

Article

Effects of Biochar and Straw Amendment on Soil Fertility and Microbial Communities in Paddy Soils

Hao Xia ¹, Jia Shen ¹, Muhammad Riaz ², Cuncang Jiang ³, Chaolong Zu ¹, Chaoqiang Jiang ^{1,*} and Bo Liu ^{4,*}¹ Industrial Crop Institute, Anhui Academy of Agricultural Sciences (AAAS), Hefei 230001, China² College of Resources and Environment, Zhongkai University of Agriculture and Engineering, Guangzhou 510225, China³ Microelement Research Center, College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, China⁴ Key Laboratory of Fertilization from Agricultural Wastes, Ministry of Agriculture and Rural Affairs, Institute of Plant Protection and Soil Fertilizer, Hubei Academy of Agricultural Sciences, Wuhan 430064, China

* Correspondence: chaoqiang@163.com (C.J.); liubohz@126.com (B.L.)

† These authors contributed equally to this work.

Abstract: Straw and biochar, two commonly used soil amendments, have been shown to enhance soil fertility and the composition of microbial communities. To compare the effects of straw and biochar on soil fertility, particularly focusing on soil dissolved organic matter (DOM) components, and the physiochemical properties of soil and microbial communities, a combination of high-throughput sequencing and three-dimensional fluorescence mapping technology was employed. In our study, we set up four treatments, i.e., without biochar and straw (B0S0); biochar only (B1S0); straw returning only (B0S1); and biochar and straw (B1S1). Our results demonstrate that soil organic matter (SOM), available nitrogen (AN), and available potassium (AK) were increased by 34.71%, 22.96%, and 61.68%, respectively, under the B1S1 treatment compared to the B0S0 treatment. In addition, microbial carbon (MBC), dissolved organic carbon (DOC), and particulate organic carbon (POC) were significantly increased with the B1S1 treatment, by 55.13%, 15.59%, and 125.46%, respectively. The results also show an enhancement in microbial diversity, the composition of microbial communities, and the degree of soil humification with the application of biochar and straw. Moreover, by comparing the differences in soil fertility, DOM components, and other indicators under different treatments, the combined treatments of biochar and straw had a more significant positive impact on paddy soil fertility compared to biochar. In conclusion, our study revealed the combination of straw incorporation and biochar application has significant impacts and is considered an effective approach to improving soil fertility.

Keywords: biochar; straw; soil microorganism; soil DOM; carbon components

Citation: Xia, H.; Shen, J.; Riaz, M.; Jiang, C.; Zu, C.; Jiang, C.; Liu, B. Effects of Biochar and Straw Amendment on Soil Fertility and Microbial Communities in Paddy Soils. *Plants* **2024**, *13*, 1478. <https://doi.org/10.3390/plants13111478>

Academic Editors: Haijun Sun and Nigel Gale

Received: 24 April 2024

Revised: 20 May 2024

Accepted: 26 May 2024

Published: 27 May 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Soils are a limited resource that sustain terrestrial life and can provide essential ecosystem functions for humans [1]. The maintenance and stability of soil fertility are crucial for ensuring food security in China [2]. However, intensive farming reduces organic matter, soil structure, and fertility [3]. Unreasonable fertilization harms soil quality, worsens pollution, and endangers human health [4]. For example, it leads to soil nutrient imbalances, structure destruction, and issues like acidification and salinization [5]. Additionally, the application of nitrogen, phosphorus, and potassium fertilizers can significantly reduce the richness of soil bacterial communities [6]. Thus, addressing how to improve the soil structure, farmland fertility, crop yield, and sustainable agricultural development is an urgent issue.

With the increase in agricultural production, the yield of crop straw has been consistently increasing and maintaining a high level. Returning crop straw to the field directly

fertilizes the soil, improving its structure, fertility, and quality [7,8]. Straw contains rich nutrients (C, N, P, and K), which increase the content of soil organic carbon (SOC) and soil fertility [9]. Unreasonable straw returning to the field can also reduce crop emergence rates and exacerbate the occurrence of soil-borne diseases [10]. Additionally, biochar is a carbon-rich solid produced from agricultural and forestry waste through high-temperature and oxygen-limited conditions [11,12]. Biochar contains a considerable amount of organic carbon (>60%), and the carbon in biochar is mostly aromatic carbon [13,14]. Biochar can significantly reduce soil bulk density and increase the total soil porosity and moisture content [15,16]. Biochar, straw, and other organic materials have been shown to increase the soil organic carbon (SOC) content, improve soil structure, and enhance microbial community diversity [8]. However, the positive impact of biochar is particularly pronounced on acidic soils [12]. Biochar is primarily composed of inert carbon, whereas straw consists mostly of activated carbon that is more readily utilized by microorganisms [17]. Additionally, straw and biochar have different C/N ratios, leading to varying rates of decomposition. Straw decomposes organic matter like cellulose, polysaccharides, and proteins at a faster pace compared to biochar [18].

The soil carbon pool is crucial for soil quality and productivity, contributing significantly to its physical, chemical, and biological characteristics [19,20]. Unstable organic carbon is easily oxidized and decomposed, serving as an indicator for assessing soil quality and productivity [21]. Returning straw to the field can improve soil carbon storage and soil fertility in a short period of time [22]. To date, several studies have investigated how returning straw to the field can greatly enhance soil organic matter, humic acid, humin content, and humification [23,24]. A meta-analysis has shown that straw returning significantly increases soil organic carbon concentration and soil active carbon composition, promoting the formation of soil macroscopic aggregates [25]. Biochar application enhances soil organic carbon and microbial biomass carbon, thereby influencing soil carbon composition through improved microbial community structure [26,27]. Extracellular enzymes in the soil play an important role in regulating the decomposition of soil organic matter and nutrient cycling processes [28]. Various studies have assessed that biochar and straw can alter the activity of soil extracellular enzymes by affecting soil physicochemical properties [8,29].

In this study, we used straw and biochar as research materials to conduct field experiments on paddy soils in central China. Through field experiments, we investigated the impact of applying straw and biochar on soil nutrients, carbon components, enzyme activity, and the microbiome to reveal their potential for improving soil quality in paddy soils. We explored the connection between soil carbon composition, enzyme activity, and microbial community under various treatments using enzymatic techniques, soil DOM 3D fluorescence, and high-throughput sequencing. To be specific, the main hypotheses we wanted to validate in this study were the following: (1) explore the effects of straw and biochar on organic matter, carbon components, and DOM components in rice soil; (2) explore the intrinsic relationship between soil chemical factors and soil microbial communities; and (3) choose the most effective treatment to enhance the rice soil quality.

2. Materials and Methods

2.1. The Experimental Design

This field experiment was conducted at the Xiangyang experimental farm, Hubei province, China (112°07'19" E, 32°00'36" N). The study site is within the subtropical monsoon climate zone (15~16 °C), with precipitation and annual sunshine hours of 820~1100 mm and 1800~2100 h, respectively. The soil was paddy soil (Acrisols) collected from the topsoil layer (0–20 cm). The physicochemical properties of the tested soil were measured as described below. The organic matter was 24.51 g·kg⁻¹; pH was 5.58; and the available N, P, and K were 92.77, 23.39, and 94.94 mg·kg⁻¹, respectively. The straw used was wheat straw, with an average nutrient content of N (0.54%), P (0.09%), K (1.25%), and C (44.51%). The biochar was produced from rice straw at 500 °C, and its physical properties were analyzed as follows: pH, EC, C, N, P, and K were 9.60, 1850 µs/cm, 46.79%, 0.71%,

0.52%, and 5.30%, respectively. The specific fertilization information for each experiment is detailed as follows: the amounts of N, P, and K fertilizers applied in the rice season were 150, 39, and 75 kg/hm², respectively; in the wheat season, the amounts of N, P, and K fertilizers applied were 120, 33, and 50 kg/hm², respectively. Rice–wheat rotation is the typical cropping system in this area. Rice is typically transplanted in early June of each year and harvested in September, while wheat is usually sown in early October and harvested in early May of the following year. The trial commenced on 21 May 2019, with soil sampling conducted on 25 September 2021. Biochar, straw, and fertilizer were applied to the fields annually in May for a period of 3 years (2019–2021). The other field management practices remained consistent with the local farming practices.

The experiment consisted of four types of field management practices based on the results of our previous studies [8,12,29]: without biochar and straw (B0S0); biochar only (B1S0, 3.5 t/hm²); straw returning only (B0S1, 6 t/hm²); and biochar and straw (B1S1, 3.5 t/hm² for biochar, 6 t/hm² for straw), with four replicates of each treatment (n = 16). The size for each plot was 20 m² (4 * 5 m).

2.2. Sample Collection and Determination

The soil samples were collected from the tillage layer (0–20 cm), and all stones and large plant fragments were removed. The soil samples were divided into three parts: one part was air-dried and used to measure the soil basic chemical properties [30]; another part was stored at –20 °C and used to measure soil enzymatic activities; and another part was stored at –80 °C and used to measure soil microorganisms.

Soil pH and SOM were measured with a pH meter (water/soil = 2.5/1) and chromic acid redox titration, respectively. Soil AK, AP, and AN were measured using the flame photometer method, molybdenum–antimony anti-spectrophotometric method, and alkali-hydrolytic diffusion method, respectively. MBC and MBN were measured using the chloroform fumigation–extraction method. DOC and DON were measured using a C/N analyzer. EOC and POC were measured using 333 mol L^{–1} of KMnO₄ and (NaPO₃)₆, respectively. Fluorometry was used to measure the activities of soil extracellular enzymes (NAG, ACP, LAP, POX, and CAT) with a multifunctional microplate reader (Scientific Fluoroskan Ascent FL, Thermo, Waltham, MA, USA) [31].

The soil total DNA was extracted using the E.Z.N.A.[®] DNA Kit (OmegaBio-tek, Norcross, GA, USA). DNA quality and purity were evaluated with a NanoDrop 2000 (NanoDrop Technologies, Wilmington, DE, USA) and visualized via electrophoresis on 1% agarose gels. The primers for bacteria were 515F (5'-GTGCCAGCMGCCGCGG-3') and 806R (5'-GGACTACHVGGGTWTCTAAT-3'). The primers for fungi were ITS1F (5'-CTTGGT CATTAGAGGAAGTAA-3') and ITS2R (5'-GCTGCGTTCTTCATCGATGC-3'). PCR products were recovered and purified using 2% agarose gel and Axy Prep DNA Gel Extraction Kits (Axygen Biosciences, Union City, CA, USA). Sequencing was performed on an Illumina MiSeq with the assistance of Shanghai Majorbio Bio-pharm Technology Co., Ltd.

Fluorescence Spectroscopy DOM: The soil sample was extracted with 1 mol·L^{–1} at 20 °C (200 r·min^{–1}, 24 h). The samples were centrifuged (5000 r·min^{–1}, 15 min) and filtered with a 0.45 µm glass fiber filter membrane [32]. The DOM solution was measured using a multi-mode spectroscopy analyzer (BioTek, Winooski, VT, USA). The excitation wavelength (λ_{Ex}) was set at 5 nm, the emission wavelength (λ_{Em}) at 5 nm, and the scanning speed at 2400 nm/min. The measurement covered an excitation wavelength range of 200–440 nm and an emission wavelength range of 250–600 nm [33]. The C1, C2, and C3 represented different fluorescence component characteristics and were subjected to source analysis (Table S1).

2.3. Data Analysis

The sequencing of microorganisms was performed using the Fastp (version 0.20.0) and Flash software (version 1.2.7). We used the UPARSE software (version 7.0) to cluster OTU sequences and excluded chimeras with 97% similarity. The 16S rRNA database (Silva

v138) and ITS database (Silva v138) were analyzed using a confidence threshold of 0.70. All sequencing data were combined for further analysis (alpha diversity analysis, beta diversity analysis, differential species analysis, and correlation and model prediction analysis) using the R software (version 4.2.3). Excel 2023 and SPSS Statistics 23.0 (IBM, Armonk, NY, USA) were used for data analysis. The data for the chemical properties of the soil are represented as the mean \pm S.E. of triplicate data ($n = 3$). Fluorescence spectroscopy data were analyzed using MATLAB 2007. All graphs were created using the Origin software (version 8.0), R software (version 4.2), and Adobe Illustrator 2021.

3. Results

3.1. Effect of Various Treatments on Soil Chemical Properties in Paddy Soils

Table 1 shows that there are differences in the soil chemical properties under the different treatments. The SOM, AN, and AK differed significantly among the treatments, but the soil pH and AP did not show significant variations. Compared to the B0S0 treatment, the SOM, AN, and AK were increased by 34.71%, 22.96%, and 61.68%, respectively, under the B1S1 treatment (Table 1). Additionally, the AN and AK were increased by 22.28% and 46.48%, respectively, by the B0S1 treatment compared to the B1S0 treatment. These results show that biochar and straw addition could effectively increase soil fertility. The results were analyzed with a two-way ANOVA, and we found that straw had a significant influence on SOM, AN, and AK, while biochar only had a remarkable influence on SOM ($p < 0.05$) (Table 1).

Table 1. Effects of biochar and straw on soil basic chemical properties in paddy soils.

Treatment	pH	SOM (g/kg)	AN (mg/kg)	AP (mg/kg)	AK (mg/kg)
B0S0	5.61 \pm 0.12 a	24.66 \pm 0.67 c	97.86 \pm 7.08 b	29.05 \pm 3.02 a	91.04 \pm 4.72 b
B1S0	5.76 \pm 0.17 a	29.47 \pm 2.13 b	92.81 \pm 7.12 b	30.11 \pm 3.85 a	99.36 \pm 6.48 b
B0S1	5.65 \pm 0.23 a	30.92 \pm 2.22 ab	113.49 \pm 5.83 a	30.68 \pm 12.07 a	145.54 \pm 20.62 a
B1S1	5.61 \pm 0.15 a	33.22 \pm 2.03 a	120.23 \pm 2.2 a	34.24 \pm 3.87 a	147.2 \pm 10.47 a
B	0.28	10.78 *	0.06	0.35	0.50
S	0.32	21.43 **	39.80 **	0.54	52.44 **
B*S	0.86	1.35	2.98	0.10	0.22

Note: Lowercase letters indicate significant differences in biochar and straw addition among the different treatments with a Duncan's test ($p < 0.05$). Values are the means \pm SD ($n = 3$). The statistical results of a two-way analysis of variance are expressed as F-value and p -value. * $p < 0.05$; ** $p < 0.01$.

A further analysis showed that the carbon (C) and nitrogen (N) components had different changes under the different treatments (Table 2). Compared to the B0S0 treatment, the MBC, DOC, and POC were significantly increased with the straw or biochar addition (Table 2). They increased from 174.67, 79.65, and 4.91 mg/kg under the B0S0 treatment to 270.97, 92.07, and 11.07 mg/kg under the B1S1 treatment (Table 2), respectively. The respective increases were 55.13%, 15.59%, and 125.46% in MBC, DOC, and POC. In addition, the DON also increased from 5.10 mg/kg under the B0S0 treatment to 6.46 mg/kg under the B1S1 treatment (Table 2). Furthermore, the MBC/MBN ratio increased with straw addition, while it decreased with biochar application (Table 2). Additionally, compared to the B1S0 treatment, the MBC, DON, and DOC were increased by 85.81%, 39.77%, and 34.06% under the B0S1 treatment (Table 2), respectively. Moreover, biochar had a significant influence on the soil MBC, DON, DOC, and POC, and straw also had noticeable effects on the soil MBC, DOC, and POC ($p < 0.05$). The interaction effect of biochar and straw on the soil MBC, DOC, and POC was significant ($p < 0.05$). The activities of ACP and NAG decreased with biochar or straw addition. Compared to the B0S0 treatment, the activities of ACP and NAG decreased by 14.42% and 11.69% under the B1S1 treatment (Table S2), respectively.

Table 2. Effects of biochar and straw additions on soil carbon and nitrogen components in paddy soils.

Treatment	MBN (mg·kg ⁻¹)	MBC (mg·kg ⁻¹)	DON (mg·kg ⁻¹)	DOC (mg·kg ⁻¹)	EOC (mg·kg ⁻¹)	POC (mg·kg ⁻¹)	MBC/MBN	DOC/DON
B0S0	4.59 ± 0.67 a	174.67 ± 24.57 c	5.10 ± 0.60 b	79.65 ± 3.85 c	21.91 ± 2.13 a	4.91 ± 0.27 c	38.11 ± 2.90 ab	15.71 ± 1.26 a
B1S0	5.81 ± 0.32 a	190.75 ± 5.43 c	5.13 ± 0.48 b	81.12 ± 1.16 c	21.08 ± 2.56 a	8.20 ± 1.43 b	32.95 ± 2.83 b	15.92 ± 1.64 a
B0S1	6.75 ± 1.80 a	354.43 ± 13.00 a	7.17 ± 0.50 a	108.75 ± 2.79 a	19.79 ± 1.94 a	7.71 ± 1.25 b	55.39 ± 16.07 a	15.23 ± 1.36 a
B1S1	6.28 ± 1.53 a	270.97 ± 36.37 b	6.46 ± 0.08 a	92.07 ± 6.86 b	22.98 ± 2.19 a	11.07 ± 1.33 a	43.98 ± 6.02 ab	14.27 ± 1.15 a
B	3.37	95.41 **	41.18 **	67.88 **	0.36	0.01 *	7.73 *	1.85
S	0.27	6.41 *	1.67	9.78 *	0.01	0.86 *	2.65	0.23
B*S	1.39	13.99 **	1.96	13.93 **	1.03	2.47 *	0.38	0.56

Note: Lowercase letters indicate significant differences in biochar and straw addition among the different treatments with a Duncan's test ($p < 0.05$). Values are means ± SD ($n = 3$). The statistical results of two-way analysis of variance are expressed as F-value and p -value. * $p < 0.05$; ** $p < 0.01$.

3.2. Effect of the Various Treatments on Three-Dimensional Fluorescence Spectral Characteristics of Soil DOM

A closer inspection of Table 3 reveals changes in the three-dimensional fluorescence spectral characteristics of soil DOM with biochar or straw addition. The FI decreased with biochar and straw addition (Table 3). Additionally, the BIX decreased by 11.29% under the B1S1 treatment compared to the B0S0 treatment, while the UV254 increased by 135.71% (Table 3). Moreover, Table 3 listed the proportions of C1, C2, and C3 as 46.32–49.28%, 44.34–44.43%, and 7.34–9.28%, respectively. Compared to the B0S0 treatment, C1 decreased from 49.28% to 46.41%, while C3 increased from 7.34% to 9.25% under the B1S1 treatment (Table 3).

Table 3. Effects of biochar and straw addition on soil DOM fluorescence components, fluorescence spectral parameters, and ultraviolet spectral parameters in paddy soils.

Treatment	Fluorescence Index (FI)	Biological Index (BIX)	UV254	The Distribution of Fluorescence Components		
				C1%	C2%	C3%
B0S0	2.10 ± 0.03 a	0.62 ± 0.04 a	0.14 ± 0.02 c	49.28 ± 1.48 a	43.38 ± 2.47 a	7.34 ± 0.99 a
B1S0	1.98 ± 0.03 b	0.55 ± 0.02 a	0.26 ± 0.01 b	49.72 ± 2.46 a	44.43 ± 6.22 a	9.18 ± 1.85 a
B0S1	2.06 ± 0.05 ab	0.57 ± 0.08 a	0.23 ± 0.02 b	46.32 ± 8.66 a	44.41 ± 7.47 a	9.28 ± 1.20 a
B1S1	2.02 ± 0.09 ab	0.55 ± 0.04 a	0.33 ± 0.01 a	46.41 ± 4.37 a	44.34 ± 2.58 a	9.25 ± 2.61 a
B	5.83 *	1.81	124.12	0.01	0.03	0.78
S	0.01	0.68	71.79 **	1.15	0.02	0.95
B*S	1.24	0.89	1.19	0	0.03	0.83

Note: Lowercase letters indicate significant differences in biochar and straw addition among the different treatments with a Duncan's test ($p < 0.05$). Values are means ± SD ($n = 3$). The statistical results of two-way analysis of variance are expressed as F-value and p -value. * $p < 0.05$; ** $p < 0.01$.

3.3. Effect of the Various Treatments on Soil Bacteria and Fungi in Paddy Soils

Soil samples were collected from various treatments to study the alterations in the soil microbial populations by biochar and straw application. The dominant bacteria were Actinobacteriota, Proteobacteria, Chloroflexi, Acidobacteriota, and Myxococcota (Figure 1A). Additionally, the dominant fungi were Ascomycota, Mortierellomycota, and Basidiomycota. Compared to the B0S0 treatment, the abundance of dominant genera significantly increased with biochar or straw addition (Figure 1B). We found a significant difference in the composition of microbial communities (bacteria and fungi) with biochar and straw addition (Figure 1C,D). Among all treatments, the number of dominant genera was the highest under the B0S1 treatment, while it was the lowest under the B0S0 treatment (Figure 2A and Figure S1A). The top five biomarkers were p_Firmicutes, c_Clostridia, o_Xanthomonadales, f_Rhodanobacteraceae, and f_Clostridiaceae with straw addition alone. However, g_norank_f_Chthoniobacteraceae and g_Nitrosospora were enriched under the B0S0 treatment (Figure 2B and Figure S1B). Unlike bacterial changes, the number of dominant genera in fungi was the highest with only biochar addition, while it was the highest under the B1S1 treatment. The top five biomarkers were g_Fusarium, f_Cordycipitaceae, g_unclassified_o_Tremellales, f_unclassified_o_Tremellales, and p_Glomeromycota under

the B1S0 treatment, while g_AspERGILLUS, f_AspERGILLACEAE, and g_Curvularia were enriched with the B1S1 treatment (Figure S1B).

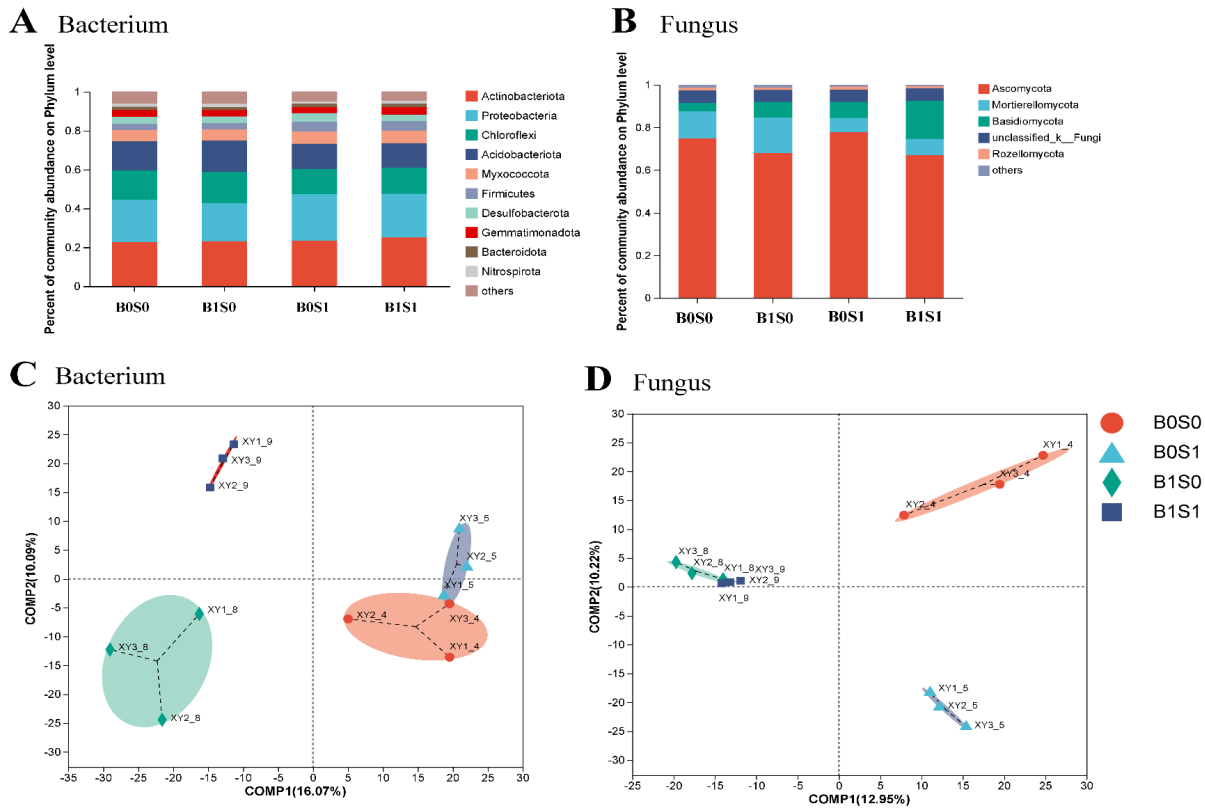


Figure 1. The community composition (A,B) and beta diversity (C,D) of soil bacterial (A,C) and fungal (B,D) communities under the different management measures.

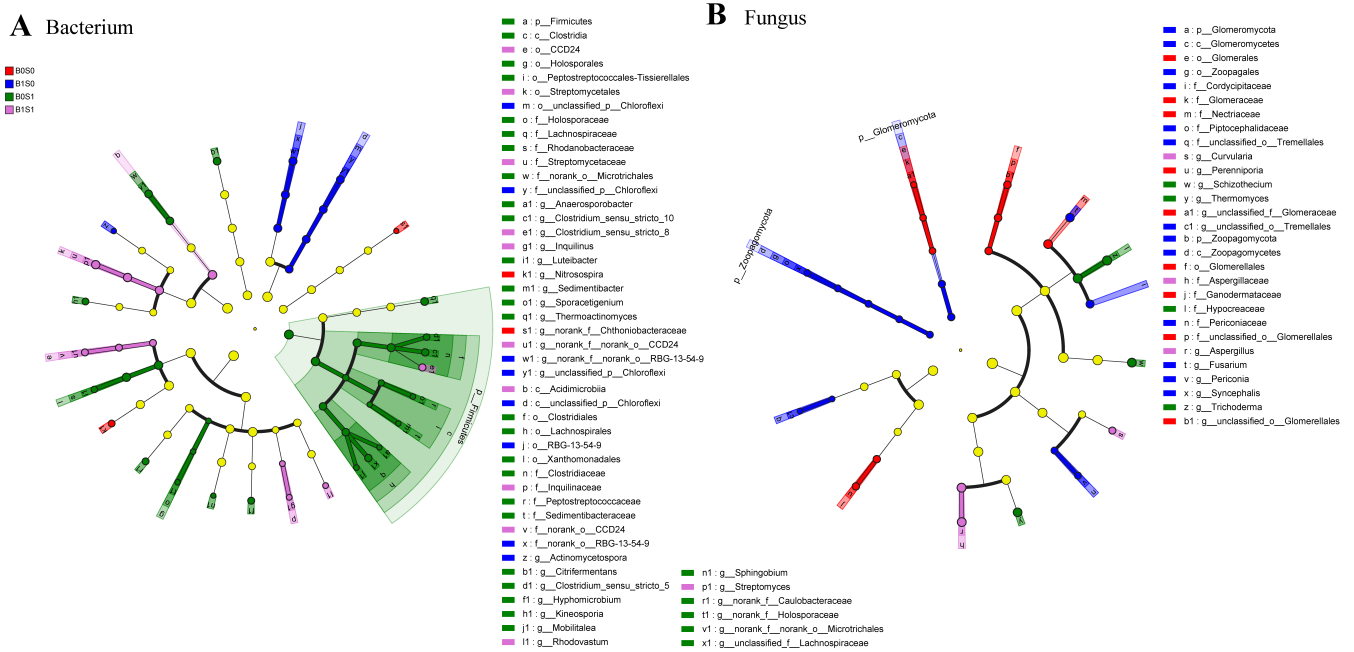


Figure 2. The LefSe analysis of soil bacterial (A) and fungal (B) communities under the different management measures. The taxa with significantly different abundances among the different treatments are represented by dots with different colors, and from the center outward, they represent the phylum, class, order, family, and genus levels.

3.4. The Relationship between Soil Environment and Microorganisms under Different Treatments

Our subsequent objective was to investigate the connections between the soil microbiome and environmental factors. It was found that there was a tight link between the soil microbiome (bacteria and fungi) and environmental factors ($p < 0.05$) (Figure 3). The Procrustes analysis findings (bacteria $R = 0.9970$, $p < 0.05$; fungi $R = 0.9539$, $p < 0.05$) show that the soil bacteria and fungi varied significantly with the soil chemical properties (Figure 3). Additionally, the analysis of the RDA indicated that the soil microbiome (bacteria and fungi) changed in response to the surrounding conditions (Figure 4). AK, AN, POC, and MBC were the main important environmental factors for soil bacterial community composition, and ACP, β G, and CAT were important soil enzymes for soil bacteria (Figure 4A,B). Moreover, POC, SOM, AN, AK, and MBN were major soil environmental indices for soil fungi, and ACP, CAT, POX, and β G were also prominent soil factors for the fungal community structure (Figure 4C,D). In addition, a correlation analysis was performed using a Pearson correlation analysis to explore the relationship between the soil microbiome (bacteria and fungi) and environmental factors (Figure 5). The results in Figure 5A also demonstrate that AK is the most important index influencing the soil bacterial community composition, and most soil bacterial communities always maintain significant ($p < 0.05$) negative associations with the soil AK. The relative abundance of Firmicutes had a strong positive association with the soil chemical properties (Figure 5A). Moreover, the soil AN, AK, DON, MBC, and DOC had significant negative correlations with soil fungi at the phylum level (Mortierellomycota, Glomeromycota, and Zoopagomycota) (Figure 5B).

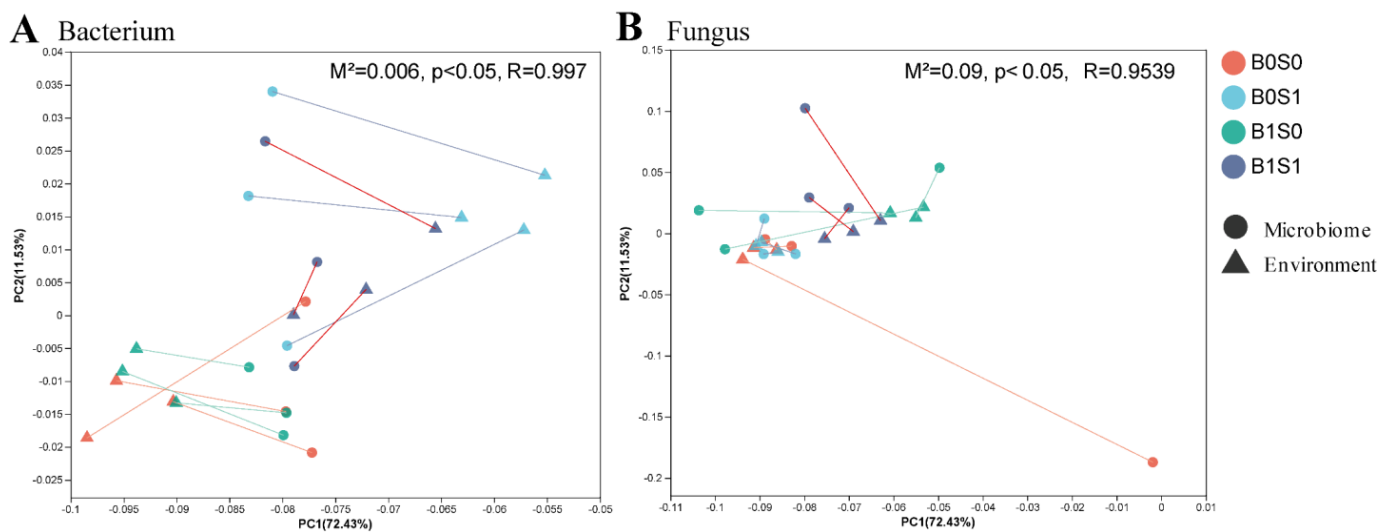


Figure 3. The Procrustes analysis between the soil microbiome (soil bacteria (A) and fungi (B)) and environment index under the different management measures.

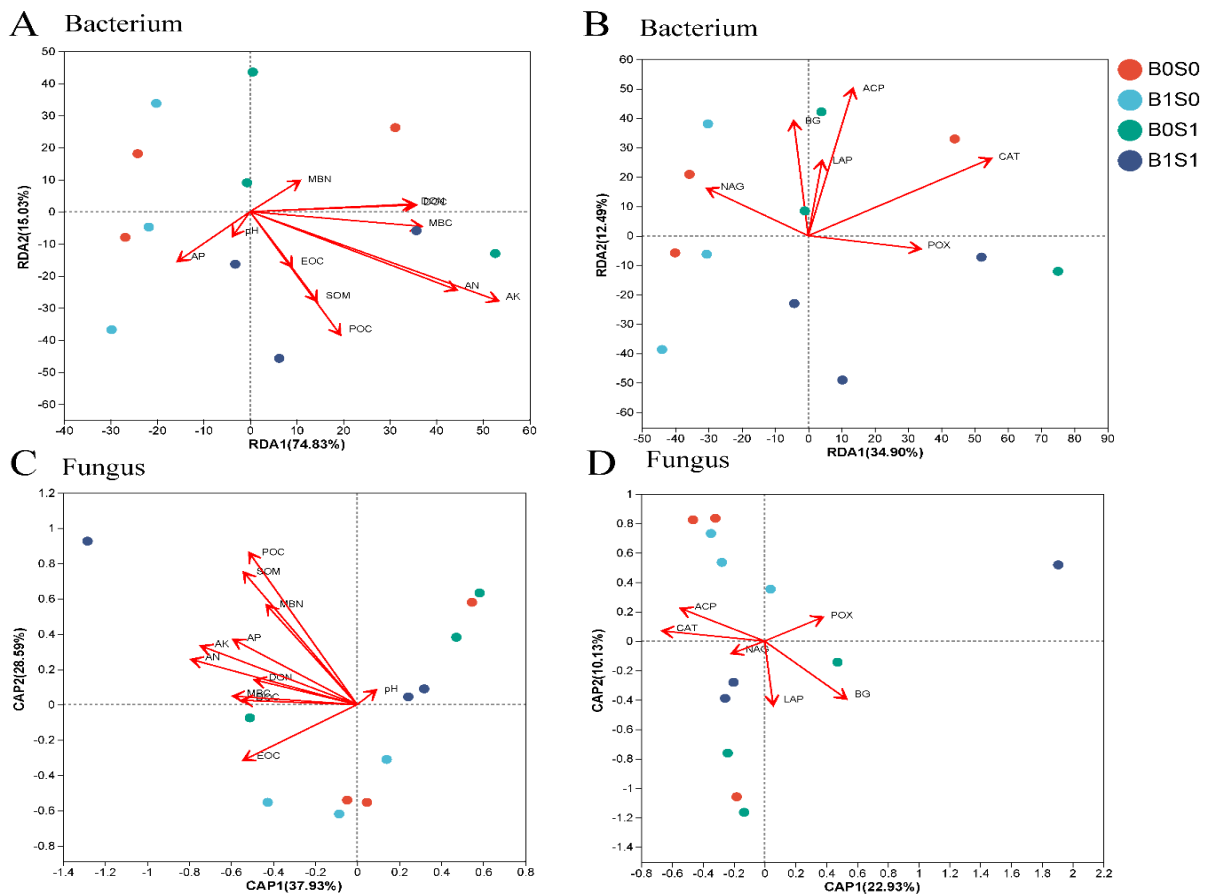


Figure 4. Redundancy analysis (RDA) based on the OTU level between the soil microbiome (soil bacteria (A,B) and fungi (C,D)) and environment index (soil fertility indicators (A,C) and soil enzyme activity (B,D)) under the different management measures.

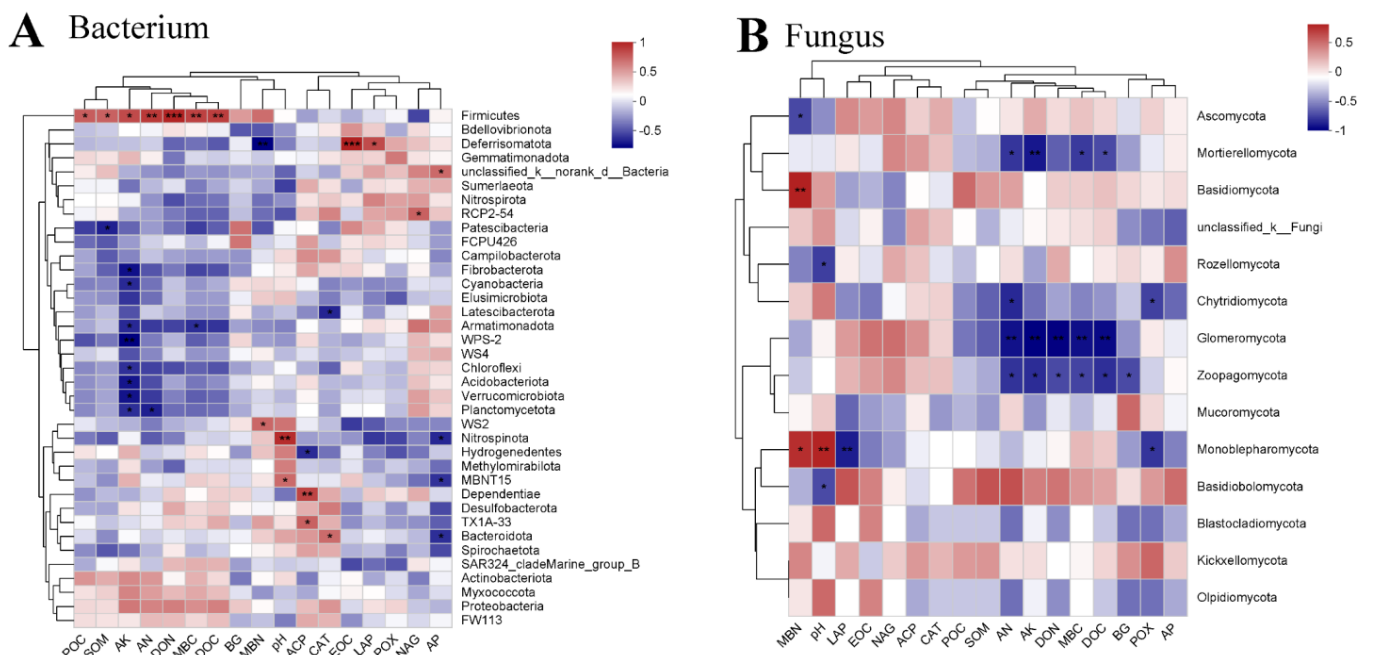


Figure 5. The correlation analysis between the soil microbiome (soil bacteria (A) and fungi (B)) and environment index under the different management measures. * Indicates correlation at different levels (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

4. Discussion

4.1. Effects of Biochar and Straw on the Soil Chemical Properties in Paddy Soils

Soil nutrient levels impact plant growth, metabolism, and other factors [34]. The current study found that biochar and straw significantly improved soil available nutrients, especially carbon components (Tables 1 and 2). There are several possible explanations for this result: (1): Biochar and straw are organic materials rich in carbon, which can increase soil organic carbon concentration and improve soil nutrient status [35,36]. (2): Returning biochar and straw to the field boosts soil microbial activity, leading to increased nutrient release and improved soil organic matter and fertility [8]. (3): Biochar and straw can improve crop root biomass, enhancing soil organic carbon and nutrient levels [37]. The study found that the AN did not significantly change with varying amounts of biochar application (Table 1). This could be attributed to the fact that an excessive biochar (high C/N ratio of biochar) application may enhance microbial nitrogen fixation, leading to a reduced nitrogen availability for plants in the soil and lower nitrogen mineralization utilization rate [38]. Xia et al. [39] found crop straw and biochar returning to the soil significantly increased the soil carbon component (DOC, MBC, POC, and ROC). Another important finding was that biochar had more distinct effects on the soil carbon components (Table 2). Several factors could explain this observation. (1): Biochar contains rich pore structures, which can reduce the rate of soil nutrient release and reduce nutrient loss [40]. (2): Biochar has a higher charge density, which can effectively absorb soil nutrients and improve nutrient utilization [41]. (3): Biochar is more decomposed, and soluble carbon is more readily available under pyrolysis treatment at high temperatures [42]. (4): The carbon in straw is mainly activated carbon, while the carbon in biochar is mostly inert [43]. One interesting finding was that some available nutrients were increased less notably compared to the biochar treatment with straw addition (Table 1). A possible explanation for this might be that the chemical properties and pore structure are changed in straw during the pyrolysis process [44]. The content of elements (N, H, and O) in biochar decreases with the increase in the carbonization temperature [45]. The strong adsorption of biochar in soil pores can reduce the availability of free nutrients [46]. Many reports found that soil enzymes were affected by different management measures [47].

Extracellular enzymes in the soil participate in soil biogeochemical cycling through processes such as the catalysis, degradation, transformation, and synthesis of soil organic matter [48]. The results of this study indicate that the soil extracellular enzymes (ACP and NAG) changed with biochar and straw addition (Table 3). The activities of the soil β G, CBH, NAG, and LAP significantly increased with straw and biochar addition [8]. A possible explanation for this might be that straw and biochar could provide soil available nutrients for soil microorganisms, which could incite soil enzymes [49]. Moreover, the soil enzyme activity had varying responses to biochar and straw addition in our study (Table 3). This discrepancy could be attributed to two factors: (1) Biochar pores can adsorb necessary substrates, boost soil enzyme activity, and enhance enzymatic reaction efficiency. (2) The potentially harmful substances (organic pollutants and heavy metals) in biochar decrease soil enzymes and microbial activity [50]. Compared to the application of biochar alone, straw application is more effective in enhancing soil fertility and increasing carbon components (Tables 1 and 2). We hypothesize that this may be due to one of the following reasons: As the carbonization temperature increases during the biochar preparation process, the content of active carbon components in the biochar decreases [51]. (1) Substances with a high carbon-to-nitrogen (C/N) ratio are less likely to decompose in soil. Thus, the carbon present in straw is more readily accessible to soil microorganisms compared to the carbon in biochar [52]. (2) Straw application can lead to an excitation effect on soil organic matter in the initial stages, while biochar tends to remain stable in the soil as it is resistant to decomposition [53].

4.2. Effects of Biochar and Straw on Soil 3D Fluorescence Spectral Characteristics of Soil DOM in Paddy Soils

Soil dissolved organic matter (DOM) is an active component of SOM, composed of humic acids, proteins, organic acids, and amino acids [54]. Dissolved organic matter (DOM) plays a critical role in the breakdown of soil nutrients, as well as in the growth and metabolism of microorganisms in the field [55]. The current study found that the value of FI was greater than 1.9 under all treatments, suggesting that microbial metabolism provides the majority of DOM [56]. Moreover, the value of the BIX lower than 1 under all treatments indicated the autochthonous or biological production of DOM components sourced from terrestrial DOM [57]. In addition, the FI decreased with the biochar and straw treatment (Table 3). These results suggest biochar and straw increase the soil microbial diversity, promoting the decomposition of plant residues [58]. Biochar exhibits a strong chemical stability and has the ability to absorb soil organic molecules as it undergoes a slow decomposition process, ultimately aiding in the formation of humus [59]. Furthermore, the value of UVA254 increased with biochar and straw addition, indicating the degree of soil SOM humification was enhanced with straw and biochar addition (Table 3). This result may be explained by the fact that returning straw to the field is beneficial for increasing the degree of DOM humification and the hydrophobic component content [32]. Moreover, straw and biochar promoted the percentage of C3, while decreasing the percentage of C1 (Table 3). Straw and biochar decomposition increases soil DOM aromaticity, humification degree, and molecular weight, leading to the accumulation of tyrosine, humic acid, and fulvic acid components [60]. Wu et al. [61] found microorganisms break down straw in the field to convert organic carbon into smaller DOM fractions. However, some studies have demonstrated that the porous structure of biochar readily adsorbs soluble organic carbon from the soil, leading to an encapsulation effect and suppression of soil microorganism activity, ultimately resulting in a reduction in soil organic carbon mineralization [62]. In addition, the return of straw to fields has a limited impact on increasing soil organic carbon storage in the short term, with carbon emissions during its rapid decomposition being the primary source of greenhouse gases, leading to negative environmental consequences [63].

4.3. Effect of Various Treatments on Soil Microorganisms in Paddy Soils

In our study, we also found that biochar and straw alter the composition of the soil microbial community (Figure 1). There are multiple potential explanations for this result [8,12,46]: (1) straw and biochar may offer readily available nutrient content and carbon sources for soil microorganisms; (2) the combination of biochar and straw could establish optimal soil moisture and temperature conditions, thereby enhancing the diversity of soil microbial communities; and (3) biochar and straw may serve as effective shelters for microorganisms. In addition, straw and biochar could increase the abundance of beneficial microorganisms in paddy soils (Figure 2 and Figure S2). For example, straw could promote the abundance of p_Firmicutes, and biochar could promote the abundance of p_Glomeromycota and p_Zoopagomycota (Figure S2). Several factors could explain this observation: (1) adding organic matter can supply carbon sources and energy, which greatly increases soil microbial activity (particularly the growth of R-type microorganisms) [64]; and (2) adding different organic substances to the soil to keep a variety of organic matter for soil microorganisms, maintaining diversity in agricultural ecosystems [65]. Zhou et al. [66] found that adding more than six types of organic matter can effectively prevent tomato wilt disease (particularly in carbohydrates and fatty acids). Based on the plant–soil feedback effect, long-term intensive agriculture leads to a decrease in the soil organic matter content, nutrient depletion, and the frequent occurrence of soil-borne diseases [67]. In our study, biochar and straw are common organic materials that can greatly enhance soil organic matter and available nutrients (Tables 1 and 2). These findings could be used to explain why exogenous organic matter can alter the structure of soil microbial communities. In addition, substances such as polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), and environmental persistent free radicals (EPFRs)

found on the surface of biochar have the potential to impede the growth and metabolic functions of specific microorganisms [68]. Furthermore, through a correlation analysis, Procrustes analysis, and redundancy analysis, there was a close relationship between soil microorganisms and soil physicochemical properties (Figures 3–5). For example, the relative abundance of p_Firmicutes was significantly correlated with the soil nutrients (POC, SOM, AK, AN, DON, and MBC). Many studies found that p_Firmicutes were crucial for facilitating plant nitrogen fixation, organic matter degradation, environmental remediation, soil fertility, and crop growth within the ecological environment [69,70].

Microorganisms can decompose organic matter, promote crop growth, and maintain the nutritional balance and health of the soil [71,72]. Soil pH changes can impact nitrogen-fixing bacteria abundance and community structure, reduce nitrification-related microorganisms (p_Nitrospinota), and inhibit nitrifying bacteria activity [73,74]. Gao et al. [75] found that soil bacterial and fungal communities increased with more biochar, and the timing of biochar application affected soil microbial diversity. In addition, a negative correlation was found between the relative abundance of soil fungi (p_Glomeromycota and p_Zoopagomycota) and soil nutrient level (Figure 5). The p_Glomeromycota can form arbuscular mycorrhizas with terrestrial plants, which can assist plants in absorbing inorganic salts and nutrients from the soil, especially in poor soils [76,77]. Thus, applying straw or biochar to the soil can activate soil microorganisms, maintain soil microbial diversity, and improve soil health.

5. Conclusions

This study investigates the impact of straw and biochar on soil fertility, organic matter, dissolved organic matter (DOM) components, and microbial communities in field experiments. The findings indicate that biochar and straw effectively enhanced soil fertility, particularly soil organic matter and available potassium levels. In addition, biochar and straw increased soil particulate organic carbon (POC), microbial biomass carbon (MBC), and total organic carbon contents to different extents. When compared, straw has a more pronounced effect on increasing the soil carbon component than biochar. Furthermore, biochar and straw increased the soil microbial diversity, which promoted the decomposition of plant residues. Additionally, the degree of soil SOM humification was enhanced with straw and biochar addition. Thus, biochar and straw enhanced the structure of microbial communities and suppressed the proliferation of harmful bacteria through the restoration of soil organic matter and essential nutrients. In general, the utilization of biochar, straw incorporation into the soil, and the combination of straw incorporation and biochar application have been shown to enhance soil fertility, soil carbon sequestration capacity, and the soil microenvironment. Particularly, the combination of straw incorporation and biochar application has demonstrated the most significant impact and is considered an effective approach to improving soil fertility.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/plants13111478/s1>. Figure S1: The three fluorescence fractions and loading maps of DOM of paddy soil. (A–C): represented the different fluorescence fractions; (D): Different Fluorescence characteristics and source analysis; Figure S2: The LEfSe analysis of soil bacterial (A) and fungus (B) under different management measures. The taxa with significantly different abundances among different treatments are represented by dots with different colors, and from the center outward, they represent the phylum, class, order, family, and genus levels; Table S1: Description and significance of characteristic parameters of ultraviolet-visible spectroscopy of dissolved organic matter; Table S2: Effects of biochar and straw on soil enzyme activity in paddy soil.

Author Contributions: C.J. (Chaoqiang Jiang) and B.L.: assistance in the design and supervision of this work; H.X.: writing—original draft, maintenance of the experiment process, and finding soil physicochemical parameters; C.Z. and J.S.: validation, writing—review and editing; M.R. and C.J. (Cuncang Jiang): reviewed the article. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by The National Key Research and Development Program of China (2021YFD1901205), Hubei Academy of Agricultural Sciences Major Achievements Cultivation Project (2017CGPY01), Youth Foundation of Hubei Academy of Agricultural Sciences (2022NKYJJ07), Youth Foundation of Institute of Plant Protection and Soil Fertilizer, Hubei Academy of Agricultural Sciences (2021ZTSQJ14) and Anhui Academy of Agricultural Sciences Achievement Transformation Project (2024YL037).

Data Availability Statement: Data are contained within the article and Supplementary Materials.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Berendse, F.; van Ruijven, J.; Jongejans, E.; Keesstra, S. Loss of Plant Species Diversity Reduces Soil Erosion Resistance. *Ecosystems* **2015**, *18*, 881–888. [[CrossRef](#)]
- Shen, J.; Zhang, L.; Guo, J.; Ray, J.L.; He, J. Impact of long-term fertilization practices on the abundance and composition of soil bacterial communities in Northeast China. *Appl. Soil Ecol.* **2010**, *46*, 119–124. [[CrossRef](#)]
- Glaser, B.; Lehmann, J.; Zech, W. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal—A review. *Biol. Fertil. Soils* **2002**, *35*, 219–230. [[CrossRef](#)]
- Li, Y.X.; Riaz, M.; Xia, H.; Wang, J.Y.; Wang, X.L.; Jiang, C.C. Effect of biochar and nitrogen fertilizers on maize seedling growth and enzyme activity relating to nitrification. *Soil Use Manag.* **2023**, *39*, 1467–1476. [[CrossRef](#)]
- Zhou, K.; Cheng, T.; Zhu, Y.; Cao, W.; Ustin, S.L.; Zheng, H.; Yao, X.; Tian, Y. Assessing the Impact of Spatial Resolution on the Estimation of Leaf Nitrogen Concentration Over the Full Season of Paddy Rice Using Near-Surface Imaging Spectroscopy Data. *Front. Plant Sci.* **2018**, *9*, 964. [[CrossRef](#)]
- Cui, X.; Zhang, Y.; Gao, J.; Peng, F.; Gao, P. Long-term combined application of manure and chemical fertilizer sustained higher nutrient status and rhizospheric bacterial diversity in reddish paddy soil of Central South China. *Sci. Rep.* **2018**, *8*, 16554. [[CrossRef](#)] [[PubMed](#)]
- Yu, Q.; Hu, X.; Ma, J.; Ye, J.; Sun, W.; Wang, Q.; Lin, H. Effects of long-term organic material applications on soil carbon and nitrogen fractions in paddy fields. *Soil Tillage Res.* **2020**, *196*, 104483. [[CrossRef](#)]
- Liu, B.; Xia, H.; Jiang, C.; Riaz, M.; Yang, L.; Chen, Y. 14 year applications of chemical fertilizers and crop straw effects on soil labile organic carbon fractions, enzyme activities and microbial community in rice-wheat rotation of middle China. *Sci. Total Environ.* **2022**, *841*, 156608. [[CrossRef](#)] [[PubMed](#)]
- Liu, P.; He, J.; Li, H.; Wang, Q.; Lu, C.; Zheng, K.; Liu, W.; Zhao, H.; Lou, S. Effect of straw retention on crop yield, soil properties, water use efficiency and greenhouse gas emission in China: A meta-analysis. *Int. J. Plant Prod.* **2019**, *13*, 347–367. [[CrossRef](#)]
- Zhang, W.M.; Chen, W.F.; Meng, J.; Jin, L.; Guo, W.; Zhao, H.L. Study of Straw-Biochar on Utilization Potential, Industry Model and Developing Strategy in Northeast China. *Sci. Agric. Sin.* **2019**, *52*, 2406–2424. (In Chinese)
- Lehmann, J.; Rillig, M.C.; Thies, J.; Masiello, C.A.; Hockaday, W.C.; Crowley, D. Biochar effects on soil biota—A review. *Soil Biol. Biochem.* **2011**, *43*, 1812–1836. [[CrossRef](#)]
- Xia, H.; Riaz, M.; Tang, X.; Yan, L.; El-Desouki, Z.; Li, Y.X.; Wang, X.L.; Jiang, C.C. Insight into mechanisms of biochar-fertilizer induced of microbial community and microbiology of nitrogen cycle in acidic soil. *J. Environ. Manag.* **2023**, *336*, 117602. [[CrossRef](#)]
- Lehmann, J. A handful of carbon. *Nature* **2007**, *447*, 143–144. [[CrossRef](#)] [[PubMed](#)]
- Baiamonte, G.; Crescimanno, G.; Parrino, F.; de Pasquale, C. Effect of biochar on the physical and structural properties of a sandy soil. *Catena* **2019**, *175*, 294–303. [[CrossRef](#)]
- Karhu, K.; Mattila, T.; Bergström, I.; Regina, K. Biochar addition to agricultural soil increased CH₄ uptake and water holding capacity—Results from a short-term pilot field study. *Agric. Ecosyst. Environ.* **2011**, *140*, 309–313. [[CrossRef](#)]
- Fu, Q.; Zhao, H.; Li, H.; Li, T.; Hou, R.; Liu, D.; Ji, Y.; Gao, Y.; Yu, P. Effects of biochar application during different periods on soil structures and water retention in seasonally frozen soil areas. *Sci. Total Environ.* **2019**, *694*, 133732. [[CrossRef](#)] [[PubMed](#)]
- Gu, M.Y.; Tang, G.M.; Ge, C.H.; Ma, H.G.; Zhang, Z.D.; Xu, W.L. Effects of straw incorporation modes on microbial activity and functional diversity in sandy soil. *Chin. J. Eco-Agric.* **2016**, *24*, 489–498. (In Chinese)
- Shi, Z.; Deng, C.; Luo, S.S.; Wang, S.J.; Gao, Q. Effects of Straw and Biochar on the Activities of Key Enzymes in Carbon, Nitrogen and Phosphorus Cycle of Aggregates in Northeast Black Soil. *Chin. J. Soil Sci.* **2023**, *54*, 1128–1136. (In Chinese)
- Lal, R. Soil carbon sequestration impacts on global climate change and food security. *Science* **2004**, *304*, 1623–1627. [[CrossRef](#)]
- Liu, E.; Tecler, S.G.; Yan, C.; Yu, J.; Gu, R.; Liu, S.; He, W.; Liu, Q. Long-term effects of no-tillage management practice on soil organic carbon and its fractions in the northern China. *Geoderma* **2014**, *213*, 379–384. [[CrossRef](#)]
- Xu, J.H.; Sun, Y.; Gao, L.; Cui, X.Y. A review of the factors influencing soil organic carbon stability. *Chin. J. Eco-Agric.* **2018**, *26*, 222–230. (In Chinese)
- Jin, Z.; Shah, T.; Zhang, L.; Liu, H.; Peng, S.; Nie, L. Effect of straw returning on soil organic carbon in rice-wheat rotation system: A review. *Food Energy Secur.* **2020**, *9*, e200. [[CrossRef](#)]

23. Malhi, S.S.; Lemke, R.; Wang, Z.H.; Chhabra, B.S. Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality, and greenhouse gas emissions. *Soil Tillage Res.* **2006**, *90*, 171–183. [[CrossRef](#)]
24. Hou, J.X.; Zhang, S.M.; Yuan, J.C. Effects of maize straw-derived organic materials on improving soil nutrient availability and enzyme activities in a mollisol. *J. Plant Nutr. Fertil.* **2021**, *27*, 610–618. (In Chinese)
25. Liu, C.; Lu, M.; Cui, J.; Li, B.; Fang, C. Effects of straw carbon input on carbon dynamics in agricultural soils: A meta-analysis. *Glob. Chang. Biol.* **2014**, *20*, 1366–1381. [[CrossRef](#)]
26. Busch, D.; Kammann, C.; Grünhage, L. Simple biotoxicity tests for evaluation of carbonaceous soil additives: Establishment and reproducibility of four test procedures. *J. Environ. Qual.* **2012**, *41*, 1023–1032. [[CrossRef](#)]
27. Ghani, W.A.W.A.K.; Mohd, A.; da Silva, G. Biochar production from waste rubber-wood-sawdust and its potential use in C sequestration: Chemical and physical characterization. *Ind. Crops Prod.* **2013**, *44*, 18–24. [[CrossRef](#)]
28. Zi, H.B.; Hu, L.; Wang, C.T. Responses of soil bacterial community and enzyme activity to experimental warming of an alpine meadow: Effects of warming on soil microorganisms. *Eur. J. Soil Sci.* **2018**, *69*, 429–438. [[CrossRef](#)]
29. Xia, H.; Riaz, M.; Saba, B.; Yan, L.; Li, X.Y.; Wang, J.Y.; Jiang, C.C. Assessing the impact of biochar on microbes in acidic soils: Alleviating the toxicity of aluminum and acidity. *J. Environ. Manag.* **2023**, *345*, 118796. [[CrossRef](#)]
30. Bao, S.D. *Soil And Agricultural Chemistry Analysis*; China Agriculture Press: Beijing, China, 2000.
31. Deforest, J.L. The influence of time, storage temperature, and substrate age on potential soil enzyme activity in acidic forest soils using MUB-linked substrates and l-DOPA. *Soil Biol. Biochem.* **2009**, *41*, 1180–1186. [[CrossRef](#)]
32. Liu, C.; Bai, X.D.; Zhao, H.C.; Huang, Z.H.; Liu, S.T.; Lu, H.B.; Liu, Z.G.; Liu, X.L. The effect mechanism of spring maize straw returning method on soil DOM spectral characteristics in cold and arid regions of China. *Ecol. Environ. Sci.* **2023**, *32*, 1419–1432. (In Chinese)
33. Chen, H.L.; Zhou, J.M.; Xiao, B.H. Characterization of dissolved organic matter derived from rice straw at different stages of decay. *J. Soils Sediments* **2010**, *10*, 915–922. [[CrossRef](#)]
34. Li, Q.; Gu, F.; Zhou, Y.; Xu, T.; Wang, L.; Zuo, Q.; Xiao, L.; Liu, J.; Tian, Y. Changes in the Impacts of Topographic Factors, Soil Texture, and Cropping Systems on Topsoil Chemical Properties in the Mountainous Areas of the Subtropical Monsoon Region from 2007 to 2017: A Case Study in Hefeng, China. *Int. J. Environ. Res. Public Health* **2021**, *18*, 832. [[CrossRef](#)] [[PubMed](#)]
35. Huang, R.; Tian, D.; Liu, J.; Lv, S.; He, X.; Gao, M. Responses of soil carbon pool and soil aggregates associated organic carbon to stover and stover-derived biochar addition in a dryland cropping mesocosm system. *Agric. Ecosyst. Environ.* **2018**, *265*, 576–586. [[CrossRef](#)]
36. Zhao, H.L.; Abdul, G.S.; Li, S.; Chen, Y.; Shi, J.; Zhang, X. Effect of straw return mode on soil aggregation and aggregate carbon content in an annual maize-wheat double cropping system. *Soil Tillage Res.* **2018**, *175*, 178–186. [[CrossRef](#)]
37. Li, C.; Li, X.P. Effect of biochar preparation and its application amount on soil carbon pool and plant growth. *J. South. Agric.* **2015**, *46*, 1786–1791. (In Chinese)
38. Robertson, S.J.; Rutherford, P.M.; López-Gutiérrez Juan, C.; Massicotte, H.B. Biochar enhances seedling growth and alters root symbioses and properties of sub-boreal forest soils. *Can. J. Soil Sci.* **2012**, *92*, 329–340. [[CrossRef](#)]
39. Xia, H.; Riaz, M.; Zhang, M.Y.; Liu, B.; Li, Y.; El-Desouki, Z. Biochar-N fertilizer interaction increases N utilization efficiency by modifying soil C/N component under N fertilizer deep placement modes. *Chemosphere* **2022**, *286*, 131594. [[CrossRef](#)]
40. Chang, Y.; Liu, W.; Mao, Y.; Yang, T.; Chen, Y. Biochar Addition Alters C: N: P Stoichiometry in Moss Crust-Soil Continuum in Gurbantünggüt Desert. *Plants* **2022**, *11*, 814. [[CrossRef](#)]
41. Niu, Z.Y.; Yan, S.; Guo, Q.Q. Effects of biochar on yield and quality of flue-cured tobacco and nutrients and carbon pool in two typical soils planted with tobacco. *Chin. J. Soil Sci.* **2017**, *48*, 155–161. (In Chinese)
42. Tomczyk, A.; Szewczuk-Karpisz, K. Effect of Biochar Modification by Vitamin C, Hydrogen Peroxide or Silver Nanoparticles on Its Physicochemistry and Tetracycline Removal. *Materials* **2022**, *15*, 5379. [[CrossRef](#)] [[PubMed](#)]
43. Shi, J.H.; Zhao, Y.; Wei, D. Insight into transformation of dissolved organic matter in the Heilongjiang River. *Environ. Sci. Pollut. Res.* **2019**, *26*, 3340–3349. [[CrossRef](#)] [[PubMed](#)]
44. Ye, X.F.; Zhou, H.J.; Yu, X.N.; Zhang, X.F.; Li, Z.P.; Fu, Z.Y.; Meng, Q. Physicochemical properties and yields of corn-stalk-biochar under different pyrolyzed temperatures. *J. Plant Nutr. Fertil.* **2017**, *23*, 1268–1275. (In Chinese)
45. Zhang, H.; Voroney, R.; Price, G. Effects of temperature and processing conditions on biochar chemical properties and their influence on soil C and N transformations. *Soil Biol. Biochem.* **2015**, *83*, 19–28. [[CrossRef](#)]
46. Wang, J.X.; Riaz, M.; Babar, S.; Xia, H.; Xia, X.Y.; Wang, J.Y.; Jiang, C.C. Iron-modified biochar reduces nitrogen loss and improves nitrogen retention in Luvisols by adsorption and microbial regulation. *Sci. Total Environ.* **2023**, *879*, 163196. [[CrossRef](#)] [[PubMed](#)]
47. Wang, C.; Lv, J.; Xie, J.; Yu, J.; Li, J.; Zhang, J.; Tang, C.; Niu, T.; Patience, B.E. Effect of slow-release fertilizer on soil fertility and growth and quality of wintering Chinese chives (*Allium tuberosum* Rottler ex Spreng.) in greenhouses. *Sci. Rep.* **2021**, *11*, 8070. [[CrossRef](#)] [[PubMed](#)]
48. Wu, X.Z.; Yan, X.; Wang, B.; Liu, R.T.; An, H. Effects of desertification on soil nutrients and extracellular enzyme activities in desert grassland. *Ecol. Environ. Sci.* **2018**, *27*, 1082–1088. (In Chinese)
49. Elzobair, K.A.; Stromberger, M.E.; Ippolito, J.A. Contrasting effects of biochar versus manure on soil microbial communities and enzyme activities in an Aridisol. *Chemosphere* **2016**, *142*, 145–152. [[CrossRef](#)] [[PubMed](#)]

50. Hussain, M.; Farooq, M.; Nawaz, A.; Al-Sadi, A.M.; Solaiman, Z.M.; Alghamdi, S.S.; Ammara, U.; Ok, Y.S.; Siddique, K.H.M. Biochar for crop production: Potential benefits and risks. *J. Soils Sediments* **2017**, *17*, 685–716. [[CrossRef](#)]
51. He, Y.H.; Zhou, X.H.; Jiang, L.L.; Li, M.; Du, Z.G.; Zhou, G.Y.; Shao, J.J.; Wang, X.H.; Xu, Z.H.; Bai, S.H.; et al. Effects of biochar application on soil greenhouse gas fluxes: A meta-analysis. *GCB Bioenergy* **2017**, *9*, 743–755. [[CrossRef](#)]
52. Zhang, A.F.; Cheng, G.; Hussain, Q.; Zhang, M.; Feng, H.; Dyck, M.; Sun, B.H.; Zhao, Y.; Chen, H.X.; Chen, J.; et al. Contrasting effects of straw and straw-derived biochar application on net global warming potential in the Loess Plateau of China. *Field Crops Res.* **2017**, *205*, 45–54. [[CrossRef](#)]
53. Wang, J.Y.; Xiong, Z.Q.; Kuzyakov, Y. Biochar stability in soil: Meta-analysis of decomposition and priming effects. *GCB Bioenergy* **2016**, *8*, 512–523. [[CrossRef](#)]
54. Bernd, M.; Karsten, K. Controls of bioavailability and biodegradability of dissolved organic matter in soils. *Geoderma* **2003**, *113*, 211–235.
55. Welikala, D.; Robinson, B.H.; Moltchanova, E. Soil cadmium mobilisation by dissolved organic matter from soil amendments. *Chemosphere* **2021**, *271*, 129536. [[CrossRef](#)] [[PubMed](#)]
56. Ma, J.; Pei, D.; Zhang, X.; Lai, Q.; He, F.; Fu, C.; Liu, J.; Li, W. The Distribution of DOM in the Wanggang River Flowing into the East China Sea. *Int. J. Environ. Res. Public Health* **2022**, *19*, 9219. [[CrossRef](#)] [[PubMed](#)]
57. Li, W.; Wang, K.; Han, G.; Wang, H.; Tan, N.; Yan, Z. Integrated diagnosis and time-series sensitivity evaluation of nutrient deficiencies in medicinal plant (*Ligusticum chuanxiong* Hort.) based on UAV multispectral sensors. *Front. Plant Sci.* **2023**, *13*, 1092610. [[CrossRef](#)] [[PubMed](#)]
58. Biederbeck, V.O.; Janzen, H.H.; Campbell, C.A. Labile soil organic matter as influenced by cropping practices in an arid environment. *Soil Biol. Biochem.* **1994**, *26*, 1647–1656. [[CrossRef](#)]
59. Li, H.Y.; Lin, T.; Wang, Z.J.; Zhao, H.C.; Zheng, J.P.; Lv, Y.D.; Qian, Y.D.; Fan, M.Y. Effects of biochar continuous returning on soil nutrients, enzyme activities and humus components in soda saline-alkali paddy field soil. *Agric. Res. Arid. Areas* **2022**, *40*, 135–142. (In Chinese)
60. Zhang, H.Y.; Yang, Q.X.; Yang, Q. Compositional characteristics and photochemical activity of dissolved organic matter derived from straw in aquatic environment. *China Environ. Sci.* **2020**, *40*, 2521–2528. (In Chinese)
61. Wu, Y.P.; Liu, T.; Peng, Q.A. Greenhouse gas emissions in red soil as influenced by different C/N residues under nitrogen applications. *J. Agro-Environ. Sci.* **2014**, *33*, 2053–2062. (In Chinese)
62. Mitchell, P.J.; André, J.S.; Soong, R.; Simpson, M.J. Shifts in microbial community and water-extractable organic matter composition with biochar amendment in a temperate forest soil. *Soil Biol. Biochem.* **2015**, *81*, 244–254. [[CrossRef](#)]
63. Zimmerman, A.R.; Gao, B.; Ahn, M.Y. Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biol. Biochem.* **2011**, *43*, 1169–1179. [[CrossRef](#)]
64. Blagodatskaya, E.; Kuzyakov, Y. Active microorganisms in soil: Critical review of estimation criteria and approaches. *Soil Biol. Biochem.* **2013**, *67*, 192–211. [[CrossRef](#)]
65. Cai, Z.C.; Huang, X.Q.; Zhao, J. Principles and Practice of Building Healthy Microbial Community to Control Soil-borne Crop Disease in Intensive Agriculture. *Acta Pedol. Sin.* **2023**, *60*, 1213–1220. (In Chinese)
66. Zhou, X.; Liu, L.L.; Zhao, J. High carbon resource diversity enhances the certainty of successful plant pathogen and disease control. *New Phytol.* **2023**, *237*, 1333–1346. [[CrossRef](#)]
67. Putten, W.H.V.D.; Bardgett, R.D.; Bever, J.D.; Bezemer, T.M.; Casper, B.B.; Fukami, T. Plant–soil feedbacks: The past, the present and future challenges. *J. Ecol.* **2013**, *101*, 265–276. [[CrossRef](#)]
68. Tan, C.L.; Liu, Y.; Huang, X.G.; Zhang, J.Y.; Luo, W.H. Effect of biochar on soil microbial metabolic activities. *Chin. J. Eco-Agric.* **2022**, *30*, 333–342. (In Chinese)
69. Zhao, Z.; Ma, Y.; Feng, T. Assembly processes of abundant and rare microbial communities in orchard soil under a cover crop at different periods. *Geoderma* **2022**, *406*, 115543. [[CrossRef](#)]
70. Lyu, B.C.; Sun, H.; Qian, J.Q.; Liang, H.; Zhu, J.P.; Zhang, Q.S.; Shan, C.; Zhang, Y.Y. Interaction between root exudates of medicinal plants and rhizosphere microorganisms and its application in ecological planting of Chinese medicinal materials. *China J. Chin. Mater. Med.* **2024**, *49*, 2128–2137. (In Chinese)
71. Xu, M.; Xian, Y.; Wu, J.; Gu, Y.; Yang, G.; Zhang, X. Effect of biogas slurry addition on soil properties, yields, and bacterial composition in the rice-rape rotation ecosystem over 3 years. *J. Soils Sediments* **2019**, *19*, 2534–2542. [[CrossRef](#)]
72. Górska, E.B.; Stępien, W.; Cunha, A. Microbial diversity as an indicator of a diversified cropping system for luvisols in a moderate climate. Case study—Long term experiments from Poland. *Ecol. Indic.* **2022**, *141*, 109–133. [[CrossRef](#)]
73. Che, J.; Zhao, X.Q.; Zhou, X.; Jia, Z.J.; Shen, R.F. High pH-enhanced soil nitrification was associated with ammonia-oxidizing bacteria rather than archaea in acidic soils. *Appl. Soil Ecol.* **2015**, *85*, 2129. [[CrossRef](#)]
74. Tang, H.; Yu, M.; Wang, Y.; Han, X.; Wei, D. Effects of long-term fertilization on nifH gene diversity in agricultural black soil. *Afr. J. Microbiol. Res.* **2012**, *6*, 2659–2666.
75. Gao, G.; Yan, L.; Tong, K.Q.; Yu, H.L.; Lu, M.; Wang, L.; Niu, Y.S. The potential and prospects of modified biochar for comprehensive management of salt-affected soils and plants: A critical review. *Sci. Total Environ.* **2024**, *912*, 169618. [[CrossRef](#)]

76. Smith, S.E.; Smith, F.A. Roles of arbuscular mycorrhizas in plant nutrition and growth: New paradigms from cellular to ecosystem scales. *Annu. Rev. Plant Biol.* **2011**, *62*, 227–250. [[CrossRef](#)]
77. Volpe, V.; Chitarra, W.; Cascone, P. The association with two different Arbuscular mycorrhizal fungi differently affects water stress tolerance in tomato. *Front. Plant Sci.* **2018**, *9*, 1480. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.