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Soil Habitats Are Affected by Fungal Waste Recycling on Farmland in Agro-Pastoral Ecotone in Northern China

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Abstract: As part of the ecological barrier and an essential element of food security, the agro-pastoral ecotone is vital in northern China. Since soil fertility in northern China is low due to frequent surface disturbances, it is necessary to improve the properties of the soil. This study aims to examine the impact of fungal residue return on soil properties based on six treatments (CK: 0 kg/40 m^2; R3: 90 kg/40 m^2; R5: 150 kg/40 m^2; R7: 210 kg/40 m^2; R9: 270 kg/40 m^2; R11: 330 kg/40 m^2;) of fungal residue return concentration experimental data from 0 to 30 cm soil depth. The results showed that the effect of fungal residue returning on soil habits was greater at 0–10 cm of the surface layer. The bulk density can be reduced to 25.83% of CK, and water content can be increased up to 26.26%. Adding fungal residue to the field led to a greater increase in soil parameters (SOM and AP), and this characteristic effect continued as the return concentration increased. The number of soil bacteria and actinomycetes remained stable, and the amount of fungi was at its lowest. Compared with CK, the number of bacteria, fungi, and actinomycetes increased by 1.94 times, 1.46 times, and 1.71 times, respectively. After the residue was returned to the field, AK had the strongest correlation with other factors ($p < 0.01$), and microorganism and enzyme activities were strongly correlated ($p < 0.01$). In conclusion, this study presents a new method of resource utilization of downstream wastes in the food industry while simultaneously providing natural, pollution-free improvements to the soil, which is very beneficial to increasing crop yield.

Keywords: fungus return; agro-pastoral ecotone; soil properties; soil fertility

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1. Introduction

Northern China's agro-pastoral ecotone is a fragile ecosystem prone to environmental degradation [1–3] and is a transitional type between arid and semi-arid climates [4]. Many agro-pastoral ecotones face survival and developmental challenges, such as overgrazing, over-cultivation, and overcutting, due to rapid population growth. These regions may experience severe desertification that affects the development of the regional economy and society as a whole [5–7]. The central and western parts of Inner Mongolia are the core areas of the agro-pastoral ecotone in northern China. Five cities, including Hohhot, Baotou, Ordos, Ulanqab, and Bayannur, cover an area of about 250,600 km^2, including Wuchuan County [8]. The region uses the characteristics of the farming–pastoral junction to form a commodity grain base whilst also protecting the ecological beauty of Hohhot, the capital of Inner Mongolia. This ecotone is pivotal for ecological security, social stability, and economic development as it is an economic link between an agricultural zone and a pastoral area. Wuchuan County of Hohhot City experiences the wind erosion and desertification of the northern foothill of Yinshan. The poor soil, arid climate, and other natural factors in the region, in addition to the low level of agricultural production, coupled with increasing population pressures, increased storage capacity, and improper management, create threats of poverty and desertification in this region. There is an urgent need for reasonable methods to improve productivity in order to meet both food security needs and achieve sustainable development. Nevertheless, excessive fertilization is common in this situation [9,10]; thus, it is necessary to reduce fertilizer application, promote adequate supplies of food and other agricultural products, and achieve sustainable rural development are necessary.

As an efficient and reasonable renewable resource, straw resources are used to satisfy China's economic growth demand (by saving scarce natural resources); however, they also serve as a basis for environmental protection and social sustainability in the country [11]. Straw-return technology is more mature than that of fungal residue-return. Fungal residue is the remaining medium waste that remains after the cultivation and harvest of edible fungi; this is an inorganic, nutrient-rich material with high porosity [12,13]. China's edible fungi industry is well developed, with edible fungi production reaching 40.614 million tons of edible fungi produced in 2020; assuming that the average amount of mushroom dregs is about five times that of the edible fungi, this amounts to about 200 million tons of mushroom dregs [14]. Many domestic slag treatments for natural stacking or burning waste resources result in environmental pollution. Many reports have demonstrated the advantages of mushroom dregs as a supplement for fertilizers. Meng et al. [15] determined whether composts containing fungal residues and pig manure can positively affect N, *p*, and K values. Studies have reported that the mushroom residue that remains after the cultivation of mushroom bran is rich in numerous bacterial proteins, lignin, and various nutrients, providing a good source of organic fertilizer and soil amendment [16,17]. The treatment of edible fungus cultivation waste as organic fertilizer can not only improve soil fertility but also reduce environmental pollution, forming a positive cycle for the agricultural ecosystem. At the same time, it also reduces the number of bacteria in the cultivation environment of edible fungi and promotes the healthy and sustainable development of the edible fungi industry [18].

Changes in soil fertility may affect nutrient cycling. Microorganisms are the most dynamic part of the soil ecosystem; soil microbial populations serve as an index of soil fertility, as they are essential to soil biochemical activity and nutrient transformation and utilization [19,20]. Their functions are carried out by soil enzymes, which control the direction and intensity of biochemical reactions. Fungal residue improves organic carbon and sucrase activity, enhances bacteria diversity, and changes the dominant flora [21]. And when it is residue returned to the farmland, it can significantly affect urease activity and increase the number of fungi, bacteria, and actinomycetes [22]. Other studies have demonstrated that the application of mushroom residue significantly increased soil urease activity and the number of actinomycetes and fungi [23]. Based on this, it is essential to consider the application of mushroom residue from the perspective of different soil properties.

Therefore, mixed application of animal manure and mushroom residue can enrich the utilization of waste fungal residue. The objectives of this study were to compare the effects of different treatments of residue management on soil contents and the correlation between the soil's physical and chemical properties and microbial quantity and enzyme activity that efficiently provide references for the efficient organic agriculture use of residues.

2. Materials and Methods

2.1. Study Area

We conducted a field experiment in Wu Chuan County (40°47′~41°23′ N, 110°31′~111°53′ E) in Hohhot, northern China. This area lies at the northern foot of Yinshan Mountain in a pastoral ecotone. The area falls within the temperate zone of continental climate. With an average temperature of 3.0 °C, it receives an average rain of 360 mm a year, mostly falling from July to August. The most common soil type is chestnut soil. The major crops are potato (*Solanum tuberosum*), naked oats (*Avena sativa*), and buckwheat (*Fagopyrum esculentum*) [24].

2.2. Experimental Design and Field Management

In this study, all experiments were carried out in the Inner Mongolia Agricultural University long-term dry farmland experimental base and were mainly focused on the observation of plant growth and development and water and fertilizer conservation in dry farmlands. The geographical features and climatic factors were consistent. The soil type used within the study site is chestnut soil, and the soil in this area has been threatened by wind erosion and salinization for a long time. As shown in Table 1, the soil fertility was maintained at a low level.

Table 1. Baseline soil values of experimental plot.

Soil Depth (cm)	SOM (g/kg)	AN (mg/g)	AP (mg/g)	AK (mg/g)	TN (g/kg)	TP (g/Kg)	TK (g/Kg)
0–10	14.98	58.12	4.51	110.13	0.89	0.42	36.77
10–20	14.72	56.03	3.62	96.25	0.91	0.26	37.83
20–30	14.91	48.17	2.73	96.45	0.76	0.34	30.66

Note: SOM: soil organic matter; AN: soil alkali-hydrolyzable nitrogen; AP: soil available phosphorus; AK: soil available potassium; TN: soil total nitrogen; TP: soil total phosphorus; TK: total potassium in soil.

The experimental materials were soil amendments formed via the co-fermentation of a large amount of discarded fungal residue (nitrogen: 1.5–2%, phosphorus: 0.5–0.8%, potassium: 1.5–2%, and organic matter comprised 30–40%) and organic fertilizer (cow manure, organic matter: 15–25%.) around the sample plot. Before it was returned to the field, the fermented fungal residue was packed into packaging bags for easy transportation (30 per package). The amount returned to the field was determined at 6 gradient levels based on the previous pre-experiment was determined (CK/R3/R5/R7/R9/R11; CK was used as the control. Each returning concentration was set with 5 replicates, and the specific returning amount is shown in Table 2. The experiment followed the block design, and the amount of returning farmland was randomly distributed. The area of the plot was 40 m^2 (4 m × 10 m). To prevent permeable lateral flow, 0.5 m wide ridges were built between adjacent plots with no marginal effect. The experiment was carried out during the spring tillage period (May) of 2019. The residue was laid on the surface and rotary tilled to 0–30 cm, and the naked oats with good local adaptability were planted for three consecutive years. The seeds were sown in drills, with row spacing of 15–20 cm [25]. After harvesting the plant parts were harvested in early September 2022, soil sampling was performed. The experimental sampling points have been reserved. According to the growth characteristics of crops, no irrigation treatment was carried out, but weeds were removed during the growth period. For protection against pests and diseases, chemical agents with less impact on crops were used. There were no other factors that interfered with the experiment (Figure 1).

Table 2. Return amounts for different treatments.

Treatment	Value (kg/40 m^2)
CK	0
R3	90
R5	150
R7	210
R9	270
R11	330

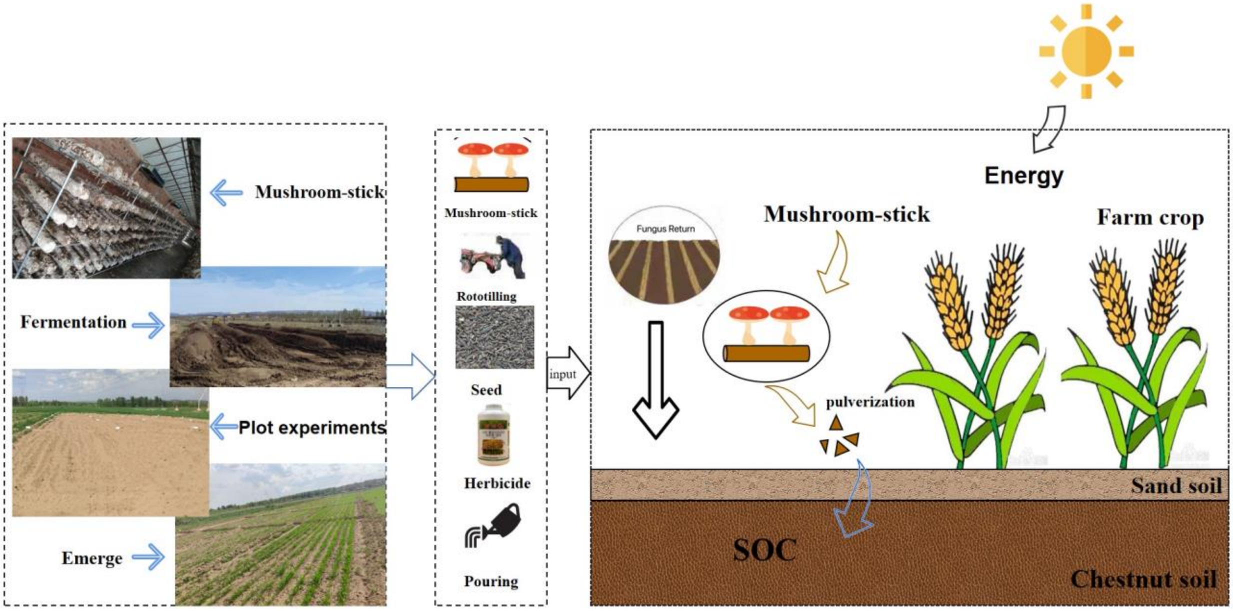


Figure 1. Experimental schematic diagram.

2.3. Collection and Determination of Soil Samples

The experimental sampling was carried out under the condition that no precipitation event occurred within one week of plant harvest. The 0–30 cm soil layer (divided into 0–10 cm, 10–20 cm, and 20–30 cm layers) was randomly sampled and mixed in each unit according to the 5-point sampling method, using a 100 cm^3 ring knife to determine of the soil's physical properties. We removed all residues of plants and residues found in the soil samples. We then mixed the topsoil evenly and divided it into two parts, which were then sealed in equal amounts in plastic bags. To determine the soil's chemical properties, one part of the soil was naturally air-dried, while the other part was stored in a refrigerator at 4 °C for subsequent microbial and enzymatic activity measurement. Soil bulk density (SBD), soil porosity (SP), and soil water content (SWC) were determined using the ring knife gravimetric method; soil organic matter (SOM) was determined using the potassium dichromate volumetric method and the external heating method; alkaline hydrolysis nitrogen (AN) was determined using the Conway diffusion dish method; alkaline phosphorus (AP) was determined using the Mo-Sb colorimetry, and quantified via spectrophotometry; alkaline pootassium (AK) was determined using a flame photometer [25]. Three soil enzymes were selected, including soil sucrase (SS), urease (SU), and acid phosphatase (SAP). The culture mediums of bacteria, fungi, and actinomycetes were NA, PDA, and CSA, respectively. The fungi, bacteria, and actinomyces were measured by plate colony counting [26]. Several soil samples were mixed, and one gram of suspension (dry weight equivalent) was prepared in 10 mL of water. This soil suspension was serially diluted (10^{-2}, 10^{-3}, and 10^{-4}) using modified Gao's No. 1 medium for bacteria, potato–sucrose medium for fungi, and medium for actinomycetes [27]. The samples were cultured (2 d for bacteria, 3 d for fungi, and 5 d for actinomycetes) in an incubator at 30 °C. Sucrase activity was determined using 3,5-dinitro salicylic acid colorimetric analysis; urease activity was determined using phenol–sodium hypochlorite coloration; acid phosphatase activity was measured using the triphenylphosphonium-4-amino-antipyrine colorimetric method, in which three duplicates were tested [28].

(1) SBD

$$\mathrm{SBD}\ (\mathrm{g/cm^3}) = \frac{\mathrm{W_1 - W_0}}{\mathrm{V}}$$

where V is the ring knife volume (cm^3); W_1 is the weight of the soil + ring knife after drying (g); and W_0 is the ring knife weight (g).

(2) SP

$$SP(\%) = \left(\frac{W_2 - W_1}{v}\right) \times 100\%$$

where V is the ring knife volume (cm^3); W_2 is the water-saturated soil + ring knife weight (g); and W_1 is the weight of soil + ring knife after drying (g).

(3) SWC

$$SWC(\%) = \frac{W_3 - W_1}{W_1} \times 100\%$$

where W_3 is the weight of the wet soil just taken by the ring knife (g), and W_1 is the weight of soil + ring knife after drying (g).

2.4. Data Calculations and Analysis

Using Excel 2019 and SPSS 25.0, the experimental data were processed and statistically analyzed. Origin2022b, a software package for rendering images, was used for image processing. The analysis of variance was performed using the one-way ANOVA and the LSD method to determine whether the differences between the treatments were statistically significant. A correlation analysis was carried out to test for a relationship. The tables were created using the Excel 2019 software.

3. Results

3.1. Effects of Fungal Residue Return on Soil Physical Properties

It has been shown that fungal residue can improve soil quality by influencing the physical properties of bulk density and the porosity of soil. Following the application of fungal residue, the soil's physical properties were found to be improved (Table 3). The physical properties of the different soil layers under different treatments were the same. As the return concentration increased, the bulk density of the soil also changed accordingly. Specifically, the fungal residues promoted a reduction in the bulk density of the soil and were lower than that of CK, while the bulk density of the soil generally increased with the depth of the soil. The difference in SBD among different treatments was most significant in the 0–10 cm soil depth layer; in addition, porosity was increased by up to 12.12%, water content was increased by up to 26.26%, and bulk density was reduced by up to 25.83%. Different treatments had a hierarchical effect on the soil's physical properties after residue return, and the soil porosity and soil water content were significantly higher in the 0–10 cm and 10–20 cm soil layers than in the 20–30 cm soil layers ($p < 0.05$). The soil porosity and soil water content of different treatments were arranged as follows: R11 > R9 > R7 > R5 > R3 > CK, the soil porosity of R11 was higher than other treatments, reaching 45.67%. The soil bulk density content was CK > R3 > R5 > R7 > R9 > R11, with similar trends in the 0–20 cm soil layer and no apparent regularity observed in the 0–30 cm layer, which had the minimum value of 1.12 g/cm^3. In the 0–10 cm and 20–30 cm soil layers, the bulk density of the soil in R7 was significantly lower than that of the other treatments ($p < 0.05$), while the bulk density of the soil in R5 was substantially higher than that in R7 in the 10–20 cm soil layer. There was a significant difference in the soil porosity of R9 in the 0–10 cm and 10-20 cm soil layers ($p < 0.05$); however, the soil water content in the 20–30 cm soil layer did not differ significantly from those of the other treatments ($p < 0.05$).

Table 3. The effects of different treatments on soil physical properties.

Treatment	Soil Bulk Density (g/cm^3)			Soil Porosity (%)			Soil Water Content (%)		
	0–10 (cm)	10–20 (cm)	20–30 (cm)	0–10 (cm)	10–20 (cm)	20–30 (cm)	0–10 (cm)	10–20 (cm)	20–30 (cm)
CK	1.51 ± 0.02 a	1.58 ± 0.06 a	1.59 ± 0.03 a	41.13 ± 1.30 a	40.21 ± 1.38 a	39.60 ± 0.90 a	2.97 ± 0.06 a	3.08 ± 0.06 a	3.23 ± 0.04 a
R3	1.50 ± 0.02 a	1.52 ± 0.04 a	1.58 ± 0.04 a	41.53 ± 0.80 a	41.27 ± 0.61 a	39.50 ± 0.89 a	3.01 ± 0.02 a	3.15 ± 0.08 a	3.27 ± 0.02 a
R5	1.47 ± 0.05 a	1.47 ± 0.03 b	1.52 ± 0.05 a	41.67 ± 0.90 a	41.36 ± 0.60 a	39.73 ± 1.06 a	3.18 ± 0.01 b	3.28 ± 0.03 b	3.28 ± 0.02 a
R7	1.35 ± 0.11 b	1.48 ± 0.03 b	1.50 ± 0.02 b	42.37 ± 0.88 a	41.97 ± 0.87 a	40.17 ± 1.44 a	3.35 ± 0.04 b	3.52 ± 0.03 b	3.24 ± 0.11 a
R9	1.23 ± 0.04 b	1.46 ± 0.01 b	1.46 ± 0.06 b	43.63 ± 1.17 b	42.63 ± 1.07 b	41.60 ± 0.90 a	3.45 ± 0.04 b	3.74 ± 0.10 b	3.22 ± 0.07 a
R11	1.12 ± 0.05 b	1.45 ± 0.03 b	1.42 ± 0.03 b	45.67 ± 1.50 b	43.29 ± 1.50 b	44.40 ± 1.97 b	3.75 ± 0.05 b	3.81 ± 0.06 b	3.24 ± 0.03 a

Note: Different letters indicate significant differences ($p < 0.05$) among different treatments.

3.2. Effects of Fungal Residue Return on Soil Chemical Properties

With the change in the soil physical properties, the soil chemical properties are also improved (Figure 2). The soil chemical properties also increased to varying degrees in response to different treatments, except for soil AN and AK. With the increase in return concentration, AN first decreased and then increased, while AK first increased and then decreased. When treated with fungal residue ($p < 0.05$), the soil AP content was significantly higher than observed when treated with CK, increasing from 2.4–4.4 mg/kg to 4.0–13.6 mg/kg. As the chemical content of the soil varied between the different treatments, there was a hierarchical pattern in the distribution. The chemical content of the soil was enriched in the 0–10 cm layer, reflecting the surface enrichment effect in terms of nutrient content. In the different soil layers, the soil chemical composition of each treatment showed additional variability depending on the treatment. Generally, in the 0–10 cm soil layer, the order of the individual chemical contents was roughly R11 > R9 > R7 > R5 > R3 > CK, while in the 10–20 cm and 20–30 cm soil layers, the trend was slightly different. The SOM of the soil layer increased by 35.33–45.64% in comparison to those of CK, while the AN increased by 58.06–78.33%. The average SOM values were 17.21 g/kg, 17.32 g/kg, and 15.87 g/kg in the 0–10 cm, 10–20 cm, and 20–30 cm layers, respectively. The average AN values were 66.75 mg/kg, 63.18 mg/kg, and 59.44 mg/kg in the 0–10 cm, 10–20 cm, and 20–30 cm layers, respectively. The soil AP in the 0–10 cm soil layer ranged from 4.4 mg/kg to 13.6 mg/kg. The AP content of the 10–20 cm soil layer varied from 3.7 mg/kg to 6.7 mg/kg. The AP content of the 20–30 cm soil layer changed from 2.4 mg/kg to 4.0 mg/kg.

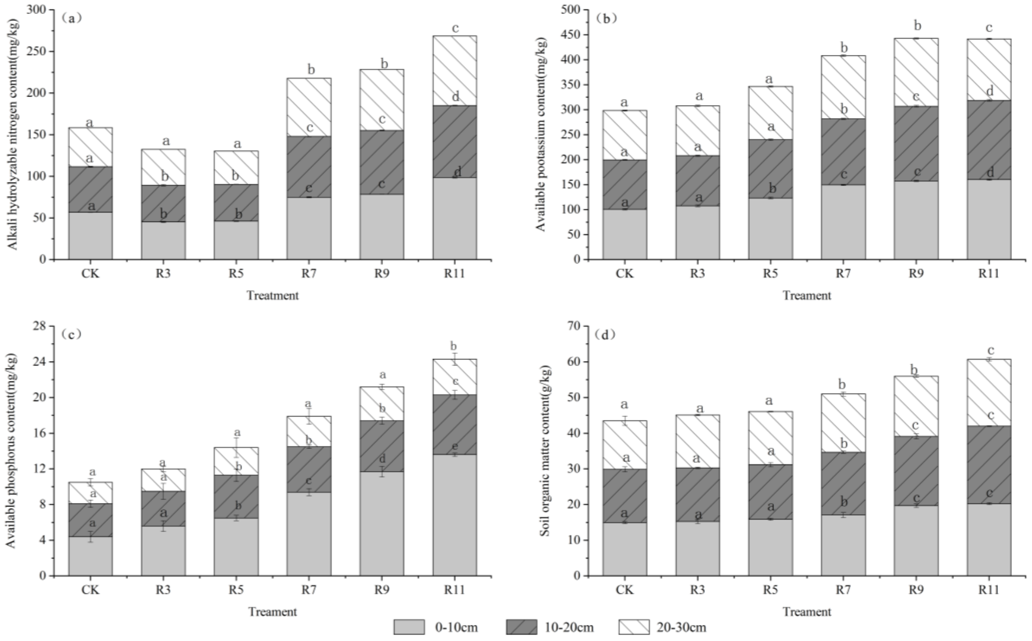


Figure 2. Effects of returning fungal residue return on soil chemical properties. Note: Different letters indicate significant differences ($p < 0.05$) among different treatments. (**a**): Alkaline hydrolysis nitrogen (AN); (**b**): Alkaline pootassium (AK); (**c**): Alkaline phosphorus (AP); (**d**): Soil organic matter (SOM).

3.3. Effects of Returning Fungus Residue on Microbial Quantity

With the increase in return concentration, the amount of bacteria and actinomycetes first increased and then decreased, and the amount of fungi showed a continuous increase (Table 4). Of the three microorganisms, the amount of fungi was the lowest. Under different concentrations of mushroom residue return, the proportion of bacteria was 58.13–61.39%; the proportion of fungi was 0.75–1.00%; and actinomycetes accounted for 37.82–40.8%. The number of bacteria and actinomycetes observed after the R9 treatment increased by 1.96 and 1.76 times, respectively, compared with CK, and the number of fungi increased by 1.45 times at the R11 concentration.

Table 4. Number of soil microorganisms in 0–30 layers.

Treatment	Number of Bacteria ($\times 10^5$ cfu/g)	Proportion (%)	Number of Fungi ($\times 10^3$ cfu/g)	Proportion (%)	Number of Actinomycetes ($\times 10^5$ cfu/g)	Proportion (%)	Total Microorganisms ($\times 10^5$ cfu/g)
CK	64	58.13%	110	1.00%	45	40.87%	110.10
R3	68	58.55%	114	0.98%	47	40.47%	116.14
R5	95	59.26%	131	0.82%	64	39.92%	160.31
R7	111	59.53%	145	0.78%	74	39.69%	186.45
R9	126	61.00%	155	0.75%	79	38.25%	206.55
R11	125	61.39%	160	0.79%	77	37.82%	203.60

Treatment with fungal residue significantly increased the number of bacteria, fungi, and actinomycetes compared with CK (Figure 3). Meanwhile, the number of actinomycetes fungal residue returns significantly increased microbe numbers only in the 0–10 cm and 10–20 cm layers. The R7 treatment significantly increased the number of bacteria and fungi in the 0–10 cm layer. However, there was no significant difference between the 10–20 cm and the 20–30 cm layers. The microbial content was highest in R9 and R11. Neither the 10–20 cm nor 20–30 cm concentrations showed significant differences in the number of actinomycetes. It was found that the number of bacteria did not differ significantly between R3 and R5, but it was substantially higher in R7, R9, and R11 for all layers. The amount of aboveground fungi showed a similar trend to the changes in bacterial counts in the 0–10 cm layer.

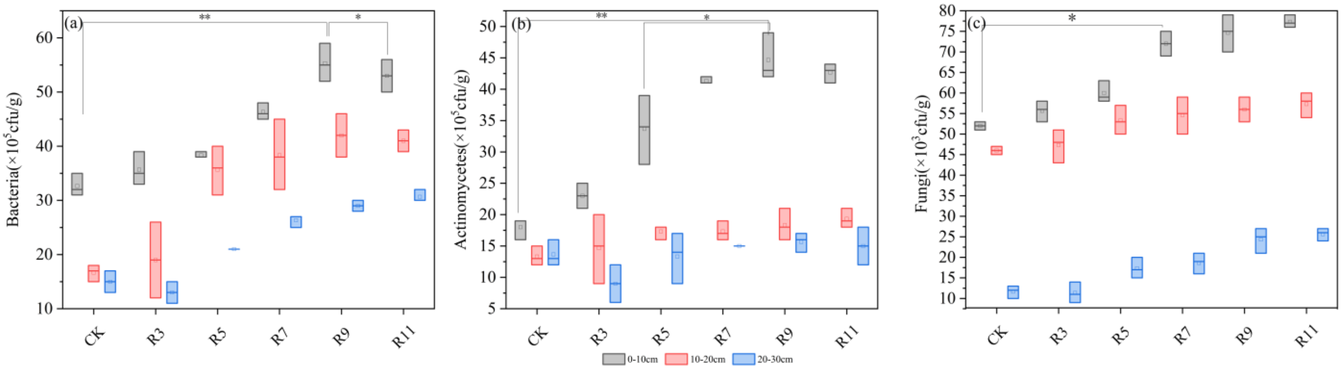


Figure 3. Effects of return fungal residue on microbial quantity. Note: The significance levels are * $p < 0.05$; ** $p < 0.01$. (**a**): Number of bacteria; (**b**): Number of actinomycetes; (**c**): Number of fungi.

3.4. Effects of Returning Fungus Residue on Enzyme Activity

Soil urease (SU), soil sucrase (SS), and soil alkaline phosphatase(SAP) were selected to characterize the effect of fungal residue inputs on soil enzymes(Figure 4). The activities of soil urease and soil sucrase decreased with the increasing soil depth, but soil alkaline phosphatase showed a trend of first decreasing and then increasing with depth. In the soils under fungal residue treatment, the soil enzyme activities were superior to those of CK, and the activities of SU, SS, and SAP increased to 4–49%, 3–63%, and 3–77%, respectively. The

0–10 cm layer activities were similar except for R9, for which there was a slight decrease in the enzyme activity of SAP, while those of R11 were close to the CK values. The SS activity had lower values in 20–30 cm compared to the other layers, reaching the lowest value of 11.49 g/d/g in the CK treatment. In terms of the maximum enzyme activity of SU at different layers, values above 73.62 mg/d/g were recorded at R11, while a lower value of 43.93 mg/d/g was obtained in CK. In the 0–30 cm soil layer, SS activity was characterized by R11 > R9 > R7 > R5 > R3 > CK; in the 0–10 cm soil layer, SU activity was represented by R9 > R7 > R5 > R3 > R11 > CK; in the 10–20 cm soil layer, SU activity was characterized by R7 > R9 > R11 > R5 > R3 > CK; in the 20–30 cm soil layer, SU activity was represented by R9 > R11 > R7 > R5 > R3 > CK. SAP activity first increased and then decreased with increasing return in the same soil layer.

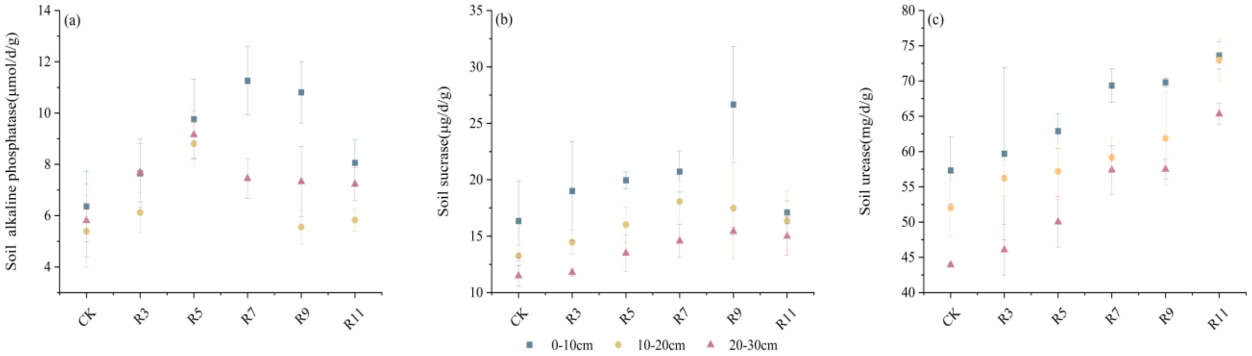
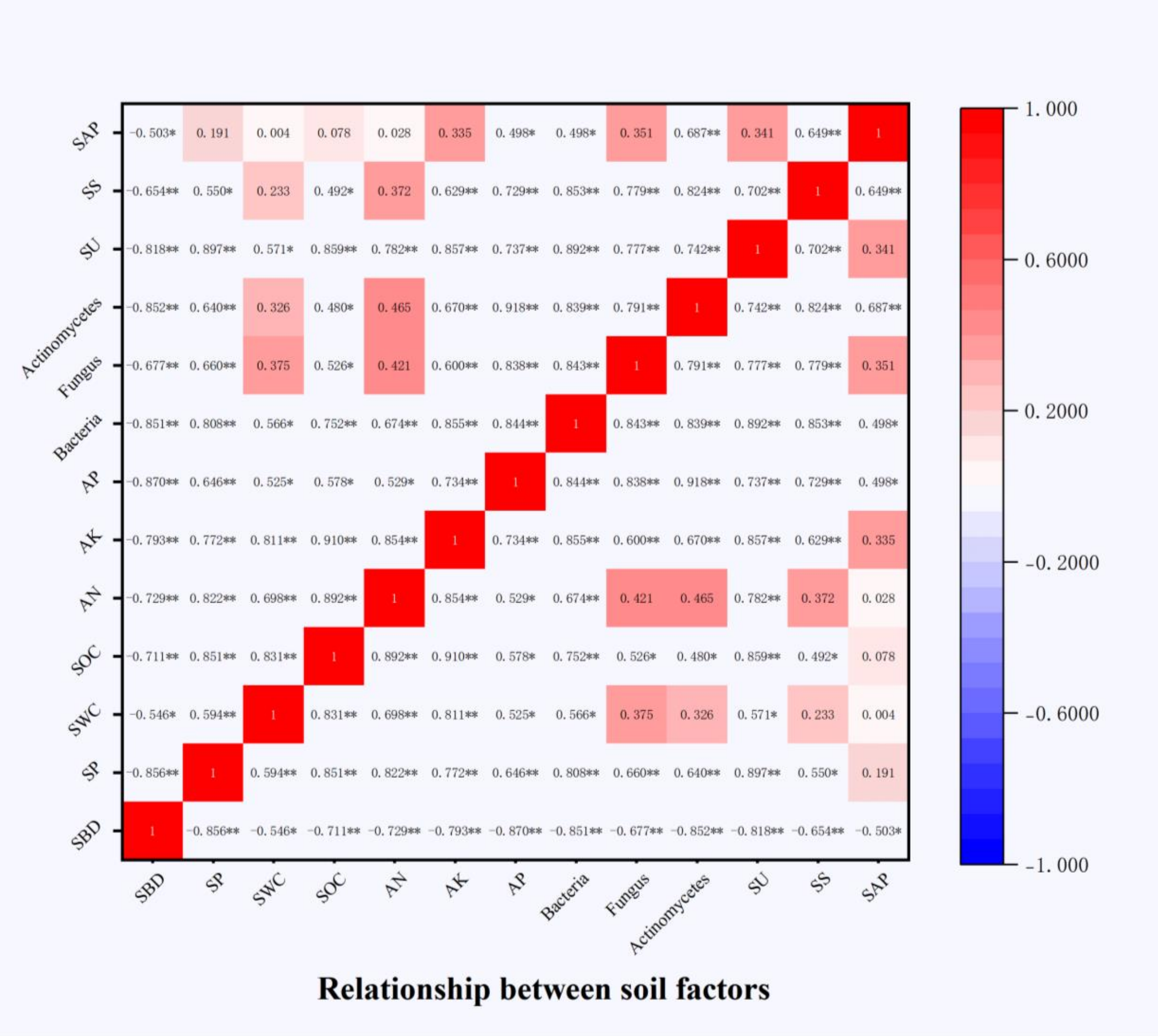


Figure 4. Effects of fungal residue return on enzyme activity. (**a**): Soil acid phosphatase (SAP); (**b**): Soil sucrase (SS); (**c**): Soil urease (SU).

3.5. Relationship between Soil Factors

Soil nutrients are an important indicator of soil fertility and also affect the growth and development of plants and the activity of soil microorganisms. The soil factors interacted with each other (Figure 5). The SBD was negatively correlated with the other parameters. Furthermore, SBD was significantly negatively correlated with SAP and SWC ($p < 0.05$). SWC was not strongly correlated with SAP, SS, Fungi, and Actinomycetes. The positive correlations between various chemical properties are very strong, showing the same amount of bacteria and SU. Bacterial content was positively correlated with SAP ($p < 0.05$) and significantly positively correlated with fungi, Actinomycetes, SS, and SU ($p < 0.01$). Fungi content was significantly positively correlated with Actinomycetes, SS, and SU ($p < 0.01$), but the correlation with SAP was weak. Actinomycetes counts were significantly positively correlated with SS, SU, and SAP ($p < 0.01$). SU was significantly positively correlated with SS ($p < 0.01$), but the correlation with SAP was weak. SS was significantly positively correlated with SAP ($p < 0.01$). AP and bacteria content were correlated with other soil factors, and the correlations between bacteria and other factors were stronger. SAP was only correlated with SBD, AP, bacteria, actinomycetes, and SS. SWC and AN had no correlation with SAP, SS, actinomycetes, and fungi.



	SBD	SP	SWC	SOC	AN	AK	AP	Bacteria	Fungus	Actinomycetes	SU	SS	SAP
SAP	−0. 503*	0. 191	0. 004	0. 078	0. 028	0. 335	0. 498*	0. 498*	0. 351	0. 687**	0. 341	0. 649**	1
SS	−0. 654**	0. 550*	0. 233	0. 492*	0. 372	0. 629**	0. 729**	0. 853**	0. 779**	0. 824**	0. 702**	1	0. 649**
SU	−0. 818**	0. 897**	0. 571*	0. 859**	0. 782**	0. 857**	0. 737**	0. 892**	0. 777**	0. 742**	1	0. 702**	0. 341
Actinomycetes	−0. 852**	0. 640**	0. 326	0. 480*	0. 465	0. 670**	0. 918**	0. 839**	0. 791**	1	0. 742**	0. 824**	0. 687**
Fungus	−0. 677**	0. 660**	0. 375	0. 526*	0. 421	0. 600**	0. 838**	0. 843**	1	0. 791**	0. 777**	0. 779**	0. 351
Bacteria	−0. 851**	0. 808**	0. 566*	0. 752**	0. 674**	0. 855**	0. 844**	1	0. 843**	0. 839**	0. 892**	0. 853**	0. 498*
AP	−0. 870**	0. 646**	0. 525*	0. 578*	0. 529*	0. 734**	1	0. 844**	0. 838**	0. 918**	0. 737**	0. 729**	0. 498*
AK	−0. 793**	0. 772**	0. 811**	0. 910**	0. 854**	1	0. 734**	0. 855**	0. 600**	0. 670**	0. 857**	0. 629**	0. 335
AN	−0. 729**	0. 822**	0. 698**	0. 892**	1	0. 854**	0. 529*	0. 674**	0. 421	0. 465	0. 782**	0. 372	0. 028
SOC	−0. 711**	0. 851**	0. 831**	1	0. 892**	0. 910**	0. 578*	0. 752**	0. 526*	0. 480*	0. 859**	0. 492*	0. 078
SWC	−0. 546*	0. 594**	1	0. 831**	0. 698**	0. 811**	0. 525*	0. 566*	0. 375	0. 326	0. 571*	0. 233	0. 004
SP	−0. 856**	1	0. 594**	0. 851**	0. 822**	0. 772**	0. 646**	0. 808**	0. 660**	0. 640**	0. 897**	0. 550*	0. 191
SBD	1	−0. 856**	−0. 546*	−0. 711**	−0. 729**	−0. 793**	−0. 870**	−0. 851**	−0. 677**	−0. 852**	−0. 818**	−0. 654**	−0. 503*

Figure 5. Relationship between soil factors. Red indicates positive correlations between parameters, and blue indicates negative correlations between parameters. The significance levels are * $p < 0.05$; ** $p < 0.01$.

4. Discussion

Soil productivity assessment is a sensitive indicator of the impact of treatments on soil processes, representing the potential of soil in agroecosystems. Fungal residue has a similar principle of action to straw after returning to the field. Straw is integrated into the soil using tilling methods, and the physical and chemical properties of the soil will be deeply affected. Adding fungal residue to soil will inevitably affect the soil's organic matter, which influences a wide range of physical, chemical, and biological properties of soils [29]. In the experiment, the increase of fungal residues is effective in increasing the content of soil organic matter. Fungal residue has the characteristics of a low bulk density and high porosity, and returning it to the soil has been shown to reduce the soil bulk density, increase soil porosity, and improve soil aeration and water retention characteristics [30,31]. Our results showed that the soil bulk density of different return treatments decreased by 10.69–25.83%. Previous studies have shown that returning mushroom residue return to fields will increase soil organic matter content [32]. In this experimental study, it was concluded that organic matter increased with the increase in the concentration of mushroom residue returned to the field. This is inconsistent with the research conclusion of Gregorich et al. [33,34]. The reason for this conclusion may be that the amount of mushroom residue returned to the field was different from the type of soil, and therefore, the soil micro-ecological cycle differed in differences, and hence, the organic matter showed a continuous increase. Nitrogen, phosphorus, and potassium are essential nutrients for plant growth and development [35]. Wang et al. found that the application of organic fertilizer to soil can improve the nitrogen supply capacity of the soil [36]. In this study, the alkali-hydrolyzable nitrogen showed a trend of first decreasing and then increasing with the increase in residue concentration, probably because the consumption rate of the alkali-hydrolyzable was greater than the mineralization degree of the fungal residue [37]. In both the R9 and R11 treatments, the available hydrolysis nitrogen content was significantly higher than that in the control ($p < 0.05$). The soil available nitrogen contents in the R3 and R5 treatments were lower than the control, which may be related to factors such as tillage methods and cultivated crop types, but the specific mechanism behind this requires further study. Our results showed that a small decrease in available N was found in the R3 and R5 treatment compared to that in the CK treatment on the 0–30 cm soil layer. This was possibly due to N-mineralization and N uptake by crops. Yao et al. [38] also reported that available N in the fertilization treatment showed that a combination of organic fertilizer and mushroom residue could reduce the available N content in the soil in a short period of time. Under different returning concentrations, the available P content was higher than the CK treatment. The increase in available P in mushroom residue may be due to the high microbial activity caused by the addition of organic manure, which accelerated the phosphorus cycle [39].

Soil microorganisms are a sensitive and active part of soil properties. Dynamic changes in soil microorganisms can accurately reflect the changes in soil quality and play a dominant role in maintaining the stability of the ecosystem, soil nutrient decomposition and transformation process, and anti-interference [40–42]. Compared with other physical and chemical properties, soil microbial quantity and enzyme activity were more sensitive [43,44]. In this study, the changes in soil enzyme activity between different concentrations and soil layers after the residue was returned to the field were observed, indicating that the difference between different treatments was not significant at 20–30 cm; this may be because the nutrients required for microbial survival could not be provided due to the increase in soil depth. In our experiment, the number of soil microorganisms in the R11 treatment showed a downward trend because the R11 treatment provided more available soil nutrients, which may cause excess organic matter and make it difficult to achieve decomposition. Most reports indicated an increase in soil enzyme activity in organic crop treatments [45–48]. Many studies have shown that soil fertility levels are closely related to the type and activity of soil enzymes [49–51]. Deng Ouping [52] found that the in situ return of mushroom residue could significantly increase sucrase activity, and the activation of the enzymes and soil nutrients showed a good correlation. Hu et al. [22] showed that the sucrase and catalase activities were inhibited by the in situ return of mushroom residue. Phosphatase can participate in the decomposition of phosphorus. The results of Teng et al. [23] showed that applying Postreatus residue could increase soil catalase activity. The different results may have occurred because the soil enzyme activity is affected by various factors, such as other types of mushroom residue, soil types, planting systems, and climatic conditions. Our results also showed that soil microbial activity was significantly positively correlated with soil organic matter, available P, and K because the climatic conditions in the region made the above substances more convenient for microbial transformation and utilization.

5. Conclusions

These results indicated that the return of fungal affected soil aeration and permeability at different treatments. The water content can be increased by 26.26%. We found that the content of soil bulk density and soil water content in the same treatment were sensitized to porosity. The contents of soil available phosphorus, organic matter, and alkali-hydrolyzable nitrogen were higher under the condition of R11 (330 kg/40 m^2). The addition of fungal residue to the field helped to improve soil parameters (SOM and AP), and this effect increased as the return concentration increased. Compared with CK, the number of bacteria, fungi, and actinomycetes increased by 1.94 times, 1.46 times, and 1.71 times, respectively.

The trend of sucrase activity in the different soil layers was inconsistent. AK was strongly correlated with the other factors, and the microorganisms and enzyme activities were strongly associated ($p < 0.01$). The efficient use of fungal residue in the agro-pastoral ecotone of northern China is a sustainable and green biological measure. The conclusion provides a new method for the resource utilization of downstream wastes in the food industry. At the same time, as a pollution-free natural local good improver, it is very beneficial in terms of increasing the crop yield. Moreover, if this measure can be used in a large area of fragile land that is affected by desertification and salinization, the benefits of water storage and soil moisture conservation will be of great significance to the prevention and control of these issues.

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