agronomy

MDPI

Article

Analysis of Tobacco Straw Return to the Field to Improve the Chemical, Physical, and Biological Soil Properties and Rice Yield

Jie Huang [1], Xinyue Wang [1], Lili Yang [2], Yuanhuan Li [2], Bing Xia [1], Hailin Li [1] and Xiaohua Deng [1,*]

[1] College of Agriculture, Hunan Agricultural University, Changsha 410125, China; 2624555016@stu.hunau.edu.cn (J.H.); 1468909857@stu.hunau.edu.cn (X.W.); xiabing@hunau.edu.cn (B.X.); lihl@hunau.edu.cn (H.L.)

[2] College of Botanical Science and Technology, Hunan Biological and Electromechanical Polytechnic, Changsha 410125, China; yanglili@hnbemc.edu.cn (L.Y.); liyuanhuan@hnbemc.edu.cn (Y.L.)

* Correspondence: yzdxh@hunau.edu.cn; Tel.: +86-13974934919

Abstract: Straw incorporation into soil contributes significantly to the sustainable development of agriculture. To investigate the impact of tobacco straw returns on a tobacco–rice replanting system, we designed an experiment with two straw return levels and a control group: T1 (full return), T2 (root return), and CK (no straw return). Over a three-year field experiment in rice fields in South China, we assessed the effects of tobacco straw return on soil quality, microbial diversity, dry matter accumulation, and yield composition of rice. The results demonstrated that returning tobacco straw to the field effectively enhanced rice yield by positively influencing various soil physical, chemical, and biological properties. Compared to those in the CK treatment, as the soil porosity increased from 9.0% to 12.4%, the mean weight diameter of the soil aggregates substantially increased, ranging from 28.7% to 45.2%. There were significant increases in soil organic matter, total nitrogen, and alkaline dissolved nitrogen. Soil sucrase activity increased between 29.8% and 44.9%, and urease activity increased between 4.3% and 62.2% over the three consecutive years of straw return. The diversity index of soil fungi significantly increased. Additionally, rice yield increased markedly, ranging from 1.8% to 5.1%. Overall, the enhancement effect of T1 surpassed that of T2. According to our comprehensive analysis, the incorporation of tobacco straw into the field was found to enhance the physical properties of the soil, elevate soil enzyme activity, and increase the abundance of soil microorganisms. Consequently, this practice led to improved rice yield and a reduction in agricultural waste output. Overall, the return of tobacco straw to the field represents a clean and dependable approach in rice-cultivated tobacco areas to improve soil health and rice productivity.

Keywords: straw return; soil nutrients; soil enzyme activity; soil microorganisms; rice yield

Citation: Huang, J.; Wang, X.; Yang, L.; Li, Y.; Xia, B.; Li, H.; Deng, X. Analysis of Tobacco Straw Return to the Field to Improve the Chemical, Physical, and Biological Soil Properties and Rice Yield. *Agronomy* **2024**, *14*, 1025. https://doi.org/10.3390/agronomy14051025

Academic Editor: Claudio Ciavatta

Received: 23 April 2024
Revised: 9 May 2024
Accepted: 10 May 2024
Published: 11 May 2024

1. Introduction

Straw is a biomass resource that contains a substantial amount of organic matter and essential nutrients such as nitrogen, phosphorus, and potassium that are vital for plant growth. In southern China, the predominant agricultural practice in tobacco cultivation is the tobacco–rice replanting mode [1]. Given that the soil predominantly consists of rice soil and is characterized by a sticky texture and limited permeability, rice crop growth can be adversely affected. Implementing straw returns to fields holds significant ecological and environmental importance for preserving farmland fertility, mitigating reliance on chemical fertilizers, enhancing the carbon sequestration capacity of terrestrial soils, facilitating the soil nitrogen cycle [2,3], curbing environmental pollution stemming from combustion, and fostering a sustainable agricultural production cycle [4].

The practice of returning straw to the field directly impacts soil quality, subsequently influencing crop growth through alterations in the soil environment. Soil aggregates, as fundamental components of soil structure, play pivotal roles in water and heat transport, as well as in the storage, supply, and transformation of soil nutrients. The stability of soil

aggregates serves as a crucial indicator of overall soil structure stability [5]. Prior research has indicated that straw return to fields can enhance soil aggregate stability and ameliorate soil structure; however, outcomes may vary based on factors such as the return mode, soil type, and climate of the experimental area [6,7].

Soil enzyme activity serves as a bioactivity index for soil and a key evaluation parameter for soil fertility. The activity of soil enzymes is intricately linked to the abundance of microorganisms, organic matter content, and nutrient elements in the soil, making it a pivotal indicator for assessing soil quality [8]. Xu Jianglai et al. [9] conducted a study in central Jiangsu Province to investigate the impact of straw return on soil fertility and rice yield. Their findings revealed that straw return at levels of 50% and 75% resulted in increased soil catalase and sucrase activities, consequently leading to enhanced crop yields.

In studies involving maize [10], rice [11], and rice–wheat rotation [12,13], it has been observed that the incorporation of straw into a field not only significantly influences the stability of the soil structure and potential soil fertility, but also exerts a considerable impact on the abundance and diversity of soil microbial communities. Soil, as the "natural medium" for microorganisms, is the richest resource base for bacterial species. Soil microorganisms are the most dynamic components of terrestrial ecosystems; additionally, they are sensitive to changes in climate and the soil microbiological environment, and they play pivotal roles in soil ecosystems [14]. The composition and diversity of soil microbial populations largely govern the cycling, decomposition, and energy flow of nutrients in the soil. By regulating changes in the soil environment, these microbial populations can alter the composition and diversity of soil microorganisms and, consequently, influence the functioning of the soil ecosystem. Soil microorganisms actively participate in crucial biochemical reaction processes, such as ammonification, nitrification, nitrogen fixation, and sulfation, within the soil. They play a vital role in promoting the decomposition of straw, as well as the decomposition and synthesis of soil organic matter, and contribute to the transformation of nutrients [15]. The impact of straw return on the soil microbial community is intricate, with divergent outcomes observed by different researchers due to variations in cropping patterns, straw types, length of straw return, soil background, soil types, and research methods. Further investigations are warranted for diverse regions, cropping patterns, and soil types. Despite numerous studies examining the effects of various straw return modes on soil properties and crop yields, the response of soil physicochemical and biological properties to tobacco straw remains unclear. Therefore, it is imperative to delve into the mechanisms through which tobacco straw return influences soil quality and biodiversity within agroecosystems in rice–tobacco areas in China.

In this study, the impact of the in situ field return of tobacco straw was comprehensively evaluated across multiple dimensions, including soil bulkiness, aggregate structure, enzyme activity, microbial diversity, and rice yield. This assessment was conducted through a three-year field experiment to elucidate the factors contributing to the improvement in soil quality and rice yield through the in situ field return of straw. The findings of this study can serve as a theoretical foundation for establishing a model for in situ tobacco straw return, thereby fostering the sustainable development of agriculture in the studied area.

2. Materials and Methods

2.1. Materials for Testing

The field trial was conducted in Yujiaao Town, Ningxiang City (112.29° E, 28.19° N), spanning from 2018 to 2020. The tobacco straw used for the experiment originated from the stems and roots left after the harvest of cured tobacco in the designated field. The rice variety employed was Xiangzaoxian 45, whose cultivation period extends 100 days into the autumn season. The compound fertilizer used had a N:P:K ratio of 10:10:10. The soil characteristics of the experimental field were as follows: pH 7.8, 16.4 g/kg organic matter, 1.5 g/kg total nitrogen, 1.2 g/kg total potassium, 6.8 g/kg total potassium, 83.8 mg/kg alkaline dissolved nitrogen, 13.9 mg/kg effective phosphorus, and 69.1 mg/kg fast-acting potassium; the soil texture was clay loam. The tobacco straw utilized in the study had

an organic carbon content of 48.8%, a total nitrogen content of 1.1%, a total phosphorus content of 0.2%, a total potassium content of 1.7%, and a carbon-to-nitrogen ratio of 45.6.

2.2. Experimental Design

The experiment was structured with three distinct treatments: T1, involving the complete return of tobacco roots and stems to the field after the harvest of cured tobacco in the tobacco–rice replanting mode, with an average annual amount of 1848.3 kg/ha; T2, entailing the return of subterranean roots to the field following the harvest of cured tobacco, where tobacco stems were chopped off and removed from the experimental field, and the average annual root return to the field was 757.4 kg/ha; and CK, the control group, where in the tobacco–rice replanting mode, all roots and stems were entirely removed from the field after the harvest of cured tobacco. The experimental plots were systematically organized into randomized groups, each occupying an area of 60 m^2 (10 m × 6 m). The experiment was conducted with 3 replications, totaling 9 plots. To maintain isolation, each plot was enclosed by a ridge and enveloped with plastic film. Separate irrigation ditches were constructed to prevent water runoff between plots. The tobacco straw was meticulously chopped into small sections measuring 10–20 cm and uniformly distributed across the experimental field. The straw was subsequently plowed and thoroughly integrated into the soil. Rice seeds were sown in late July after germination, at a rate of 75 kg/ha. Urea was applied at a rate of 423.9 kg/ha, with the urea-to-base fertilizer, tiller fertilizer, and spike fertilizer ratio set at 4:2:4. Potassium sulfate was applied at 283.3 kg/ha, with the ratio of potassium sulfate to base fertilizer and spike fertilizer set at 7:3. Calcium and magnesium phosphorus fertilizers were applied at a rate of 750 kg/ha, all of which were utilized as base fertilizers. Following sowing, to maintain a low field border without stagnant water, pretilachlor was sprayed three days after sowing to control weed growth. Shallow irrigation and fertilization were carried out during the 3-leaf period to stimulate tillering, and adequate seedlings were established under sunlight. Shallow water was maintained during the boot stage to protect the developing rice grains, and alternating wet and dry irrigations were applied after spiking. Irrigation was stopped five days before harvesting to allow the ditch water to naturally recede. Urea was then applied at 225 kg/ha, and compound fertilizer was applied at 150 kg/ha. Following the rice harvest, straw was returned to the field, and tobacco planting resumed in the subsequent year.

2.3. Test Items and Measurement Methods

2.3.1. Soil Sampling

Following the rice harvest, three points were selected within each plot, and soil columns measuring 15 cm × 15 cm × 20 cm (length, width, and height) were carefully excavated with a shovel. These rectangular soil columns were gently placed in rigid plastic boxes to prevent compression during transportation, ensuring the preservation of the original soil structure during transit to the laboratory. Concurrently, a 5-point sampling method was used to collect tillage soil from a 0 to 20 cm depth in each plot, creating mixed soil samples. These samples were then divided into two portions: one portion was immediately frozen in liquid nitrogen and stored at −80 °C in a refrigerator for the subsequent determination of soil enzyme activity and soil microorganisms; the second portion was air-dried, finely ground, and passed through a 1 mm sieve for the determination of soil nutrients.

2.3.2. Determination of Soil Bulk Density and Porosity

The soil bulk density and porosity were determined using the ring knife method [16].

2.3.3. Determination of Soil Aggregates

Dry-stable and water-stable aggregates with particle sizes >0.25 mm and <0.25 mm were separated using the methods outlined by Shavinoff and Yoder [17].

Dry sieving method: take 50 g of the prepared air-dried soil samples, put them into the sieve set (with the aperture of the sieve set at 2 mm, 0.5 mm, 0.25 mm, and 0.053 mm), and carefully sieve them for 15 min, so as to obtain five groups of agglomerates: >2, 2–0.5, 0.5–0.25, and 0.25–0.053 mm.

Wet sieving method: take 50 g of prepared air-dried soil samples in a large number of 1000 mL cylinders, slowly inject tap water, wet the soil so that the soil gradually saturates, allow to rest for 10 min and shake, and then place in the agglomerate analyzer (Japan, DIK-2001) for the wet sieving process, at an oscillation frequency of 15 r/min, time 30 min, to obtain five groups of agglomerates: >2, 2–0.5, 0.5–0.25, and 0.25–0.053 mm.

The assessment of soil aggregate stability relied primarily on the total quantity of water-stable aggregates > 0.25 mm and the mean weight diameter (MWD) of the aggregates. Calculation of the MWD was performed as follows:

$$MWD = \sum_{i=1}^{n} d_i w_i$$

where d_i is the mean diameter of aggregates of size i, and w_i is the percentage of aggregates of size i.

2.3.4. Determination of Soil Nutrients

The soil pH and contents of organic matter, alkaline dissolved nitrogen, fast-acting phosphorus, fast-acting potassium, total nitrogen, total phosphorus, and total potassium were determined using the soil agrochemical analysis [18].

2.3.5. Measurement of Soil Enzyme Activities

Soil sucrase and urease activity were determined via $Na_2S_2O_3$ titration and the indophenol blue colorimetric method, respectively [19].

2.3.6. Soil Microbial Diversity Detection

A 0.5 g sample was weighed, and microbial macrogenomic DNA extraction was conducted, following the instructions of a soil DNA extraction kit (DP336-02, Tiangen, Beijing, China). The DNA concentration and purity were assessed using a NanoDrop microspectrophotometer (model NanoDrop 2000, Thermo Fisher Scientific, Waltham, MA, USA). Genomic DNA bands were visualized by agarose gel electrophoresis using an electrophoresis instrument (model DYY-6C, Beijing Liuyi Instrumentation Factory, Beijing, China) and a gel imaging system (model Tanon-2500, Shanghai Tianneng Science and Technology Co., Shanghai, China). The genomic DNA of the bacterial 16S rRNA V3–V4 region and of the fungal ITS2 region was amplified using PCR. The primer sequences, PCR system, and amplification conditions used were described previously [20,21]. The PCR products were detected by agarose gel electrophoresis, and the products from the second round of amplification were purified using AMPure XP beads. Quantification was carried out using the ABI Step One Plus Real Time PCR System (Life Technologies, Waltham, MA, USA). Subsequently, sequencing was conducted on the Illumina HiSeq 2500 platform in accordance with the PE250 mode pooling of the NovaSeq 6000 platform.

The bipartite sequence data obtained from the initial downsequencing were spliced to reconstruct the original sequence, and the final valid sequence was obtained following filtering, chimera removal, and quality control. The sequences were subsequently clustered at a 97% similarity level to derive operational taxonomic units (OTUs). These OTUs were taxonomically annotated using the SILVA [22] and ITS2 [23] taxonomic databases to generate annotations at various classification levels, including domain, phylum, class, order, family, genus, and species. Abundance profiles of species at different taxonomic levels (kingdom, domain, phylum, class, order, family, genus, and species) were generated, and the community structure at each taxonomic level was analyzed using the R language (version 4.2.0) tool. QIIME (version 1.9.1) [24] was used to calculate alpha diversity indices

and beta diversity, including richness indices (Chao1 [25] and ACE [26] indices) and diversity indices (Shannon [27] and Simpson [28] indices), based on the OTU results.

Determination of dry matter and yield composition of rice: three 1 m^2 areas were selected per plot, the rice plants were harvested on flat land, panicles were hand-threshed, and the filled spikelets were separated by submerging them in tap water. The filled spikelets were then oven-dried at 70 °C to stabilize mass for determining individual grain mass. The investigation and statistical analysis included parameters such as the effective number of rice spikes, fruiting rate, number of sound grains per spike, and thousand-grain weight (with a water content of 14%) [29].

2.4. Statistical Analysis

Data processing and statistical analysis were conducted using Excel 2019 and SPSS 25.0. One-way analysis of variance (ANOVA) was used, and multiple comparisons between treatments were performed using Duncan's method ($p < 0.05$). Within the same year, comparisons were denoted by lowercase letters, indicating differences at the $p < 0.05$ level.

3. Results

3.1. Effect on the Soil Bulk Density and Porosity of Paddy Fields

3.1.1. Impact on Soil Bulk Density

As illustrated in Figure 1a, the variations in soil bulk density among the different treatments were not significant in 2018 or 2019. However, in 2020, the rice soil bulk density in the T1 treatment was significantly lower than that in the CK treatment. Specifically, compared with that in the CK treatment, the rice soil bulk densities in the T1 and T2 treatments in which tobacco straw was returned to the field decreased by 5.3% and 3.8%, respectively.

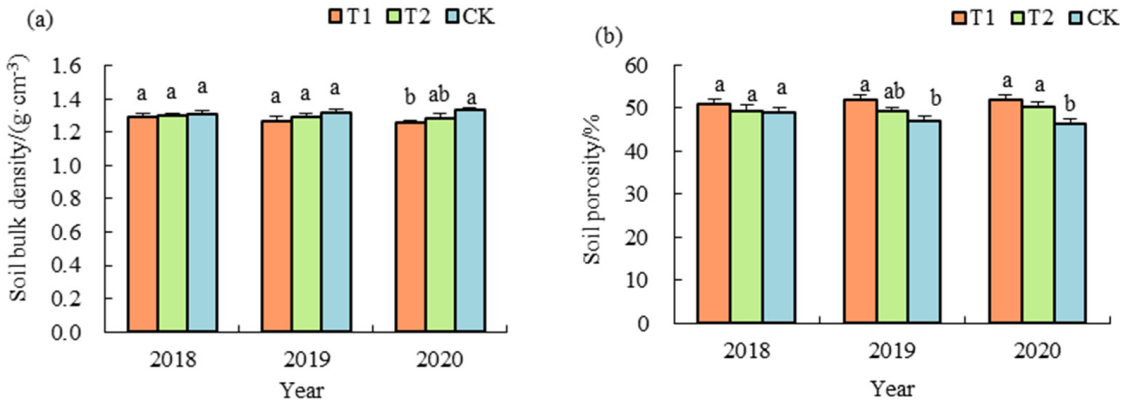

Figure 1. Effect of tobacco straw return on soil bulk density (**a**) and porosity (**b**) in paddy fields. Different letters (a, b) indicate significant differences between different treatments according to one-way ANOVA (Duncan, $p < 0.05$).

3.1.2. Effects on Soil Porosity

As depicted in Figure 1b, the difference in soil porosity was not significant in 2018. In 2019, the rice soil porosity in the T1 treatment was significantly greater than that in the CK treatment, and in 2020, the rice soil porosities in both the T1 and T2 treatments were significantly greater than that in the CK treatment. Specifically, in 2019, compared with that in the CK treatment, the soil porosities in the T1 and T2 treatments, in which tobacco straw was returned to the field, increased by 10.5% and 4.6%, respectively. In 2020, compared with that in the CK treatment, the soil porosities in the T1 and T2 treatments, in which tobacco straw was returned to the field, increased by 12.4% and 9.0%, respectively.

3.2. Effects on the Particle Size Distribution and Stability of Rice Field Soil Aggregates

Effect on the Particle Size Distribution of Soil Aggregates

Soil aggregates serve as the fundamental components of soil structure, and their particle size distribution characteristics and stability are closely tied to the soil water, fertilizer, air, and heat conditions. As shown in Table 1, the proportion of rice soil aggregates larger than 2 mm significantly increased with the increase in tobacco straw return, while the proportion of rice soil aggregates with a size ranging from 0.25 to 0.53 mm notably decreased. Starting in 2018, the disparities among T1, T2, and CK in terms of the proportion of rice soil aggregates 2~0.5 mm and 0.5~0.25 mm in size were not significant. However, the proportion of rice soil aggregates < 0.053 mm in size in T1 was significantly lower than that in CK. The proportions of rice soil aggregates > 2 mm in the T1 and T2 treatments were 24.5% and 10.0% greater than that in the CK treatment, respectively, while the proportions of aggregates 0.25~0.53 mm in size in T1 and T2 were 14.3% and 8.2% lower than that in the CK treatment, respectively. The total quantities of rice soil aggregates > 0.25 mm were 19.9% and 12.5% greater than that in CK for T1 and T2, respectively. The MWD values for T1 and T2 were 18.18% and 8.26% greater than that in CK, respectively.

Table 1. Effect of tobacco straw return on the particle size distribution and mean weight diameter of soil aggregates in paddy fields.

Year	Treats	Particle Size Distribution/%					Total Amount of >0.25 mm Paddy Soil Water-Stable Aggregates/%	MWD/mm
		>2 mm	2~0.5 mm	0.5~0.25 mm	0.25~0.053 mm	<0.053 mm		
2018	T1	72.4 ± 2.6 a	12.0 ± 1.3 a	9.3 ± 1.0 a	4.2 ± 1.6 c	2.1 ± 1.6 b	93.7 ± 3.4 a	1.4 ± 0.0 a
	T2	62.5 ± 2.5 b	12.4 ± 1.2 a	11.3 ± 1.0 a	10.4 ± 1.7 b	3.4 ± 2.6 b	86.2 ± 1.0 b	1.3 ± 0.0 ab
	CK	47.9 ± 1.2 c	14,0 ± 1.1 a	11.9 ± 0.9 a	18.5 ± 1.5 a	7.7 ± 1.0 a	73.7 ± 0.9 c	1.2 ± 0.0 b
2019	T1	73.3 ± 1.3 a	10.3 ± 3.0 a	8.6 ± 2.9 a	4.3 ± 1.4 c	3.5 ± 1.4 b	92.2 ± 2.1 a	1.6 ± 0.0 a
	T2	64.7 ± 1.5 b	11.2 ± 2.1 a	91 ± 2.9 a	10.4 ± 1.0 b	4.6 ± 2.5 b	85.0 ± 3.9 b	1.4 ± 0.0 b
	CK	47.4 ± 0.7 c	13.6 ± 1.3 a	11.5 ± 1.2 a	20.5 ± 2.1 a	7.0 ± 1.7 a	72.4 ± 2.1 c	1.1 ± 0.0 c
2020	T1	77.1 ± 2.7 a	7.9 ± 2.7 a	6.9 ± 3.7 a	4.9 ± 1.5 c	3.2 ± 2.3 b	91.9 ± 4.3 a	1.7 ± 0.0 a
	T2	65.2 ± 1.5 b	10.4 ± 3.0 a	9.1 ± 2.9 a	11.0 ± 1.1 b	4.2 ± 2.4 b	84.7 ± 2.0 b	1.4 ± 0.0 b
	CK	45.7 ± 1.6 c	12.8 ± 1.3 a	11.5 ± 1.2 a	22.9 ± 2.3 a	7.1 ± 1.7 a	69.9 ± 5.1 c	1.2 ± 0.0 c

Different letters (a, b, and c) indicate significant differences between different treatments according to one-way ANOVA (Duncan, $p < 0.05$).

Starting in 2019, the differences among T1, T2, and CK in terms of the proportion of rice soil aggregates 2~0.5 mm and 0.5~0.25 mm in size were not notable, with the proportion of aggregates < 0.053 mm in T1 being markedly lower than that in CK. The proportions of rice soil aggregates > 2 mm in the T1 and T2 treatments surpassed that in the CK treatment by 25.9% and 17.3%, respectively. Simultaneously, the proportions of rice soil aggregates 0.25~0.53 mm in size were 16.3% and 10.1% lower than that of CK for T1 and T2, respectively. The overall quantities of rice soil aggregates > 0.25 mm were 19.8% and 12.6% greater than that of CK for T1 and T2, respectively. The MWD values for T1 and T2 were 37.0% and 24.4% greater than that of CK, respectively.

Starting in 2020, the differences among T1, T2, and CK in terms of the proportion of rice soil aggregates in the range of 0.5 to 0.25 mm were not significant. However, the proportion of rice soil aggregates with a size ranging from 2 to 0.5 mm and <0.053 mm in T1 was significantly lower than that in CK. The proportions of rice soil aggregates > 2 mm in the T1 and T2 treatments were 31.4% and 19.5% greater than that in the CK treatment, respectively. Moreover, the proportions of rice soil aggregates in the range of 0.25 to 0.53 mm were 18.0% and 11.9% lower than that in the CK treatment for T1 and T2, respectively. The total quantities of rice soil aggregates >0.25 mm were 21.94% and 14.78% greater than that of CK for T1 and T2, respectively. The MWD values for T1 and T2 were 45.2% and 28.7% greater than that of CK, respectively.

3.3. Effect on Soil Nutrients in Rice Fields

The three-year soil nutrient test data are presented in Table 2. Regarding the rice soil pH, the differences among the treatments were not significant in 2018 or 2019. However, in 2020, the rice soil pH was notably lower in the T1 and T2 treatments than in the CK treatment.

Table 2. Effect of tobacco straw return on soil nutrients.

Year	Treats	pH	OM/(g·kg^{-1})	TN/(g·kg^{-1})	TP/(g·kg^{-1})	TK/(g·kg^{-1})	AN/(mg·kg^{-1})	AP/(mg·kg^{-1})	AK/(mg·kg^{-1})
2018	T1	7.76 ± 0.02 a	17.1 ± 0.3 a	1.7 ± 0.0 a	1.54 ± 0.0 a	6.9 ± 0.1 a	90.2 ± 3.1 a	12.8 ± 1.2 a	74.9 ± 4.0 a
	T2	7.75 ± 0.04 a	17.0 ± 0.2 a	1.7 ± 0.0 b	1.49 ± 0.0 a	6.9 ± 0.3 a	89.8 ± 2.7 b	13.9 ± 0.6 a	69.5 ± 3.4 ab
	CK	7.77 ± 0.03 a	16.0 ± 0.3 b	1.6 ± 0.0 b	1.47 ± 0.1 a	6.9 ± 0.1 a	84.0 ± 1.7 c	13.2 ± 0.5 a	68.3 ± 2.5 b
2019	T1	7.75 ± 0.04 a	17.8 ± 0.3 a	1.7 ± 0.0 a	1.59 ± 0.0 a	6.9 ± 0.3 a	91.1 ± 1.4 a	13.8 ± 1.3 a	73.7 ± 2.1 a
	T2	7.82 ± 0.06 a	17.1 ± 0.3 a	1.6 ± 0.0 b	1.53 ± 0.0 a	6.9 ± 0.2 a	88.8 ± 2.3 b	13.1 ± 1.2 a	69.5 ± 2.4 ab
	CK	7.78 ± 0.03 a	16.2 ± 0.3 b	1.6 ± 0.0 b	1.49 ± 0.0 a	6.7 ± 0.3 a	83.1 ± 2.1 c	13.5 ± 1.0 a	67.4 ± 3.2 b
2020	T1	7.72 ± 0.02 b	18.4 ± 0.2 a	1.7 ± 0.0 a	1.64 ± 0.0 a	6.8 ± 0.0 a	105.4 ± 3.8 a	13.9 ± 1.4 a	81.3 ± 2.7 a
	T2	7.76 ± 0.02 b	17.6 ± 0.2 a	1.6 ± 0.0 b	1.60 ± 0.0 a	6.7 ± 0.0 a	94.7 ± 4.8 b	14.7 ± 0.6 a	79.9 ± 2.7 ab
	CK	7.82 ± 0.02 a	16.1 ± 0.4 b	1.6 ± 0.0 c	1.5 ± 0.0 a	6.7 ± 0.1 a	87.0 ± 1.5 c	13.4 ± 0.5 a	71.4 ± 6.8 b

Different letters (a, b, and c) indicate significant differences between different treatments according to one-way ANOVA (Duncan, $p < 0.05$).

In terms of rice soil organic matter, data across all three years indicated that the rice soil organic matter contents in the T1 and T2 treatments were significantly greater than that in the CK treatment. This suggests that the incorporation of a certain amount of tobacco straw into the field contributes to the enhancement of rice soil organic matter.

Concerning the total contents of nitrogen, phosphorus, and potassium in rice soil, during 2018 and 2019, the total nitrogen content in the rice soil in the T1 treatment was significantly greater than that in the T2 and CK treatments. In 2020, the total nitrogen content in the rice soil in the T1 treatment was significantly greater than that in the T2 treatment, and the total nitrogen content in the rice soil in both the T1 and T2 treatments was significantly greater than that in the CK treatment. Across all three years, there were no significant differences in the total phosphorus or potassium contents of the rice soil among the T1, T2, and CK treatments.

Regarding the contents of fast-acting nitrogen, phosphorus, and potassium in rice soil, over the three years, the alkaline dissolved nitrogen content in the rice soil in both the T1 and T2 treatments was significantly greater than that in the CK treatment. Additionally, the alkaline dissolved nitrogen content in the rice soil in the T1 treatment was significantly greater than that in the T2 treatment. Throughout the three years, there were no significant differences in the effective phosphorus content of the rice soil among the different treatments. The fast-acting potassium content in the rice soil in the T1 treatment was significantly greater than that in the CK treatment, as observed from the data collected across all three years.

3.4. Impact on the Biological Properties of Paddy Soil

3.4.1. Impact on Sucrase and Urease Activities in Paddy Soil

Soil sucrase actively participates in the metabolic breakdown of soil organic matter, and the enzymatic byproducts play a crucial role in crop growth. Therefore, soil sucrase activity serves as a direct indicator of soil biological activity and provides valuable insights into soil vitality. As depicted in Figure 2a, the rice soil sucrase activity exhibited an upward trend with increasing applications of tobacco straw. In 2018, the rice soil sucrase activities in T1 and T2 were 22.8% and 5.0% greater than that in CK, respectively. However, compared with that in the CK treatment, the soil sucrase activity in only the T1 treatment significantly increased. In 2019, the rice soil sucrase activities in T1 and T2 increased by 38.4% and 18.7%, respectively, compared to that in the CK treatment; both increases were statistically significant. In 2020, the rice soil sucrase activities in T1 and T2 were increased by 44.9%

and 29.8%, respectively, compared to those in CK, with both T1 and T2 demonstrating significantly greater sucrase activity than CK.

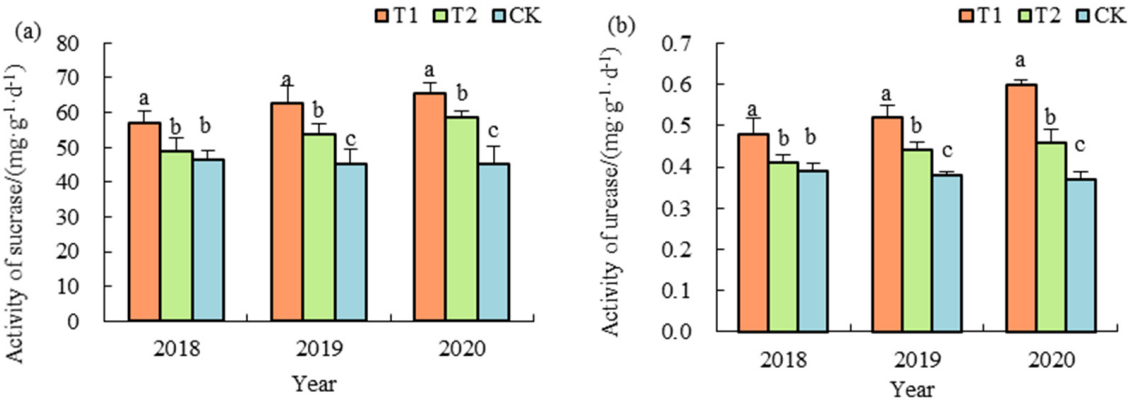

Figure 2. Effect of tobacco straw return on sucrase (**a**) and urease (**b**) activities in paddy soil. Different letters (a, b, and c) indicate significant differences between different treatments according to one-way ANOVA (Duncan, $p < 0.05$).

Soil urease plays a crucial role in converting soil urea into ammonium nitrogen, with the nitrogen produced serving as a vital source for crop nitrogen supply. Therefore, soil urease activity serves as an indicator of the level and capacity of soil nitrogen provision. As shown in Figure 2b, the rice soil urease activity exhibited an increasing trend with increasing tobacco straw return. In 2018, the rice soil urease activities in T1 and T2 were 23.1% and 5.1% greater than that in CK, respectively. However, compared with that in the CK treatment, only the rice soil urease activity in the T1 treatment significantly increased. In 2019, compared with that in the CK treatment, the soil urease activity in the T1 and T2 treatments increased by 36.8% and 15.8%, respectively, and both were significantly greater. In 2020, the rice soil urease activities in T1 and T2 were increased by 62.2% and 4.3%, respectively, compared to those in CK, with both T1 and T2 demonstrating significantly greater urease activity than CK.

3.4.2. Impact on Soil Microbial Alpha Diversity in Paddy Fields

Alpha diversity metrics reflect the abundance and diversity of species within individual samples. The alpha diversity indices for the bacterial and fungal communities in the soil samples from each treatment are presented in Table 3. Bacterial diversity indices did not exhibit significant differences among treatments over the three years. In contrast, the straw return treatment significantly enhanced the fungal Shannon, Simpson, Chao1, and ACE indices compared to those of the control, with the differences becoming more pronounced over the course of the three-year study.

Table 3. Diversity and abundance of bacteria and fungi under different straw return treatments.

Classification	Year	Treats	Shannon	Simpson	Chao1	Ace
Bacteria	2018	T1	10.6 ± 0.0 a	0.98 ± 0.01 a	5187.3 ± 17.5 a	5369.1 ± 12.4 a
		T2	10.2 ± 0.0 a	0.98 ± 0.02 a	5163.4 ± 16.5 a	5358.3 ± 21.5 a
		CK	10.3 ± 0.0 a	0.95 ± 0.01 a	4952.2 ± 20.2 a	5190.4 ± 32.5 a
	2019	T1	10.7 ± 0.0 a	0.98 ± 0.02 a	6342.6 ± 20.9 a	6548.0 ± 22.7 a
		T2	10.4 ± 0.0 a	0.97 ± 0.01 a	6328.7 ± 18.4 a	6479.6 ± 32.6 a
		CK	10.3 ± 0.0 a	0.96 ± 0.01 a	6257.7 ± 11.1 a	6449.6 ± 35.1 a
	2020	T1	11.2 ± 0.0 a	0.99 ± 0.02 a	6365.6 ± 24.0 a	6702.4 ± 32.7 a
		T2	11.0 ± 0.0 a	0.98 ± 0.01 a	6334.4 ± 20.5 a	6651.1 ± 45.8 a
		CK	10.4 ± 0.0 a	0.97 ± 0.01 a	6264.7 ± 16.6 a	6488.9 ± 31.8 a

Table 3. *Cont.*

Classification	Year	Treats	Shannon	Simpson	Chao1	Ace
Fungi	2018	T1	5.0 ± 0.2 a	0.85 ± 0.02 a	752.1 ± 14.9 a	732.8 ± 7.6 a
		T2	4.6 ± 0.1 a	0.79 ± 0.01 b	690.4 ± 12.6 b	701.6 ± 24.2 ab
		CK	3.6 ± 0.3 b	0.52 ± 0.02 c	640.6 ± 10.9 c	652.8 ± 23.7 b
	2019	T1	5.0 ± 0.3 a	0.88 ± 0.03 a	776.2 ± 18.9 a	761.6 ± 8.9 a
		T2	4.3 ± 0.2 a	0.81 ± 0.04 a	753.9 ± 19.6 ab	724.1 ± 12.1 b
		CK	3.1 ± 0.3 b	0.57 ± 0.02 b	676.8 ± 21.5 b	656.4 ± 11.8 c
	2020	T1	5.9 ± 0.2 a	0.92 ± 0.00 a	785.8 ± 12.5 a	792.4 ± 16.2 a
		T2	5.1 ± 0.4 b	0.83 ± 0.01 b	755.8 ± 11.0 b	737.2 ± 15.5 b
		CK	4.0 ± 0.1 c	0.59 ± 0.04 c	684.1 ± 9.7 c	675.5 ± 12.1 c

Different letters (a, b, and c) indicate significant differences between different treatments according to one-way ANOVA (Duncan, $p < 0.05$).

3.4.3. Impact on the Structure of Soil Fungal Communities in Paddy Fields

The species composition analysis results were visualized using stacked plots depicting the variation in species abundance at each taxonomic level for different samples. The 10 species with the highest mean abundance values across all samples were selected for detailed display. All the other species were collectively grouped into the "Other" category, while tags that could not be annotated to a specific level were categorized as "Unclassified".

The species composition of the soil fungal community at the phylum and genus levels following straw return is illustrated in Figure 3. At the phylum level (Figure 3a), Ascomycota was the fungal phylum with the highest relative abundance across treatments, followed by Ciliophyta. The relative abundance of the fungal community exhibited significant annual variation, with Ascomycota being dominant in 2018 and 2020 and Ciliophyta dominating in 2019. Figure 3b shows the composition of fungal genera in the samples from each treatment. In 2018, Aspergillus and Scutellinia exhibited the highest relative abundances. In 2019, Aspergillus and Coelastrella were predominant, while in 2020, Aspergillus, Penicillium, and Fusarium had the highest relative abundances.

3.4.4. Impact on the Structure of Soil Bacterial Communities in Rice Fields

The composition of the soil bacterial community at the phylum and genus levels following straw return is presented in Figure 4. At the phylum level (Figure 4a), Chloroflexi and Planctomycetes had the highest relative abundances in the soils of each treatment, followed by Actinobacteria, Proteobacteria, Acidobacteria, and Gemmatimonadetes. Figure 4b shows the composition of the bacterial genera in the soil samples from each treatment. Gemmatimonas had the highest relative abundance, followed by Gemmata. Other notable genera included Anaeromyxobacter, Bryobacter, Gaiella, Aquisphaera, and Pirellula.

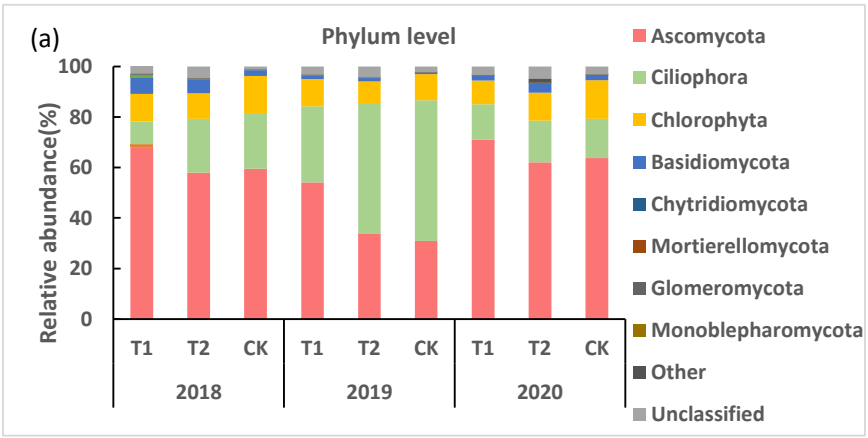

Figure 3. *Cont.*

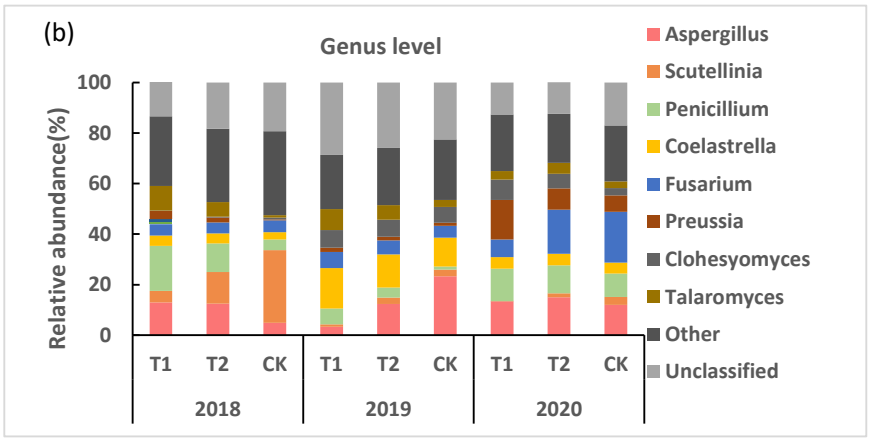

Figure 3. Histogram of fungal community distribution at the phylum (**a**) and genus (**b**) levels.

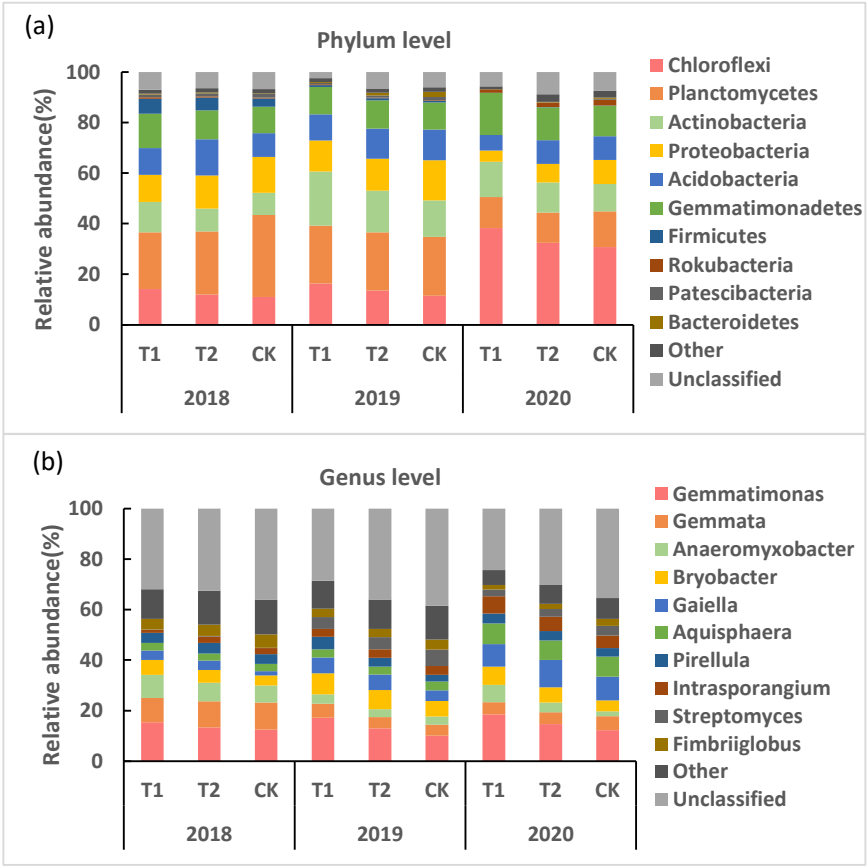

Figure 4. Histogram of bacterial community distribution at the phylum (**a**) and genus (**b**) levels.

3.4.5. Impact on Soil Fungal Beta Diversity in Paddy Fields

The principal coordinate analysis (PCoA) showed (Figure 5) that the first and second coordinate axes explained 20.7% and 15.4% of the original variance of the fungal community composition in 2018, respectively, and cumulatively 36.1%; the first and second coordinate axes explained 46.6% and 35.8% of the original variance of the fungal community composition in 2019, respectively, and cumulatively 82.4%; and the first and second coordinate axes in 2020 coordinate axis and the second coordinate axis explained 34.3% and 26.6% of the original variance in fungal community composition, respectively, cumulatively 60.9%. The separation of fungal communities under different treatments was obvious, indicating

that the fungal community structure of soil varied greatly under different treatments, and further increased with the increase in straw return years.

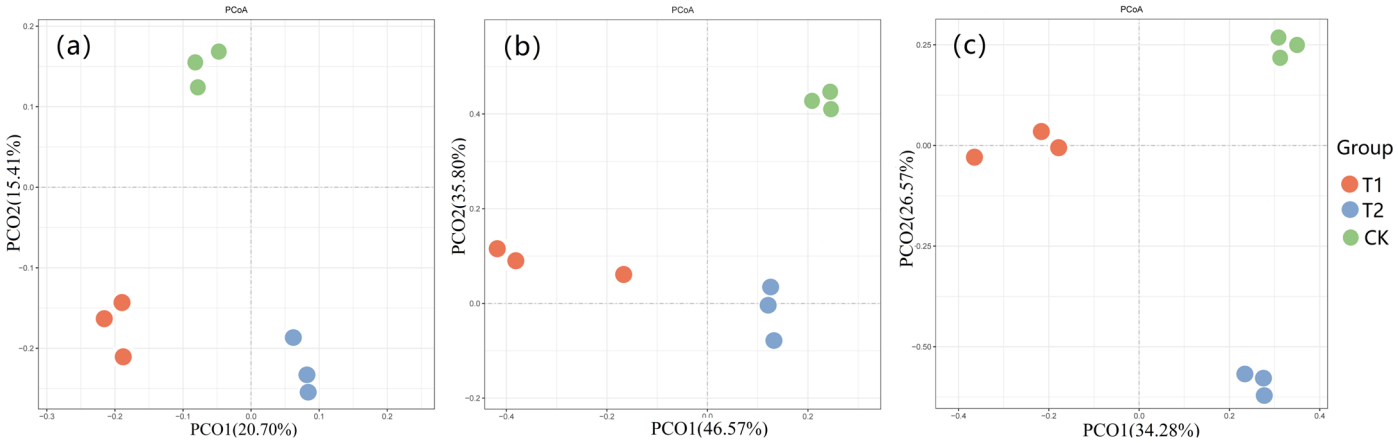

Figure 5. PCoA of fungal communities. Note: (**a**) 2018; (**b**) 2019; and (**c**) 2020.

3.4.6. Impact on Soil Fungal Beta Diversity in Paddy Fields

The PCoA showed (Figure 6) that the first and second coordinate axes explained 46.6% and 24.9% of the original variables of the bacterial community components in 2018, respectively, and cumulatively 71.5%; in 2019, the first coordinate axis and the second coordinate axis explained 50.8% and 17.1% of the original variables of the bacterial community components, respectively, and cumulatively 67.9%; in 2020, the first and second coordinate axes explained 25.9% and 12.9% of the original variables of the bacterial community composition, respectively, and cumulatively 37.1%. The separation of bacterial communities under different treatments was obvious, indicating that the bacterial community structure of soil varied greatly under different treatments, and further increased with the increase in straw return years.

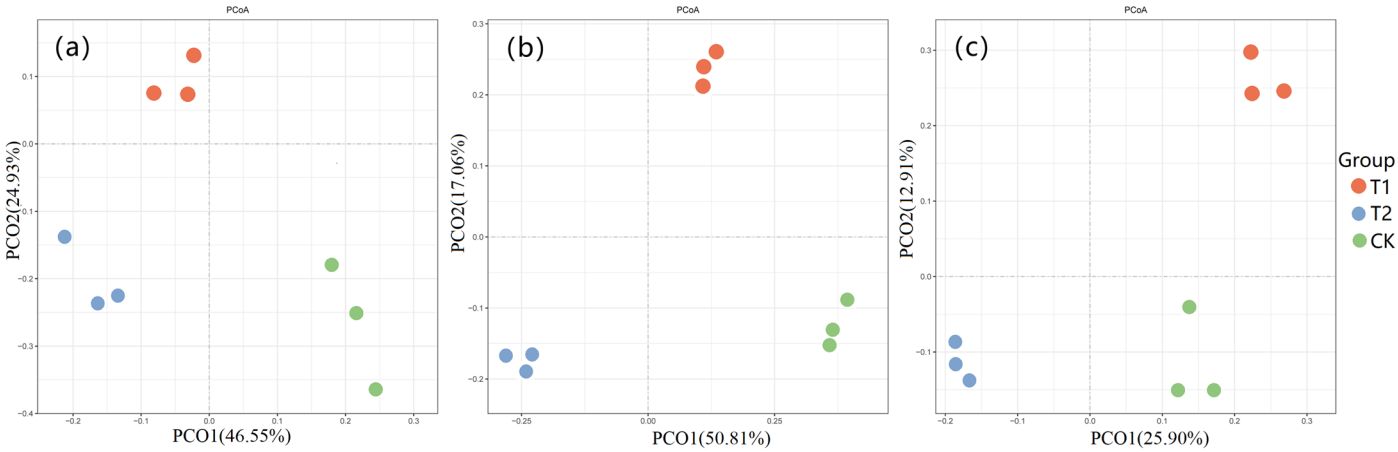

Figure 6. PCoA of bacterial communities. Note: (**a**) 2018; (**b**) 2019; and (**c**) 2020.

3.5. Effect on the Dry Matter Quality of Rice

As depicted in Figure 7, the differences in rice dry matter quality among the treatments were not significant in 2018. In 2019, the rice dry matter quality in T1 was significantly greater than that in CK, representing a 5.0% improvement, and the total rice dry matter content in T1 was significantly greater than that in T2 and CK. In 2020, both the dry matter quality of rice straw and the total dry matter content of rice were significantly greater than those in the CK treatment. The dry matter quality of rice in T1 was significantly greater than that in T2 and CK, with T1 exhibiting a 10.5% increase relative to that in CK. The

rice harvest indices ranged from 43.5% to 45.3%, with no significant differences observed among the treatments.

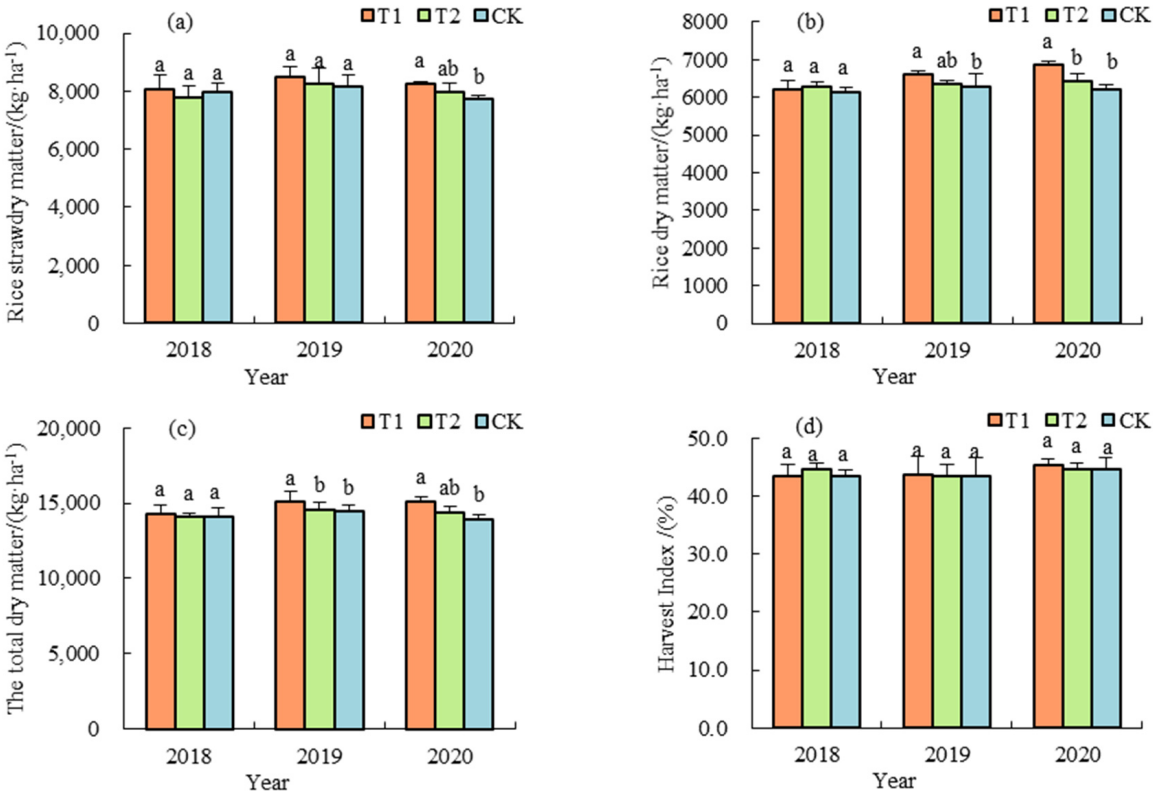

Figure 7. Effect of tobacco straw return on rice straw dry matter (**a**), rice dry matter (**b**), total dry matter (**c**) and harvest index (**d**). Different letters (a, b) indicate significant differences between different treatments according to one-way ANOVA (Duncan, $p < 0.05$).

3.6. Impact on Rice Yield and Its Components

As depicted in Table 4, straw return to the field had no significant effect on the increase in rice thousand-grain weight. However, when the full amount of straw was returned to the field, it significantly increased the effective number of rice spikes, the fruiting rate, and the number of sound grains per spike, thereby contributing to an overall increase in rice yield. There was no significant difference in rice yield among the treatments in 2018. In 2019 and 2020, the rice yield in the T1 treatment was significantly greater than that in the CK treatment, with increases of 5.4% and 5.1%, respectively.

Table 4. Effect of tobacco straw return on rice yield and its components.

Year	Treats	Effective Panicle /($\times 10^4$ Panicle·ha^{-1})	Seed Setting Rate/%	Grain Number /(Grain·Panicle^{-1})	1000-Grain Weight /g	Yield /(kg·ha^{-1})
2018	T1	331.6 ± 5.1 a	85.5 ± 3.2 a	88.7 ± 1.2 a	25.0 ± 0.8 a	6167.7 ± 208.5 a
	T2	328.6 ± 6.1 a	84.0 ± 1.8 ab	82.0 ± 2.3 b	24.7 ± 0.3 a	6147.5 ± 227.2 a
	CK	311.5 ± 5.1 b	81.4 ± 1.7 b	81.1 ± 2.8 b	24.1 ± 0.5 a	6086.0 ± 245.3 a
2019	T1	333.5 ± 10.8 a	88.8 ± 1.3 a	92.6 ± 1.4 a	25.1 ± 0.1 a	6347.8 ± 134.2 a
	T2	324.6 ± 6.1 a	84.9 ± 1.7 ab	79.8 ± 4.8 b	24.9 ± 0.1 a	6137.1 ± 117.5 ab
	CK	304.5 ± 12.6 b	80.7 ± 1.1 b	81.7 ± 3.9 b	24.2 ± 0.2 a	6025.6 ± 279.7 b
2020	T1	357.4 ± 16.1 a	86.0 ± 1.2 a	87.9 ± 2.1 a	24.9 ± 0.6 a	6412.6 ± 118.4 a
	T2	347.8 ± 15.0 ab	84.3 ± 1.3 ab	86.1 ± 2.1 a	24.4 ± 0.1 a	6208.3 ± 254.3 ab
	CK	306.2 ± 3.4 b	80.2 ± 1.6 b	82.9 ± 0.5 b	24.0 ± 0.4 a	6100.1 ± 156.5 b

Different letters (a, b) indicate significant differences between different treatments according to one-way ANOVA (Duncan, $p < 0.05$).

4. Discussion

The impact of straw return on soil physicochemical properties and rice growth has been investigated in previous studies [9,11,30–32]. Soil bulk density and porosity are fundamental physical properties of soil, where a larger bulk density corresponds to a lower porosity. This study revealed that returning tobacco straw to the field could decrease the soil bulk density and enhance the soil porosity. Specifically, returning the entire quantity of tobacco straw to the field had the most significant effect on improving soil. These findings align with the findings of Zhang [33] and Liu [34].

Soil structure is a crucial factor influencing soil fertility and crop yield, and its properties are intricately linked to land use practices and management strategies. Agricultural interventions such as tillage, planting, fertilizer application, and straw return to the field impact the process of soil particle aggregation and the stability of aggregates by altering soil properties, internal environments, and biological activity [6,7,35]. Aggregates, as the fundamental units of soil structure, play vital roles in sustaining soil fertility, regulating soil aeration and water retention, and mitigating soil erosion [36]. The porous structures of aggregates provide a heterogeneous environment for soil microorganisms and facilitate the interlaced growth of crop roots [37]. Aggregates with particle sizes > 0.25 mm are termed soil agglomerates and represent the optimal soil structure. The mass percentage of agglomerates with particle sizes > 0.25 mm (R0.25) serves as an indicator of soil structure quality. A higher R0.25 content indicates greater agglomerate stability, signifying improved soil structure [38]. This enhanced stability is more conducive to water and nutrient transformations in the soil, promoting plant growth and thereby enhancing soil productivity. A higher R0.25 content, therefore, indicates a superior soil structure. The results of this study revealed that the quantity of returned tobacco straw influenced the distribution ratio and stability of soil aggregates across various grain sizes. The MWD serves as a crucial metric for assessing soil aggregate stability. In essence, stronger stability corresponds to a larger MWD [39]. Returning tobacco straw to the field effectively enhanced the MWD value of the soil. Compared to the control, the incorporation of tobacco straw increased the presence of water-stable aggregates with sizes larger than 0.25 mm. This increase bolstered the stability of the soil aggregates, mitigated the degradation of the soil structure, and decreased the proportion of aggregates smaller than 0.25 mm. The primary mechanism underlying this phenomenon is the introduction of fresh straw, a rich organic residue, into the sub-tillage soil. This process leads to the continuous release of nutrients, heightened microbial activity, and the decomposition of various organic components within the straw, including organic acids, humic substances, polysaccharides, lignin, and other soil-binding agents. As a result, these components contribute to the formation of microaggregates by entangling soil particles. Furthermore, they facilitate the cementation of larger aggregates [40–42].

Numerous studies have consistently demonstrated that an optimal quantity of straw returned to the field can markedly enhance soil organic matter and increase the content of essential nutrients such as nitrogen, phosphorus, and potassium. Under the experimental conditions of this study, where tobacco straw was returned to the field in a flooded state, the nutrients were initially released into the water [43], followed by their subsequent incorporation into the soil. Research by Yang et al. [44] indicated that the direct application of crop straw and the use of decomposed organic fertilizer yield comparable effects in terms of soil fertilization, both of which significantly contribute to the improvement of soil physical and chemical properties. Moreover, Lao et al. [45] pointed out that long-term straw return, coupled with an appropriate amount of chemical fertilizer, is an effective strategy for soil cultivation and yield enhancement. Key indicators, including the accumulation of soil organic matter and the bioavailability of fast-acting nitrogen, phosphorus, and potassium, exhibited a highly significant positive correlation with the quantity of straw returned to the field. Xu et al. [46] observed a significant decrease in soil pH after the return of straw to the field, coupled with a notable increase in soil total phosphorus and soluble potassium content. Additionally, the soil organic matter content increased at rice maturity. In alignment with these findings, our experiment revealed that the tobacco straw return

treatment increased the soil organic matter, total nitrogen, alkaline dissolved nitrogen, and fast-acting potassium contents. Interestingly, a slight decrease in pH was observed. This pH reduction was primarily attributed to the nutrient-rich nature of tobacco straw, which, during decomposition, generated organic acids, contributing to the soil acidity. These results are largely consistent with those of previous research.

Soil enzyme activities exhibit a significant correlation with soil physicochemical properties, fertility status, and agricultural practices and serve as crucial indicators for assessing soil fertility [46]. The findings from this study indicate a noteworthy increase in soil sucrase and urease activities following the return of tobacco residue to the field. The elevated soil enzyme activities can be attributed, in part, to the increased microbial population resulting from the return of tobacco straw. This phenomenon may be attributed to improved soil permeability due to the incorporation of tobacco residue, which leads to reduced rooting resistance in rice. Consequently, the symbiotic interaction between rice roots and soil microorganisms intensifies, augmenting soil enzyme activities.

The application of crop residues to soil has been demonstrated to influence the structure of bacterial communities [47]. Straw, which is rich in organic matter and nutrients, not only enhances soil fertility, but also serves as a habitat for soil organisms to colonize [48]. In the present study, the Shannon and Simpson indices for fungi in the straw-returned treatments revealed a significant increase in the diversity of the fungal communities. Moreover, the Chao1 and ACE indices indicated a notable increase in the abundance of fungal communities in the straw-returned treatments. This is likely attributed to the mineralization of organic matter during straw return, which depletes oxygen from the soil and consequently elevates the relative abundance of parthenogenetic anaerobic microorganisms or anaerobic microorganisms in the soil [49]. In accordance with Liu et al. [50], straw return plays a crucial role in influencing soil microbial species and soil enzymes. Previous investigations have demonstrated that direct straw return leads to a more substantial improvement in soil microbial abundance than biochar does [51]. The type and activity of soil microorganisms also play pivotal roles in the decomposition of straw [52]. At the bacterial phylum level, the relative abundances of Chloroflexi and Actinobacteria were greater in the T1 and T2 treatments than in the CK treatment. Chloroflexi, characterized by filamentous bacteria, are active exclusively under aerobic conditions and primarily consume carbohydrates, facilitating the degradation of hemicellulose in straw [53]. Many members of Actinobacteria are recognized for their capacity to degrade lignocellulose [54], contributing to the decomposition of tobacco residues. At the bacterial phylum level, the relative abundances of Gemmatimonas and Bryobacter were greater in the T1 and T2 treatments than in the CK treatment. Members of Gemmatimonas and Bryobacter have been reported to possess the ability to decompose organic matter in the soil, including cellulose and lignin [55,56]. At the fungal phylum level, the dominant phylum with the highest abundance in the fungal community was Ascomycetes, a group of saprophytic fungi known for producing cellulases capable of decomposing organic matter in the soil, such as cellulose and lignin. The plant residues from the straw returned to the field released nutrients under the degradation by Ascomycetes [57]. The results indicated that the relative abundance of Ascomycetes in the straw-returned treatments was significantly greater than that in the CK treatment. At the fungal genus level, the relative abundance of the beneficial fungus Penicillium increased with straw return, while the relative abundance of Fusarium, a soil-borne root rot pathogen of tobacco [58], decreased. Tobacco straw return treatment was shown to enhance microbial diversity, alter microbial (bacterial and fungal) community composition, and increase the abundance of beneficial microorganisms. These findings align with those of the study by Chen et al. [59]. It was previously suggested that rice straw return has a comparatively lesser impact on microbial communities [60]. This may be attributed to the fact that straw return predominantly influences fungal communities, given their ability to secrete numerous extracellular enzymes for the degradation of recalcitrant materials in straw [61,62]. As a result, the impact of straw return on bacteria communities was found to be less pronounced.

There are discrepancies in the findings regarding the impact of straw return on rice yield. Li Fengbo et al. [63] conducted a study in Jiangsu and revealed no significant effect on rice yield when straw was returned to the field. This difference might be attributed to the high carbon-to-nitrogen ratio of straw, which makes it challenging for microorganisms to decompose naturally, leading to slow decomposition in the soil, and ultimately serving as a delayed fertilizer source [64]. In Heilongjiang, Shan Tibo et al. [65] reported that the quantity of returned straw significantly influenced the number of grains in spikes and the fruiting rate of rice, with higher amounts contributing to increased yield.

5. Conclusions

In the rice planting field, the incorporation of tobacco straw back into the soil led to a reduction in soil bulk density and an increase in soil porosity. The quantity of tobacco straw returned to the field influenced the distribution and stability of the soil aggregates of varying sizes, effectively enhancing the MWD of the soil. Compared to that in the CK treatment, the reintroduction of tobacco straw elevated the content of water-stable aggregates with a particle size greater than 0.25 mm, thereby enhancing the soil aggregate stability. This approach concurrently decreased the rate of soil structure disruption and decreased the content of aggregates with a particle size less than 0.25 mm. Furthermore, the tobacco straw return treatment resulted in increased levels of soil organic matter, total nitrogen, alkaline dissolved nitrogen, and fast-acting potassium, with a slight decrease in soil pH. Moreover, soil sucrase and urease activities, in addition to soil microbial community diversity, significantly increased. The application of tobacco straw to the field positively influenced rice parameters, such as the fruiting rate and the number of sound grains per spike, contributing to an overall increase in rice yield. Compared to T2, T1 exhibited greater efficacy in different treatments. Advocating for the widespread adoption of this practice in tobacco–rice replanting areas promises environmental benefits and favorable rice yields.

Author Contributions: Conceptualization, J.H. and X.W.; methodology, J.H., X.W., L.Y. and X.D.; software, J.H., B.X. and H.L.; validation, J.H., B.X. and H.L.; formal analysis, J.H., Y.L. and X.D.; investigation, J.H., L.Y. and X.D.; resources, X.W., B.X., L.Y. and H.L.; data curation, J.H., Y.L. and X.D.; writing—original draft preparation, J.H.; writing—review and editing, J.H. and X.D.; visualization, J.H.; supervision, X.W., Y.L. and X.D.; project administration, X.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We gratefully acknowledge the Key Laboratory of Multi-cropping and Farming System, Ministry of Agriculture, for providing the necessary equipment for this study.

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

References

1. Jin, Z.; Liang, W.; Li, Y.; Wang, X. Effect of Continuous and Multiple Cropping of Tobacco-Rice on Economic Attributes and Quality of Flue-cured Tobacco. *Chin. Tob. Sci.* **2014**, *35*, 22–27. [CrossRef]
2. Hu, Q.; Liu, T.; Ding, H.; Li, C.; Yu, M.; Liu, J.; Cao, C. The effects of straw returning and nitrogen fertilizer application on soil labile organic carbon fractions and carbon pool management index in a rice-wheat rotation system. *Pedobiologia* **2023**, *101*, 150913. [CrossRef]
3. Gao, Y.; Shao, Y.; Wang, J.; Hu, B.; Feng, H.; Qu, Z.; Liu, Z.; Zhang, M.; Li, C.; Liu, Y. Effects of straw returning combined with blended controlled-release urea fertilizer on crop yields, greenhouse gas emissions, and net ecosystem economic benefits: A nine-year field trial. *J. Environ. Manag.* **2024**, *356*, 120633. [CrossRef]
4. Ibrahim, M.; Cao, C.G.; Zhan, M.; Li, C.F.; Iqbal, J. Changes of CO_2 emission and labile organic carbon as influenced by rice straw and different water regimes. *Int. J. Environ. Sci. Technol.* **2013**, *12*, 263–274. [CrossRef]
5. Zhu, G.Y.; Shangguan, Z.P.; Deng, L. Variations in soil aggregate stability due to land use changes from agricultural land on the Loess Plateau, China. *Catena* **2021**, *200*, 105181. [CrossRef]

6. Zhao, H.L.; Shar, A.G.; Li, S.; Chen, Y.L.; Shi, J.L.; Zhang, X.Y.; Tian, X.H. 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]
7. Li, Y.; Abalos, D.; Arthur, E.; Feng, H.; Siddique, K.H.M.; Chen, J. Different straw return methods have divergent effects on winter wheat yield, yield stability, and soil structural properties. *Soil Tillage Res.* **2024**, *238*, 105992. [CrossRef]
8. Panneerselvam, P.; Senapati, A.; Mitra, D.; Priyadarshin, A.; Shadangi, S.; Behera, S.; Kumar, U.; Kumar, A.; Shahid, M.; Sharma, S.; et al. Enhancing soil quality and yield through microbial assisted in-situ residue management in rice-rice cropping system in Odisha, Eastern India. *J. Environ. Manag.* **2024**, *358*, 120916. [CrossRef]
9. Xu, J.; Yin, S.; Hu, N.; Gu, Z.; Wang, B.; Zhu, L. Effects of annual straw return on soil nutrients, microbial activity and yield in rice-wheat rotation farmland. *J. Appl. Environ. Biol.* **2015**, *21*, 1100–1105.
10. Fan, W.; Wu, J. Short-term effects of returning granulated straw on soil microbial community and organic carbon fractions in dryland farming. *J. Microbiol.* **2020**, *58*, 657–667. [CrossRef]
11. Liu, L.; Ding, M.J.; Zhou, L.K.; Chen, Y.; Li, H.P.; Zhang, F.M.; Li, G.; Zhou, Z.F.; Zhang, Y.; Zhou, X.X. Effects of Different Rice Straw on Soil Microbial Community Structure. *Agron. J.* **2020**, *113*, 794–805. [CrossRef]
12. Bai, N.; Zhang, H.; Zhou, S.; Sun, H.; Lv, W. Long-term effects of straw return and straw-derived biochar amendment on bacterial communities in soil aggregates. *Sci. Rep.* **2020**, *10*, 7891. [CrossRef] [PubMed]
13. Yu, C.; Li, Y.; Mo, R.; Deng, W.; Zhu, Z.; Liu, D.; Hu, X. Effects of long-term straw retention on soil microorganisms under a rice-wheat cropping system. *Arch. Microbiol.* **2020**, *202* (Suppl. S1), 1915–1927. [CrossRef] [PubMed]
14. Pankhurst, C.E.; Ophel, K.K.; Doube, B.M. Biodiversity of soil microbial communities in agricultural systems. *Biodivers. Conserv.* **1996**, *5*, 197–209. [CrossRef]
15. Li, X.; Wang, Q.; Xu, F. Effects of rice straw returned to the field on the adsorption-desorption of soil potassium, phosphorus and zinc and their effectiveness. *J. Cent. China Agric. Univ.* **2000**, 227–232. [CrossRef]
16. Soil Physics Research Laboratory; Nanjing Soil Research Institute; Chinese Academy of Sciences. *Method for the Determination of Soil Physical Properties*; Science Press: Beijing, China, 1978.
17. Six, J.; Elliott, E.T.; Paustian, K. Soil structure and soil organic matter: II. A normalized stability index and Effect of mineralogy. *Soil Sci. Soc. Am. J.* **2000**, *64*, 1042–1049. [CrossRef]
18. Bao, S. *Soil Agrochemical Analysis*; China Agricultural Press: Beijing, China, 2000.
19. Guan, S.-Y. *Soil Enzymes and Their Research Methods*; Agricultural Press: Beijing, China, 1986.
20. Guo, M.; Wu, F.; Hao, G.; Qi, Q.; Li, R.; Li, N.; Wei, L.; Chai, T. Bacillus subtilis improves immunity and disease resistance in rabbits. *Front. Immunol.* **2017**, *8*, 354. [CrossRef] [PubMed]
21. Toju, H.; Tanabe, A.S.; Yamamoto, S.; Sato, H. High-coverage ITS primers for the DNA-based identification of ascomycetes and basidiomycetes in environmental samples. *PLoS ONE* **2012**, *7*, e40863. [CrossRef] [PubMed]
22. Elmar, P.; Christian, Q.; Katrin, K.; Fuchs, B.M.; Wolfgang, L.; Jrg, P. SILVA: A comprehensive online resource for quality checked and aligned ribosomal RNA sequence data compatible with ARB. *Nucleic Acids Res.* **2007**, *35*, 7188–7196. [CrossRef] [PubMed]
23. Ankenbrand, M.J.; Keller, A.; Wolf, M.; Schultz, J.; Frster, F. ITS2 database V: Twice as much. *Mol. Biol. Evol.* **2015**, *32*, 3030–3032. [CrossRef]
24. Caporaso, J.G.; Kuczynski, J.; Stombaugh, J.; Bittinger, K.; Bushman, F.D.; Costello, E.K.; Fierer, N.; Peña, A.G.; Goodrich, J.K.; Gordon, J.I.; et al. QIIME allows analysis of high-throughput community sequencing data. *Nat. Methods* **2010**, *7*, 335–336. [CrossRef] [PubMed]
25. Chao, A.; Yang, M.C.K. Stopping rules and estimation for recapture debugging with unequal failure rates. *Biometrika* **1993**, *80*, 193–201. [CrossRef]
26. Chao, A. Nonparametric Estimation of the Number of Classes in a Population. *Scand. J. Stat.* **1984**, *11*, 265–270.
27. Shannon, C.E. A mathematical theory of communication. *Bell Syst. Tech. J.* **1948**, *27*, 379–423. [CrossRef]
28. Simpson, E.H. Measurement of Diversity. *Nature* **1949**, *163*, 688. [CrossRef]
29. Li, G.; Zhang, J.; Yang, C.; Liu, Z.; Wang, S.; Ding, Y. Population Characteristics of High-Yielding Rice under Different Densities. *Agron. J.* **2016**, *108*, 1415–1423. [CrossRef]
30. Liu, Y.; Li, J.; Jiao, X.Y.; Li, H.D.; Hu, T.S.; Jiang, H.Z.; Mahmoud, A.L. Effects of biochar on water quality and rice productivity under straw returning condition in a rice-wheat rotation region. *Sci. Total Environ.* **2022**, *819*, 152063. [CrossRef] [PubMed]
31. Yang, S.Q.; Chen, L.M.; Xiong, R.Y.; Jiang, J.L.; Liu, Y.Q.; Tan, X.M.; Liu, T.J.; Zeng, Y.J.; Pan, X.H.; Zeng, Y.H. Long-term straw return improves cooked indica rice texture by altering starch structural, physicochemical properties in South China. *Food Chem. X* **2023**, *20*, 100965. [CrossRef] [PubMed]
32. Wang, J.; Wang, D.; Zhang, G. Effects of straw return with nitrogen fertilizer on rice yield and economic benefits under rice-wheat rotation in Taihu Lake area. *Chin. J. Ecol. Agric.* **2011**, *19*, 265–270. [CrossRef]
33. Zhang, C.; Mu, P.; Shang, J. Effects of long-term continuous straw return on soil physicochemical properties, enzyme activities and yield traits. *Res. Soil Water Conserv.* **2018**, *25*, 92–98.
34. Liu, J.; Zhang, Y.; Cui, G. Effects of straw return on soil physicochemical properties and wheat yield. *Hebei Agric. Sci.* **2017**, *21*, 44–48+98.
35. Cheng, Y.; Ren, H.; Liu, P.; Dong, S.T.; Zhang, J.W.; Zhao, B.; Li, G.; Liu, S.K. Effects of different cultivation and management modes on soil aggregate composition and its carbon and nitrogen distribution in agricultural soils. *J. Appl. Ecol.* **2016**, *27*, 3521–3528.

36. Zhao, J.S.; Chen, S.; Hu, R.G. Aggregate stability and size distribution of red soils under different land uses integrally regulated by soil organic matter, and iron and aluminum oxides. *Soil Tillage Res.* **2017**, *167*, 73–79. [CrossRef]
37. Wang, Y.; Hu, N.; Ge, T.; Kuzyakov, Y.; Wang, Z.L.; Li, Z.; Tang, Z.; Chen, Y.; Wu, C.; Lou, Y. Soil aggregation regulates distributions of carbon, microbial community and enzyme activities after 23-year manure amendment. *Appl. Soil Ecol.* **2017**, *111*, 65–72. [CrossRef]
38. Zhang, S.T.; Ren, T.; Cong, W.F.; Fang, Y.T.; Zhu, J.; Zhao, J.; Cong, R.H.; Li, X.K.; Lu, J.W. Oilseed rape-rice rotation with recommended fertilization and straw returning enhances soil organic carbon sequestration through influencing macroaggregates and molecular complexity. *Agric. Ecosyst. Environ.* **2024**, *367*, 108960. [CrossRef]
39. Zhang, Y.; Sheng, Z.; Wang, Y.; Su, S.; Ling, B.; Wu, C.; Zeng, X. Long-term manure application enhances the stability of aggregates and aggregate-associated carbon by regulating soil physicochemical characteristics. *Catena* **2021**, *203*, 105342. [CrossRef]
40. Sodhi, G.; Beri, V.; Benbi, D.K. Soil aggregation and distribution of carbon and nitrogen in different fractions under long-term application of compost in rice-wheat system. *Soil Tillage Res.* **2009**, *103*, 412–418. [CrossRef]
41. Xue, Y.; Xue, W.; Zhang, S. Effects of long-term different fertilization on small soil agglomerate cementation. *J. Plant Nutr. Fertil.* **2015**, *21*, 1622–1632.
42. Du, J.; Zhang, B.; Xie, H. Effects of different fertilization treatments on soil protein content of ballooning. *Soil Bull.* **2011**, *42*, 573–577.
43. Cheng, J.; Huang, J.; Deng, X.; Huang, G.; Yang, L.; Zhang, W.; He, M.; Li, F.; Xie, P.; Pei, X. Characteristics of tobacco stubble flooding decay and its effect on water quality. *China Tob. Sci.* **2019**, *40*, 33–41. [CrossRef]
44. Yang, Z.; Lu, Y.; Zhang, F. Comparative analysis of fertilizing effect of straw returned to field and rotted organic fertilizer on rice soil. *J. Agric. Eng.* **2008**, *24*, 214–218.
45. Lao, X.; Sun, W.; Wang, Z. Effects of straw return and fertilizer application on soil fertility. *Soil Sci. J.* **2003**, *40*, 618–623.
46. Yu, L.; Zhang, Y.; Wang, Y.; Yao, Q.; Yang, K. Effects of slow-release nitrogen and urea combined application on soil physico-chemical properties and fungal community under total straw returning condition. *Environ. Res.* **2024**, *252*, 118758. [CrossRef] [PubMed]
47. Jiang, C.; Zu, C.; Riaz, M.; Li, C.; Zhu, Q.; Xia, H.; Dong, Q.; Shen, J. Influences of tobacco straw return with lime on microbial community structure of tobacco-planting soil and tobacco leaf quality. *Environ. Sci. Pollut. Res. Int.* **2024**, *31*. [CrossRef]
48. Delcher, A.L.; Bratke, K.A.; Powers, E.C.; Salzberg, S. Identifying bacterial genes and endosymbiont DNA with Glimmer. *Bioinformatics* **2007**, *23*, 673–679. [CrossRef]
49. Chen, Z.M.; Wang, H.Y.; Liu, X.W. Changes in soil microbial community and organic carbon fractions under short-term straw return in a rice-wheat cropping system. *Soil Tillage Res.* **2017**, *165*, 121–127. [CrossRef]
50. Liu, B.; Xia, H.; Jiang, C.C.; Riaz, M.; Yang, L.; Chen, Y.F.; Fan, X.P.; Xia, X.E. 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]
51. Li, H.; Li, B.Z.; Zou, D.S. Impacts of rice straw and its biochar product on the amounts of soil microbial biomass carbon and nitrogen and the mineralization of soil organic nitrogen in subtropical croplands. *Res. Agric. Mod.* **2015**, *36*, 303–308.
52. Song, K.; Zhou, C.; Li, H.; Zhou, Z.; Ni, G.; Yin, X. Effects of rumen microorganisms on straw returning to soil at different. *Eur. J. Soil Biol.* **2023**, *114*, 103454. [CrossRef]
53. Wegner, C.E.; Liesack, W. Microbial community dynamics during the early stages of plant polymer breakdown in paddy soil. *Environ. Microbiol.* **2016**, *18*, 2825–2842. [CrossRef]
54. Rong, L.; Zhao, L.; Zhao, L.; Cheng, Z.P.; Yao, Y.M.; Yuan, C.L.; Wang, L.; Sun, H.W. LDPE microplastics affect soil microbial communities and nitrogen cycling. *Sci. Total Environ.* **2021**, *773*, 145640. [CrossRef] [PubMed]
55. Guo, L.; Zheng, S.; Cao, C.; Li, C.F. Tillage practices and straw-returning methods affect topsoil bacterial community and organic C under a rice-wheat cropping system in central China. *Sci. Rep.* **2016**, *6*, 33155. [CrossRef]
56. Liu, J.; Yu, Z.; Qin, Y.; Hu, X.J.; Zhang, W. Distinct soil bacterial communities in response to the cropping system in a Mollisol of northeast China. *Appl. Soil Ecol.* **2017**, *119*, 407–416. [CrossRef]
57. Liu, S.; Han, Y.; Zhu, X. Effects of cotton stalk charcoal modulation on the structure and function of inter-root soil fungal communities in alkaline cadmium-contaminated rice. *Environ. Sci.* **2020**, *41*, 3846–3854.
58. Gai, X.T.; Jiang, N.; Lu, C.H.; Xia, Z.Y.; He, Y.S. First Report of Tobacco Fusarium Root Rot Caused by *Fusarium verticillioides* in China. *Plant Dis.* **2021**, *105*, 3762. [CrossRef]
59. Chen, J.; He, J.; Zhang, Y.; Huang, J.; Chen, Z.F.; Zeng, W.A. Effects of tobacco plant residue return on rhizosphere soil microbial community. *Ann. Microbiol.* **2022**, *72*, 42. [CrossRef]
60. Maarastawi, S.A.; Frindte, K.; Linnartz, M.; Knief, C. Crop rotation and straw application impact microbial communities in Italian and Philippine soils and the rhizosphere of *Zea mays*. *Front. Microbiol.* **2018**, *9*, 1295. [CrossRef] [PubMed]
61. Pan, F.; Li, Y.; Chapma, S.J.; Khan, S.; Yao, H. Microbial utilization of rice straw and its derived biochar in a paddy soil. *Sci. Total Environ.* **2016**, *559*, 15–23. [CrossRef]
62. Zhang, X.F.; Xin, X.L.; Zhu, A.N.; Yang, W.L.; Zhang, J.B.; Ding, S.J.; Mu, L.; Shao, L.L. Linking macroaggregation to soil microbial community and organic carbon accumulation under different tillage and residue managements. *Soil Tillage Res.* **2018**, *178*, 99–107. [CrossRef]

63. Li, F.; Niu, Y.; Gao, W. Effects of tillage and straw return on soil physicochemical properties and yield of direct seeded rice fields. *Soil Bull.* **2008**, *39*, 549–552.
64. Li, F.; Wei, H.; Cao, J. Degradation rate of straw returned to the field in calcareous soil and its effect on soil fertility (in English). *J. Resour. Ecol.* **2015**, *6*, 217–223.
65. Shan, T.; Wei, H.; Wang, A. The effects of rice straw returned to the field with chemical nitrogen fertilizer on the growth and development, yield and quality of rice. *J. Jiangxi Agric. Univ.* **2010**, *32*, 265–270.