the soil matrix (Gong et al., 2024; Islam et al., 2023). Moreover, root exudates from different plant species in mixed cropping systems enrich the inter-root microbial community, fostering beneficial interspecies interactions and improving soil microbial diversity (Wang et al., 2021, 2020). Beyond structural enhancements, mixed cropping also regulates soil moisture dynamics by modulating plant transpiration, thereby reducing surface evaporation and improving overall water retention capacity (Cheng et al., 2023; Yang et al., 2021).

Given these mechanisms, both AMF inoculation and mixed cropping hold considerable promise for enhancing soil quality and supporting phytoremediation efforts in arid and semi-arid coal mine dumps. However, the interactive effects of AMF inoculation and mixed cropping, particularly their combined influence on soil pore structure and infiltration dynamics in mine drainage areas, remain poorly understood. Elucidating these interactions is crucial for developing effective ecological restoration strategies in degraded mining environments.

To investigate the mechanisms by which AMF inoculation and mixed planting of *Sophora japonica* and *Medicago sativa* influence soil pore structure and infiltration dynamics in mine drainage areas, this study proposed the following hypotheses:

1. Both AMF inoculation and mixed planting significantly affect root morphology, root density, and root chemical properties.
2. The development of plant root systems directly modifies soil pore structure and infiltration characteristics.
3. AMF inoculation and mixed planting indirectly influence soil pore space and infiltration properties by altering root system architecture and function.

This study aimed to provide empirical evidence on the role of AMF and mixed cropping in regulating soil hydrological properties, thereby offering new insights into sustainable strategies for ecological restoration in degraded mining landscapes.

Materials and Methods

Study Area

The soil used in this study was collected from a dump site at an opencast coal mine in the Heidaigou mining region, located in Jungar Banner, Ordos City, Inner Mongolia, northern China (39°43'–39°49' N, 111°13'–111°20' E) (Fig. 1). This region is characterized by a typical medium-temperate, semi-arid

continental climate, with an annual mean temperature of 7.2 °C, reaching a maximum of 38.3 °C and a minimum of -30.9 °C. The annual precipitation ranges from 231 to 460 mm, with an average of 404 mm, while annual evaporation is significantly higher, averaging 2,082 mm. The region also receives an annual mean of 3,119.3 hours of sunlight.

The soil exhibits a loess-like texture, and its physicochemical properties within the top 40 cm of the profile are as follows: organic matter content of 8.32 g kg⁻¹, total nitrogen (N) of 0.38 g kg⁻¹, available phosphorus (P) of 0.78 mg kg⁻¹, and available potassium (K) of 21.51 mg kg⁻¹.

Experimental Design

The experiment was conducted during the 2018–2019 growing seasons at the Heidaigou mining area, specifically within the inner dump at the 1300-platform north. A two-factor split-plot design was implemented to examine the effects of AMF inoculation and plant species composition on soil characteristics.

The first factor was the AMF inoculation treatment, consisting of two levels: a control treatment without AMF inoculation (CK) and an AMF inoculation treatment (AMF). *Funneliformis mosseae* (F.m), an AM fungus, was inoculated with *A. fruticosa*. The fungal inoculant was applied in granular solid form. During planting, seedlings were first placed into the soil pit, followed by the addition of 50 g of the fungal inoculant directly to their root systems before backfilling the soil.

The second factor involved plant species composition, which included two planting schemes: (1) a monoculture of *Amorpha fruticosa* and (2) a mixed planting of *A. fruticosa* and *Medicago sativa* (alfalfa). This factorial design resulted in four treatment groups, each replicated across four plots: (1) control (CK), (2) AMF inoculation alone (AMF), (3) mixed planting without AMF inoculation (MIX), and (4) AMF inoculation combined with mixed planting (A-M). Each plot measured 34 × 44 m (Fig. 1), with *A. fruticosa* planted at a density of 2 × 2 m. In the mixed-planting treatment, *M. sativa* was sown in a circular pattern around *A. fruticosa* within a 50-cm radius.

Soil Sampling and Measurements

Soil sampling was conducted in September 2022. Prior to sample collection, a comprehensive assessment of soil quality was performed across all experimental plots, confirming no significant differences in baseline soil properties. Soil samples were collected within a 20-cm radius of the central plant and at a depth of 20 cm from the surface. For sample extraction, PVC tubes (5 cm in diameter and 5 cm in height) were used. Before inserting the tubes, the surface soil was carefully removed, and an appropriately sized soil section was excavated. The root system connecting the sample to the surrounding soil was meticulously severed with a utility knife, and excess surrounding soil was stripped away. The PVC tubes were then pressed into the soil at a uniform speed to ensure maximal compaction of the sample inside the tube. The lower soil portion was carefully trimmed before sealing the soil

columns with gauze and plastic film, wrapping them in a sponge, and transporting them immediately and with caution to the laboratory for X-ray CT scanning to prevent any structural damage or moisture loss.

Following CT scanning, root samples were carefully extracted from each PVC column. The cleaned roots were arranged in a transparent root tray, ensuring that individual roots did not overlap. A ScanMaker i800 Plus (Microtek, Hsinchu, Taiwan) was used to scan high-resolution digital images of the roots. Morphological characteristics, including root length (RL, m), root surface area (RS, cm²), average root diameter (RD, mm), and root volume (RV, mm³), were analyzed using RhizoPheno root processing software (Zhejiang TOP Cloud-Agri, Hangzhou, China).

Immediately after imaging, root samples were oven-dried and weighed to determine root dry mass (DM, g). Root density parameters were calculated as follows:

Root biomass density (RBD, mg·cm⁻³) = DM per unit soil volume

Root length density (RLD, mm·cm⁻³) = RL per unit soil volume

Root surface area density (RSD, mm²·cm⁻³) = RS per unit soil volume

Root volume density (RVD, mm³·cm⁻³) = RV per unit soil volume

Additionally, key morphological traits were derived:

Specific root length (SRL, m·g⁻¹) = RL / DM

Root tissue density (RTD, g·cm⁻³) = DM / RV

Specific root surface area (SRA, cm²·g⁻¹) = RS / DM

Dried root samples were finely ground and passed through a 2-mm sieve for chemical analysis. Root carbon (RC) content (%) and root nitrogen (RN) content (g/kg) were quantified using a Vario MACRO cube elemental analyzer (Elementar Analysensysteme, Germany). Root phosphorus (RP) content (g/kg) was determined using the alkali diffusion method, and the root C/N ratio was subsequently calculated.

CT Scanning and Image Analysis

Undisturbed soil cores extracted from PVC rings were subjected to high-resolution scanning using an ACTIS300-320/225 Industrial CT scanner (China University of Mining and Technology, Beijing). The X-ray source parameters were set at a voltage of 100 kV and a current of 100 µA. During scanning, the sample table underwent a continuous 360° horizontal rotation at a uniform speed. A total of 700 high-precision, low-noise images were captured, each with a resolution of 60 µm. The acquired images were processed using Avizo 9.0 software for 3D reconstruction and visualization.

To mitigate boundary effects, the central portion of each scanned image was extracted for further analysis. Each voxel corresponded to a volume of $60 \times 60 \times 60 \mu\text{m}$, resulting in a $30 \times 30 \times 30 \text{ mm}$ sub-volume for subsequent pore structure analysis. A 3D median filter (six-neighbor connectivity, one iteration) was applied to reduce image noise. After filtering, grayscale images were converted into binary images using an interactive thresholding module, which allowed users to manually define grayscale intervals through visual feedback.

For the initial segmentation of macropores from the soil matrix, a strength range division tool was employed to automatically estimate threshold values for differentiating materials of varying densities. This preliminary threshold was then manually refined to enhance voxel classification, ensuring a more precise distinction between pore spaces and solid soil components. Following segmentation, macropores were reconstructed and visualized in three dimensions, enabling a detailed assessment of their size, spatial distribution, and key structural attributes. These included pore length, width, thickness, volume, spatial orientation, surface area, and equivalent diameter, providing a comprehensive characterization of the soil's pore architecture.

Extraction and Modeling of Connected Pores

The Avizo software was utilized to identify and extract connected pore networks from the 3D reconstructed data cube (Li et al., 2021). Using the "and not image" module, pores were classified into connected and isolated types, with the morphological characteristics of isolated pores analyzed separately. For connected pores, key structural parameters were quantified, including fractal dimension (FD) (calculated via Avizo's embedded "fractal dimension" module), pore connectivity, porosity, and absolute permeability. To further delineate the pore-fracture space, the "Separate Objects" module was employed, facilitating the classification of connected and labeled pore fractures. Subsequently, an equivalent pore network model (PNM) was constructed using the "Generate Pore Network Model" template. Based on this model, additional pore structural attributes were derived, including the pore coordination number, equivalent pore diameter, and throat equivalent diameter, providing a comprehensive assessment of the soil's pore architecture.

Statistical Analysis

All experimental data were organized using Microsoft Excel 2016 and subsequently analyzed and visualized using Origin 2021. One-way analysis of variance (ANOVA) was performed on each set of test index data using the IBM SPSS 26.0 software package (IBM, Armonk, NY), with results expressed as mean $\pm$ standard error.

To construct a path model illustrating the influence of AMF inoculation and mixed planting on soil permeability characteristics, partial least squares path modeling (PLS-PM) was conducted using the "plspm" package in RStudio.

Results

Visualization of Soil Pores

The 3D renderings of the soil pore network, connected pore network, and PNM under different treatments are presented in Fig. 2. Each cube model displayed in the figure represents a volume of 30 mm × 30 mm × 30 mm, with all visualized pores exceeding 60 µm in size, consistent with the scanning resolution.

Among all treatments, the CK treatment exhibited the smallest and least developed pore network and connected pore system. In contrast, both AMF inoculation (AMF) and mixed planting (MIX) treatments led to a notable enlargement of soil pores, albeit to varying degrees. When analyzing the distribution of connected pores, the A-M treatment demonstrated the most even and homogeneous pore distribution within the soil core. Meanwhile, in the AMF and MIX treatments, intricate root structures were visibly interwoven within the pores, highlighting the complex interactions between root systems and soil structure.

The PNM provided a more detailed comparative visualization of pore connectivity across treatments. The CK treatment exhibited the simplest and least developed network, characterized by fewer ball-and-stick connections, indicating minimal pore-throat complexity. The AMF and MIX treatments, however, displayed distinct distribution patterns, with the MIX treatment exhibiting a more uniform pore-throat distribution. Notably, larger diameter pores (large red spheres in the PNM) were observed in the AMF, MIX, and A-M treatments, with the A-M treatment displaying the highest structural complexity.

Taken together, these results indicated that both AMF inoculation and mixed planting treatments significantly enhanced soil pore network development, with the A-M treatment producing the most optimized and interconnected pore structure.

The geometric characteristics of connected pores and independent pores under different treatments are summarized in Tables 1 and 2, respectively. A comparison of the connected pore characteristics revealed no statistically significant differences in pore length, width, or thickness among the treatments (Table 1). However, the equivalent diameter of pores in treatments incorporating *M. sativa* was significantly larger ($P < 0.05$) than in treatments without mixed planting. In terms of connected pore volume, the CK treatment exhibited the smallest value (542.75 mm³), whereas the A-M treatment achieved the largest (2,499.12 mm³). Additionally, the volume, surface area, and porosity of connected pores were significantly higher in A-M compared to AMF and MIX, while CK had the lowest values ($P < 0.05$). Specifically, compared to CK, the AMF treatment increased pore volume, surface area, and porosity by 38.1%, 47.4%, and 72.6%, respectively. Similarly, the MIX treatment increased these parameters by 58.8%, 48.7%, and 81.8%, respectively.

Table 1
Geometric characteristics of connected pores

Sample	CK	AMF	MIX	A-M
Length (mm)	46.55 ± 4.32a	49.72 ± 5.15a	47.73 ± 3.59a	51.11 ± 4.18a
Width (mm)	32.02 ± 1.13a	32.67 ± 1.07a	32.61 ± 0.75a	32.85 ± 1.24a
Thickness (mm)	36.22 ± 0.56a	35.07 ± 0.88b	36.16 ± 0.96a	36.68 ± 0.44a
EqDiameter (mm)	10.12 ± 1.04b	11.87 ± 0.52b	13.60 ± 1.83a	16.84 ± 0.87a
Volume (mm ³)	542.75 ± 85.62c	876.81 ± 95.33b	1317.11 ± 128.65b	2499.12 ± 316.85a
Area (cm ²)	46.11 ± 5.86c	87.59 ± 9.14b	89.96 ± 10.58b	201.05 ± 19.42a
Porosity (%)	0.89 ± 0.12c	3.25 ± 0.51b	4.88 ± 0.64b	9.26 ± 0.86a
(CK, <i>A. fruticosa</i> without AMF inoculation; AM, <i>A. fruticosa</i> with AMF inoculation; MIX, a mixture of <i>A. fruticosa</i> and <i>M. sativa</i> ; A-M, mixture of <i>A. fruticosa</i> and <i>M. sativa</i> with AMF inoculation. Values with different letters are significantly different at P < 0.05.)				

Table 2
Number of independent pores and average characteristics

Sample	CK	AMF	MIX	A-M
Mean length (μm)	403.15 ± 46.87b	378.02 ± 40.25b	574.19 ± 51.24a	415.08 ± 46.29b
Mean width (μm)	190.39 ± 24.63b	192.66 ± 15.63b	264.85 ± 31.87a	191.69 ± 25.74b
Mean thickness (μm)	168.74 ± 20.65b	176.04 ± 16.87b	230.01 ± 22.89a	170.37 ± 13.91b
Mean EqDiameter (μm)	202.56 ± 24.92b	207.71 ± 18.44b	270.13 ± 33.71a	207.22 ± 19.35b
Total volume (mm ³)	263.99 ± 33.14c	366.77 ± 49.33b	555.39 ± 79.56a	300.49 ± 29.43b
Mean volume (μm)	0.014 ± 0.002b	0.016 ± 0.001b	0.056 ± 0.002a	0.017 ± 0.002b
Mean area (μm)	0.27 ± 0.04b	0.26 ± 0.03b	0.69 ± 0.05a	0.29 ± 0.04b
Total porosity (%)	0.98 ± 0.13b	1.36 ± 0.18b	2.06 ± 0.38a	1.11 ± 0.43b
Pore number	19022.00 ± 3129.38b	23208.00 ± 2956.65a	9836.00 ± 1596.92c	17999.00 ± 2138.46b
(CK, <i>A. fruticosa</i> without AMF inoculation; AM, <i>A. fruticosa</i> with AMF inoculation; MIX, a mixture of <i>A. fruticosa</i> and <i>M. sativa</i> ; A-M, mixture of <i>A. fruticosa</i> and <i>M. sativa</i> with AMF inoculation. Values with different letters are significantly different at P < 0.05.)				

Table 2 presents the average geometric characteristics of independent pores (pores not part of the connected pore network) across treatments. The MIX treatment exhibited significantly higher ($P < 0.05$) values than other treatments for average pore length, width, thickness, equivalent diameter, volume, and surface area. However, when examining total independent pore volume, CK exhibited the smallest volume (263.99 mm^3), whereas there was no significant difference between AMF and A-M (366.77 mm^3 and 300.69 mm^3 , respectively). The MIX treatment had the largest independent pore volume (555.39 mm^3).

Furthermore, analyzing the number of independent pores across treatments revealed that AMF had the highest number of independent pores, which was significantly greater than in the other treatments ($P < 0.05$). These findings indicated that AMF inoculation and mixed planting not only enhanced connected pore structures but also influenced the distribution and characteristics of independent pores, ultimately improving soil porosity and infiltration potential.

Characteristics of Connected Pores

The characteristic parameters of the connected pores across different treatments are illustrated in Fig. 3. Compared to CK, both AMF inoculation and mixed planting significantly increased the FD of connected pores ($P < 0.05$), with the highest value (2.44) observed in the A-M treatment, which combined inoculation and mixed planting. Soil permeability within the connected pores was calculated separately, revealing that the A-M treatment exhibited the highest permeability (8.48 d), which was significantly greater than in all other treatments ($P < 0.05$). The AMF treatment (4.52 d) demonstrated a 74.7% increase in permeability compared to CK (1.14 d). However, there was no significant difference in permeability between AMF and MIX treatments.

The tortuosity of connected pores followed the trend $\text{AMF} > \text{MIX} > \text{A-M} > \text{CK}$, with CK exhibiting significantly lower tortuosity than all other treatments. Specifically, tortuosity in CK was reduced by 43.9%, 35.9%, and 33.8% compared to AMF, MIX, and A-M, respectively.

The connectivity of pores was significantly lower in CK, whereas both AMF (0.71) and MIX (0.70) treatments significantly improved pore connectivity. The A-M treatment achieved the highest connectivity (0.89); however, the difference between A-M, AMF, and MIX treatments was not statistically significant. Nevertheless, A-M connectivity was 46.4% higher than CK ($P < 0.05$). These findings indicated that AMF inoculation and mixed planting markedly enhanced soil pore connectivity, fractal complexity, and permeability, with the A-M treatment achieving the most optimal pore network characteristics.

The differences in root system characteristics across treatments are presented in Fig. 4. Analysis of root density parameters revealed that both AM fungi inoculation and mixed *M. sativa* planting enhanced RBD, RLD, RSD, and RVD within the soil cores. Specifically, RLD and RVD followed the pattern $\text{A-M} > \text{MIX} > \text{AMF} > \text{CK}$, with all treatments significantly outperforming CK ($P < 0.05$). The A-M treatment exhibited the highest values across all root density characteristics, indicating that the combined inoculation and mixed planting approach had the greatest positive impact on root system development.

In contrast, variations in root morphology parameters among treatments were less pronounced. However, treatments involving AMF inoculation (AMF and A-M) significantly enhanced mean RD and RTD ($P < 0.05$). While the MIX treatment did not significantly affect RD, it led to a notable increase in SRL. No significant differences were detected among treatments for root SRA.

Root chemical composition followed a similar trend, with RC, RN, and RP concentrations displaying a general pattern of AMF > A-M > MIX > CK. Among these, the AMF treatment showed the most significant increases in RC, RN, and RP levels, all reaching statistical significance ($P < 0.05$). These results suggested that AMF inoculation and mixed planting not only enhanced root density but also influenced root morphology and nutrient composition, with the A-M treatment demonstrating the most substantial improvements in overall root system development.

Principal component analysis (PCA) revealed that the first principal component (PC1) carried the highest loading weight, and its PCA values were used as predictive indicators for fine root traits (Fig. 5a–c). The analysis demonstrated that root density traits, including RLD, RBD, RSD, and RVD, were positively correlated with each other.

Regarding root morphology traits, mean RD, SRL, and SRA displayed negative correlations with RTD. Similarly, root chemical characteristics, including RC, RN, and RP, were positively correlated with one another.

Furthermore, linear regression analysis between mycelium density and root traits (Fig. 5d–f) indicated that mycelium density explained 62.7% of the variation in root density traits, 77.6% of root morphology traits, and 67.0% of root chemical traits. All relationships exhibited significant positive correlations, confirming that AMF played a crucial role in regulating fine root development, morphology, and nutrient composition.

Mechanisms of AMF and Mixed Planting on Soil Pore Structure and Infiltration Properties

To elucidate the underlying mechanisms by which AMF inoculation and mixed planting influence soil pore structure and infiltration properties, PLS-PM was performed to construct a structural equation model (SEM) (Fig. 6). The model demonstrated a goodness of fit (GOF) of 0.809, indicating robust explanatory power.

The model's key findings revealed a strong predictive capacity for root and soil characteristics, with predictors accounting for 91.3% (R^2) of the variation in root density, 84.3% (R^2) in root morphology, and 71.0% (R^2) in root chemical traits. Similarly, soil macropore connectivity exhibited high explanatory power, with 91.3% (R^2) of the variation in connected pores and 77.6% (R^2) in independent pores being accounted for by the model. Notably, changes in soil pore percolation characteristics were explained by 92.6% (R^2), underscoring the significant influence of root traits on soil permeability. The analysis revealed that AMF inoculation had a significant positive effect ($P < 0.05$) on root density, root morphology, and

root chemical characteristics. Among these, root morphology traits exhibited a highly significant positive effect ($P < 0.01$) on connected pores and also exerted a moderate positive effect (0.339) on soil percolation characteristics.

Furthermore, changes in connected pores significantly influenced soil seepage characteristics, with the two showing a strong positive correlation. However, AMF inoculation did not directly impact soil pore percolation, as its effects were mediated primarily through root morphology changes. Additionally, root density and chemical characteristics exhibited only limited effects on both connected and independent pores. These results underscored the critical role of AMF and mixed planting in optimizing soil pore architecture and enhancing infiltration properties, primarily by modifying root morphology and promoting the formation of connected pores.

The impact of mixed planting treatments on soil pore structure and seepage characteristics was assessed using PLS-PM (Fig. 7). The SEM exhibited a GOF of 0.796, indicating a strong explanatory capacity.

The model analysis yielded key results demonstrating strong predictive power across various root and soil parameters. Predictors accounted for 89.6% (R^2) of the variation in root density, 90.4% (R^2) in root morphology, and 57.1% (R^2) in root chemical traits. Additionally, the model explained 94.2% (R^2) of the variation in connected pores and 81.9% (R^2) in independent pores. Notably, changes in soil pore percolation characteristics were explained by 93.3% (R^2), reinforcing the substantial influence of root traits on soil permeability. The results indicated that mixed planting had a highly significant positive effect on root density ($P < 0.01$) and a significant positive effect on root morphology ($P < 0.05$). Although root density positively influenced the formation of connected pores (0.549), this effect was not statistically significant. However, root morphology had a highly significant positive effect on the formation of connected pores, which, in turn, exhibited a highly significant positive influence on soil percolation characteristics. These findings suggested that while mixed planting predominantly enhanced root density, it was the changes in root morphology that primarily influenced soil pore connectivity and infiltration properties. Similar to AMF inoculation, the effect of mixed planting on soil seepage was indirect, mediated through modifications in root morphology and the formation of connected pores.

Discussion

Effect of AMF and Mixed Planting on Root System Characteristics

This study examined the morphological, density-related, and chemical attributes of plant root systems following AMF inoculation and mixed planting treatments, recognizing that root development plays a pivotal role in improving soil structure and restoring ecosystem functionality within the compacted soil layers of open-pit dumps (Feng et al., 2020; Moraes et al., 2020). Our findings demonstrated that both AMF inoculation and mixed planting significantly enhanced root density and morphological traits (Fig. 4).

These results suggested that the combination of AMF and *M. sativa* mixed planting fostered a mutually beneficial symbiotic relationship within *S. japonica* stands, facilitating ecological restoration in arid coal mine dumps.

Vegetation establishment in open-pit dumps is severely constrained by extreme soil compaction, nutrient depletion, and water scarcity (Feng et al., 2019). A fundamental challenge in ecological restoration lies in how plant root systems can effectively acquire sufficient energy and spatial resources to sustain growth. Previous studies have shown that AMF facilitate deeper root penetration, improving plant access to water and essential nutrients (Bi et al., 2018). Simultaneously, mixed planting enhances species interactions by optimizing competition and cooperation, thereby promoting a complementary spatial distribution of root systems and mitigating the intense resource competition characteristic of monocultures (Gao et al., 2018; Huang et al., 2023; Zhang et al., 2022).

Our findings corroborated this synergistic effect, as both AMF inoculation and mixed planting contributed to the formation of a high-density root network (Fig. 2) (Brassard et al., 2011). This extensively interconnected root system plays a critical role in improving soil physical structure (Hu et al., 2015) and enhancing soil water retention capacity (Cheng et al., 2023), a crucial adaptation for plant survival in the high-pressure, low-porosity environment of mining dumps.

Regarding root morphological traits, AMF inoculation significantly increased mean RD and RTD, while mixed planting notably enhanced SRL (Fig. 4). These results indicated that AMF and mixed planting collectively facilitated root system expansion in open-pit dumps, thereby improving nutrient and water uptake efficiency (Lee et al., 2023). Additionally, prior research has demonstrated that AMF symbiosis influences plant carbon and nitrogen metabolism (Diao et al., 2022), aligning with the increased RC and RN contents observed in our study (Fig. 4). In mixed planting systems, interspecies nutrient competition and complementarity further regulate plant survival and adaptation (Liu et al., 2024). The differential nitrogen and phosphorus uptake capacities of *A. fruticosa* and *M. sativa* provided a substantial advantage for plant growth under the nutrient-deficient conditions of open-pit dumps. Collectively, these findings confirmed the synergistic interactions between microorganisms and plants, underscoring the potential of AMF inoculation and mixed planting as an integrated strategy for enhancing plant survival and soil rehabilitation in degraded mining landscapes. More broadly, this study offered novel insights into harnessing microbial-plant interactions to optimize vegetation establishment in extreme environments characterized by drought and severe soil compaction.

Effects and Mechanisms of AMF and Mixed Planting on Soil Pore Structure and Infiltration Properties

By utilizing 3D X-ray CT scanning, this study reconstructed soil pore networks and classified them into connected pores and independent pores for detailed analysis (Tables 1 and 2). The results revealed that connected pores in the A-M treatment were the most uniformly distributed, while AMF and MIX treatments exhibited complex interwoven root networks within the connected pores (Zheng et al., 2023). Additionally, the A-M treatment produced the most intricate PNM (Fig. 2), suggesting that AMF

inoculation and *M. sativa* mixed planting effectively facilitated the reorganization and stabilization of soil particles, leading to the formation of more stable pore structures (Rillig and Mummey, 2006).

These structural improvements not only enhanced soil permeability and water retention capacity but also created favorable conditions for root growth, ultimately reinforcing the ecological functionality of the soil (Gong et al., 2024). Moreover, A-M treatment exhibited optimal pore connectivity and infiltration properties (Fig. 3), suggesting that AMF and mixed planting directly contributed to the optimization of soil pore structure by promoting extensive root expansion and penetration (Tang et al., 2024; Zhang et al., 2017). Root growth plays a dual role, mechanically restructuring soil particles and biochemically stabilizing soil aggregates through root exudates, which act as natural binding agents (Li et al., 2022). The resulting complex pore network significantly enhances both soil permeability and water retention capacity. Additionally, AMF-mediated increases in RD contributed to the formation of larger pores, directly improving water infiltration capacity (Du et al., 2024).

To further elucidate the underlying mechanisms, we employed PLS-PM (Figs. 6 and 7). Our analysis highlighted a bidirectional interaction between plant root systems and soil pore structures:

1. Root traits significantly influenced soil pore formation and connectivity through their morphological, density, and chemical characteristics (Xiao et al., 2024).
2. Optimized soil pore networks, in turn, promoted root growth and functionality, reinforcing a positive feedback loop (Nosalewicz and Lipiec, 2014).

Our findings demonstrated that AMF exerted significant positive effects on root density, root morphology, and root chemical composition (Fig. 5). Through their interaction with plant root systems, AMF indirectly modified soil physical structure (Aminzadeh et al., 2025). Meanwhile, mixed planting significantly enhanced root density and morphological traits, with root morphological changes emerging as the most influential factor in expanding soil pore space in compacted soils.

For instance, AMF inoculation significantly enhanced root morphology, establishing a structural foundation for root-driven pore formation in compacted soils (Du et al., 2024). In arid and highly compacted environments, the development of an intricate three-dimensional root network stabilizes the soil matrix, facilitates water retention, and supports plant growth (Hu et al., 2024). Moreover, the synergistic interaction between AMF and mixed planting yielded remarkable benefits: AMF enhanced plant resilience, expanded root uptake zones, and improved the absorption of essential mineral nutrients (Wu et al., 2024). Simultaneously, *M. sativa* mixed planting substantially increased overall root density and interpenetration, leading to a greater proportion of macropores within the soil (Zhang et al., 2025). This dual mechanism highlighted the complementary roles of AMF and mixed planting in promoting both root development and soil pore optimization.

Our results further demonstrated that improvements in soil pore architecture, in turn, facilitated root system expansion and functionality. A well-structured pore network significantly enhanced soil infiltration and water retention, ensuring consistent moisture availability for root uptake (Liu et al., 2023).

Notably, the highly interconnected and uniformly distributed pore system observed under the A-M treatment promoted efficient water and air diffusion throughout the soil matrix (Jia et al., 2024).

These findings underscored the dynamic and reciprocal relationship between root system development and soil pore/infiltration properties (Zhou et al., 2021). Both AMF inoculation and mixed planting substantially contributed to soil remediation in arid mine dumps, with root systems serving as a fundamental driver of these ecological improvements (Zhang et al., 2025).

This study provided a practical and scientifically validated strategy for ecological reconstruction in degraded mine dumps. By leveraging the synergistic effects of AMF and mixed planting, this approach offered a sustainable method to enhance soil structure, improve water retention, and promote plant growth in extreme environments characterized by drought and compaction.

Conclusions

In the compacted soils of arid and semi-arid mining dumps, AMF inoculation and mixed planting strategies demonstrated exceptional potential in promoting the growth of *A. fruticosa* while simultaneously enhancing soil structural integrity. These treatments significantly improved root density parameters, including RLD, RVD, and RBD, as well as key morphological traits such as RD and RTD. As a result, plant roots exhibited greater penetration capacity and a more extensive exploration of the soil environment.

These enhancements in root system architecture facilitated the formation of a highly interconnected pore network within the compacted soil, leading to substantial structural improvements. In particular, the characteristics of connected pores, including increased connectivity and volume, were markedly enhanced, optimizing water transport pathways and significantly improving soil infiltration capacity. Crucially, these effects were not direct but were mediated through modifications in root morphology. Both AMF inoculation and mixed planting indirectly optimized soil pore structure and infiltration dynamics by regulating root growth and development.

Collectively, these findings provided mechanistic insights into how AMF and mixed planting contributed to soil structural enhancement and hydrological function. Their synergistic effects underscored their viability as an effective ecological restoration strategy for rehabilitating open-pit mining dumps in arid and semi-arid regions.

Declarations

Conflict of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Acknowledgments

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Figures

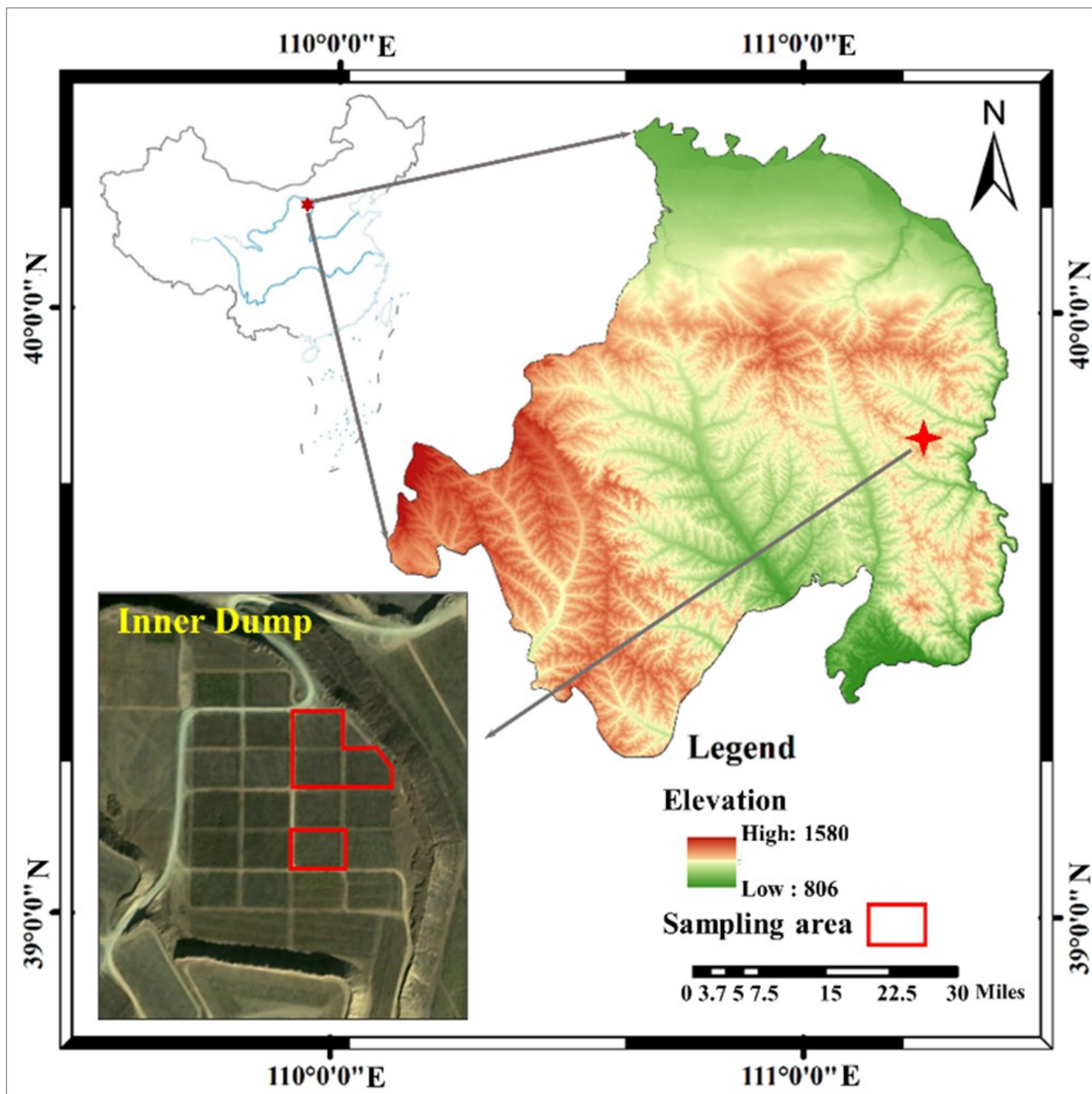


Figure 1

Location of study site.

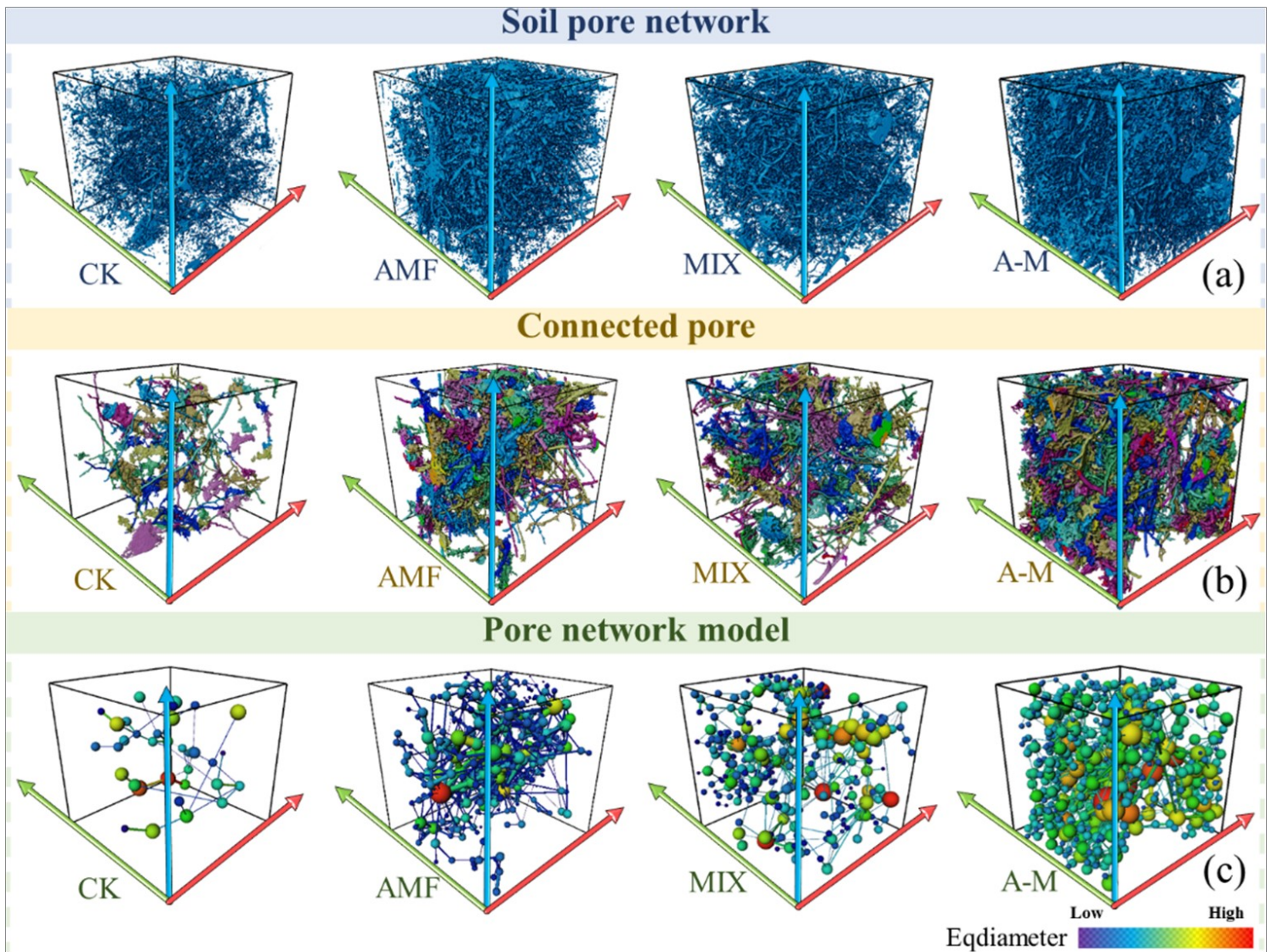


Figure 2

The 3D visualization workflow of the soil macropore network, reconstructed from a single CT scan slice of different soil samples (each measuring $30 \times 30 \times 30$ mm) using Avizo software. (a) Representation of the overall soil pore network, (b) visualization of the interconnected soil pores, and (c) the PNM, illustrating macropore connectivity. In (c), the PNM depicts pores as spheres and channels as sticks, with a color gradient indicating pore and throat thickness, darker hues (red) signify thicker macropore throats.

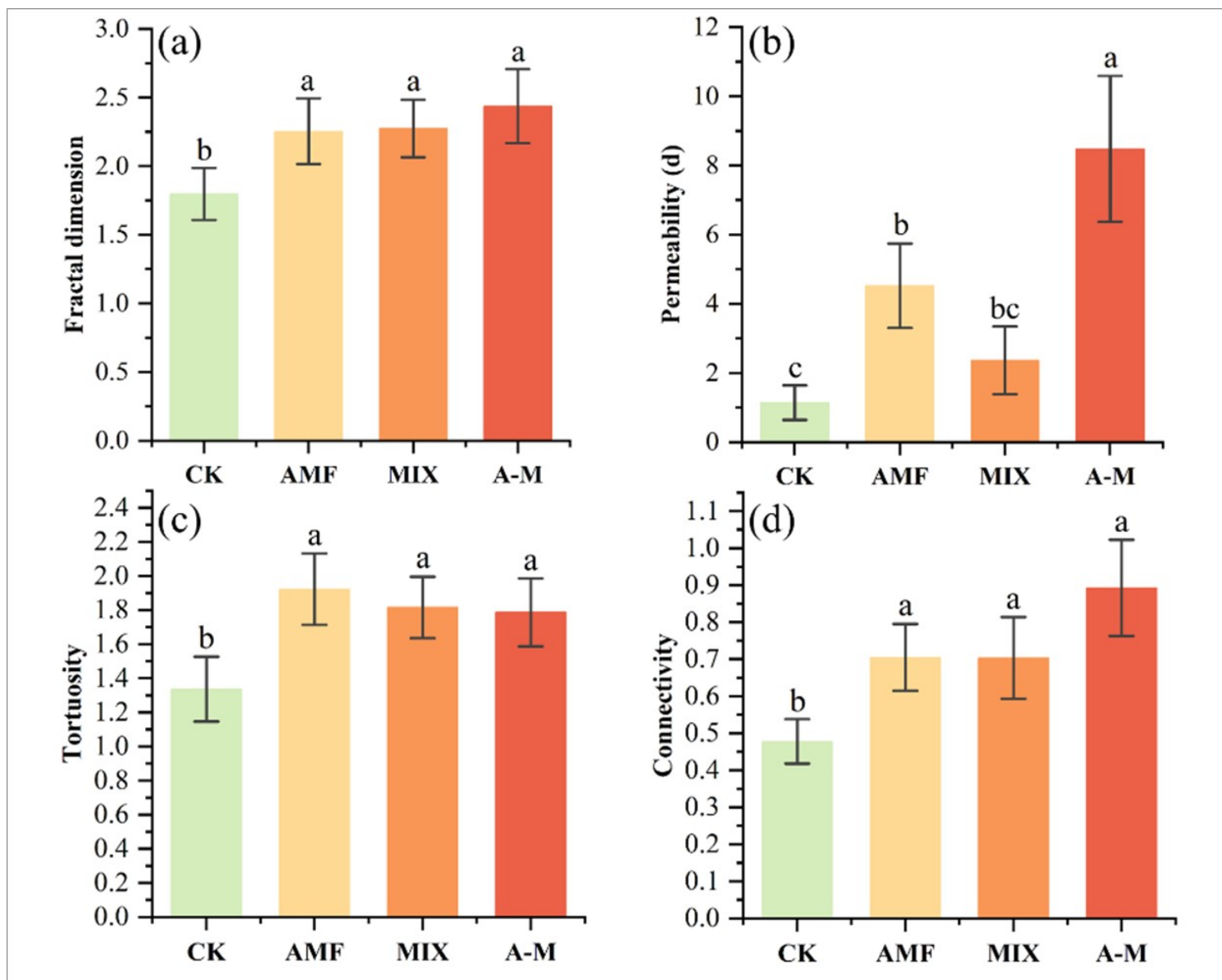


Figure 3

Connectivity pore characteristics and permeability: (a) FD, (b) absolute permeability, (c) tortuosity, (d) connectivity. Values with different letters are significantly different at $P < 0.05$.

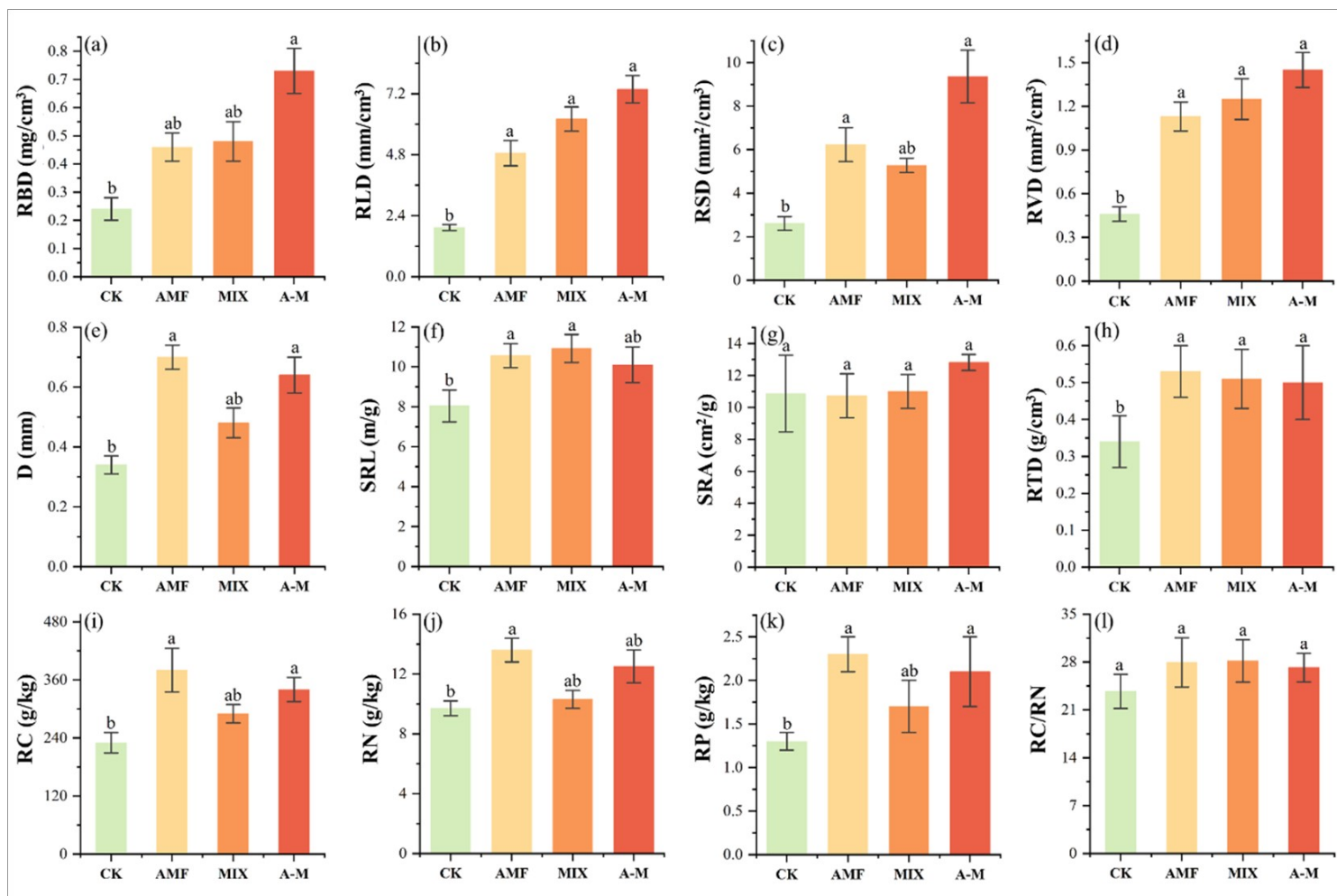


Figure 4

Root traits under different treatment conditions. (a–d) Morphological characteristics; (e–h) Root density properties, representing the total number of roots per unit soil volume; (i–l) Root chemical properties. Different letters indicate statistically significant differences at $P < 0.05$.

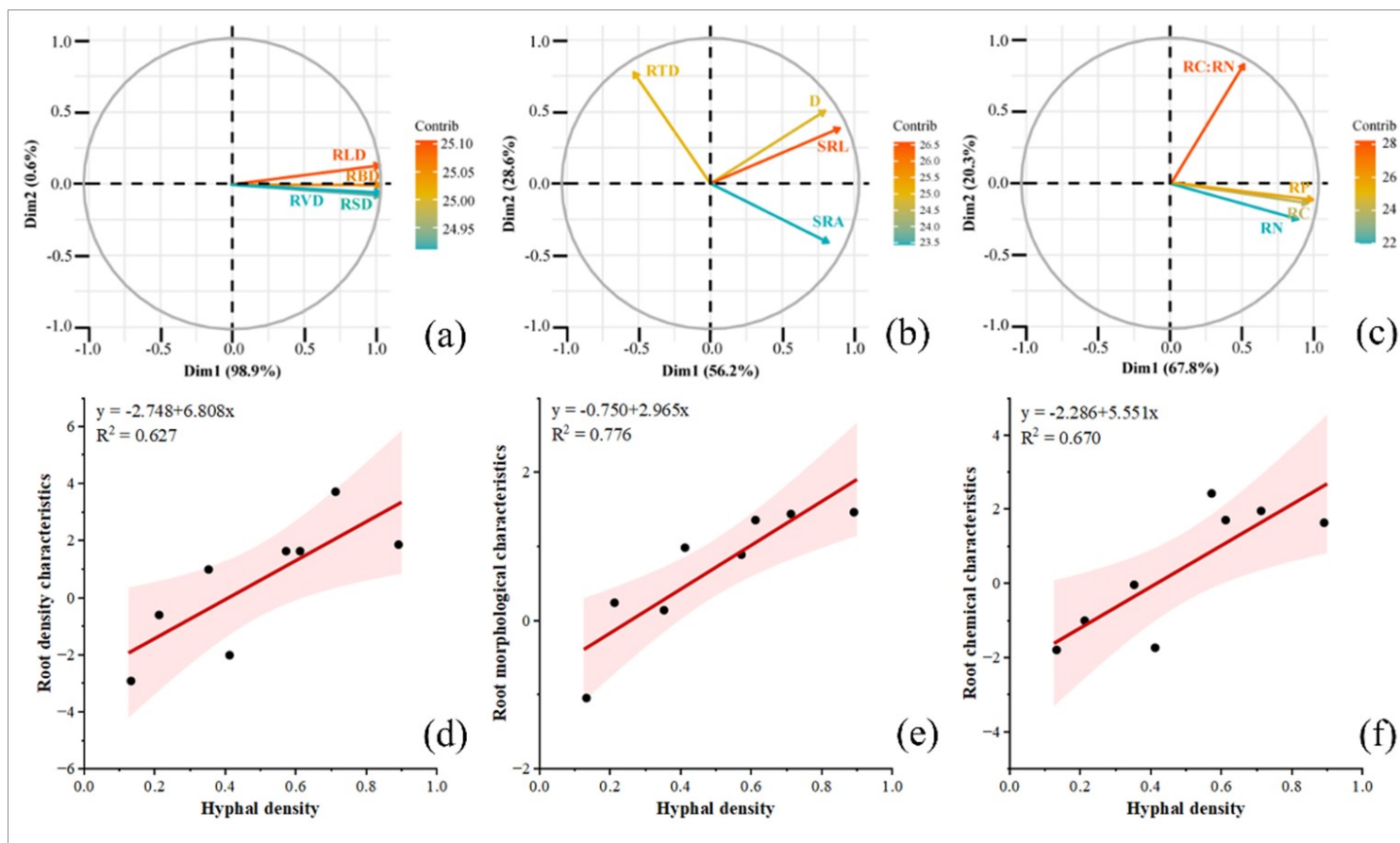


Figure 5

PCA of the mean concentrations of root traits under different treatments (a–c) and their correlation with mycelium density (d–f). In the PCA plots, Dim 1 and Dim 2 represent the first and second principal components, respectively, with the percentages indicating the proportion of variance explained by each axis. The intensity of the carrier color of each variable reflects its contribution (%) to the total variance.

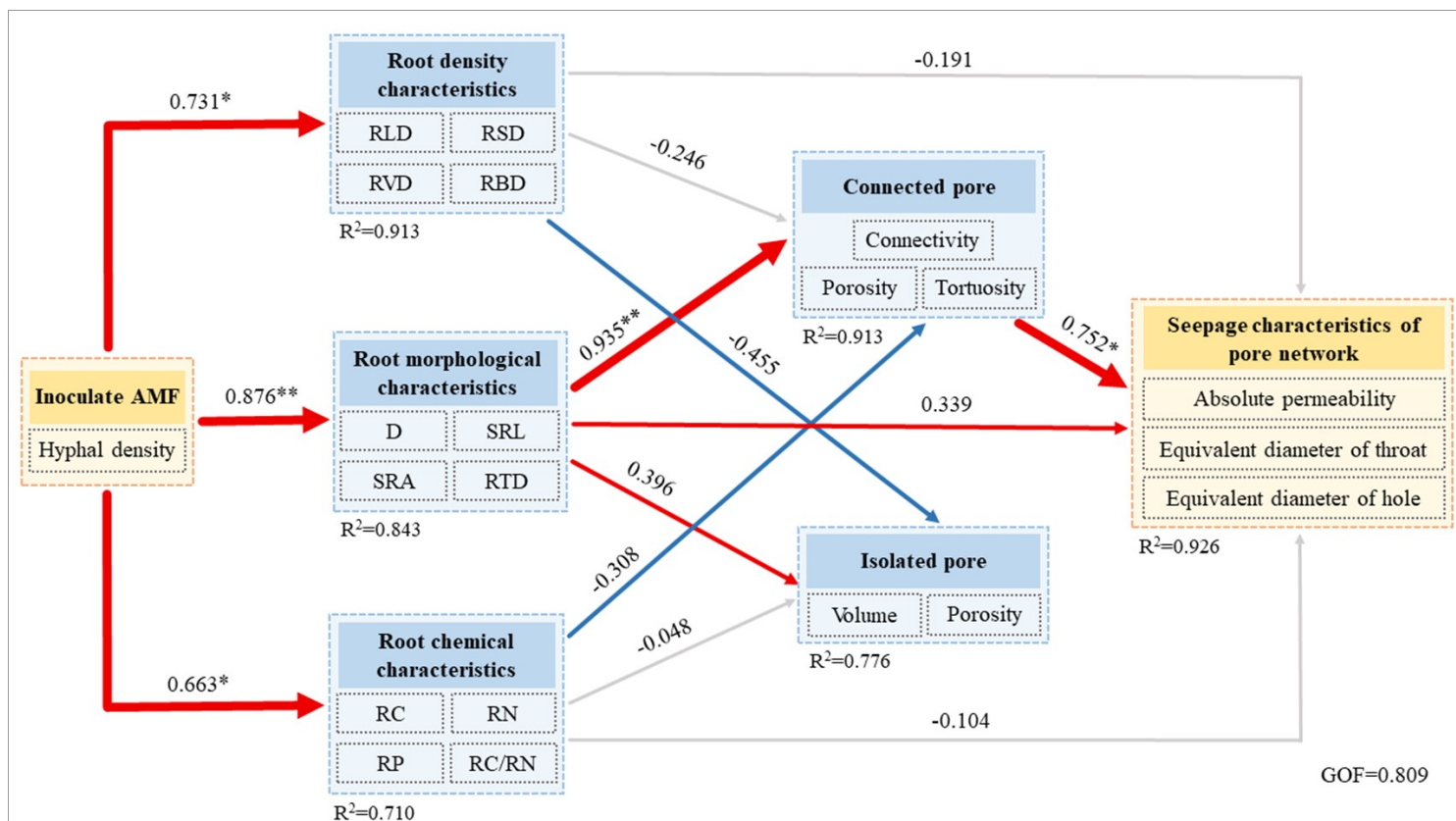


Figure 6

PLS-PM of AMF on soil pore and infiltration characteristics. Red lines indicate a positive effect, while blue lines indicate a negative effect. Numbers near the arrows are normalized path coefficients. Significant values are indicated by * ($P < 0.05$), ** ($P < 0.01$), and the numbers near the boxes indicate the variance explained by the model (R^2). GOF means goodness of fit.

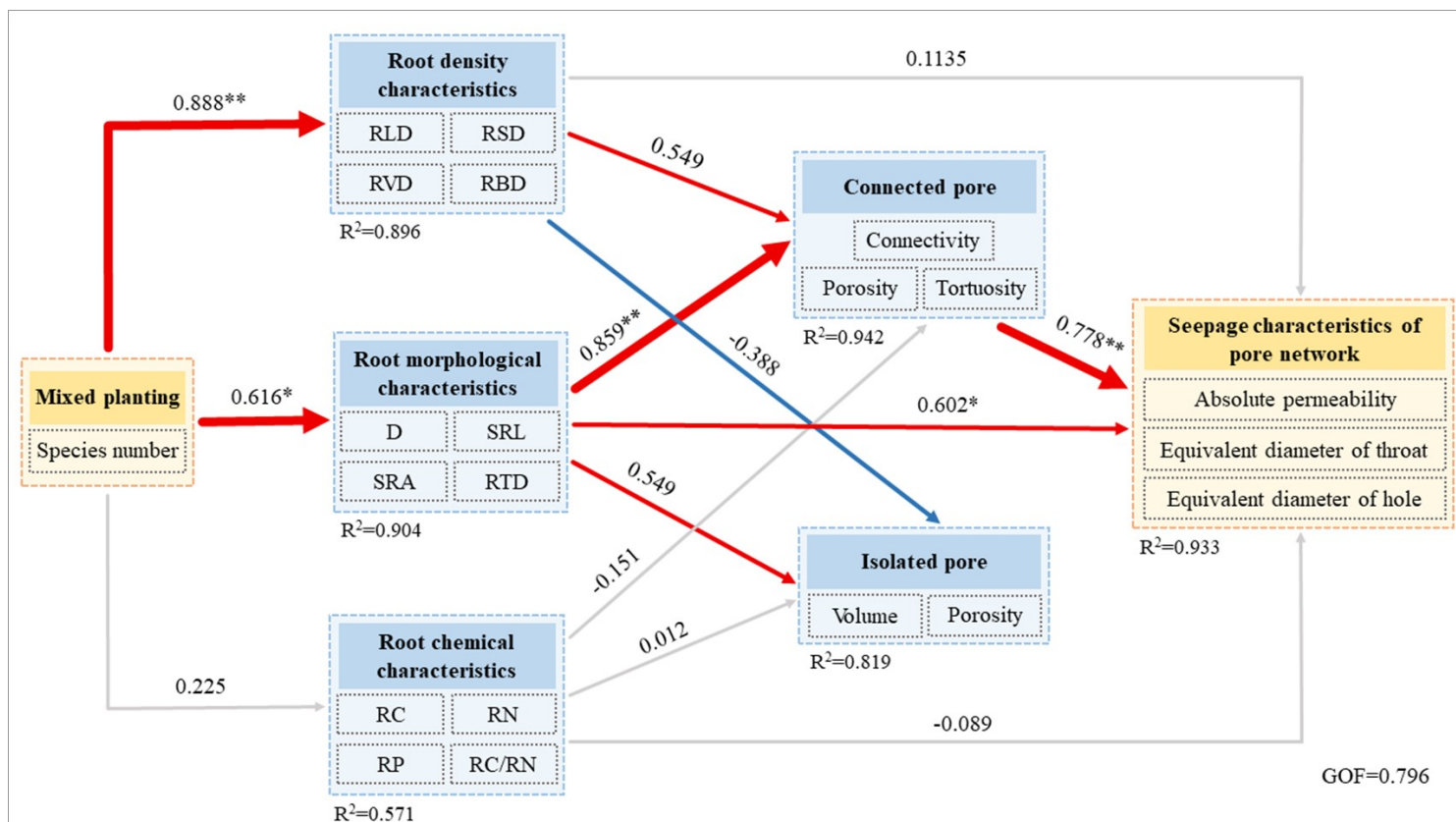


Figure 7

PLS-PM illustrating the impact of mixed cropping on soil pore structure and infiltration characteristics. Red lines denote positive effects, while blue lines indicate negative effects. Numbers adjacent to the arrows represent standardized path coefficients, with statistically significant values marked as * ($P < 0.05$) and ** ($P < 0.01$). The numbers within the boxes denote the variance explained by the model (R^2), and GOF represents the goodness of fit.