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Synergistic enhancement of soil multifunctionality by biochar and arbuscular mycorrhizal fungi via improved nutrient supply in coal mining reclaimed soils

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Abstract

Coal mining activities cause the destruction of surface vegetation, degradation of the soil structure, and severe loss of organic matter, thereby reducing soil multifunctionality. Biochar (BIO) and arbuscular mycorrhizal fungi (AMF) play crucial roles in mediating soil quality and crop production, especially in resource-constrained poor soils. However, little research has documented the synergistic effects of BIO + AMF on soil multifunctionality in coal-mine reclamation areas. Here, a three-year field investigation was carried out to evaluate the effects of four treatments: CK (traditional planting, no AMF and no BIO), AMF (AMF without biochar), BIO (biochar without AMF), and BIO + AMF (biochar and AMF). The findings demonstrated that the BIO + AMF treatment significantly modified the soil physical structure, increasing the soil water retention while decreasing the soil bulk density. The application of biochar supplemented with AMF notably increased the soil enzyme activity, nutrient supply, and the alpha and beta diversities of the soil bacterial and fungal communities. Moreover, biochar and AMF synergistically enhanced soil multifunctionality, and a random forest model revealed that the combination of AMF inoculation and biochar application increased maize production, which was driven mainly by soil enzyme activity, and that soil multifunctionality was regulated mainly by the nutrient supply function. These results highlight that biochar combined with AMF inoculation had significant synergistic effects on improving maize productivity and multifunctionality, providing a nature-based restoration strategy for use in reclaimed soil.

Highlights

- AMF and biochar regulated reclaimed soil function via improved structure, microbial diversity, and nutrient cycling.
- AMF + biochar synergistically increased soil nutrient supply to boost reclaimed soil multifunctionality.
- This research presents a nature-based strategy for restoring degraded land and realizing the potential for sustainability in reclaimed soils.

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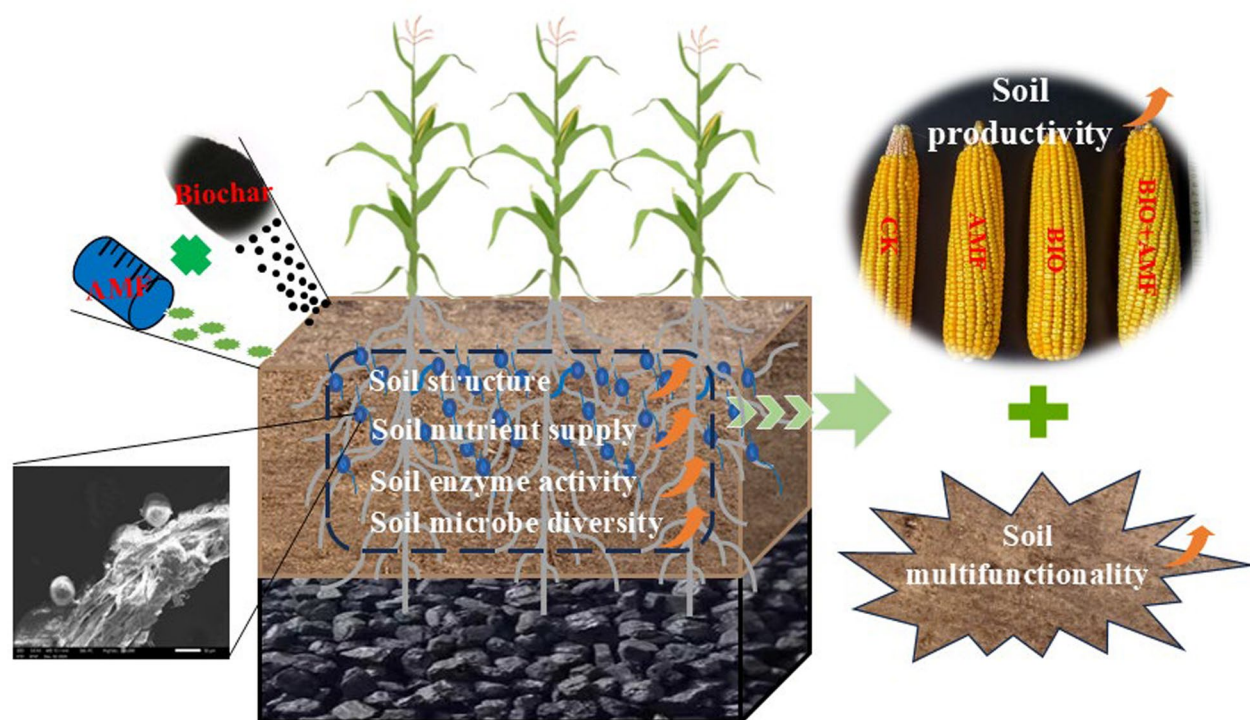
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Keywords Biochar, Arbuscular mycorrhizal fungi, Synergistic effect, Soil multifunctionality, Coal mining reclaimed soil

Graphical Abstract



1 Introduction

Currently, approximately 23% of the global soil area is facing degradation, and the area of degraded land is expanding at a rate of 5–10 million hectares per year (Maestre et al. 2025). According to statistics, more than 49.5 million square kilometres of global land is occupied by large-scale industrial and mining activities. Mining activities can destroy entire natural-social-human ecosystems, especially soil and vegetation, leading to a decline in ecosystem multifunctionality and environmental degradation (Sontter et al. 2020; Van Der Heide et al. 2020). Coal mining activities severely degrade terrestrial ecosystems by destroying surface vegetation and disrupting key soil functions, including soil conservation and carbon sequestration (Goswami 2015; Chen et al. 2025). Underground excavation and subsequent subsidence directly compromise soil structure and reduce its water-holding capacity (Li et al. 2025). These disturbances severely impede nutrient cycling, leading to substantial fertility loss (Wang et al. 2025a). Furthermore, they diminish microbial community diversity and weaken essential ecological processes

such as nutrient transformation and pollutant degradation (Xu et al. 2025). Soil is a complex system of abiotic and biotic components that can simultaneously maintain a variety of ecosystem functions and services, including production functions, water regulation functions and nutrient regulation functions (Hu et al. 2021). Recently, a number of studies have used the ecosystem multifunctionality index to assess soil ecosystem functioning, providing a quantitative assessment of potential soil health functions (Liu et al. 2025). Soil multifunctionality reflects the comprehensive service ability of soil, including maintaining high biodiversity, increasing carbon sequestration, and improving nutrient cycling (Wang et al. 2024). Soil monofunctionality and multifunctionality are determined mainly by plant structural and morphological diversity (Jing et al. 2015). In addition, microorganisms play a crucial role in enhancing soil multifunctionality and sustaining soil health by affecting nutrient cycling, microbe activity, and soil aggregate structure (Zhang et al. 2025). Therefore, enhancing soil multifunctionality via scientifically informed management practices and elucidating the

impacts of these interventions are essential for promoting the sustainability of soil ecosystems.

Soil organisms play an indispensable role in maintaining soil multifunctionality and processes. As ecosystem engineers, arbuscular mycorrhizal fungi (AMF) can form symbiotic associations with approximately 90% of terrestrial plant species root systems (Yang et al. 2022; Duan et al. 2021), scavenging a wide array of nutrients and transferring them to plant hosts in exchange for carbohydrates, lipids, and labile carbon, and enhancing the adaptation of their host plants in poor environments (Cheng et al. 2020). Numerous studies have confirmed that AMF typically exert beneficial influences on both host plant development and soil quality through the establishment of symbiotic relationships with AMF, which can enhance their root architecture and amplify root surface area, thereby facilitating more efficient acquisition and utilization of nutrients and water (Abdalla et al. 2023). AMF can facilitate phosphorus uptake by plants under water stress conditions and shape the evolution of host plant adaptation to drought (Tang et al. 2024). In diverse cropping systems, AMF inoculation affects resource allocation and interspecific coexistence among symbiotic plant species, and AMF can mitigate interspecific competition by influencing resource allocation among neighboring plants through mycelial bridges (Zhu et al. 2023). In recent years, with the large numbers of fertilizers, pesticides, and other anthropogenic disturbances, the effects of AMF on neutral symbionts and even pathogens/parasites have weakened (Dai et al. 2014). Therefore, more research is needed to elucidate the different responses of plant productivity and soil multifunctionality to AMF inoculation under environmental stress. More importantly, investigating the response of soil multifunctionality to AMF inoculation is critical for assessing the impact of AMF use on soil health and agricultural sustainability in coal-mine reclamation areas.

On the other hand, as a common agricultural practice, the addition of biochar is widely recognized as an emerging strategy for enhancing soil carbon sequestration, improving crop productivity, mitigating greenhouse gas emissions, and promoting eco-environmental health (Wu et al. 2018; Zhang et al. 2019; Pokharel et al. 2020). Biochar is a carbon-rich material that is generated through the pyrolytic conversion of organic material under low-oxygen conditions (Abbott et al. 2018). Biochar also affects soil nutrients by altering microorganisms and microbial metabolic activity and diversity, both of which affect soil nutrient availability and quality (Chen et al. 2013; Sun et al. 2022). Similarly, owing to its unique porous structure and adsorption capacity and release of mineral nutrients, biochar has been widely used in soil remediation (Nguyen et al. 2023). Biochar addition can

affect the soil pore size, increase soil porosity, and reduce soil capacity (Wang et al. 2017). In addition to effectively changing the physicochemical and mechanical properties of soil, aggregate stability can be further improved by biochar application (Han et al. 2021). Biochar application can effectively increase the water-holding capacity of soil, improve hydraulic parameters, and significantly increase crop yield (Duarte et al. 2023). Recent studies have shown that the combination of biochar and AMF can promote plant root growth, increase the AMF colonization rate and the length of extra-root mycelia, and subsequently promote nutrient uptake through the mycorrhizal pathway (Liang et al. 2019; Wen et al. 2022). However, little has been reported on the mechanism underlying the effects of the biochar combined with AMF on soil multifunctionality and productivity in coal-mine reclamation areas.

As a major byproduct of coal mining, coal gangue poses significant challenges to enterprises, society, and the environment because of the difficulty of its disposal and the large amount that accumulates (Wang et al. 2025a). The utilization of coal gangue in land reclamation represents a synergistic approach, offering the dual benefits of promoting resource recovery and mitigating the human-land conflict (Wang et al. 2025b). Therefore, we hypothesized that biochar addition and AMF inoculation have synergistic effects on enhancing reclaimed-soil multifunctionality in coal-mine agroecosystems by increasing nutrient supply and enzyme activity. To verify this hypothesis, a three-year field experiment was conducted in reclaimed coal-mining soil to assess the synergistic responses of key soil physical, chemical, and biological properties, as well as overall soil productivity. The specific objectives were to: (1) evaluate the effect of AMF inoculation and biochar amendment on maize agronomic performance in reclaimed mine agroecosystems; (2) analyze changes in soil physicochemical properties following AMF inoculation and biochar application; (3) characterize the responses of soil microbe communities to these amendments in reclaimed mine settings; and (4) elucidate how shifts in nutrient availability and enzyme activities mediate soil multifunctionality and productivity under combined biochar and AMF treatments. This study offers novel insights into the rehabilitation of reclaimed soils and highlights the potential of integrated AMF and biochar applications in restoring severely degraded soils in mining regions.

2 Materials and methods

2.1 Experimental site

Three-year (2023–2025) field observations were made at the Field Base of Soil Health Laboratory of Shanxi Province (Tunlan Mine, Gujiao), China (37°53' N, 112° 06' E)

(Additional file 1: Fig. S1). In June 2012, the Tunlan mine in Nanliang village was filled with a byproduct (gangue), and the reclaimed land area reached 15.3 hm² by December 2013. The coal gangue was used in layered backfilling, specifically one layer of coal gangue followed by one layer of loess. This method consists of placing 8–10 m of coal gangue in the mine and covering it with 70 cm of raw loess; an upper layer of coal gangue is then added after compaction with bulldozers, and the maximum thickness of the surface soil, which consists of raw loess, is not more than 1 m. The raw loess mainly comes from the mountains surrounding the reclaimed mine. The study area is a temperate continental climate; the mean annual temperature is 9.5 °C, ranging from –25 °C to 39.4 °C. Annual precipitation averages 460 mm, while evaporation ranges between 1770 and 2080 mm. The predominant soil type is classified as calcareous cinnamon soil. Key physicochemical properties of the reclaimed soils are summarized in Table S1.

2.2 Experimental materials

The Zeyi No. 1 maize variety was provided by Shanxi Deyufeng Agricultural Science and Technology Co. (Shanxi, China). The raw material of the biochar was maize straw (200 mesh), provided by Henan Zhengzhou Qixin Water Purification Materials Company (Henan, China), with a pH value of 8.0, a fixed carbon content of 50.3%, a specific gravity of 430.0 g L⁻¹, an ash content of 10.0%, an organic content of 80.2%, a phosphorus content of 0.97%, a potassium content of 2.83%, and a nitrogen content of 1.51% (Additional file 1: Table S2).

The tested AMF species was *Funnelformis mosseae*, which was provided by Qingdao Agricultural University (Shandong, China) and propagated in a pot culture with clover grown in a sand–soil mixture for three months. *Funnelformis mosseae* is a suitable candidate strain for application in poor soils due to its alkaline tolerance, high-efficiency phosphorus uptake capacity, and distinctive mycelial morphology. The river sand (2 mm) and raw loess (2 mm) used were sterilized by autoclaving (120 °C, 120 min) and mixed completely and homogeneously at 1:1 (m/m) to serve as the culture substrate for the AMF strains. The inoculated bacterial agent was composed of spores, hyphae, root segments and the substrate, and the density of fungal spores ranged from 50 to 80 per 10 g.

2.3 Experimental design

A field trial was set up beginning in April 2023, and the sample plots were in reclaimed agricultural fields that had been continuously planted with maize for three years on coal gangue. The present study was conducted in a randomized block group design in a three-year field experiment from 2023 to 2025, with four treatment

levels: control (traditional planting, CK), inoculated AMF (AMF), biochar addition (BIO), and biochar + AMF treatment (BIO + AMF), with three replications for each treatment. The plots were 4 m × 4 m = 16 m² and were surrounded by compacted and raised ridges, with a spacing of 1 m.

The maize seeds were sown annually on April 28 and harvested on October 1. Planting was conducted using a precision spot seeder, with a row spacing of 50 cm and plant spacing of 35 cm. Two seeds were placed per hole at a depth of approximately 3 cm. After sowing, the holes were immediately filled to ensure that the seeds were sufficiently bonded to the soil and to ensure that the seeds were emergent. Biochar was added at a rate of 7812.5 kg ha⁻¹ and spread evenly on the ground surface before sowing each year, after which it was mixed with the 0–20 soil layer using a rototiller. AMF fungicide was added around the root system of the maize 20 days after seedling emergence, and 20 g of AMF fungicide was applied to each plot. In addition, field management was consistent across the plots.

2.4 Sample collection and determination

Soil samples were collected in 2025 from the same layer three times from each plot and mixed into one sample; then, the dead leaves were quickly removed. Soil samples were divided into two portions: one was air-dried naturally for the assessment of soil physicochemical parameters, while the other was immediately transported to the laboratory under low-temperature conditions in sealed containers for subsequent analysis of soil microbial community structure and enzyme activities.

Six plants were selected from each plot to determine their agronomic indicators, biomass, and yield. The Tannin-Panlan staining method was employed to assess mycorrhizal infection (Mcgonigle et al. 1990). The gas adsorption method (BET method) was used to determine the specific surface area and pore structure of the soil. Soil moisture content was obtained by the drying method. Soil temperature was recorded by an automatic recorder, and changes in soil temperature were observed (Elitech RC-5, provided by the Jiangsu Institute of Metrology) throughout the reproductive period. Soil bulk density (SBD) was measured using the ring-knife method. Soil total porosity (STP) was calculated based on Eq. (1). Soil pH was determined with a water-to-soil ratio of 2.5:1. Soil enzyme activities were assessed using commercial assay kits. Soil organic carbon (SOC) content was determined by potassium dichromate oxidation with external heating, and total nitrogen (TN) was analyzed via the Kjeldahl digestion method followed by measurement on a fully automated nitrogen analyzer. The determination of soil total phosphorus (TP) was carried out

using the molybdenum–antimony colorimetric method. The determination of total potassium (TK) was carried out by the NaOH melt–flame photometric method. Alkali–hydrolysed nitrogen (AN) was carried out by the alkali–hydrolysed diffusion method. Available phosphorus (AP) was carried out using the NaHCO₃-leaching–molybdenum–antimony antimonial colorimetric method. Available potassium (AK) was quantified via the ammonium acetate extraction–flame photometry approach. Soil organic carbon mineralization by alkaline absorption method (Bao 2000; Zhou et al. 2020).

$$STP = 93.947 - 32.995 \times SBD \quad (1)$$

where *STP* represents the total soil porosity (%), and *SBD* represents the soil bulk density.

2.5 Determination of soil microbial community diversity and relative abundance

Total DNA was extracted from soil samples using a commercial soil DNA isolation kit. For bacterial community analysis, the V3–V4 region of the 16S rRNA gene (approximately 480 bp) was amplified and sequenced with reference to the silva_138_1 database. For fungal community analysis, the ITS1 region was selected based on the unite_9 database. Bacterial amplification was performed using the primers 338F (ACTCCTACGGGAGGCAGCA) and 806R (GGACTACHVGTWTCTAAT). Fungal amplification employed the primers (GGAAGTAAAAGTCGTAACAAGG) and ITS2 (GCTGCGTTC TTCATCGATGC). All PCR products were sequenced and analyzed on the Illumina HiSeq platform.

2.6 Calculation of soil multifunctionality (SMF)

In this study, six single functions, namely, the soil structure function, production function, nutrient supply function, bacterial community function, fungal community function, and enzyme activity function, were established to calculate soil multifunctionality (Wang et al. 2024). Specifically, the six function groups were as follows: (1) the soil bulk density and moisture content were selected to represent the soil structure function; (2) plant height, stem thickness, leaf area index, effective stick length, thousand-grain weight, and yield represent the production function; (3) pH, SOC, TN, AN, AP, and TK represent the nutrient supply function; (4) B-Chao1, B-Observed_species, B-Shannon, B-Simpson, Gemmatimonadota, and Patescibacteria represent the bacterial community function; (5) F-Chao1, F-Observed_species, F-Shannon, F-Simpson, Ascomycota and Basidiomycota represent the fungal community function; and (6) sucrase, phosphatase, β-glucosidase, urease, and cellulase represent the enzyme activity function.

Prior to calculating the multifunctionality index, all 31 individual functions were standardized by Z-score normalization followed by transformation to a 0–1 scale (Eq. 2). The six ecosystem function categories were identified and computed by averaging the corresponding standardized individual functions within each category (Eq. 3). The multifunctionality of the soil was calculated by using the weighted average method (Eq. 4).

$$x'_{ij} = \frac{x_{ij} - x_{avg}}{x_{sd}} \quad (2)$$

$$S_i = \sum_{j=1}^m w_j \cdot x'_{ij} \quad (3)$$

$$SMF = \sum_{i=1}^n w_i \cdot S_i \quad (4)$$

where x'_{ij} is the data standardized value, x_{ij} is the j^{th} index measured value, x_{avg} is the j^{th} index mean, x_{sd} is the j^{th} index standard deviation, S_i represents the individual ecosystem services index, w_j is the j^{th} index weight ($\sum_{j=1}^m w_j = 1$), and w_i represents the i^{th} ecosystem service weight ($\sum_{i=1}^n w_i = 1$).

To assess the robustness of our soil multifunctionality framework, we conducted a leave-one-function-out analysis. For each iteration, we recalculated the multifunctionality index after sequentially removing one of the component soil functions. The resulting values were then correlated with the original multifunctionality index. This approach tested the sensitivity of the overall index to the inclusion of any single function.

2.7 Data analysis

The data were processed using SPSS 22.0 software (USA) and RStudio software (Lucent Technologies, USA). Two-factor ANOVA was employed to analyze the effects of AMF, BIO, and the interactions between AMF and BIO. The minimum significant difference (LSD) ($P < 0.05$) was used to evaluate the average difference among the treatments ($n = 3$). Nonmetric multidimensional scaling (NMDS) was used to analyze the soil microbial β diversity by the Bray–Curtis method. Pearson correlation analysis was performed by OriginPro 2024b on the basis of the original data. The random forest model used the “rfPermute, ggplot2, psych, reshape2, patchwork, randomForest, and rfUtilities” packages in R to test the correlation between soil multifunctionality and soil productivity and single functionality. OriginPro 2024b software was used to create the figures.

3 Results

3.1 Dynamic of maize agronomic traits and production under different treatments

There were significant positive effects of the AMF and BIO treatments and their interactions on maize yield and key growth parameters compared with those of the control (Table 1). Among all the treatments, the BIO treatment increased grain yield by 51.69% compared to CK ($P < 0.05$), followed closely by the combined BIO+AMF treatment (50.47%; $P < 0.05$), whereas the use of the AMF treatments alone substantially increased yield (26.91%; $P < 0.05$). These yield improvements were supported by superior agronomic traits, including increased plant height, thicker stems, greater leaf area index, coarser cobs, and greater effective cob length. Notably, the BIO treatment consistently outperformed the other treatments in terms of thousand-grain weight and fresh biomass, whereas the BIO+AMF treatment resulted in the greatest increase in cob length (24.25 cm). Two-way ANOVA revealed a significant interaction effect between the AMF and BIO treatments on the agronomic indicators and yield characteristics of maize plants.

3.2 The changes of soil mycorrhizal infection and soil micropore structure to different treatments

Inoculation with AMF significantly enhanced mycorrhizal colonization rates, as well as root development and distribution in the soil. As shown in Fig. 1a, compared to the non-inoculated treatment, AMF inoculation alone

significantly increased hyphal length and vesicle density. In the BIO+AMF treatment, both parameters were markedly higher than in all other treatments. Figure 1b shows that maize root systems developed substantially more fine roots following AMF inoculation and biochar application relative to the control, with the BIO+AMF treatment achieving the highest density. Compared to the control, mycorrhizal colonization rates and hyphal lengths in root systems significantly increased after AMF inoculation ($P < 0.05$), with the BIO+AMF treatment showing the greatest increase at 179.9% and 105.3%, respectively (Fig. 1c). BET analysis revealed notable alterations in soil pore structure following biochar application and AMF inoculation (Fig. 1d). Compared to the control, the BIO+AMF treatment exhibited a significantly larger specific surface area and pore volume than the other treatments. Two-way ANOVA indicated a significant interactive effect between biochar application and AMF inoculation on soil pore structure.

3.3 Response of soil physical and chemical characteristics to different treatments

The experimental results revealed significant improvements in soil physical characteristics under the BIO and AMF treatments, with particularly notable effects on soil structure and water relationships (Fig. 2). Although soil temperature did not significantly change across treatments compared with that in the CK treatment, the BIO application alone markedly increased the soil

Table 1 Maize agronomic traits index and yield under different treatment levels

Treatment	Plant height (m)	Stem diameter (mm)	Leaf area index	Cob length (cm)	Cob coarse (mm)	Effective cob length (cm)
CK	2.79±0.06b	24.47±0.59b	3.42±0.05b	20.33±0.21c	50.72±0.53c	16.08±0.69b
AMF	3.11±0.03a	28.69±0.02a	3.95±0.05a	22.98±0.14b	52.85±0.29b	22.22±0.19a
BIO	3.23±0.02a	28.41±0.34a	3.81±0.16a	23.17±0.33ab	54.60±0.54a	21.92±0.35a
BIO+AMF	3.17±0.09a	27.87±0.62a	4.13±0.07a	24.25±0.69a	54.31±0.25ab	21.33±0.21a
AMF	**	**	***	***	*	***
BIO	***	**	**	***	***	***
BIO*AMF	***	***	NS	NS	*	***
Treatment	Coarse maize cob (mm)	Hundred-grain weight (g)	Thousand grain weight (g)	Fresh biomass (kg ha ⁻¹)	Dry biomass (kg ha ⁻¹)	Yield (kg ha ⁻¹)
CK	25.98±0.28b	33.02±0.04c	332.22±0.17b	11,019.38±89.29d	6615.00±131.80c	7088.01±39.83c
AMF	27.53±0.17a	36.29±0.31b	359.17±6.61a	29,193.75±446.47c	10,479.38±154.66b	8995.22±62.10b
BIO	28.36±0.24a	37.09±0.15a	365.77±0.25a	39,858.75±187.91a	11,424.38±33.75a	10,751.91±83.51a
BIO+AMF	27.82±0.51a	36.63±0.10ab	362.40±0.25a	37,648.13±664.80b	10,293.75±44.65b	10,665.34±9.56a
AMF	NS	***	***	***	***	***
BIO	**	***	***	***	***	***
BIO*AMF	**	***	***	***	***	***

Data are presented as mean ± SD of six replicates. Different letters indicate significant differences among four treatments at the 0.05 level. *** represent $P < 0.001$, ** represent $P < 0.01$, * represent $P < 0.05$, and NS represent no significant different (the same in the below)

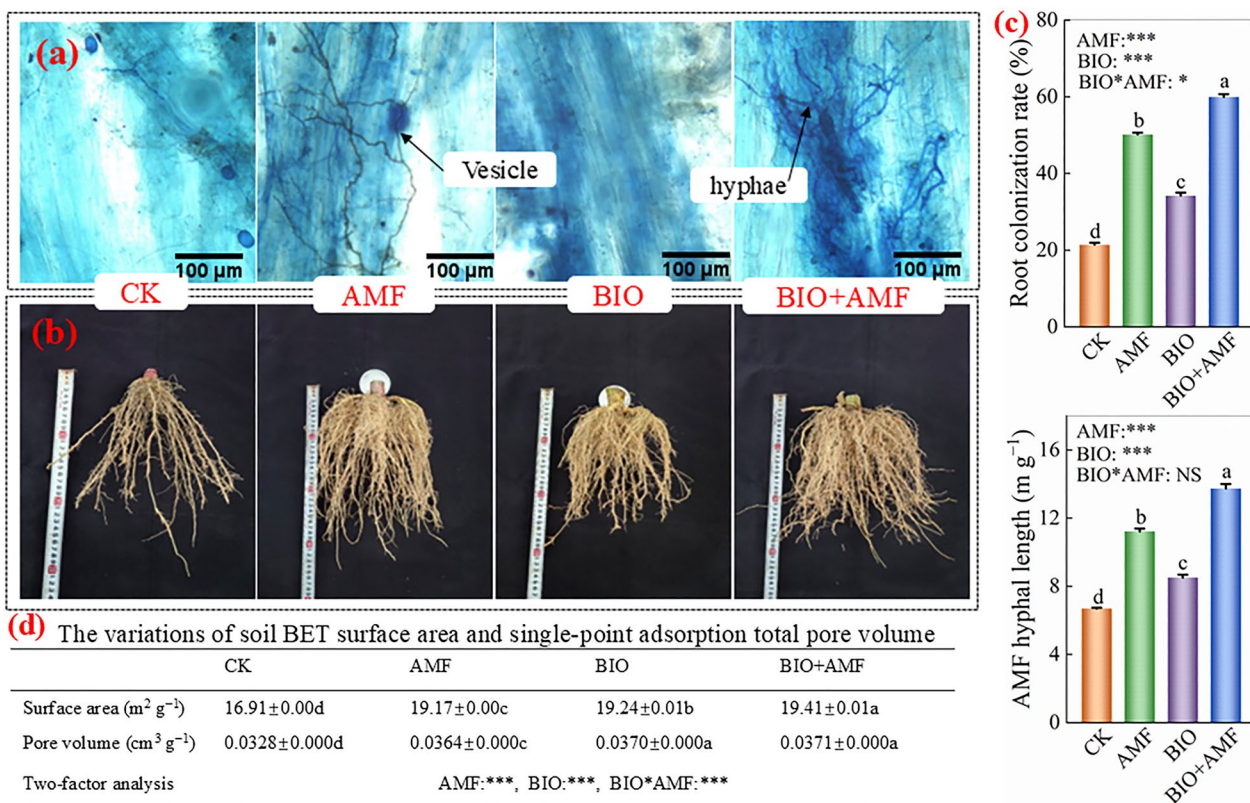


Fig. 1 The variations of soil mycorrhizal colonization (a), maize root diagram (b), AMF colonization rate & extra-matrical AMF hyphal length (c), and soil micropore structure (d) in response to the AMF inoculation and biochar addition. CK, control. AMF, inoculation with AMF without biochar. BIO, biochar addition without AMF. BIO + AMF, biochar addition with AMF inoculated. Different letters indicate significant differences among four treatments at the 0.05 level. Bars indicate the Tukey's HSD tests at $P < 0.05$ ($n = 3$)

water content ($P < 0.05$). Both the BIO and AMF treatments markedly reduced the SBD and increased the STP ($P < 0.05$), and their combination (BIO + AMF) exerted synergistic effects on these parameters. In addition, compared with the CK treatment, the BIO + AMF treatment significantly improved most of the soil nutrient parameters ($P < 0.05$), with the combined BIO + AMF treatment demonstrating particularly notable increases in the SOC, AP contents, and C accumulated mineralization ($P < 0.05$) (Table 2; Additional file 1: Fig. S5). Compared with the CK treatment, treatment with AMF alone significantly increased the AN concentration to 32.34 mg kg⁻¹, and the BIO treatment resulted in superior soil TN and TK; interestingly, compared with the control treatment, the BIO treatment significantly reduced the soil pH ($P < 0.05$). Two-way ANOVA revealed a broad interaction effect between the AMF and BIO treatments on the SBD, STP and soil nutrient parameters, whereas the soil temperature, water content and pH showed no obvious interaction.

3.4 Soil enzyme activities under different treatments

Inoculation with AMF and biochar addition significantly increased the enzyme activity in the soil (Fig. 3a–e). The activities of S-SC, S-ALP, S-β-GC, S-UE, and S-CL significantly increased by 134.59%, 21.36%, 352.19%, 11.77%, and 8.79%, respectively, in the AMF inoculation treatment group compared with those in the control treatment group ($P < 0.05$). The activities of the above five enzymes in the BIO group significantly increased by 149.05%, 102.12%, 408.30%, 36.81%, and 3.01%, respectively ($P < 0.05$). The activities of these five enzymes in the AMF + BIO treatment markedly increased by 165.07%, 73.48%, 482.79%, 93.64%, and 22.72%, respectively ($P < 0.05$). Moreover, compared with those in the single AMF and BIO treatment groups (except phosphatase), the soil enzyme activities in the BIO + AMF treatment group were significantly greater ($P < 0.05$). Notably, two-way ANOVA revealed a dramatic interaction effect between AMF inoculation and biochar addition on soil enzyme activity (Fig. 3f).

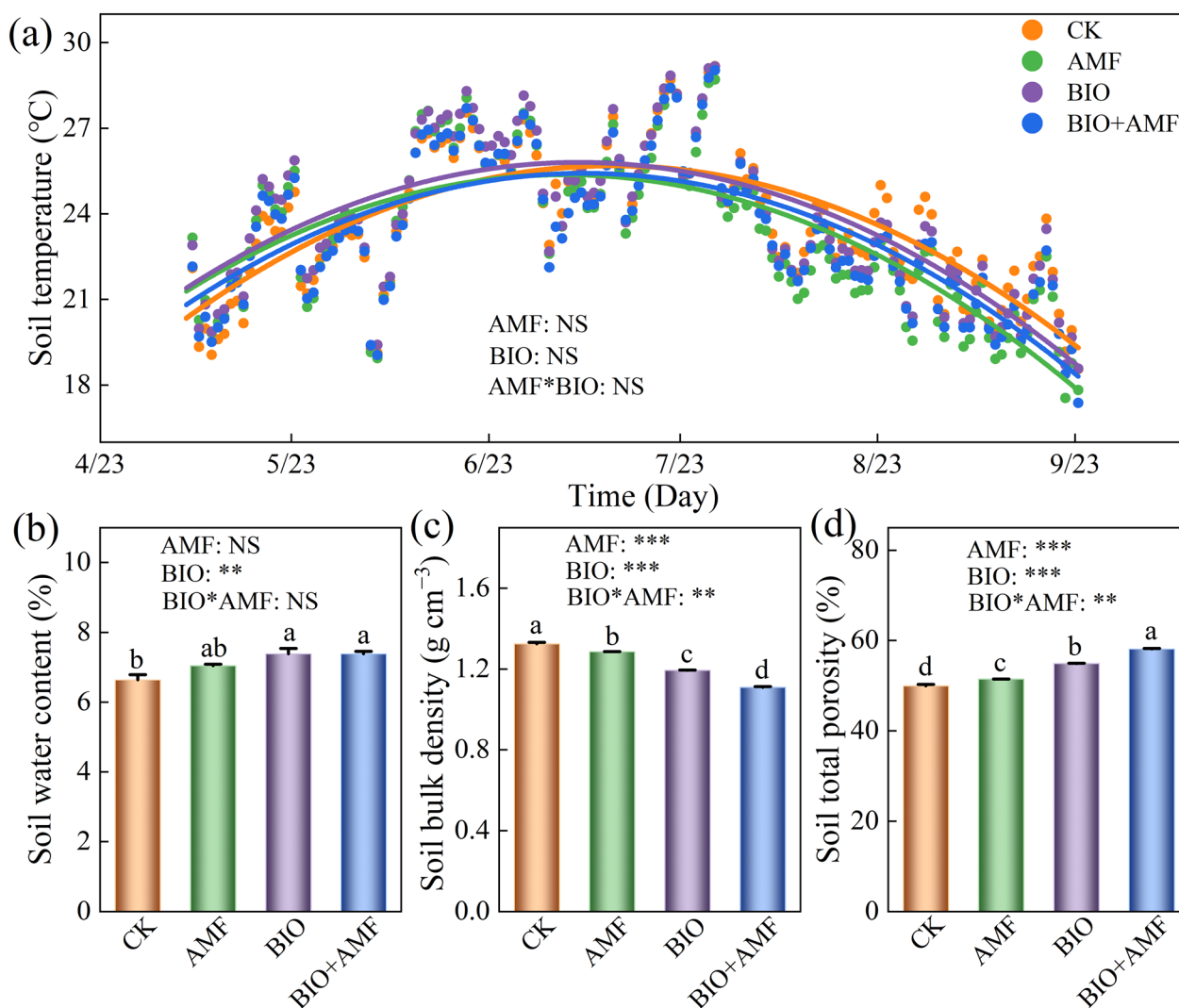


Fig. 2 The variations of soil temperature (a), soil water content (b), soil bulk density (c), and soil total porosity (d) in response to the AMF inoculation and biochar addition. CK, control. AMF, inoculation with AMF without biochar. BIO, biochar addition without AMF. BIO + AMF, biochar addition with AMF inoculated. Different letters indicate significant differences among four treatments at the 0.05 level. Bars indicate the Tukey's HSD tests at $P < 0.05$ ($n = 3$). *** represents $P < 0.001$, ** represents $P < 0.01$, and NS represents no significant different (the same in the below)

Table 2 Soil nutrient index under different treatment levels

Treatment	pH	SOC (g kg ⁻¹)	TN (g kg ⁻¹)	AN (mg kg ⁻¹)	TP (g kg ⁻¹)	AP (mg kg ⁻¹)	TK (g kg ⁻¹)	AK (mg kg ⁻¹)
CK	8.46 ± 0.01a	3.61 ± 0.01d	0.34 ± 0.00d	20.30 ± 0.07d	0.55 ± 0.00c	6.49 ± 0.03d	17.03 ± 0.01d	114.65 ± 0.08c
AMF	8.45 ± 0.00a	3.82 ± 0.01c	0.36 ± 0.00c	32.34 ± 0.17a	0.80 ± 0.01a	8.14 ± 0.02c	19.39 ± 0.01c	119.55 ± 0.08a
BIO	8.24 ± 0.02c	5.45 ± 0.01b	0.39 ± 0.00b	21.74 ± 0.54c	0.71 ± 0.00b	8.53 ± 0.03b	20.03 ± 0.01a	111.73 ± 0.15d
BIO + AMF	8.27 ± 0.01b	6.50 ± 0.01a	0.42 ± 0.00a	30.59 ± 0.36b	0.35 ± 0.00d	12.50 ± 0.03a	19.74 ± 0.01b	115.18 ± 0.13b
AMF	NS	***	***	***	***	***	***	***
BIO	***	***	***	NS	***	***	***	***
BIO*AMF	NS	***	*	**	***	***	***	***

SOC, soil organic carbon; TN, soil total nitrogen; AN, alkali-hydrolyzed nitrogen; TP, total phosphorus; AP, available phosphorus; TK, total potassium; AK, available potassium

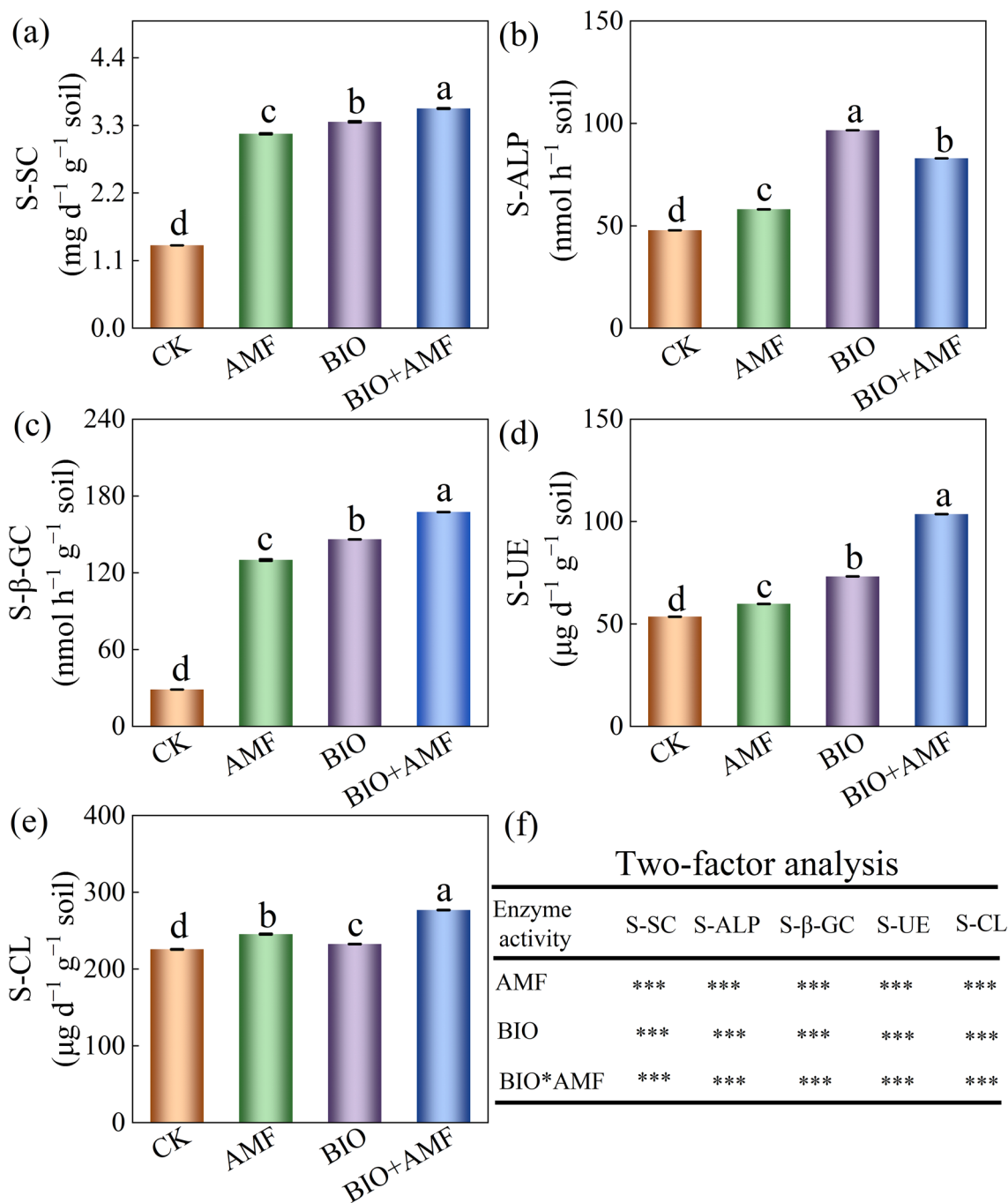


Fig. 3 The variations of soil enzyme activity in response to the AMF inoculation and biochar addition. **a** S-SC, soil sucrose activity. **b** S-ALP, soil phosphatase activity, **c** S-β-GC, soil β -glucosidase activity, **d** S-UE, soil urease activity, and **e** S-CL, soil cellulase activity

3.5 Bacterial community diversity and composition

Inoculation with AMF and biochar optimized the soil bacterial community structure (Fig. 4). The bacterial Chao1 and Shannon indices increased in the AMF and BIO treatment compared with control group but did not significantly increase, whereas the Chao1,

observed_species, Shannon and Simpson indices significantly increased ($P < 0.05$) in the BIO + AMF treatment group (Fig. 4a–d). Two-way ANOVA revealed no significant interaction effect between AMF inoculation and biochar addition on soil bacterial community structure (Fig. 4e). The β-diversity of the bacterial

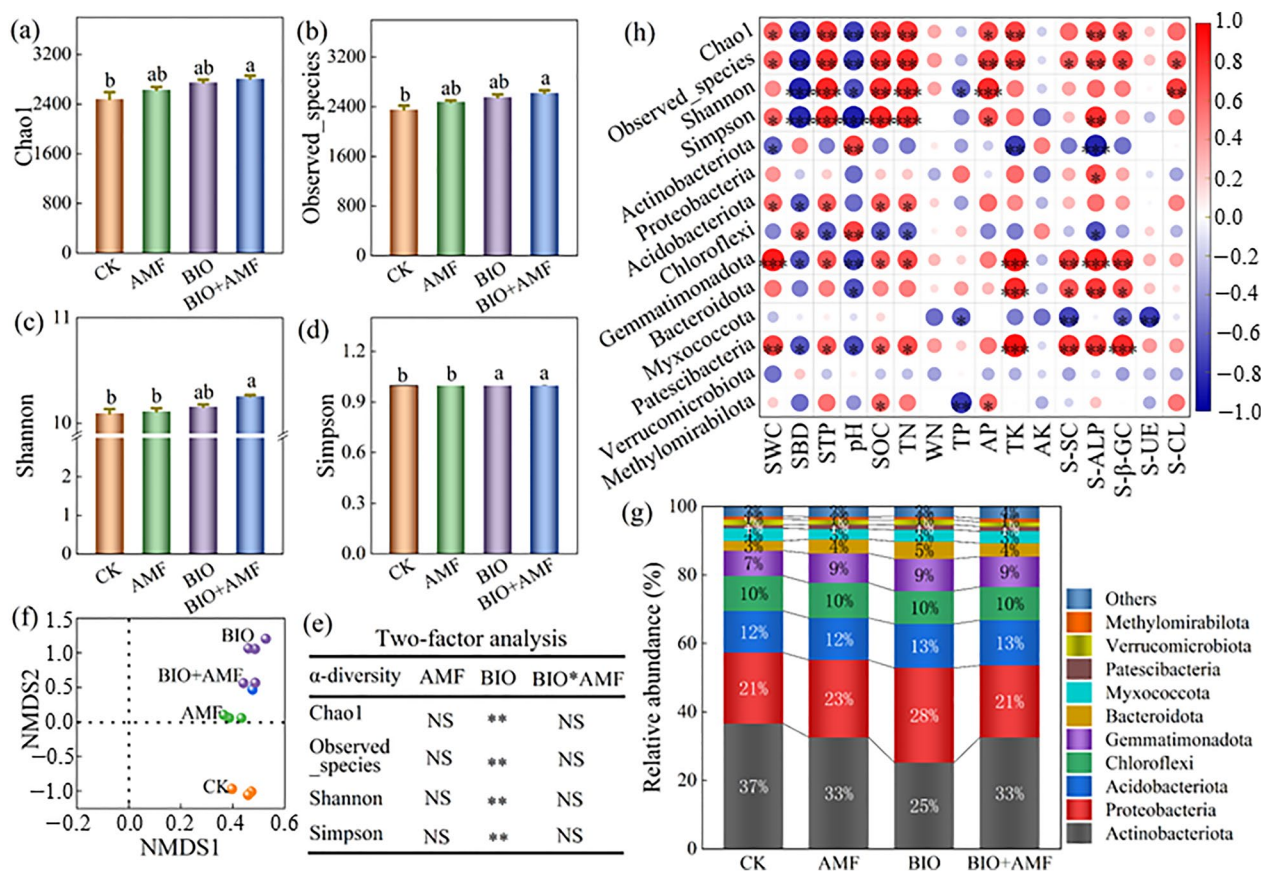


Fig. 4 The bacterial community in response to the AMF inoculation and biochar addition. **a–e** Dynamic of alpha diversity of bacterial community. **f** Change of beta diversity of bacterial community. **g** Top ten bacterial relative abundance at phylum level. **h** Correlation analysis of bacterial diversity and phylum level with soil physical and chemical properties. *** represents $P < 0.001$, ** represents $P < 0.01$, and * represents $P < 0.05$ (the same in the below)

community after inoculation with AMF and biochar addition showed a significant partitioning trend from the control treatment, further indicating that the bacterial community in the AMF, BIO, and BIO+AMF treatment groups significantly differed from that in the control group (Fig. 4f). In the bacterial community analysis, we detected 10 dominant bacterial phyla, in which the relative abundance of Proteobacteria, Gemmatimonadota, Bacteroidota and Patescibacteria was markedly greater than in the control treatment group after inoculation with AMF and biochar addition ($P < 0.05$), whereas the relative abundance of Actinobacteria decreased significantly, and the decrease was the most significant ($P < 0.05$) in the BIO treatment (Fig. 4g; Additional file 1: Fig. S2). Correlation analyses revealed that the bacterial diversity parameters were positively correlated with SWC, STP, SOC, TN, AP, and S-ALP and significantly negatively correlated with SBD and pH (Fig. 4h). Gemmatimonadota and Patescibacteria abundance was dramatically positively correlated with SWC,

STP, SOC, TN, TK, S-SC, S-ALP, and S-β-GC but significantly negatively correlated with SBD and pH.

3.6 Diversity and composition of the fungal community

Inoculation with AMF and biochar altered the soil fungal community structure (Fig. 5). The Chao1, observed_species, Shannon, and Simpson indices were significantly greater in the AMF and BIO treatment groups than in the control, with the exception of the Simpson index ($P < 0.05$). However, the above four parameters obviously increased in the BIO+AMF treatment group compared with the CK ($P < 0.05$) (Fig. 5a–d). Two-way ANOVA revealed that there was a dramatic interaction effect between inoculation with AMF and biochar addition on the Chao1 index, whereas there was no significant interaction effect on the remaining three parameters (Fig. 5e). The β diversity of the fungal communities after inoculation with AMF and biochar tended to clearly differ from that in the control group, and that in the AMF and BIO+AMF treatment groups tended to be similar,

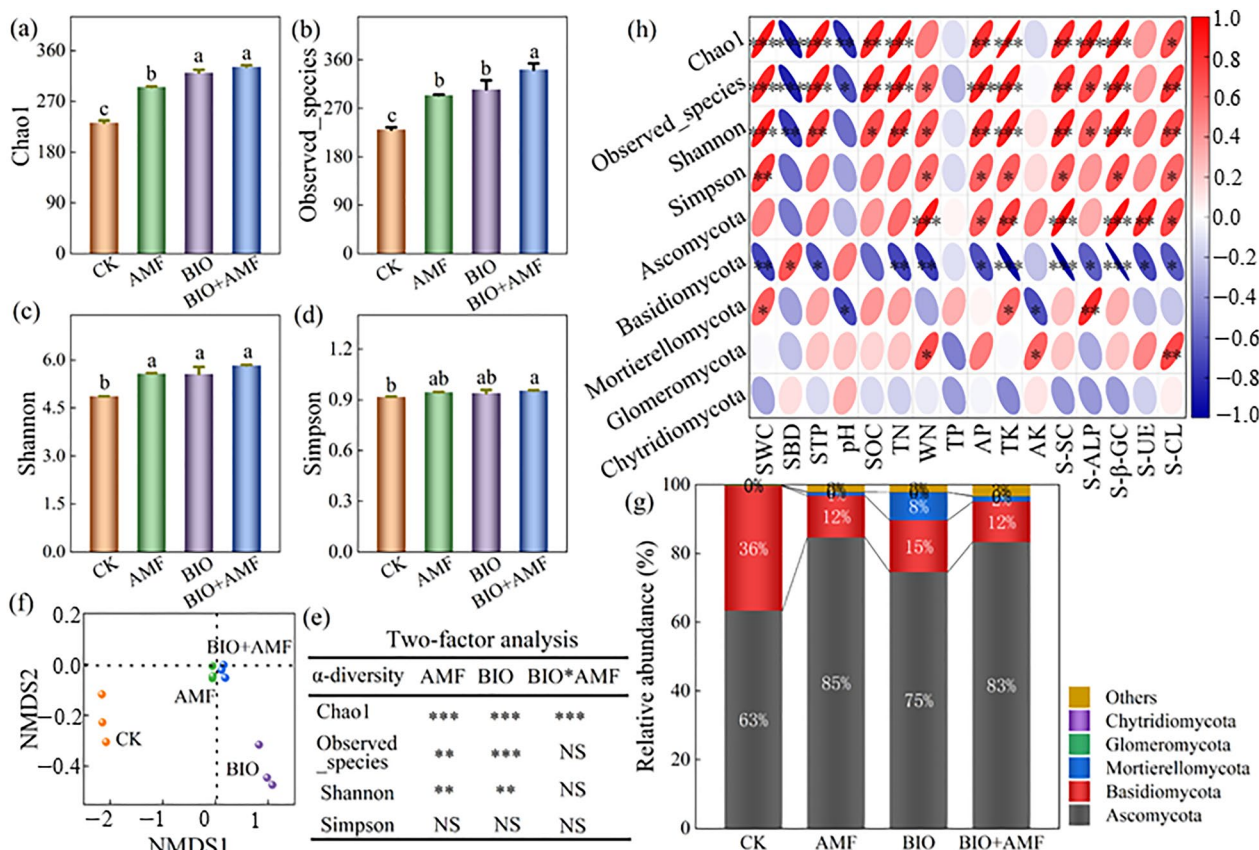


Fig. 5 The fungal community in response to the AMF inoculation and biochar addition. **a–e** Dynamic of alpha diversity of fungal community. **f** Change of beta diversity of fungal community. **g** Top five fungal relative abundance at phylum level. **h** Correlation analysis of fungal diversity and phylum level with soil physical and chemical properties

which further indicated that the differences among the fungal communities in the AMF, BIO, and BIO + AMF groups (Fig. 5f). In the fungal community analysis, we detected five dominant fungal phyla, among which the Ascomycota abundance was obviously higher than in the control treatment group after inoculation with AMF and the addition of biochar ($P < 0.05$), and the abundance in the AMF-inoculated treatment group was significantly greater than in the BIO group ($P < 0.05$) (Fig. 5g; Additional file 1: Fig. S3). The relative abundance of Basidiomycota obviously decreased compared to the control ($P < 0.05$). The results of the correlation analysis revealed that fungal Chao1, observed_species, and the Shannon indices were significantly positively correlated with SWC, STP, SOC, TN, AP, TK, S-SC, S-ALP, S-β-GC, and S-C negatively correlated with SBD and pH. Ascomycota abundance was positively correlated with WN, AP, TK, S-SC, S-β-GC, S-UE, and S-CL. Basidiomycota abundance was positively correlated with SBD and negatively correlated with SWC, STP, TN, WN, AP, TK, S-SC, S-ALP, S-β-GC, S-UE, and S-CL (Fig. 5h).

3.7 Soil multifunctionality under AMF inoculation and biochar addition

Inoculation with the AMF and biochar addition significantly enhanced soil multifunctionality (Fig. 6). Compared with control, the soil productivity function, nutrient supply function, bacterial community function, fungal community function, enzyme activity function, and soil multifunctionality significantly increased by 102.45%, 93.05%, 74.81%, 107.52%, 85.66%, and 99.47%, respectively, in the single AMF treatment group ($P < 0.05$) (Fig. 6a–g). The soil productivity function, nutrient supply function, bacterial community function, fungal community function, enzyme activity function, and soil multifunctionality dramatically increased by 147.24%, 102.38%, 153.03%, 121.95%, 125.86%, and 134.26%, respectively, in the single BIO treatment group ($P < 0.05$). Similarly, compared with the other three treatment groups, the BIO+AMF treatment group also broadly enhanced soil monofunctionality and multifunctionality, in which the nutrient supply function, fungal community function, enzyme activity function, and soil multifunctionality were significantly greater ($P < 0.05$).

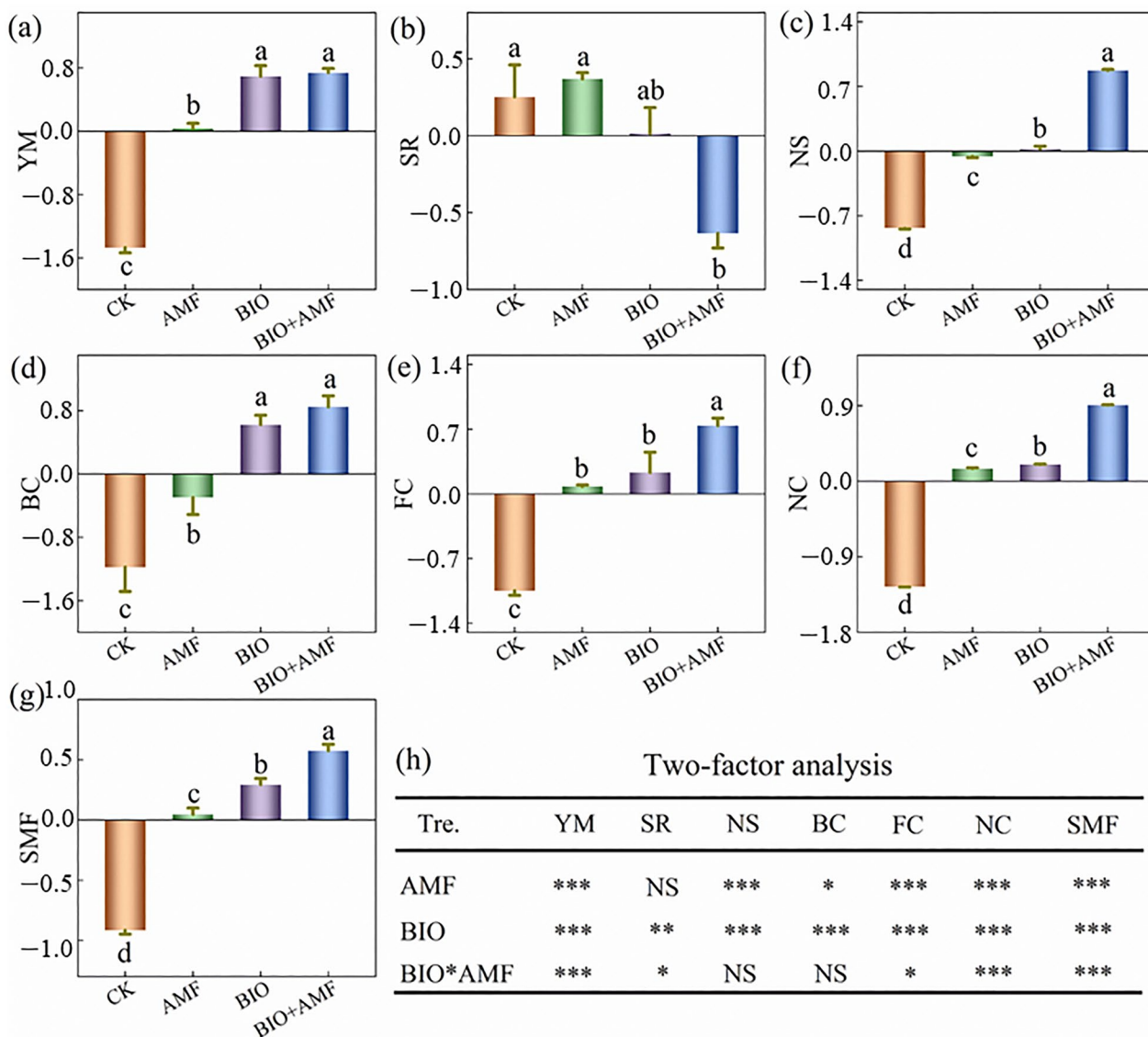


Fig. 6 Soil multifunctionality and single functions in response to the AMF inoculation and biochar addition. **a** YM, soil productivity function. **b** SR, soil structure function. **c** NS, nutrient supply function. **d** BC, bacterial community function. **e** FC, fungal community function. **f** NC, enzyme activity function. **g** SMF, soil multifunctionality

Two-way ANOVA revealed that inoculation with AMF and biochar addition had significant interaction effects on the soil productivity function, soil structure function, fungal community function, enzyme activity function, and soil multifunctionality, whereas there was no significant interaction effect on the nutrient supply function or bacterial community function (Fig. 6h).

3.8 Correlation analysis of production and multifunctionality with soil physicochemical biology

The results of the linear regression analyses revealed that soil multifunctionality after inoculation with AMF and biochar addition was positively correlated with the productivity function, nutrient supply function,

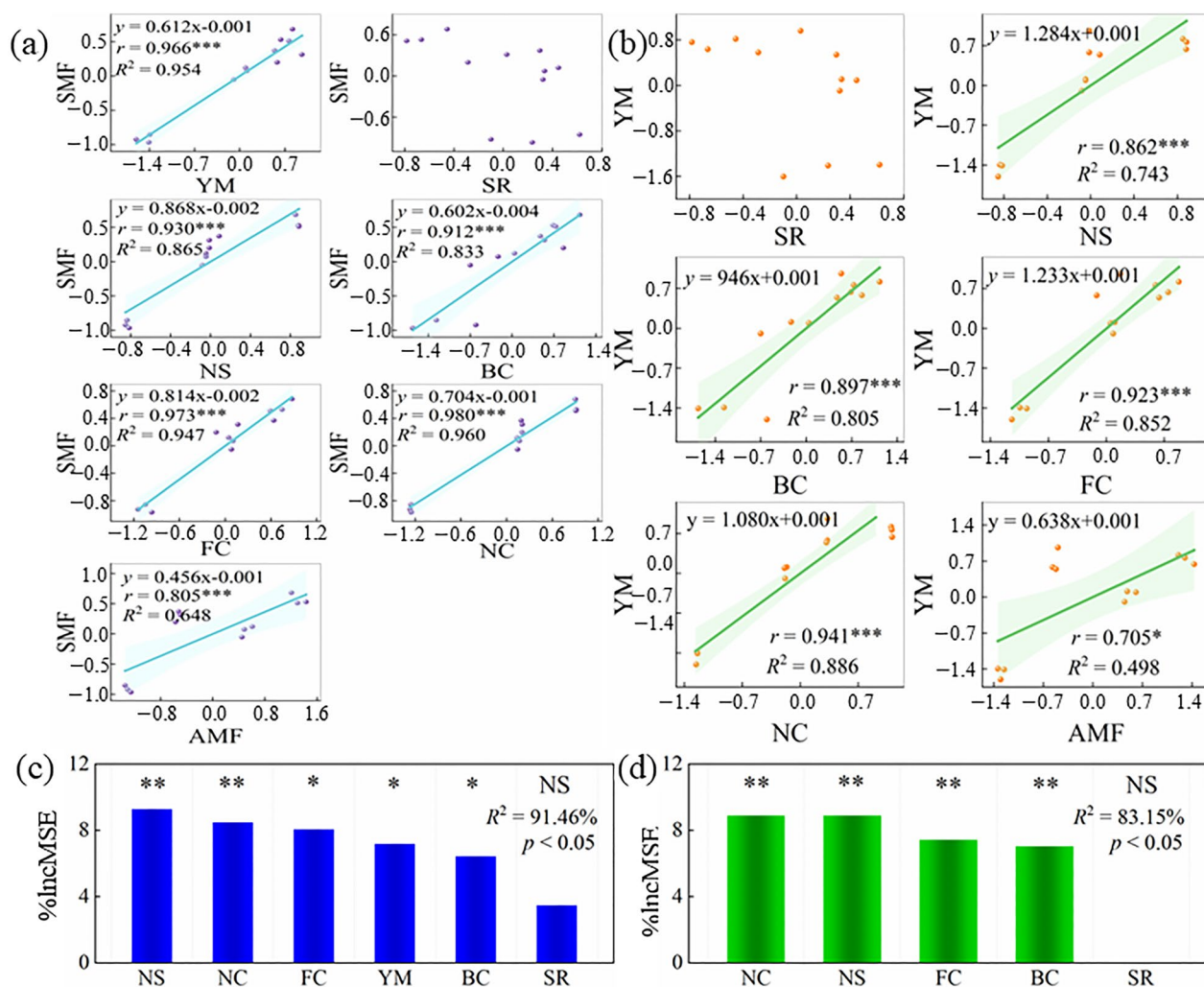


Fig. 7 The linear relationships with soil multifunction (a) and yield maintenance (b) with other single functions, and random forest models identifying the impact degree of each single function to soil multifunctionality (c) and yield (d). SMF, soil multifunctionality. YM, production function. SR, soil structure function. NS, nutrient supply function. BC, bacterial community function. FC, fungal community function. NC, enzyme activity function. AMF, AMF inoculation function

bacterial community function, fungal community function, enzyme activity, and AMF function, whereas there was no significant correlation with soil structural function (Fig. 7a; Additional file 1: Fig. S6). Similarly, we found that the soil productivity function was markedly positively correlated with the nutrient supply function, bacterial community function, fungal community function, enzyme activity, and AMF function but was not significantly correlated with the soil structure function (Fig. 7b). The random forest model revealed that among the six single soil functions, the soil nutrient supply function was the main contributor to soil multifunctionality after inoculation with AMF and biochar addition, followed by the soil enzyme activity function (Fig. 7c),

whereas the soil enzyme activity function was the main contributor to the soil productivity function, followed by the soil nutrient supply function (Fig. 7d).

4 Discussion

4.1 Soil properties and nutrient parameters under AMF inoculation and biochar application

Our results demonstrated that biochar amendments and AMF inoculation significantly increased the soil water content but decreased the SBD, especially in the BIO + AMF treatment (Fig. 2). This is presumably linked to the unique structural characteristics of biochar, which has a large specific surface area and high porosity, enabling it to adsorb and store water (Tuyishimire

et al. 2022; Jia et al. 2024). Similar outcomes have been reported by Guo et al. (2025), who found that biochar can significantly increase field capacity and plant-available water, thereby increasing the soil moisture content and soil water storage, possibly because biochar application increases the hydrophobicity associated with sandy soils (Liang et al. 2021). In this study, in terms of improving soil water retention capacity and soil pore structure, a combination of biochar addition and AMF inoculation was significantly superior to a single application of biochar or a single inoculation of AMF. In terms of improving soil structure, numerous studies have shown that biochar addition and AMF inoculation significantly decrease SBD and increase soil porosity (Rosenthal and Gunn 2025), which is consistent with our findings. The reason for this might be that as a highly porous material, biochar amendment significantly enhances the soil water-holding capacity, as biochar has higher surface area and pore volume that can adsorb and retain moisture, reducing water evaporation loss and maintaining high soil moisture levels (Razzaghi et al. 2020). Additionally, the addition of biochar reduces SBD, increases soil porosity, promotes soil aggregates formation, and improves soil aeration (Cen et al. 2021). AMF further stabilize soil structure through their extensive mycelial networks, which can wrap around soil particles, promote the large aggregates formation, and enhance soil erosion resistance (Abdalla et al. 2023). Additionally, the glucan-related soil proteins secreted by AMF act as organic binding agents, interacting with functional groups on the biochar surface to further increase soil aggregate stability (Thomopoulos et al. 2025).

Biochar addition and AMF inoculation also contribute to the cultivation of soil nutrient contents. Our study demonstrated that the soil pH significantly decreased in the BIO + AMF treatment group, whereas the soil TN, AN, and TP contents dramatically increased (Table 2). This increase may be attributed to the biochar and AMF application to the soil; biochar is rich in stable organic carbon, and its aromatic structure resists microbial degradation, thereby increasing soil organic carbon content over the long term and improving the stability of the soil carbon pool (Woolf et al. 2010). Additionally, the functional groups of biochar can immobilize inorganic nitrogen in the soil through electrostatic adsorption and complexation, thereby reducing nitrogen leaching and enhancing nitrogen use efficiency (Gu et al. 2022). When AMF inoculation expands the absorption range of root systems through its extraradical mycelium, it promotes plant absorption of nutrients such as nitrogen, phosphorus, and potassium (Degens 1997). In addition, AMF have

a particularly strong ability to activate insoluble phosphorus, with mycelium-secreted organic acids and phosphates decomposing organic and inorganic phosphorus compounds in the soil to increase phosphorus availability (Gill et al. 2025). Previous studies have demonstrated that phytate compounds introduced via biochar enhance the availability of multiple nutrients, including phosphorus, in rhizosphere soils. These compounds act as carbon sources and specific substrates for phosphorus-cycling microorganisms, thereby promoting the mineralization of soil organic phosphorus through a "co-metabolic stimulation effect" (Chen et al. 2015; Li et al. 2026). Furthermore, the soil available phosphorus content was optimal when biochar was combined with AMF (Table 2). In a biochar-AMF integrated system, the high cation exchange capacity of biochar can adsorb potassium, calcium, magnesium, and other base ions, reducing nutrient loss, whereas the mycelial network of AMF can efficiently transport these nutrients to plant roots (Cen et al. 2021; Rosenthal and Gunn 2025). Additionally, we found the BIO + AMF treatment enhanced the soil surface area and pore volume (Fig. 1), which means the biochar porous structure provides a habitat for microorganisms, promoting their metabolic activities, and the synergistic effect accelerates organic matter decomposition and nutrient mineralization and increases the contents of readily available nitrogen and phosphorus. This mechanism may be attributed to the unique porous structure of biochar, which creates continuous water pathways and enables plant roots to access water from a larger soil volume (Xing et al. 2019). The resulting increase in soil porosity and water content facilitates root penetration through different soil layers, thereby improving access to phosphorus sources and enhancing phosphorus uptake (Liu et al. 2023; Syakur et al. 2024). Furthermore, AMF substantially expand the plant's rhizosphere absorption area—by approximately 40-fold—through their extensive hyphal networks (Mikkelsen et al. 2008). Their fine hyphae can penetrate soil micropores inaccessible to plant roots, enabling the extraction of water and nutrients, particularly phosphorus (Zhang et al. 2014). AMF also enhance soil phosphatase activity in the rhizosphere, promoting the hydrolysis and activation of organic phosphorus (Della et al. 2020). Collectively, these mechanisms optimize soil physical properties and create more favourable conditions for plant root phosphorus uptake. However, given the diverse chemical forms of phosphorus in soil, future research should focus on elucidating the specific regulatory mechanisms governing soil phosphorus cycling through stable isotope tracing under the combined

influence of biochar and AMF, with particular emphasis on tracing phosphorus transport pathways.

4.2 Synergistic effects of AMF inoculation and biochar application on soil multifunctionality

As expected, biochar application and AMF inoculation considerably enhanced soil multifunctionality in our research (Fig. 6), which is consistent with Wang et al. (2022), who found that organic materials and microbial fertilizer improved soil ecosystem multifunctionality at long-term experimental stations. These findings can be explained by the fact that specialized soil organisms and their trophic interactions may contribute to maintaining soil multifunctionality. Our results revealed that the BIO treatment not only increased each single soil function but also enhanced multifunctionality. Moreover, correlation analysis revealed that soil multifunctionality was associated with soil physical, chemical, and biological parameters (Fig. 7), and random forest models revealed that the main driving forces were soil nutrient parameters (SOC, TN, AP, and TK) (Additional file 1: Fig. S4). SOC not only serves as the key binding agent for soil structure formation but also acts as the primary energy source driving soil biological activity. Changes in SOC content cascade through the soil system, influencing microbial metabolic activity and community structure, thereby regulating multiple ecosystem functions, including nutrient cycling and enzyme activity (Camenzind et al. 2023). TN is essential for the synthesis of proteins and nucleic acids in both plants and microorganisms; AP directly determines the size of the immediately accessible phosphorus pool, while TK reflects the soil's long-term potassium supply potential. Together, these parameters collectively characterize the fundamental fertility status of the soil (Della et al. 2020; Bo et al. 2024). According to ecological stoichiometric theory, the coupled relationships among carbon, nitrogen, and phosphorus directly regulate microbial metabolic efficiency and substrate utilization patterns (Allen and Gillooly 2009). When these fundamental nutrients are adequately supplied, soil biological communities can maintain high levels of activity and diversity, thereby driving enhanced multifunctionality—encompassing enzyme activity, decomposition, and nutrient cycling (Wang et al. 2024). We observed significant interactive effects between AMF inoculation and biochar addition on key soil nutrient indicators—including SOC, TN, and TP (Table 2)—revealing a synergistic mechanism driving soil nutrient activation and transformation. Specifically, biochar enhances AMF infection efficiency, thereby promoting organic carbon sequestration and increasing soil carbon pool stability (Han et al. 2026). Concurrently, the combined application of biochar and AMF significantly elevated soil alkaline phosphatase

activity, facilitating the conversion of organic phosphorus to inorganic forms and thereby optimizing phosphorus availability and composition (Li et al. 2022). Furthermore, the AMF–biochar combination markedly altered soil microbial community structure, enriching functional taxa associated with nitrogen cycling. This shift increased the abundance of genes involved in key nitrogen transformation processes, ultimately enhancing plant nitrogen uptake efficiency (Wen et al. 2022). Collectively, the interaction between AMF and biochar systematically optimizes soil multifunctionality through a cascading pathway of improved physical structure → enhanced biological activity → biogeochemical process driving.

Numerous studies have reported that biochar application can improve poor-environment soil health and simultaneously increase multifunctionality because of the addition of certain nutritional components, which is an alternative explanation related to its strong resistance to self-degradation (Ren et al. 2024). Additionally, we found that only the AMF-inoculated treatment markedly increased soil multifunctionality, and these results aligned somewhat with previous findings, which indicated that AMF-derived inputs, particularly easily extractable ballast protein, serve as key determinants of soil multifunctionality through the regulation of the nutrient cycle (Qiao et al. 2022). The influence of AMF on nutrient dynamics can be largely attributed to enhanced soil aggregation driven by AMF hyphae, which improves soil structural stability against wind and water erosion; this process facilitates the formation of water-stable aggregates, thereby reducing water loss and mitigating nutrient leaching (Rillig et al. 2015; Wu et al. 2016).

We found that the interactions between biochar and AMF produced robust synergistic effects on single- and multifunctionality in soil in contrast to the effects of individual biochar and AMF treatment (Fig. 6). This is important for reclaimed-soil managers; the addition of organic material and microbial fertilizers can enhance reclamation by regulating the soil nutrient supply (Ren et al. 2024; Ma et al. 2021). Numerous studies have indicated that biochar+AMF interactions contribute to improving soil quality and promoting plant growth through enhancing soil nutrient uptake and optimizing microbial community structure (Gujre et al. 2021). In our study, we found that the biomass and yield of maize plants in the biochar+AMF treatment reached the highest value compared with those in the other groups (Table 1). This may be due to the synergistic effects of biochar and AMF, which together increase signal transmission between roots and AMF, promote nutrient absorption and transport by the root system, improve soil pore structure, provide shelter for soil microorganisms, and increase soil nutrient cycling capacity (Hammer et al. 2014; Ohsowski

et al. 2018; Yang et al. 2020). Similar outcomes have been reported by Liang et al. (2019), who found that the porous structure and surface functional groups of biochar provide space and nutrients for AMF mycelial expansion, promoting efficient colonization of AMF in rice roots.

Moreover, our results revealed a significant correlation between soil productivity functions and soil enzyme activity (Fig. 7). Among all the soil functionalities examined in this study, soil enzyme activity was the most significant factor influencing soil productivity (Fig. 7d). In our study, soil enzyme activities exhibited significant positive correlations with soil nitrogen content, suggesting that AMF and biochar may synergistically regulate soil nitrogen cycling. Enhanced mineralization was observed under the combined BIO+AMF treatment (Additional file 1: Fig. S5), accompanied by significantly increased activities of urease and β -glucosidase. Urease directly catalyzes the hydrolysis of urea to ammonium nitrogen (Bo et al. 2024), while β -glucosidase—a key enzyme in carbon cycling—when elevated, typically reflects enhanced microbial capacity to mineralize nitrogen-containing organic compounds (Das et al. 2025), thereby promoting the conversion of organic nitrogen to inorganic forms. Simultaneously, we also observed significant interactive effects between AMF inoculation and biochar addition on grain weight, biomass, and yield (Table 1), reflecting a synergistic promotion of crop growth. This indicates that the combined application of biochar and AMF can enhance crop nutrient uptake efficiency through complementary mechanisms. The porous structure of biochar provides physical pathways for AMF hyphal extension, while its surface properties facilitate nutrient adsorption and slow release. Concurrently, AMF expands the nutrient acquisition range of the root system via its extensive hyphal network (Han et al. 2026). In this complementary framework—where biochar optimizes the nutrient reservoir and AMF enhances nutrient foraging efficiency—the synergy ultimately manifests as increased plant biomass and yield. Establishing this “biotic-abiotic feedback mechanism” provides a theoretical basis for designing microbial-regulated soil fertility enhancement strategies.

Additionally, correlation analysis indicated the soil multifunctionality has a positive correlation with the soil bacteria and fungi diversity (Additional file 1: Fig. S3). The application of biochar followed by AMF inoculation significantly enhances soil multifunctionality, largely attributable to the persistent carbon framework of biochar, which serves as a stable habitat and a slow-release carbon source for specific microbial communities. (Han et al. 2021); on the other hand, AMF secrete specific organic acids and sugars through their hyphae and combines them with photosynthetic carbon sources obtained from host plants, providing easily accessible energy

for the soil microbial community (Pan et al. 2024). This together stimulates the metabolic activity of bacteria and fungi, inducing them to secrete a greater variety of extracellular enzymes (Gill et al. 2025). These enzymes are adsorbed and fixed on the surfaces of biochar and mycelium–soil aggregate complexes, preventing their rapid inactivation, thereby extending their functional lifespan and enhancing catalytic efficiency (Amoakwah et al. 2022; Matinizadeh et al. 2024). Ultimately, this synergistic effect efficiently drives the decomposition of organic matter, nutrient mineralization, and cycling processes in soil by coactivating key ecological enzyme activities (Hu et al. 2024). Therefore, the combined addition, through biochar–AMF–microbial tripartite interactions, results in a more stable, efficient, and sustainable “soil enzyme reaction system”. This system not only accelerates nutrient mineralization and supply, directly enhancing soil fertility functions, but also indirectly strengthens soil ecological buffering and maintenance functions, thereby fundamentally synergistically amplifying the positive effects on soil comprehensive productivity functions. These findings support our research hypothesis that biochar addition and AMF inoculation have synergistic effects on enhancing reclaimed-soil multifunctionality by improving nutrient availability, stimulating enzyme activities, and promoting microbial diversity and abundance.

Although this study was conducted as a three-year field experiment, the data reflect the overall trends observed after three consecutive years of treatment rather than capturing intra-annual variations across individual growing seasons. Consequently, direct evidence regarding the temporal dynamics of AMF colonization following inoculation remains limited. Future research should prioritize long-term, high-frequency monitoring to elucidate the growth and reproductive patterns of AMF strains from a temporal perspective. Furthermore, the present study focused on a single AMF strain, *Funneliformis mosseae*. Our findings demonstrate that inoculation with this specific strain exerts a significant positive regulatory effect on the multifunctional properties of reclaimed soil. However, to assess the broader applicability and strain-specific effects, future studies should employ a wider range of AMF strains in inoculation validation trials. Additionally, integrating future experiments with plant tissue nutrient analysis will enable direct verification of the roles of AMF and biochar in mediating plant nutrient uptake and modulating plant–soil interactions.

5 Conclusions

This three-year field study demonstrated that the synergistic application of biochar and arbuscular mycorrhizal fungi significantly enhanced the multifunctionality of reclaimed soils in coal mining areas, offering

a sustainable, nature-based solution for ecological restoration. The combined treatment effectively improved soil physical properties by increasing the water retention capacity and reducing the bulk density, thereby creating a more favourable environment for root development and microbial activity. Moreover, the BIO + AMF treatment markedly increased the soil nutrient supply and enzyme activity, which played a pivotal role in driving soil multifunctionality. The enrichment of soil nutrient cycling functions, coupled with the increased bacterial and fungal alpha and beta diversity, underscores the importance of biological interactions in restoring degraded ecosystems. The synergistic effects of biochar and AMF not only promoted maize productivity but also reinforced the stability and resilience of the soil ecosystem. The mechanistic insights from this study highlight that soil nutrient supply and enzyme activity are key regulators of multifunctionality, suggesting that microbial-driven processes are central to ecological recovery. These findings provide a scientific foundation for optimizing restoration strategies in postmining landscapes, where soil dysfunctionality often limits plant growth and ecosystem services. In conclusion, the combined use of biochar and AMF presents a promising, ecologically sustainable approach to enhancing soil health and agricultural productivity in reclaimed areas, aligning with global goals for land degradation neutrality and climate-smart agriculture.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1007/s42773-026-00618-8>.

Additional file 1.

Author contributions

Ying Dong: Data curation, Investigation, Software, Writing—original draft. Lili Yang: Data curation, Investigation, Software, Writing—original draft. Xia He: Formal analysis, Investigation. Yijie Quan: Data curation, Investigation, Software. Yan Yang: Data curation, Investigation, Software. Huijuan Bo: Formal analysis, Investigation, Software. Wenjuan Jin: Formal analysis, Investigation, Software. Dongsheng Jin: Conceptualization, Formal analysis, Funding acquisition, Methodology, Validation, Writing—review & editing. Jianghong Bo: Project administration. Youcai Xiong: Conceptualization, Formal analysis, Project administration. Bianhua Zhang: Data curation, Software. Wenjing Zhang: Software. Qiang Zhang: Funding acquisition, Project administration. Minggang Xu: Funding acquisition, Project administration. Wei Wang: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Software, Writing—original draft, Writing—review & editing. All authors read and approved the final manuscript.

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Data availability

Data will be made available on request.

Declarations

Competing interests

The authors declare that they have no conflict of interest.

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References

- Abbott LK, MacDonald LM, Wong MTF, Webb MJ, Jenkins SN, Farrell M (2018) Potential roles of biological amendments for profitable grain production - a review. *Agric Ecosyst Environ* 256:34–50. <https://doi.org/10.1016/j.agee.2017.12.021>
- Abdalla M, Bitterlich M, Jansa J, Poeschel D, Ahmed MA (2023) The role of arbuscular mycorrhizal symbiosis in improving plant water status under drought. *J Exp Bot* 74(16):4808–4824. <https://doi.org/10.1093/jxb/erad249>
- Allen AP, Gillooly JF (2009) Towards an integration of ecological stoichiometry and the metabolic theory of ecology to better understand nutrient cycling. *Ecol Lett* 12(5):369–384. <https://doi.org/10.1111/j.1461-0248.2009.01302.x>
- Amoakwah E, Arthur E, Frimpong KA, Lorenz N, Rahman MA, Nziguheba G, Islam KF (2022) Biochar amendment impacts on microbial community structures and biological and enzyme activities in a weathered tropical sandy loam. *Appl Soil Ecol* 172:104364. <https://doi.org/10.1016/j.apsoil.2021.104364>
- Bao SD (2000) Soil and agricultural chemistry analysis. China Agriculture Press
- Bo H, Li Z, Wang W, Zhang R, Wang H, Jin D, Xu M, Zhang Q (2024) Combining organic and inorganic fertilization enhances soil enzyme activity, the bacterial community, and molecular ecological network complexity in coal mine reclamation areas. *Agronomy* 14:1427. <https://doi.org/10.3390/agronomy14071427>
- Camenzind T, Mason-Jones K, Mansour I, Rillig MC, Lehmann J (2023) Formation of necromass-derived soil organic carbon determined by microbial death pathways. *Nat Geosci* 16:115–122. <https://doi.org/10.1038/s41561-022-01100-3>
- Cen R, Feng W, Yang F, Wu W, Liao H, Qu Z (2021) Effect mechanism of biochar application on soil structure and organic matter in semi-arid areas. *J Environ Manage* 286:112198. <https://doi.org/10.1016/j.jenvman.2021.112198>
- Chen J, Liu X, Zheng J, Zhang B, Lu H, Chi Z, Pan G, Li L, Zheng J, Zhang X, Wang J (2013) Biochar soil amendment increased bacterial but decreased fungal gene abundance with shifts in community structure in a slightly acid rice paddy from Southwest China. *Appl Soil Ecol* 71:33–44. <https://doi.org/10.1016/j.apsoil.2013.05.003>
- Chen Y, Yu X, Xu D, Peng J (2025) A spatial machine learning approach to exploring the impacts of coal mining and ecological restoration on regional ecosystem health. *Environ Res* 264(2):120379. <https://doi.org/10.1016/j.envres.2024.120379>
- Chen ZM, Xiao X, Chen BL, Zhu LZ (2015) Quantification of chemical states, dissociation constants and contents of oxygen-containing groups on

- the surface of biochars produced at different temperatures. *Environ Sci Technol* 49(1):309–317. <https://doi.org/10.1021/es043468>
- Cheng H, Wang J, Tu C, Lin S, Xing D, Hill P, Chadwick D, Jones LD (2020) Arbuscular mycorrhizal fungi and biochar influence simazine decomposition and leaching. *GCB Bioenergy* 13:708–718. <https://doi.org/10.1111/gcbb.12802>
- Dai M, Hamel C, Bainard LD, Arnaud MS, Grant CA, Lupwayi NZ, Malhi SS, Lemke R (2014) Negative and positive contributions of arbuscular mycorrhizal fungal taxa to wheat production and nutrient uptake efficiency in organic and conventional systems in the Canadian prairie. *Soil Biol Biochem* 74:156–166. <https://doi.org/10.1016/j.soilbio.2014.03.016>
- Das P, Barker C, Park Y, Perreault F, Westerhoff P, Penton CR (2025) Impact of graphite nano amendments on soil enzyme activities, functional genes and microbiome composition in a soil-plant system. *Soil Biol Biochem* 203:109714. <https://doi.org/10.1016/j.soilbio.2025.109714>
- Degens BP (1997) Macro-aggregation of soils by biological bonding and binding mechanisms and the factors affecting these: a review. *Soil Res* 35(3):431–460. <https://doi.org/10.1071/s96016>
- Della MIF, Godeas AM, Scervino JM (2020) In vivo modulation of arbuscular mycorrhizal symbiosis and soil quality by fungal P solubilizers. *Microb Ecol* 79(1):21–29. <https://doi.org/10.1007/s00248-019-01396-6>
- Duan HX, Luo CL, Li JY, Wang BZ, Naseer M, Xiong YC (2021) Improvement of wheat productivity and soil quality by arbuscular mycorrhizal fungi is density- and moisture-dependent. *Agron Sustain Dev* 41:3. <https://doi.org/10.1007/s13593-020-00659-8>
- Duarte SD, Cerri CEP, Rittl TF, Abbruzzin TF, Pano BLP (2023) Biochar physical and hydrological characterization to improve soil attributes for plant production. *J Soil Sci Plant Nutr* 23(3):3051–3057. <https://doi.org/10.1007/s42729-023-01273-9>
- Gill J, Tharp CL, Suseela V (2025) Arbuscular mycorrhizal symbiosis enables efficient phosphorus uptake in sorghum accessions with contrasting root traits. *Plant Cell Environ*. <https://doi.org/10.1111/pce.15666>
- Goswami S (2015) Impact of coal mining on environment. *Eur Res* 92(3):185–196. <https://doi.org/10.13187/er.2015.92.185>
- Gu W, Wang Y, Feng Z, Wu D, Zhang H, Yuan H, Sun Y, Xiu L, Chen W, Zhang W (2022) Long-term effects of biochar application with reduced chemical fertilizer on paddy soil properties and japonica rice production system. *Front Environ Sci* 10:902752. <https://doi.org/10.3389/fenvs.2022.902752>
- Gujre N, Soni A, Rangan L, Tsang DCW, Mitra S (2021) Sustainable improvement of soil health utilizing biochar and arbuscular mycorrhizal fungi: a review. *Environ Pollut* 268:115549. <https://doi.org/10.1016/j.envpol.2020.115549>
- Guo J, Zhou H, Jia L, Wang Y, Fan M (2025) Effects of biochar from different pyrolysis temperatures on soil physical properties and hydraulic characteristics in potato farmland of arid and semi-arid regions. *Agric Water Manag* 313:109483. <https://doi.org/10.1016/j.agwat.2025.109483>
- Hammer EC, Balogh-Brunstad Z, Jakobsen I, Olsson PA, Stipp SLS, Rillig MC (2014) A mycorrhizal fungus grows on biochar and captures phosphorus from its surfaces. *Soil Biol Biochem* 77:252e–2260. <https://doi.org/10.1016/j.soilbio.2014.06.012>
- Han LF, Zhang B, Chen LY, Feng YF, Yang Y, Sun K (2021) Impact of biochar amendment on soil aggregation varied with incubation duration and biochar pyrolysis temperature. *Biochar* 3(3):339–347. <https://doi.org/10.1007/s42773-021-00097-z>
- Han S, Liang Y, Zhang DS, Wang Y (2026) Effects of combined application of biochar and arbuscular mycorrhizal fungi on soil organic carbon content and stability. *J Agro-Environ Sci* 45(1):127–138. <https://doi.org/10.11654/jaes.2025-0094>
- Hu W, Ran J, Dong L, Du Q, Ji M, Yao S, Sun Y, Gong C, Hou Q, Gong H, Chen R, Lu J, Xie S, Wang Z, Huang H, Li X, Xiong J, Xia R, Wei M, Zhao D, Zhang Y, Li J, Yang H, Wang X, Deng Y, Sun Y, Li H, Zhang L, Chu Q, Li X, Aqeel M, Manan A, Akram MA, Liu X, Li R, Li F, Hou C, Liu J, He J, An L, Bardgett RD, Schmid B, Deng J (2021) Aridity-driven shift in biodiversity-soil multifunctionality relationships. *Nat Commun* 12:5350. <https://doi.org/10.1038/s41467-021-25641-0>
- Hu W, Zhang Y, Rong X, Zhou X, Fei J, Peng J, Luo G (2024) Biochar and organic fertilizer applications enhance soil functional microbial abundance and agroecosystem multifunctionality. *Biochar* 6:3. <https://doi.org/10.1007/s42773-023-00296-w>
- Jia A, Song X, Li S, Liu Z, Liu X, Han Z, Gao H, Gao Q, Zha Y, Liu Y, Wu X (2024) Biochar enhances soil hydrological function by improving the pore structure of saline soil. *Agric Water Manag* 306:109170. <https://doi.org/10.1016/j.agwat.2024.109170>
- Jing X, Sanders NJ, Shi Y, Chu H, Classen AT, Zhao K, Chen L, Shi Y, Jiang Y, He JS (2015) The links between ecosystem multifunctionality and above- and belowground biodiversity are mediated by climate. *Nat Commun* 6:1–8. <https://doi.org/10.1038/ncomms9159>
- Li MY, Hu HB, Jin W, Ge ZW, Sun HJ, Tang ZL, Liu X (2026) Effects of biochar combined with salt-tolerant trees on phosphorus cycling bacterial community in intertidal saline soil. *Acta Ecol Sin* 46(10):1–14. <https://doi.org/10.20103/j.stxb.202503020771>
- Li SQ, Chi SQ, Lin CQ, Cai C, Yang LH, Peng KM, Huang XF, Liu J (2022) Combination of biochar and AMF promotes phosphorus utilization by stimulating rhizosphere microbial co-occurrence networks and lipid metabolites of *Phragmites*. *Sci Total Environ* 845:157339. <https://doi.org/10.1016/j.scitotenv.2022.157339>
- Li X, Du S, Hu S, Dong D, Jiang D, Cao C, Lin G, Fu J (2025) Simulation of surface water–groundwater interaction in coal mining subsidence areas: A case study of the Kuye River Basin in China. *J Hydrol* 659:133243. <https://doi.org/10.1016/j.jhydrol.2025.133243>
- Liang J, Li Y, Si B, Wang Y, Chen X, Wang X, Chen H, Wang H, Zhang F, Bai Y, Biswas A (2021) Optimizing biochar application to improve soil physical and hydraulic properties in saline-alkali soils. *Sci Total Environ* 771:144802. <https://doi.org/10.1016/j.scitotenv.2020.144802>
- Liang JF, An J, Gao JQ, Zhang XY, Song MH, Yu FH (2019) Interactive effects of biochar and AMF on plant growth and greenhouse gas emissions from wetland microcosms. *Geoderma* 346:11–17. <https://doi.org/10.1016/j.geoderma.2019.03.033>
- Liu H, Liang Y, Liu J, Zhang Q, Liu Y, Zeng J, Wang X, Yang G, Ren C, Han X (2025) Long-term no-tillage enhanced soil multifunctionality and reduced microbial metabolic entropy. *Appl Soil Ecol* 206:105876. <https://doi.org/10.1016/j.apsoil.2025.105876>
- Liu SY, Cao DY, Hang YW, Ge SH, He WY, Zhan ZY, He TY, Chen WF, Lan Y (2023) Biochar affects the distribution of phosphorus in the soil profile by changing the capacity of soil to adsorb phosphorus and its distribution within soil macroaggregates. *Land Degrad Dev* 34(8):2189–2200. <https://doi.org/10.1002/ldr.4599>
- Ma X, Geng Q, Zhang H, Bian C, Chen HYH, Jiang D, Xu X (2021) Global negative effects of nutrient enrichment on arbuscular mycorrhizal fungi, plant diversity and ecosystem multifunctionality. *New Phytol* 229:2957–2969. <https://doi.org/10.1111/nph.17077>
- Maestre FT, Guirado E, Armenteras D, Beck HE, AlShalan MS, Al-Saud NT, Chami R, Fu B, Gichenje H, Huber-Sannwald E, Speranza CI, Martínez-Valderrama J, McCabe MF, Orr B, Tang T, Metternicht G, Miess M, Reynolds JF, Stringer C, Wada Y, Duarte CM (2025) Bending the curve of land degradation to achieve global environmental goals. *Nature* 664:347–355. <https://doi.org/10.1038/s41586-025-09365-5>
- Matiniazadeh M, Nouri E, Bayranvand M, Kolarikova Z, Janoušková M (2024) Arbuscular mycorrhiza and rhizosphere soil enzymatic activities as modulated by grazing intensity and plant species identity in a semi-arid grassland. *Rhizosphere* 30:100893. <https://doi.org/10.1016/j.rhisph.2024.100893>
- Mcgonigle TP, Miller MH, Evans DG, Fairchild GL, Swan JA (1990) A new method which gives an objective measure of colonization of roots by vesicular-arbuscular mycorrhizal fungi. *New Phytol* 115(3):495. <https://doi.org/10.1111/j.1469-8137.1990.tb00476.x>
- Mikkelsen BL, Rosendahl S, Jakobsen I (2008) Underground resource allocation between individual networks of mycorrhizal fungi. *New Phytol* 180(4):890–898. <https://doi.org/10.1111/j.1469-8137.2008.02623.x>
- Nguyen TB, Sherpa K, Bui XT, Nguyen VT, Vo TDH, Ho HTT, Chen CW, Dong CD (2023) Biochar for soil remediation: a comprehensive review of current research on pollutant removal. *Environ Pollut* 337:122571. <https://doi.org/10.1016/j.envpol.2023.122571>
- Ohsowski BM, Dunfield K, Klironomos JN, Hart MM (2018) Plant response to biochar, compost, and mycorrhizal fungal amendments in post-mine sandpits. *Restor Ecol* 26(1):63e–672. <https://doi.org/10.1111/rec.12528>
- Pan X, Li Y, Zhang R, Tian D, Wang P, Song L, Quan Q, Chen C, Niu S, Zhang X, Wang J (2024) Soil microbial gene abundance rather than diversity and network complexity predominantly determines soil multifunctionality in Tibetan alpine grasslands along a precipitation gradient. *Funct Ecol* 38:1210–1221. <https://doi.org/10.1111/1365-2435.14542>

- Pokharel P, Ma Z, Chang SX (2020) Biochar increases soil microbial biomass with changes in extra- and intracellular enzyme activities: a global meta-analysis. *Biochar* 2(1):65–79. <https://doi.org/10.1007/s42773-020-00039-1>
- Qiao Y, Bai Y, She W, Liu L, Miao C, Zhu G, Qin S, Zhang Y (2022) Arbuscular mycorrhizal fungi outcompete fine roots in determining soil multifunctionality and microbial diversity in a desert ecosystem. *Appl Soil Ecol* 171:104323. <https://doi.org/10.1016/j.apsoil.2021.104323>
- Razzaghi F, Obour PB, Arthur E (2020) Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma* 361:114055. <https://doi.org/10.1016/j.geoderma.2019.114055>
- Ren T, Liao J, Jin L, Delgado-Baquerizo M, Ruan H (2024) Application of biogas-slurry and biochar improves soil multifunctionality in a poplar plantation during afforestation processes. *Plant Soil* 501:107–123. <https://doi.org/10.1007/s11104-023-05968-x>
- Rillig MC, Aguilar-Trigueros CA, Bergmann J, Verbruggen E, Veresoglou SD, Lehmann A (2015) Plant root and mycorrhizal fungal traits for understanding soil aggregation. *New Phytologist* 205:1385–1388. <https://doi.org/10.1111/nph.13045>
- Rosenthal J, Gunn KM (2025) Arbuscular mycorrhizal fungi in biochar amended soils: a review. *Soil Res* 63:SR24123. <https://doi.org/10.1071/SR24123>
- Sonter LJ, Dade MC, Watson JE, Valent RK (2020) Renewable energy production will exacerbate mining threats to biodiversity. *Nat Commun* 11:4174. <https://doi.org/10.1038/s41467-020-17928-5>
- Sun J, Jia Q, Li Y, Zhang T, Chen J, Ren Y, Dong K, Xu S, Shi NN, Fu S (2022) Effects of arbuscular mycorrhizal fungi and biochar on growth, nutrient absorption, and physiological properties of maize (*Zea mays* L.). *J Fungi* 8:1275. <https://doi.org/10.3390/jof8121275>
- Syakur S, Zaitun Z, Darusman D, Siagian GM (2024) Improving the physical properties of ex-coal mining soil planted with sweet corn (*Zea mays saccharata* L.) using pine wood and sawdust biochar. *Media Konservasi* 29(4):540–549. <https://doi.org/10.29244/medkon.29.4.540>
- Tang B, Man J, Lehmann A, Rillig M C (2024) Arbuscular mycorrhizal fungi attenuate negative impact of drought on soil functions. *Glob Change Biol* 30:e17409. <https://doi.org/10.1111/gcb.17409>
- Thomopoulos S, Munkholm LJ, Elsgaard L, Ravnskov S (2025) Tillage and residue management modulate the links between soil physical signatures and arbuscular mycorrhizal fungal biomarkers. *Geoderma* 454:117204
- Tuyishimire E, Cui J, Tang X, Sun Z, Cheng J (2022) Interactive effects of honey-suckle planting and biochar amendment on soil structure and hydraulic properties of hillslope farmland. *Agriculture* 12(3):414. <https://doi.org/10.3390/agriculture12030414>
- Van Der Heyde M, Bunce M, Dixon K, Wardell-Johnson G, White N, Nevill P (2020) Changes in soil microbial communities in post mine ecological restoration: implications for monitoring using high throughput DNA sequencing. *Sci Total Environ* 749:142262. <https://doi.org/10.1016/j.scitotenv.2020.142262>
- Wang D, Fonte SJ, Parikh SJ, Six J, Scow KM (2017) Biochar additions can enhance soil structure and the physical stabilization of C in aggregates. *Geoderma* 303:110–117. <https://doi.org/10.1016/j.geoderma.2017.05.027>
- Wang PY, Zhao ZY, Siddique KHM, Xiong XB, Tao HY, Ma Y, Mo F, Chen YL, Song YJ, Burch JWR, Ma BL, Wang S, Kavagi L, Yang FK, Xiong YC (2024) Microplastics positively mediate soil multifunctionality in dryland. *Resour Conserv Recycl* 209:107754. <https://doi.org/10.1016/j.resconrec.2024.107754>
- Wang W, Dong Y, Wang HB, Xue DH, Zhang HF, Li ZJ, Wang H, Bo HJ, Zhang WJ, Zhang BH, Xiong YC, Zhang Q, Jin DS (2025b) Long-term legume cultivation affects the soil bacterial community via altering the soil pore structure in coal mine reclamation agroecosystems. *Plant Cell Environ*. <https://doi.org/10.1111/pce.70063>
- Wang W, Dong Y, Zhang HF, Xue DH, Wang HB, Bo HJ, Xiong YC, He X, Zhang BH, Zhang WJ, Zhang Q, Xu MG, Jin DS (2025a) Leguminous crops as a nature-based strategy to restore the functionality of reclaimed soils in coal mine agroecosystem. *Appl Soil Ecol* 214:106407. <https://doi.org/10.1016/j.apsoil.2025.106407>
- Wang YF, Chen P, Wang FH, Han WX, Qiao M, Dong WX, Hu CS, Zhu D, Chu HY, Zhu YG (2022) The ecological clusters of soil organisms drive the ecosystem multifunctionality under long-term fertilization. *Environ Int* 161:107133. <https://doi.org/10.1016/j.envint.2022.107133>
- Wen Z, Chen Y, Liu Z, Meng J (2022) Biochar and arbuscular mycorrhizal fungi stimulate rice root growth strategy and soil nutrient availability. *Eur J Soil Biol* 113:103448. <https://doi.org/10.1016/j.ejsobi.2022.103448>
- Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S (2010) Sustainable biochar to mitigate global climate change. *Nat Commun* 1:56. <https://doi.org/10.1038/ncomms1053>
- Wu D, Senbayram M, Zang H, Ugurlar F, Aydemir S, Brüggemann N, Kuzyakov Y, Bol R, Blagodatskaya E (2018) Effect of biochar origin and soil pH on greenhouse gas emissions from sandy and clay soils. *Appl Soil Ecol* 129:121–127. <https://doi.org/10.1016/j.apsoil.2018.05.009>
- Wu QS, Wang S, Srivastava AK (2016) Mycorrhizal hyphal disruption induces changes in plant growth, glomalin-related soil protein and soil aggregation of trifoliolate orange in a core system. *Soil Tillage Res* 160:82–91. <https://doi.org/10.1016/j.still.2016.02.010>
- Xing XG, Liu Y, Ma XY (2019) A modified van-Genuchten model for soil-water retention modeling by considering plant additives. *Arch Agron Soil Sci* 65(4):435–449. <https://doi.org/10.1080/03650340.2018.1506583>
- Xu R, Li J, Li X, Song W (2025) Effect of coal mining subsidence on soil microbial communities in mining areas with high groundwater levels. *Environ Geochem Health* 47(7):245. <https://doi.org/10.1007/s10653-025-02554-1>
- Yang Q, Ravnskov S, Neumann Andersen M (2020) Nutrient uptake and growth of potato: arbuscular mycorrhiza symbiosis interacts with quality and quantity of amended biochars. *J Plant Nutr Soil Sci* 183(2):220e–2232. <https://doi.org/10.1002/jpln.201900205>
- Yang YM, Naseer M, Zhu Y, Ma XY, Wang S, Wang BZ, Wang J, Zhu H, Wang W, Tao HY, Xiong YC (2022) Dual effects of nZVI on maize growth and water use are positively mediated by arbuscular mycorrhizal fungi via rhizosphere interactions. *Environ Pollut* 308:119661. <https://doi.org/10.1016/j.envpol.2022.119661>
- Zhang D, Sun J, Peng S, Wang Y, Hua Q, Wu P, Lin X (2025) Paddy-upland rotation combined with manure application: An optimal strategy for enhancing soil multifunctionality. *J Environ Manage* 373:123788. <https://doi.org/10.1016/j.jenvman.2024.123788>
- Zhang F, Liu M, Li Y, Che Y, Xiao Y (2019) Effects of arbuscular mycorrhizal fungi, biochar and cadmium on the yield and element uptake of *Medicago sativa*. *Sci Total Environ* 655:1150–1158. <https://doi.org/10.1016/j.scitotenv.2018.11.317>
- Zhang L, Fan JQ, Ding XD, He XH, Zhang FS, Feng G (2014) Hyphosphere interactions between an arbuscular mycorrhizal fungus and a phosphate solubilizing bacterium promote phytate mineralization in soil. *Soil Biol Biochem* 74:177–183. <https://doi.org/10.1016/j.soilbio.2014.03.004>
- Zhou X, Ke T, Li S, Deng S, An X, Ma X, De Philippis R, Chen L (2020) Induced biological soil crusts and soil properties varied between slope aspect, slope gradient and plant canopy in the Horqin Desert of China. *CATENA* 190:104559. <https://doi.org/10.1016/j.catena.2020.104559>
- Zhu SG, Duan HX, Tao HY, Zhu L, Zhou R, Yang YM, Zhang XL, Wang WY, Zhu H, Zhang W, Wang RQ, Tao XP, Xiong YC (2023) Arbuscular mycorrhiza changes plant facilitation patterns and increases resource use efficiency in intercropped annual plants. *Appl Soil Ecol* 191:105030. <https://doi.org/10.1016/j.apsoil.2023.105030>