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Rice Straw Composting Improves the Microbial Diversity of Paddy Soils to Stimulate the Growth, Yield, and Grain Quality of Rice

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Abstract: This study aimed to explore the effects of straw compost with different proportions as replacement to chemical fertilizer on soil microorganisms as well as rice growth yield and quality. The rice variety Quan9you 063 in Fengyang, Anhui province was employed as the research subject. Four experimental treatments were set: local conventional fertilization as a control (CK) and compost substituting chemical fertilizer at 10% (T1), 20% (T2), and 30% (T3) to investigate the effects of straw composting. Our findings revealed that T1 treatment had the best rice yield-increasing effect ($p < 0.05$). Compared with CK, the rice yield, grain number per panicle, and rice polishing rate increased by 6.43%, 21.60%, and 0.47%, respectively; the chalkiness and chalky grain rate decreased by 25.77% and 55.76%, respectively. The T1 treatment achieved significantly higher relative abundance of β-Proteobacteria, *Sideroxydans*, *Methanoregula*, and *Candidatus Nitrosocosmicus*, indicating that the compost replacing 10% chemical fertilizer notably increased the microbial diversity. Hence, the replacement of 10% of chemical fertilizers with compost can enhance the rice yield.

Keywords: rice straw compost; soil microbial diversity; rice; grain yield

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1. Introduction

The production of rice, the largest food crop in China, has been increasing every year with the continuous improvement of production technology and management levels in recent years. The amount of fertilizer application also increases annually. Excessive application of chemical fertilizers is a common problem in China's rice planting industry. In 2013, China's arable land area was 122 million ha, accounting for 8.6% of the global arable land area. The input of chemical fertilizers in China's agriculture is as high as 59.119 million tons, accounting for 35.5% of the global fertilizer use. The application of chemical fertilizers per acre is 8 kg higher than the world average [1]. Unreasonable fertilization will not only reduce fertilizer utilization and increase agricultural production costs, but also cause serious damage to the soil and the environment [2]. Efficient fertilization can not only increase the fertilizer utilization efficiency, but also maintain long-term sustainable soil production [3]. The current scientific and reasonable methods of using fertilizers include organic fertilizer substitution, formula fertilization, and straw return to the field. China's straw production is as high as 1.04 billion tons per year, accounting for 1/4 of the world's total straw production [4]. However, the direct return of straw, which is commonly conducted, has negative effects, such as reduced crop emergence rates, aggravation of crop diseases and insect pests, and accumulation of toxic and harmful substances such as heavy metals in the soil [5]. Therefore, the return of high-temperature compost to the field is gradually replacing direct return to the field.

Composting technology mainly uses microbial agents, which greatly shorten the biodegradation time of crop straw and turn it into compost. Crop straw composting is not only an important measure to improve soil fertility, but also an important material condition for regulating soil microorganisms [6,7]. The content and diversity of bacteria and archaea in the soil are important criteria for judging the health of the local soil environment. With a rich and diverse soil environment of bacteria and archaea, its ecosystem is often stable and healthy [8]. Zhang et al. [9] combined the application of nitrogen, phosphorus, and potassium fertilizers with straw return to the field; the results showed that it enriched the biomass of bacteria and archaea and increased their species diversity. At the same time, the intensity of straw return to the field was greater than that of applying nitrogen, phosphorus, and potassium fertilizers. Therefore, the value and effect of straw compost return to the field should not be underestimated in terms of the diversity of soil microbial communities. Currently, research has been conducted on compost returning to the field. Zhang et al. [10] found that utilizing compost replaceing N fertilizer is an effective nutrient management strategy to maintain N uptake and yield of maize, reduce N loss, and increase soil fertility. Liu revealed that the composted pineapple residue return to the field can increase the contents of available P and K, the fruit transverse and longitudinal diameters, and the weight and yield of pineapple [11]. The composted return to the field has a significant effect on promoting soil properties and crop growth.

Compost returning to the field has not been thoroughly studied, and the most appropriate proportion of compost to replace chemical fertilizers remains unclear. The effects of reducing the application of chemical fertilizers and composting on the growth and development of rice fields and microorganisms in the soil are not commonly known. This study conducted multiple treatments to explore the effects of substitution of chemical fertilizers with different compost ratios on rice growth and development. It aimed to determine the dominant microorganisms of bacterial and archaeal communities and explain various factors that affect the structure of the microbial community. Results can be used to effectively improve rice growth, yield, and grain quality and decrease the application of chemical fertilizers to address the effects of improper fertilization. This work provides a practical guidance and a scientific theoretical basis for the application of straw fertilizer in Anhui province.

2. Materials and Methods

2.1. Experimental Site and Preparation of Composting Materials

This experiment was carried out at the Straw Industry Research Institute of Anhui University of Science and Technology (E 117°33′39′′, W 32°52′49′′) from May 2020 to November 2020. The local annual average temperature is 15 °C, the annual average precipitation is up to 1200 mm, the soil (0–20 cm depth cores) is sandy loam (USDA soil classification system), and the frost-free period is 230 d. After the wheat was harvested in June, rice was planted in field soil. The contents of organic matter, available nitrogen, available potassium, and available phosphorus in the field soil were 20.8 $g \cdot kg^{-1}$, 110.9 $mg \cdot kg^{-1}$, 115.2 $mg \cdot kg^{-1}$, and 25.8 $mg \cdot kg^{-1}$, respectively. The rice variety used in the experiment was Quan9you 063. Rice straw was used.

Composting was performed at Plant Science Park of Anhui Science and Technology University (32°87′ N, 117°5′ E, 5.2 m above sea level) (Anhui, China). Cow manure and rice straw were used as original materials and provided by local farmers and Xiaogang Village, Fengyang County, China, respectively (Table 1). The raw materials for composting were rice straw and cow manure at 2:1 compost. The contents of nitrogen, phosphorus, and potassium were 1.03%, 0.87%, and 1.35%, respectively; the organic matter content was 47.8%; and the pH was 6.67.

Table 1. Physical and chemical properties of raw materials for compost.

Materials	Moisture Content (%)	Total Organic Carbon Mass Fraction (g/kg)	pH	Total Nitrogen (g/kg)	Total Phosphorous (g/kg)	Total Potassium (g/kg)	C/N
Cow manure	61.43 ± 0.64	394.65 ± 0.36	7.25 ± 0.13	23.56 ± 0.17	28.57 ± 0.42	11.25 ± 0.17	15.83
Rice straw	13.76 ± 0.26	468.35 ± 0.42	6.41 ± 0.02	8.89 ± 0.24	3.31 ± 0.47	78.73 ± 0.25	53.79

Notes: Values in average ± standard deviation.

2.2. Experimental Design and Treatments

The four experimental treatments and their contents in the rice field are shown in Table 2. Each treatment was repeated three times, and the size of the plot was 7 m × 2 m. The proportion of fertilizer and compost in the experimental plots was equal to the amount of nitrogen released (148.5 kg·ha). The nitrogen released by compost was calculated as 29.7% of the total nitrogen. A random block arrangement was utilized.

Table 2. Four experimental treatments and their contents in rice fields.

Treatment	Processing Content		
	Compound Fertilizer	Urea	Compost
CK	375 kg/ha	225 kg/ha	0
T1	337.5 kg/ha	202.5 kg/ha	5 t/ha
T2	300 kg/ha	180 kg/ha	10 t/ha
T3	262.5 kg/ha	157.5 kg/ha	15 t/ha

On 16 May, seedling trays were used to raise seedlings for each plot. The planting amount was 75 g of rice seeds. The soil was prepared on 18 June, supplemented with compost, compound fertilizer, and 60% urea on 25 June, and transplanted on 27 June. Irrigation was conducted according to the different stages of rice growth, and timely weed control was performed. The management of the paddy field referred to the research method of Wei et al. [12]. The 40% remaining urea was applied on 15 August 2020. Rice was harvested on 30 October 2020.

2.3. Data Collection

2.3.1. Rice Growth and Quality Indicators

The tiller dynamics of rice were measured according to Wu et al. [13]. Other plant growth parameters (plant height, fresh/dry weight) were measured according to Liu et al. [14]. The height of the plants was measured by randomly choosing five planting holes for each treatment; three seedlings were placed in each hole, and each seedling was measured three times throughout each stage mentioned above. The amount of chlorophyll was measured in the second entire leaf (off the leaf vein) from the base of the plant in a different direction at each stage. Measurement was performed using a handheld portable SPAD-502 analyzer (Minolta Camera Co., Ltd., Osaka, Japan).

The spikes were dried at 80 °C for 48 h to determine the yield components. The grain quality of the harvested rice was measured after it was air-dried and kept at room temperature for 3 months [15]. The rate of polished and head rice was assessed with a Jingmi testing rice grader, while unpolished rice rate was determined using a rice huller (Jiangsu, China) (Zhejiang, China). An SDE-A light box was used to measure the degree of chalkiness (Guangzhou, China). The grain was crushed into flour by using a mesh size of 0.75 mm and a rotational speed of 10,000 revolutions per minute. Grain protein content and light transmittance were determined by Near-Infrared Analysis Instrument (Model Perten DA7200, Huddinge, Sweden) [16,17]. An Infratec 1241 grain analyzer (FOSS-TECATOR) was used to measure the amount of amylose.

2.3.2. Soil Sampling and DNA Extraction

After harvest, soil was collected using the five-point sampling method on 31 October. Five soil samples from the 5–10 cm plow layer were extracted with a soil extractor to remove impurities. The samples were immediately bagged and stored on dry ice. They were sent to the laboratory and stored at −80 °C. Soil bacteria were identified using high-throughput sequencing technology. According to Caporaso [18], polymerase chain reaction was performed on soil samples. Correlation analysis of soil microorganisms was utilized. The Illumina NovaSeq 6000 PE250 platform was used to amplify fragments: 16S rDNAV3V4 region and fragment size of 470 bp (with barcode) with the following PCR primers: 338F 5′-ACTCCTACGGGAGGCAGCA -3′806R 5′-GGACTACHVGGGTWTCTAAT-3′. The PCR products were combined in equal proportions, and sequencing analysis was carried out as previously reported [19]. With a 97% similarity, the sequences were grouped into operational taxonomic units (OTUs). The composition and diversity of the bacterial communities under various treatments were determined through a previously reported method [20].

2.4. Data Processing and Statistical Analysis

Data processing and chart drawing were performed using WPS Office 2007, and SPSS 20.0 (SPSS Inc., Chicago, IL, USA) was employed for statistical analysis. At the conclusion of each bioassay, the results were compared for all parameters by using one-way analysis of variance (ANOVA) following standard procedures at the 5% probability level. The R language (version 4.5.1) Vegan package was used to perform NMDS (nonmetric multidimensional scaling) analysis and to compare and classify species in the RDP database (version 11.5). The Venn Diagram package was used to draw Venn diagrams, and R software was used to draw the alpha diversity index diagram. We selected 30 species with high default abundance rankings, used the R-pheatmap package to draw heatmaps, and clustered them from two levels of classification information and differences between samples.

3. Results

3.1. Effect of Different Proportions of Compost Returned to the Field on the Components of Rice Yield

Different levels of compost returned to the field will have a certain effect on the yield and components of rice yield (Table 3). Compared with CK (chemical fertilizer), the T1 (10%), T2 (20%), and T3 (30%) treatments replaced by straw compost returned to the field increased the number of grains per spike, of which T1 (285.67 grains) was the most abundant. Compared with the control group in the same period, T1 increased by nearly 21.60%, specifically T1 > T3 > T2 > CK, and the yield was consistent with the maximum and minimum per spike except for the number of blighted grains. The maximum number of blighted grains was detected in T2, with a value of 34.73 grains. Compared with the larger difference between the control group and T2, the difference between T3 and T2 was not significant but increased by 41.58% compared with T1. The highest effective grains of the T1 treatment were 243.75 grains, which increased by 17.44% compared with CK treatment. The yield of the T1 treatment was the most significant. Compared with the control group in the same period, the yield of T1 increased by 6.43%, followed by T2, which increased by 2.92%. No significant difference was found between T3 and CK.

Table 3. Effect of different proportions of compost on the yield and components of rice yield.

Treatment	Number of Grains per Spike (Grain/Spike)	Number of Effective Spikes (Grain/Spike)	Number of Blighted Grains (Grain/Spike)	Thousand Grain Weight (Gram)	Yield (t·ha)
CK	234.93 ± 1.56 b	201.24 ± 0.39 a	33.00 ± 0.25 a	20.87 ± 0.64 b	8.87 ± 0.36 b
T1	285.67 ± 1.63 a	243.75 ± 0.63 b	24.53 ± 0.67 b	23.97 ± 0.38 a	9.47 ± 0.31 a
T2	230.93 ± 0.97 b	196.73 ± 0.52 a	34.73 ± 0.33 a	22.88 ± 0.88 ab	9.16 ± 0.17 ab
T3	237.50 ± 2.18 b	204.30 ± 0.20 a	33.20 ± 0.48 a	21.47 ± 0.59 ab	8.97 ± 0.21 b

Notes: Different letters indicate significant differences between treatments at $p < 0.05$.

3.2. Effect of Different Proportions of Compost Returned to the Field on the Quality of Rice

The improvement in rice quality was related to each composting treatment (Table 4). The protein content was higher in T1 but was significantly lower in T2. The content was not significantly different in T3; the chalkiness and chalky grain rate changed due to the different degrees of compost replacement, and the appearance quality of rice changed accordingly. The specific treatments with more prominent effects were the chalkiness of T1, T2, and T3, which decreased by 25.77%, 17.28%, and 21.24%, respectively. Compared with the control group, the T1 treatment significantly increased the gel consistency of rice by 17.93%. A significant difference in gel consistency was found among the treatments.

Table 4. Effect of different proportions of compost on rice appearance quality.

Treatment	Protein (%)	Chalkiness (%)	Chalkiness Rate (%)	Glue Consistency (%)	Indica Rice Amylose (%)	Unpolished Rice Rate (%)	Polished Rice Rate (%)	Head Rice Rate (%)	Light Transmittance (%)
CK	5.24 ± 0.12 a	26.04 ± 0.92 a	30.38 ± 0.26 a	119.51 ± 1.22 d	12.26 ± 0.67 ab	81.75 ± 0.65 a	73.58 ± 0.08 a	73.02 ± 0.75 a	0.77 ± 0.02 b
T1	5.32 ± 0.11 a	19.33 ± 0.46 c	13.44 ± 0.32 d	140.94 ± 0.45 a	13.40 ± 0.37 a	82.21 ± 0.29 a	74.05 ± 0.16 a	73.22 ± 0.78 a	0.82 ± 0.01 a
T2	4.96 ± 0.42 b	21.54 ± 0.69 b	26.61 ± 0.56 b	124.89 ± 0.49 c	12.38 ± 0.41 ab	82.21 ± 0.33 a	73.96 ± 0.11 a	72.16 ± 0.35 a	0.83 ± 0.03 a
T3	5.21 ± 0.03 a	20.51 ± 0.22 bc	16.71 ± 0.49 c	128.90 ± 0.87 b	11.84 ± 0.14 b	82.08 ± 0.74 a	73.68 ± 0.33 a	71.42 ± 0.16 a	0.84 ± 0.01 a

Notes: Different letters indicate significant differences between treatments at $p < 0.05$.

In the T2 composting treatment, amylose had no outstanding performance, and the T1 treatment was relatively significant; however, the replacement of 30% fertilizer (T3) correspondingly reduced the amylose content by 11.84%. Compared with CK, the brown rice rate of the other treatments increased to a certain extent, but it did not reach a significant level. Based on Table 4, the composting CK treatment led to the lowest rice polishing rate, and T1 had the highest performance. Compared with the treatment, the rice polishing rate in T1 increased by 0.47%, and the rice polishing rate was the best compared with that in T3. T1 increased by 1.8%, and the rice heading rate was not significantly different among the remaining treatments. Therefore, the rice quality indices of T1 treatment were the optimum.

3.3. Effect of Different Proportions of Compost Returned to the Field on the Growth of Rice

Figure 1 shows that at 45 days after planting, the plant height difference among the different treatments was significant. The plant height of rice in T1, which was treated with conventional chemical fertilizer combined with compost, was significantly higher than that in the other treatments ($p < 0.05$). As of day 89, the plant height value in the T1 treatment reached the highest value, which was not significantly different from those in CK and T3.

Overall, the three treatments increased the chlorophyll content of rice to a certain extent, but the increase in the chlorophyll content was more obvious in the treatment where 10% chemical fertilizer (T1) was replaced with compost ($p < 0.05$). From day 19 to day 74, the chlorophyll content in T1 increased steadily, and the increase was obvious. On day 74, the content was significantly higher than that in the other treatments, and the increase in the other treatments was unstable at this stage.

Throughout the growth period, the number of tillers gradually increased. On day 89, the number of tillers was significantly higher in T1 than in the other treatments. CK had the lowest tiller number. T1 and T3 performed the best in the number of knots, reaching the highest on day 89, and the control group had the lowest. In general, the T1 treatment was significant in the number of tillers, while CK had the lowest.

As shown in Figure 2, the fresh shoot weight in the T2 treatment was significantly higher than that in the other treatments on day 19, while the shoot fresh weight in the T3 treatment was the lowest. The fresh shoot weight gradually increased, reaching the highest value in T2 and T3 on day 58. On day 89, the root fresh weight in T2 was significantly higher than that in the other treatments, and that in CK was the lowest, indicating that compost replacement increased the dry matter accumulation of plants. The dry shoot weight decreased in the order of T3 > T1 > T2 > CK. The effects of different proportions of compost return on the accumulation of field rice were significantly higher in T1, T2, and T3 than in CK.

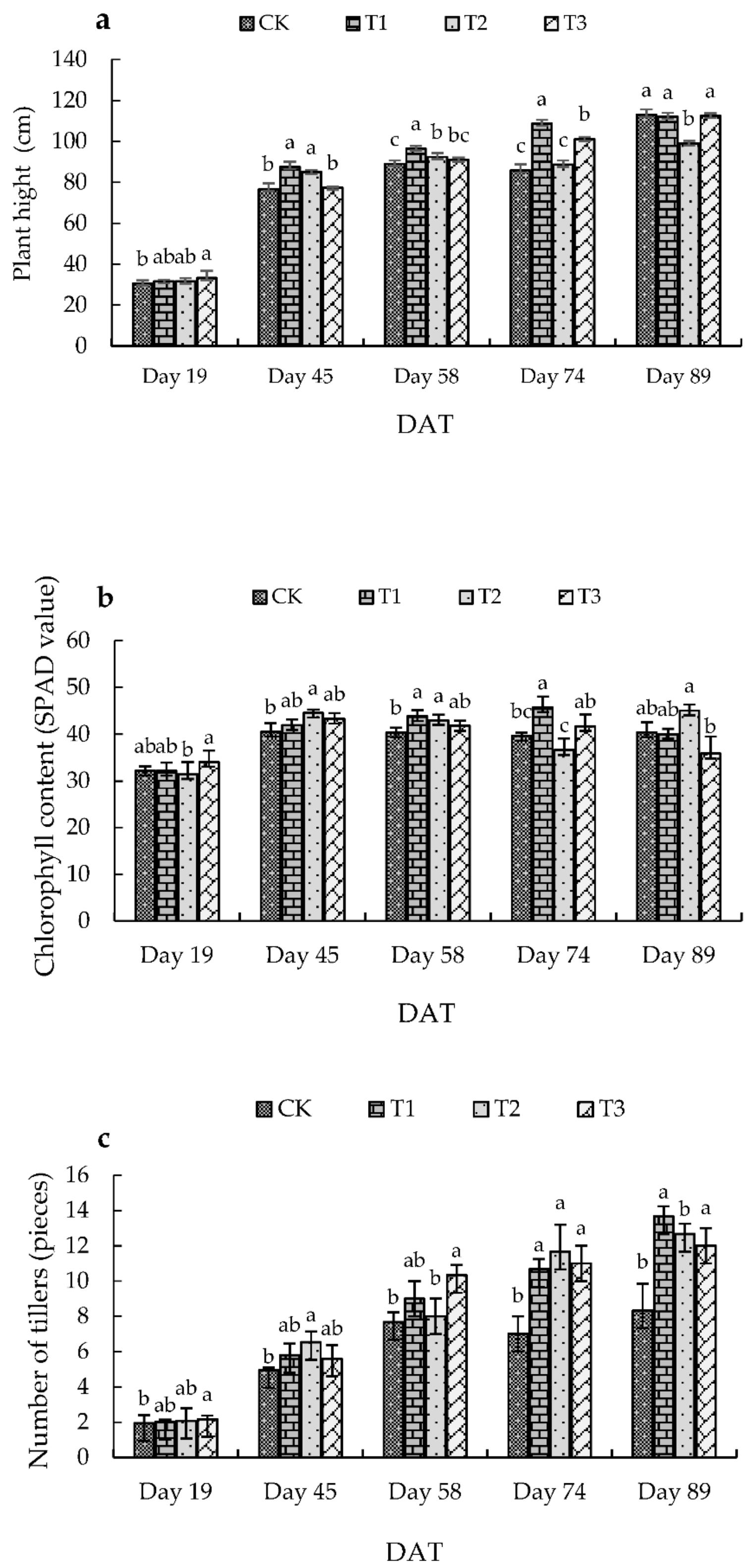

Figure 1. Influence of different proportions of compost amendments on rice plants with plant height, chlorophyll content (SPAD value), and tillers. DAT: days after transplanting. Notes: different letters indicate significant differences between treatments at $p < 0.05$. (**a**): plant height; (**b**): chlorophyll content (SPAD value); (**c**): number of tillers (pieces).

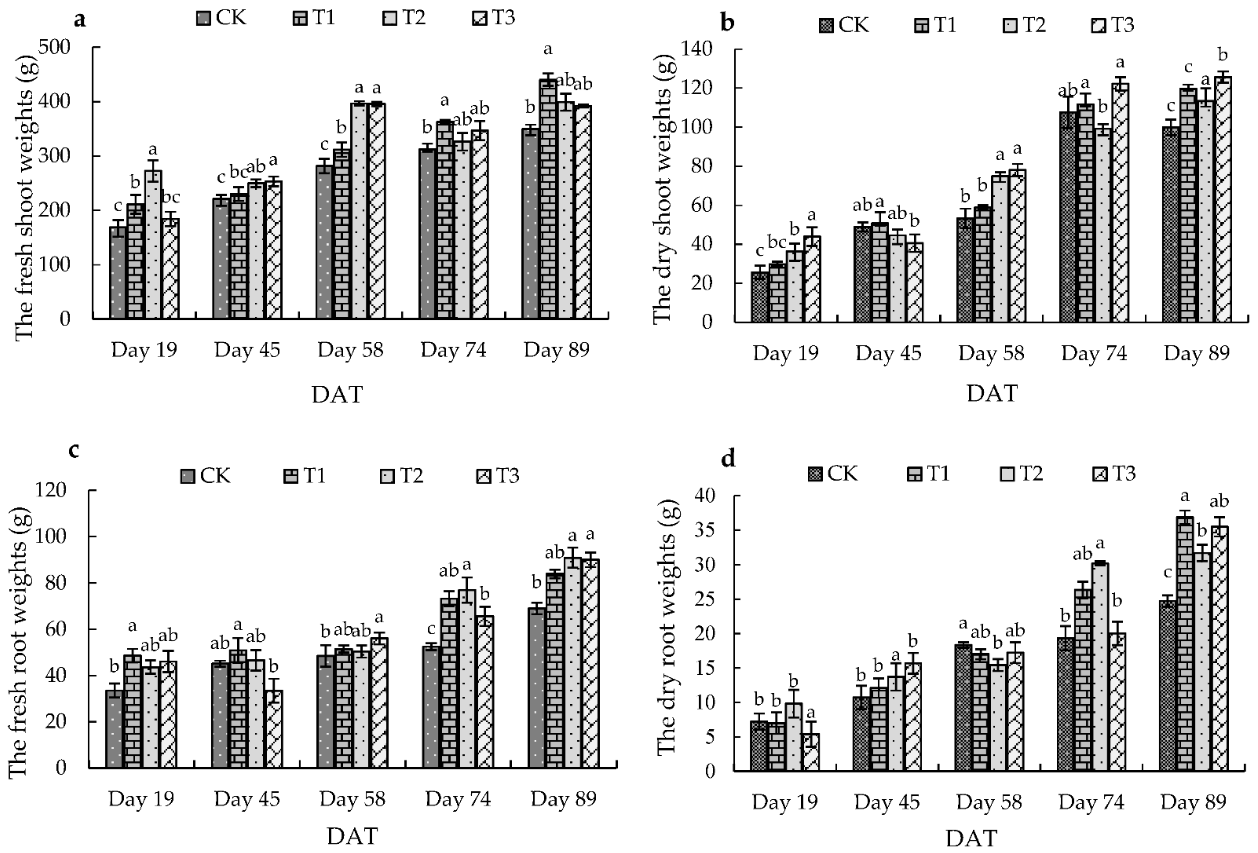

Figure 2. Effect of different proportions of compost returned to the field on (**a**) fresh shoot weight, (**b**) dry shoot weight, (**c**) fresh root weight, and (**d**) dry root weight. DAT: days after transplanting. Different letters indicate significant differences between treatments at $p < 0.05$.

3.4. Effect of Different Proportions of Compost Returned to the Soil on the Community of Bacteria and Archaea in Soil

Most microbes in the soil are bacteria. As shown in Figure 3a, the number of species (OTU, the same below) shared by CK, T1, T2, and T3 was 1669. Approximately 3367 species numbers (OTUs) were found in the soil samples processed in CK, which alone occupied 467 species, accounting for 13.87% of the total number of OTUs processed in the soil samples. Approximately 3796, 3595, and 3491 species (OTUs) were detected in the soil samples of the remaining treatments (T1, T2, and T3), respectively, and the species (OTUs) were 769, 647, and 894, respectively, accounting for 20.26%, 18%, and 25.61% of the total OTUs, respectively. In summary, the order of the number of species in the soil under different treatments was T1 > T2 > T3 > CK. Therefore, when compost replaced 10% fertilizer (T1), the number of species was the largest, and the microbial group was the most abundant. The number of CK species in the control group was the lowest, and the group of microorganisms was the least. Hence, the bacterial floral structure significantly differed between T1 and CK, and the treatment with 10% replacement by the compost had the highest number of organisms.

The Venn diagram (Figure 3b) shows that the numbers of archaeal species (OTUs) in CK, T1, T2, and T3 were 232, 358, 338, and 284, respectively. Purified fertilizer (CK) and compost substituted with 30% (T3) chemical fertilizer paddy soil had the fewest species of archaea. The number of OTUs in the T2 paddy soil was 1.5 times that in the control group. As the ratio of the compost replacement increased, the number of archaea (OTUs) decreased. The number of species (OTUs) in the four treatments (CK, T1, T2, and T3) was 83, 44, 35, and 39, respectively. The total number of microorganisms in the four paddy soils was 173. The order of the number of species in the soil in the different treatments was CK > T1 > T2 > T3. Archaea was also involved in the internal activities of paddy soil. However, as the degree of replacement of chemical fertilizers by compost increased, the number of archaea had a decreasing trend, and the microbial differences varied among the treatments. These results indicated that the number of archaea changed in succession with increasing compost usage.

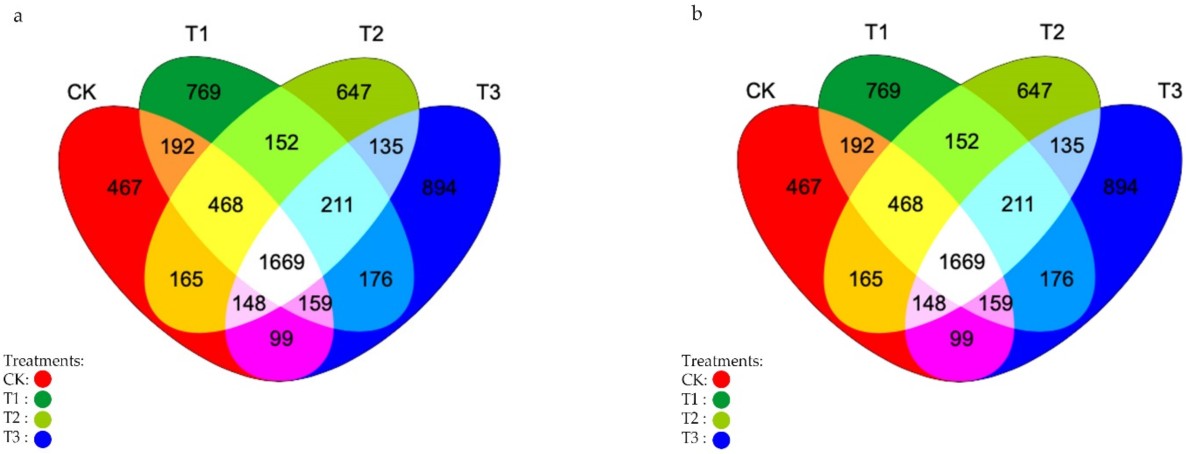

Figure 3. Venn diagrams of common or endemic species of bacterial and archaeal groups. Notes: (**a**): bacteria, (**b**): archaea. CK: chemical fertilizer 100%, T1: compost replacement 10%, T2: compost replacement 20%, T3: compost replacement 30%.

3.5. Effect of Different Proportions of Compost Returned to the Soil on the Relative Abundance of Bacteria and Archaea in Soil

The statistical chart of the alpha diversity index of bacterial communities in the four treatments was obtained. Estimation of bacterial Community by Chao1, Simpson, and Shannon Index α Diversity refers to the richness and diversity of species. Read is the total number of optimized sequences that were sorted into all OTUs.

Through the different degrees of composting, the chao1 and richness index (Figure 4a,c) of bacterial in each treatment, namely T1, T2, and T3, was higher than that in the uncomposted treatment, that is, the purified fertilizer treatment. Among them, T1 had the highest species richness. According to the Simpson index (Figure 4d), the richness was higher in T3 and CK than in T1 and T2, and T1 had the lowest value. Therefore, T1 had the highest bacterial community diversity, and T3 had the lowest bacterial community diversity.

Unlike bacteria, after different degrees of composting, the richness of archaea in each treatment showed a downward trend (Figure 5c). The richness of archaea in T3 was the lowest; the Simpson index (Figure 5d) was the highest in T3, followed by T1, and the lowest in T2. The diversity of the bacterial community was the highest in T2 and the lowest in T3.

3.6. Effect of Different Compost Return Degree Gradients on the Relative Abundance Clustering of Bacteria and Archaea in Soil

Bacteria are one of the most abundant microorganisms in soil. Bacteria with higher abundance in bacterial communities are mostly parasitic and saprophytic, and the latter occupies a large proportion under various cultivation conditions.

Figure 6 shows the dominant bacteria and archaea in each composting process. The dominant bacteria in T1 were *Sideroxydans*, Chloroflexi, *Nitrospirae*, and *β-Proteobacteria*; the archaea included *Methanoregula*, *Candidatus Nitrosocosmicus*, *Methanospirillum*, and *Methanospirillum*. The dominant bacteria in the second composting treatment included *Verrucomicrobia*, and the archaea included *Woesearchaeia*, *Methanospirillum*, and *Candidatus Nitrosocosmicus*. Bacteria in the T3 treatment included *Nitrospira* and *Acidobacteria*. The dominant archaea included *Thaumarchaeota*.

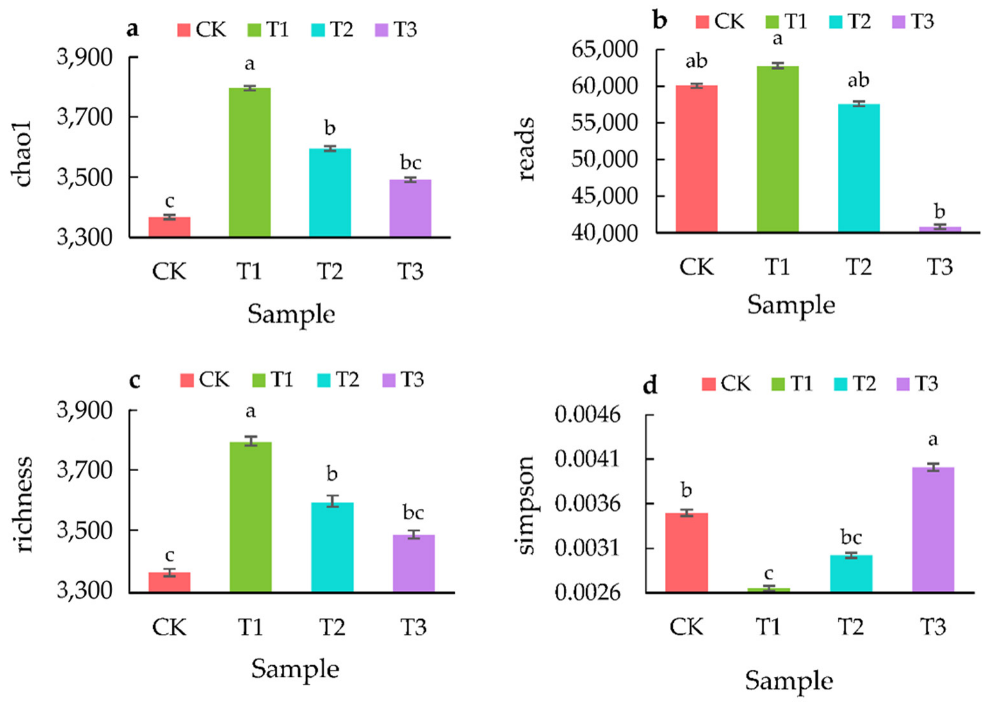

Figure 4. Statistics of the alpha diversity index of the bacterial groups. Notes: CK: chemical fertilizer 100%, T1: compost replacement 10%, T2: compost replacement 20%, T3: compost replacement 30%. (**a**): chao1, (**b**): reads, (**c**): richness, (**d**): simpson. Different letters indicate significant differences between treatments at $p < 0.05$.

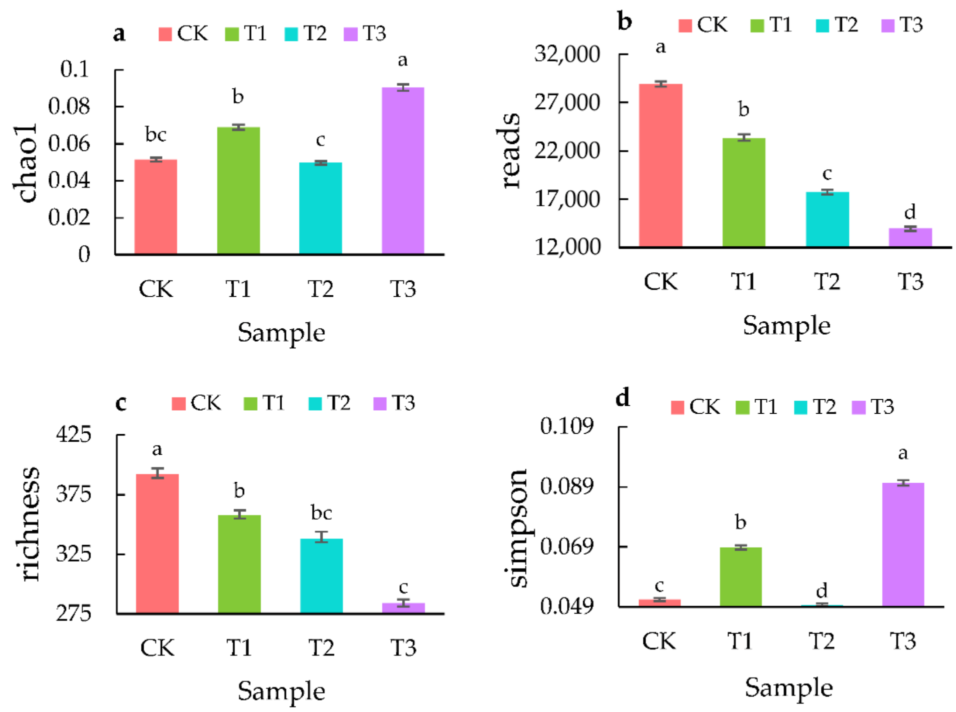

Figure 5. Statistics of the alpha diversity index of the archaeal groups. Notes: CK: chemical fertilizer 100%, T1: compost replacement 10%, T2: compost replacement 20%, T3: compost replacement 30%. (**a**): chao1, (**b**): reads, (**c**): richness, (**d**): simpson. Different letters indicate significant differences between treatments at $p < 0.05$.

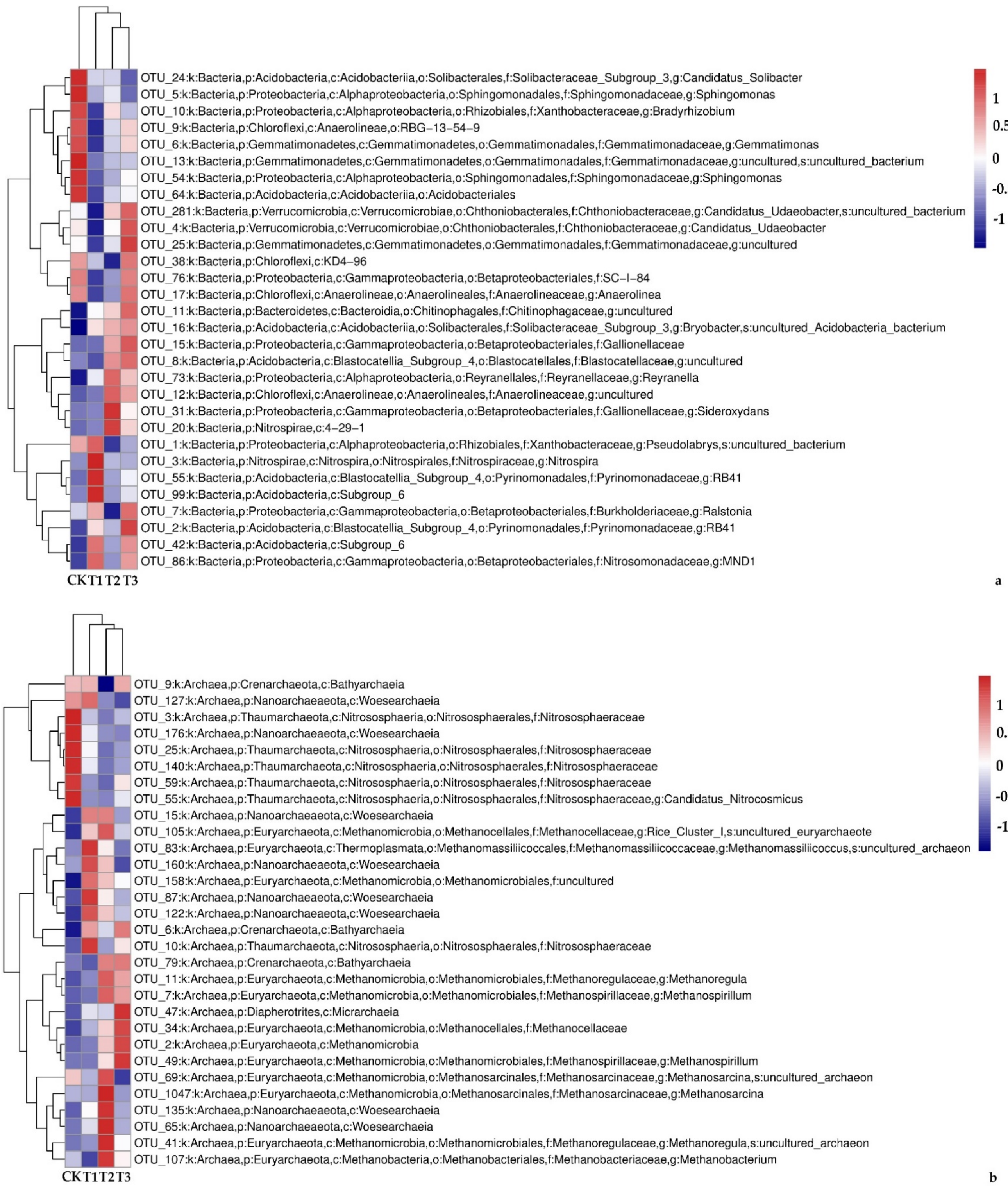

Figure 6. Clustering analysis of species abundance of bacterial (**a**) and archaeal (**b**) groups. Notes: CK: chemical fertilizer 100%, T1: compost replacement 10%, T2: compost replacement 20%, T3: compost replacement 30%.

4. Discussion

4.1. Effect of Different Proportions of Compost Returned to the Field on the Growth, Quality, and Morphological Indicators of Rice

When compost replaced 10% of chemical fertilizer, it significantly affected the rice yield, quality, and morphological indicators. When the compost replacement ratio reached 20% and 30%, the effect on rice growth and development was reduced compared with 10% replacement. Therefore, proper compost replacement significantly promoted the growth and development of rice. Relevant studies have shown that replacing some chemical fertilizers with an appropriate amount of organic fertilizer can increase the rice yield, but excessive or complete replacement of chemical fertilizer can reduce the rice yield by 2.3% to 8.6% [21]. The effective ratio of organic and chemical fertilizers can improve and regulate the growth and development of rice and increase the yield per unit area of rice, leading to a stable and high yield effect [22]. Chen et al. [23] showed through experiments that returning the entire amount of straw to the field with appropriate nitrogen fertilizers can increase the nitrogen use efficiency of rice, thereby increasing the yield. This phenomenon may arise from the fact that returning the entire amount of straw to the field can accelerate the cycle of soil nitrogen and thus improve the utilization rate of nitrogen. Dong et al. [24] showed that pig manure composting instead of 10%, 20%, and 30% fertilizer treatments increased the yields by 12.5%, 11.6%, and 5.8%, respectively, compared with a purified fertilizer treatment. Hence, pig manure composting that replaced 10% chemical fertilizer led to the highest rice yield. This result is consistent with our finding. Therefore, in the process of rice planting, replacing part of the chemical fertilizer with compost will have a more significant effect on increasing the yield than using chemical fertilizers alone. However, various factors such as variety, fertilizer structure, and management methods will affect rice nutrient absorption and accumulation and dry matter accumulation to varying degrees. In general, high yield can be explained by high nutrient absorption and accumulation of crops.

Chalkiness is a significant component that affects the appearance and grading of rice, which is defined as the proportion of white opaque regions to the overall area of the rice [25]. Light transmittance refers to the degree of transparency of fine rice and is an important component of rice appearance and quality [26]. Li et al. [27] noted that the effect of improving the quality and appearance of rice can be achieved by applying organic fertilizers and chemical fertilizers in proportion for a long time. At the same time, this combination method can reduce the rice chalky grain rate and chalkiness in the medium, thereby significantly improving the polished rice rate and the light transmittance In this experiment, the best effect was achieved when compost replaced 10% of chemical fertilizer, and the subsequent treatment decreased the effect, consistent with our results. Zhang et al. [28] pointed out that the processing quality and appearance can be improved in rice seeds, and the return of straw to the field is one of the important influencing factors. Returning straw to the field is an important method to regulate and improve the physical and chemical properties of the soil as well as increase the utilization rate of fertilizer.

Therefore, proper compost replacement is beneficial to the growth and development of rice and has a significant effect on the yield, constituent factors, and quality of rice.

4.2. Effect of Different Proportions of Compost Returned to the Field on the Soil Microbes in Paddy Soil

This experiment used straw compost instead of chemical fertilizer for corresponding treatment, and the decomposition and maturity of the straw returned to the soil will affect the soil microbial community [29]. Bei et al. [30] concluded that the amount of straw returned to the field and the amount of chemical fertilizer with different ratios have a relatively good effect on improving the soil temperature and increasing the number of microorganisms in the rhizosphere of plants. In this experiment, the CK of each composting treatment was significantly different from that of the control group in terms of bacterial flora or archaeal flora. The relative abundance of microorganisms in the treatment (T1) where the compost replaced 10% was the highest, and it was the lowest in the purified fertilizer

CK. The relative abundance of archaea was the highest in CK, followed by T1. Hence, composting may have a negative effect on the living environment of archaea. Zhao et al. [31] used the effect of adding different organic fertilizers on the number of cultivable bacteria in paddy soil and found that the biomass of bacteria in the soil increased significantly due to different composting treatments compared with the application of purified fertilizer. Chen et al. [32] reported that long-term use of organic and inorganic fertilizers in proportion profoundly affects the abundance of bacteria in the soil. At the same time, rich and diverse biomass can significantly improve the organic carbon content. Tian et al. [33] revealed that compost application was not always beneficial to soil quality and might decrease soil diversity. This difference may arise from the influence of the heavily compost application, which generated the risk of decreasing soil biodiversity. It is the existing reason that could explain the significant discrepancy in the bacterial community composition between the two studies.

The high-throughput sequencing showed that the combined application of chemical fertilizers with partial compost changed the soil microbial community structure and increased the relative abundance of bacteria and archaea.

4.3. Influence of Soil Microorganisms (Bacteria and Archaea) in Paddy Fields on Rice

Returning straw to the field can significantly change the soil bacterial community [24] and increase the abundance of *β-proteobacteria*, *Gemmatimonadetes*, and *Bacteroides* [34]. Yang et al. [35] found that returning wheat straw to the field helped increase the relative abundance of *Proteobacteria* in paddy soil; moreover, the migration of bacterial communities responded significantly to different wheat straw returning modes. In this experiment, *β-proteobacteria* was the dominant strain for composting in T1. It is similar to iron redox bacteria and is positively correlated with the increase in $NH4^{+}$-N [36]. Gordon et al. [37] showed that $NH4^{+}$–N in the soil was relatively high, thereby promoting the retention of $NH4^{+}$-N organisms. Given that rice is an ammonium-loving crop, the increase in $NH4^{+}$-N content in the soil can promote the absorption of nitrogen by the rice, thereby increasing the quality and yield of the rice crop. *Sideroxydans* was also dominant in T1. $NH4^{+}$-N has a temporary strong association with *Sideroxydans* [38]. Therefore, this explains the significant advantage of rice growth and development in composting in T1. *Gemmatimonadaceae* was the dominant bacterial family in the T2 treatment. Li et al. [39] found that *Gemmatimonadaceae* is positively correlated with the utilization ability of polymer carbon sources, explaining the improvement in the quality and yield in T2. *Nitrospira* in the phylum *Nitrospira* was the dominant strain in T3, which can oxidize nitrite to nitrate, thereby promoting the conversion of soil nitrogen. The increased application of compost can promote the transformation and absorption of nitrogen in rice soil, thereby increasing the dry matter and yield of rice and improving the accumulation of nitrogen in rice.

In terms of archaea, Steinbeiss et al. [40] showed that the application of biochar would have a certain effect on soil carbon and nitrogen content, among which the dominant genus was *Methanoregula*. In this experiment, compost was used to replace chemical fertilizers, and *Methanoregula* increased and became the dominant strain in T1. Replacing chemical fertilizers with compost can increase the content of biochar, which also has a positive effect on the growth and development of rice. *Candidatus Nitrosocosmicus*, also called ammonia-oxidizing archaea, was a dominant genus in T1 and T2. It regulates the conversion of ammonia into nitrite and plays an important role in the global nitrogen cycle [41,42]. Therefore, the replacement of compost in the field has a promoting effect on nitrogen transformation and recycling with regard to rice growth and development and has a significant positive correlation with the increase in rice yield and dry matter. *Thaumarchaeota* had the highest abundance in the T3 treatment; it is a type of autotrophic archaea which plays an important leading role in the nitrification of certain natural ecosystems and obtains energy by catalyzing ammonia oxidation. Yuan et al. [43] found that soil pH, TN, and C/N are significantly correlated with the relative abundance of the phylum *Hysteromycota*. The replacement of some chemical fertilizers with straw compost significantly increased the content and ratio of carbon and nitrogen in the soil, providing carbon and nitrogen sources for the growth of microorganisms and changing the structure of the archaeal community.

5. Conclusions

Composting instead of using a 10% chemical fertilizer, namely T1 with 337.5 kg/ha compound fertilizer combined with 202.5 kg/ha urea and 5 t/ha composting, can significantly increase the growth, yield, and quality of rice. Other treatments were not effective. Thus, an appropriate level of compost substitution can improve rice growth. Simultaneously, compost replacing 10% of the chemical fertilizer treatment, whether in regard to bacteria or archaea, increases the number of *Gemmatimonadetes*, *Sideroxydans*, and *Methanoregula*, as well as the proportion of some beneficial bacteria. Therefore, the effect of composting that replaces 10% of the chemical fertilizer is the best method. During the composting experiment, we found that some core microorganisms improved rice growth and development. In subsequent studies, the effects of adding core microbial agents on rice growth and development in compost returning experiments could be explored. Future studies should explore new ways for improving the practical technology of composting to replace chemical fertilizers.

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