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Influence of Wheat Straw Return on Yield and Grain Quality in Different Direct-Seeding Rice Production Systems

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Abstract: Direct-seeding methods have received growing interest from rice growers. Wheat straw return is an important measure in rice-wheat rotation system. This study aimed to investigate the influence of wheat straw return on the yield and grain quality in different direct-seeding rice production systems. A split-plot design was adopted for the on-farm trial. The main plots were treated with and without wheat straw return. Dry and wet direct-seeding rice production systems were used in the split plots. The results showed that the yield of direct-seeding rice was reduced by 4.2–7.3% due to wheat straw return, which may be related to a negative effect of wheat straw return on the tiller number ($p < 0.05$) and biomass accumulation ($p < 0.05$). Additionally, the content of the amylose and protein of the grain of direct-seeding rice decreased by 4.3–5.5% and 6.0–6.8%, respectively, due to wheat straw return. Furthermore, wheat straw return increased the chalkiness area and the chalkiness degree of the grain of direct-seeding rice, which may be related to the reduced protein content of the grain. However, wheat straw return improved the taste score of the cooked rice ($p < 0.05$) and the breakdown of the rapid viscosity analyzer (RVA) parameters ($p < 0.05$), and reduced the setback of the RVA parameters, probably related to an increase in the stickness of the cooked rice ($p < 0.05$) caused by the reduced amylose content of the grain. When compared to a dry direct-seeding rice production system, a wet direct-seeding rice production system has advantages in the tiller number ($p < 0.05$) and biomass accumulation, thus increasing the yield and resulting in a lower content of protein and protein components, which reduces both the chalkiness area and chalkiness degree of the grain. However, by using the wet direct-seeding method, the amylose content of the grain improved; hence, the stickness of the cooked rice ($p < 0.05$) and the breakdown of the RVA parameters decreased, and the setback of the RVA parameters increased. The above results indicated that wheat straw return reduced the yield, nutritional quality, and appearance quality of direct-seeding rice but improved the cooking quality of the grain. Although using the wet direct-seeding method is beneficial to improving the yield, it negatively impacts the grain quality of direct-seeding rice.

Keywords: wheat straw return; direct-seeding method; yield; grain quality

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1. Introduction

Rice is the primary staple food for more than half of the global population and is essential for nutrients, energy support, and grain safety of people [1]. Historically, over 70% of the rice in the world is grown on puddled soil that is first waterlogged and then rototilled before transplanting. This type of rice is commonly referred to as transplanted rice. In traditional transplanted rice systems, the seedling establishment of rice involves four fundamental stages, i.e., seedbed preparation, seedling raising, seedling pulling, and seedling transplanting stages. Each stage requires substantial labor and time costs [2]. In recent years, rice planting practices have changed dramatically in light of increased rice production costs, water resource scarcity, and labor shortages [3]; more and more growers are converting traditional transplanted rice production systems to direct-seeding rice production systems [4,5]. The direct-seeding method is a rice cultivation method in which plants are established by directly sowing rice seeds into the field [6]. The direct-seeding method is more likely to be adopted by rice growers who aim to maximize economic benefits due to low planting costs by eliminating steps, such as seedling raising and seedling pulling [7]. At the beginning of the 21st century, the direct-seeding rice planting area accounted for 21% of the total rice planting area in Asia [8].

The rice–wheat rotation system is an essential cropping regime in South Asia [9]. Open burning of wheat straw after a wheat harvest is a typical disposal method due to the limited time available to prepare for rice planting [10]. However, this is harmful to the environment and human health [11]. Wheat straw can be recycled as a biomass source [12], but this consumes massive labor resources. Due to labor scarcity, recycling wheat straw is not the preferred method of wheat straw disposal. Straw return is the process of shredding the straw of the previous crop to less than 10 cm and evenly rototilling it into the soil using rotary tillage equipment after the previous crop is harvested. [13]. Wheat straw contains many nutrients; including nitrogen, phosphorus, potassium, and silicon; and organic matter, such as cellulose, lignin, and protein. Wheat straw can be used to improve the soil structure [14]. Therefore, wheat straw return plays an important role in improving the yield and grain quality of rice. Previous studies have shown that wheat straw return increases rice yield through Meta-analysis [15,16]. In addition, wheat straw return can effectively improve the grain quality of rice. For example, Yan et al. reported that wheat straw return improved the cooking quality, appearance quality, and nutritional quality of rice grain [17]. Li et al. proved that wheat straw return not only increased the protein content of the rice grain but also reduced the chalkiness degree of rice grain [11]. Yuan et al. pointed out that straw could increase the zinc and iron content of the rice grain [18]. Most of the previous study results are based on transplanted rice systems. However, there are essential differences in seedling establishment between a direct-seeding rice production system and a transplanted rice system. There are few studies on the effects of wheat straw return on the yield and grain quality of rice in direct-seeding rice production systems.

Direct-seeding rice production systems are divided into dry and wet direct-seeding rice production systems. [8]. In a dry direct-seeding rice production system, rice seeds are sown into dry soil without puddling (1–3 cm deep) prior to irrigation. In a wet direct-seeding rice production system, pre-germinated seeds are sown into wet soil, which is puddled, precipitated, and then drained [19]. Different direct-seeding methods can cause differences in the porosity, temperature and humidity, water content, and aggregate structure of the soil [18,20], thus affecting nutrient availability [21], rice growth and yield, and grain quality [22]. However, how these differences in direct-seeding rice production systems affect the yield and grain quality of direct-seeding rice is unknown.

To this end, in this experiment, we compared the differences in the yield and grain quality of rice between various direct-seeding methods with and without wheat straw return. The objectives are (1) to assess the response of the yield and grain quality of direct-seeding rice to wheat straw return and to elucidate its response mechanism and (2) to identify suitable direct-seeding rice production systems.

2. Materials and Methods

2.1. Experimental Site and Weather Conditions

The on-farm trial was conducted in 2019 and 2020 in a rice–wheat rotation region in Yangzhou, China. The organic matter, total nitrogen, available phosphorus, and available potassium of the soil were 30.4 g kg^{-1}, 1.91 g kg^{-1}, 31.6 mg kg^{-1}, and 154 mg kg^{-1}, respectively [23]. The average daily air temperature, daily sunshine hours, and annual rainfall in 2019 were 24.9 °C, 5.5 h, and 382 mm, respectively, and those in 2020 were 24.8 °C, 3.87 h, and 1009 mm, respectively (Figure S1).

2.2. Experimental Design and Treatments

The experiment was performed using a split-plot design with four replications. Main plots were the wheat straw return treatment: non-returned wheat straw treatment (T1) and returned wheat straw treatment (T2). Split plots were the two direct-seeding rice production systems: dry direct-seeding rice production system (S1) and wet direct-seeding rice production system (S2). Thus, the experiment had four plots, i.e., T1S1, T1S2, T2S1, and T2S2, representing the plot in a dry direct-seeding production system without wheat straw return, the plot in a wet direct-seeding production system without wheat straw return, the plot in a dry direct-seeding production system with wheat straw return, and the plot in a wet direct-seeding production system with wheat straw return. The high-quality *japonica* rice variety Nanjing-9108 was selected for this experiment. In the planting area of conventional *japonica* rice, Nanjing-9108 was the fourth in China and the second in Jiangsu Province [24].

In both years, wheat was harvested with a Kubota combine [4LBZ- 145G (PRO588I-G)], and wheat straw was returned to the field (the biomasses of the returned wheat straw in 2019 and 2020 were 7.7 and 8.3 t ha^{-1}, respectively). The date for wheat straw return in both 2019 and 2020 was 9 June. The wheat straw was removed manually from the main plots that did not receive the returned wheat straw. In both dry and wet direct-seeding production systems, local machinery was used for sowing. Soil in the dry direct-seeding rice plots was dry without water puddling, and ungerminated dry rice seeds were seeded with a multifunctional seeder that performs synchronous rotary tillage and sowing (Yangzhou University). The row spacing of drill sowing, depth of rotary tillage, and seeding rate were 25 cm, 10–15 cm, and 70 kg ha^{-1}, respectively. Unlike dry direct-seeding production system, the wet direct-seeding production system involved first soaking the seeds in water for 20–24 h and then incubating them for 8–12 h. The pre-germinated seeds were then seeded on the surface of drained and puddled soil with a rice hill-drop sowing machine (South China Agricultural University). The depth of rotary tillage was 20–25 cm for the paddy soil. The hill seeding density and seeding rate were 25 $\times$ 11 cm and 70 kg ha^{-1}, respectively. The sowing dates for S1 and S2 in 2019 were 11 June and 13 June, respectively, and those in 2020 were both 11 June. When the rice growth was at the three-leaf stage, four representative plot areas of 36 m^2 were randomly selected, and the seedling density in each plot were thinned to 150 m^{-2}.

2.3. Crop Cultivation

Wet irrigation management was applied during the seedling establishment period after sowing. After the five-leaf stage, flood irrigation management was applied with a water depth of 2–3 cm until the mid-tiller stage. Then, we drained water in the fields to control ineffective tillers. After the stem elongation stage, alternate wet and dry irrigation management was applied until seven days before the rice harvest. In all plots, urea was applied with a dosage of 270 kg ha^{-1} in three splits at a ratio of 3.5:3.5:3 at the pre-sowing, four-leaf, and panicle initiation stages. Calcium superphosphate was applied with a dosage of 135 kg ha^{-1} at the pre-sowing stage, and potassium chloride was applied with a dosage of 135 kg ha^{-1} at the pre-sowing stage and again at the panicle initiation stage. The prevention and control of weeds, insects, and diseases followed local recommendations throughout the growing season during the two years.

2.4. Sampling and Measurements

2.4.1. Tillering Dynamics, Biomass, and Yield

To study tillering dynamics, we investigated three adjacent rows (1 m) every 10 days from the sowing stage to the maturity stage. To measure biomass accumulation, rice plants were sampled from three adjacent rows (50 cm) in each plot at the stem elongation, heading, and maturity stages. Each sample was oven-dried at 105 °C for 30 min and then at 80 °C to a constant weight. To determine yield components, we took three adjacent rows (2 m) to measure the panicle number, spikelet number per panicle, total spikelet number, filled-grain percentage, and grain weight. Yield was determined from a harvest area of 8 m^2 in each plot and adjusted to the standard moisture content of 0.14 g H_2O g^{-1}.

2.4.2. Grain Quality

The rice grains were naturally air-dried, stored at room temperature for three months, and then air-selected with a winnowing machine to determine the rice grain quality. The rice quality traits were determined according to China's National Standard (GB/T 17891-2017) [25]. We determined the amylose content by the amylose-iodine reaction using flour sifted through a 0.25 mm sieve. The protein content was measured by a grain analyzer instrument (Foss, DK-3400, Hilleroed, Denmark) based on near-infrared transmission. We extracted the protein components with distilled water, 5% sodium chloride, 70% ethanol, and 0.2% NaOH in the order of albumen, globulin, gliadin, and glutenin, respectively. The content of the protein components was determined by Coomassie Brilliant Blue staining. The values for the appearance quality (length to width ratio, chalkiness area, and chalkiness degree) were calculated using a rice appearance quality detector (Hangzhou Wanshen Detection Technology Co., Ltd., Hangzhou, China). The values for the cooking quality (taste score) of the cooked rice were calculated using a taste analyzer (Satake Corporation, Higashi-Hiroshima, Japan). The texture properties of the cooked rice were evaluated using a TA. XT Plus texture analyzer (Stable Micro System, Surrey, UK). The pasting properties of the rice flour were determined using a rapid viscosity analyzer (RVA, Super3, Newport Scientific, Warriewood, Australia).

2.5. Statistical Analysis

We used IBM SPSS Statistics 22 to analyze the data and compared treatment means using the least significant difference test. Graphical representations of the data were produced using Origin 9, Microsoft Excel 2019, and the R statistical programming language.

3. Results

3.1. Grain Yield and Yield Components

In both years, T2 reduced the yield of direct-seeding rice by 4.2–7.3% when compared to T1. In terms of yield components, the decrease in yield was mainly due to a reduction in total spikelet number by 2.9–7.1% and panicle number by 5.3–9.2%. Wheat straw return did not significantly affect the spikelet number per panicle, filled-grain percentage, and grain weight. When compared to S1, after wheat straw return, S2 led to an increase of 4.0–5.7% in yield. In terms of yield components, the increase in yield was mainly due to an increase of 4.7–6.5% in panicle number and 6.7–7.7% in total spikelet number. Different direct-seeding methods did not result in differences in spikelet number per panicle, filled-grain percentage, and grain weight. No significant two- or three- way interactions for yield and yield components were found (Figure 1).

3.2. Tillering Dynamics

Wheat straw return reduced the tiller number of direct-seeding rice. In both years, the tiller numbers after wheat straw return were reduced by 10.1–12.1%, 8.8–11.3%, 6.3–9.8%, and 5.3–9.2% at the highest tiller (50 days after sowing), stem elongation, heading, and maturity stages, respectively. When compared to S1, after wheat straw return, S2 had a positive effect on tillering capacity, enabling the tiller number after wheat straw return to increase by 2.9–4.7%, 3.2–5.0%, 4.0–5.7%, and 4.7–6.5% at the highest tiller, stem elongation, heading, and maturity stages, respectively (Figure 2).

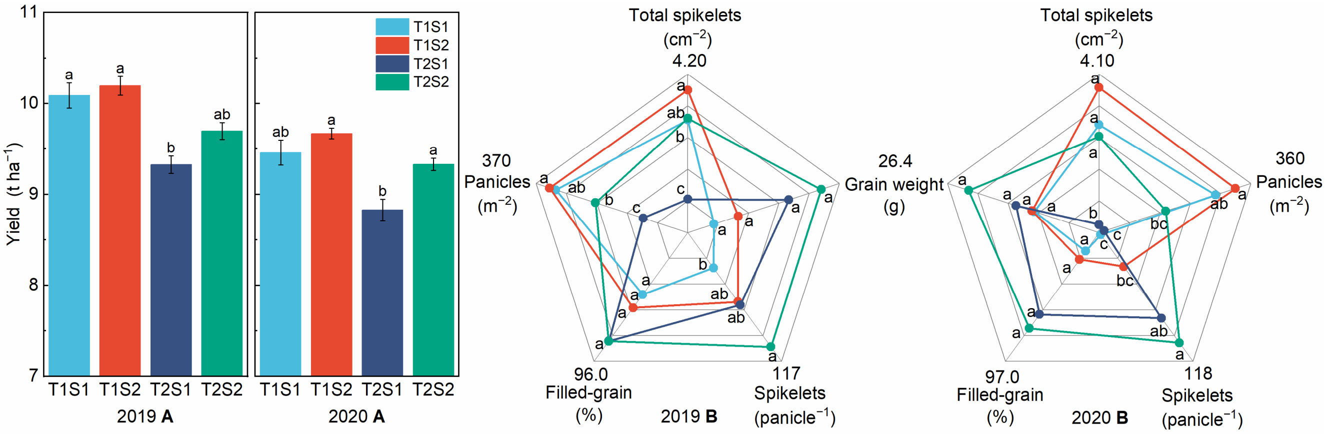

Figure 1. Influence of wheat straw return on the grain yields (A) and yield components (B) in different direct-seeding rice production systems. Error bars show standard error of replicates (n = 3). Values followed by different lowercase letters were significantly different at the 0.05 probability level among different treatments.

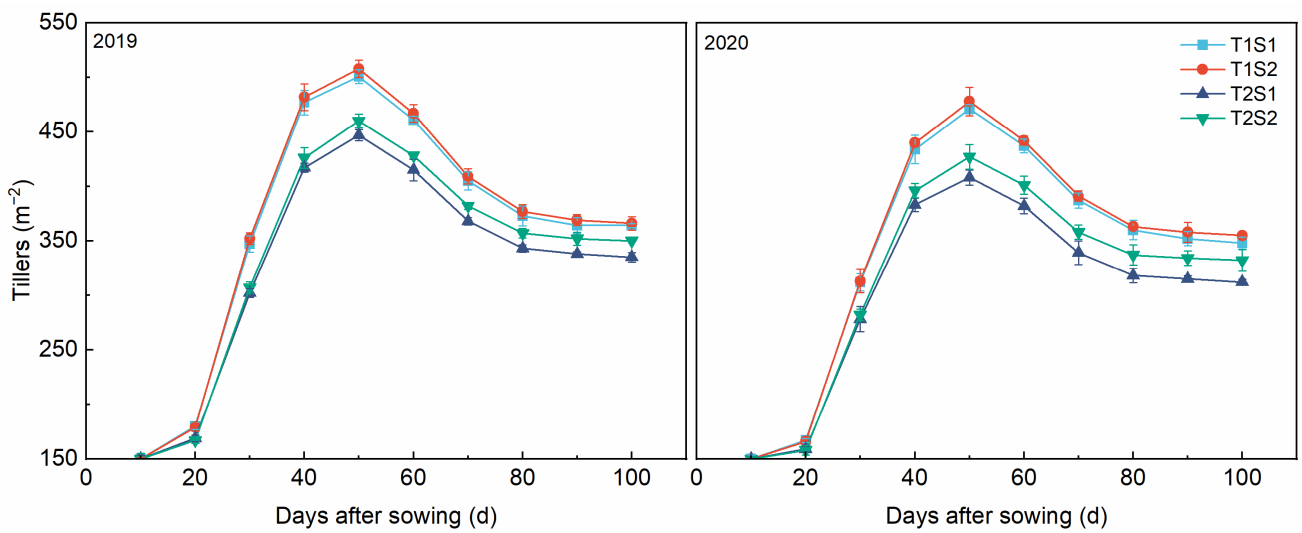

Figure 2. Influence of wheat straw return on tillering dynamics in different direct-seeding rice production systems. Error bars show standard error of replicates (n = 3).

3.3. Biomass Accumulation

In both years, T2 negatively impacted the biomass accumulation of direct-seeding rice when compared to T1. S1 had the greatest impact, causing the biomass at the maturity stage to decrease by 4.8–6.4%. The biomass accumulation from the sowing stage to the stem elongation stage and from the heading stage to the maturity stage decreased by 11.7–14.0% and 5.4–6.5%, respectively. When compared to S1, after wheat straw return, S2 led to an increase of 4.8–7.4% in biomass accumulation at the maturity stage. The biomass accumulation from the sowing stage to the stem elongation stage, from the stem elongation stage to the heading stage, and from the heading stage to the maturity stage increased by 4.7–6.3%, 3.3–4.6%, and 3.8–5.6%, respectively (Figure 3).

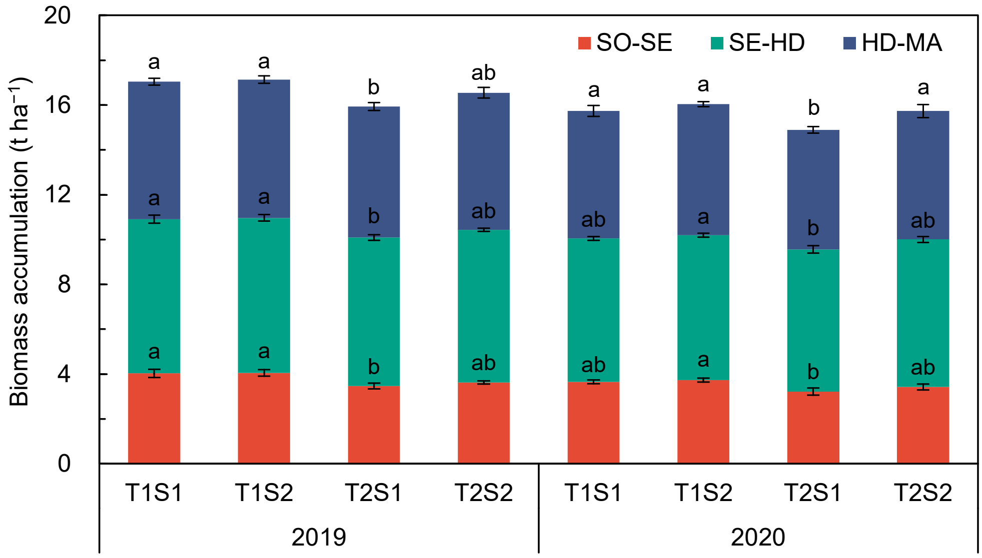

Figure 3. Influence of wheat straw return on biomass accumulation in different direct-seeding rice production systems. Error bars show standard error of replicates (n = 3). Values followed by different lowercase letters were significantly different at the 0.05 probability level among different treatments. SO-SE: sowing to stem elongation stages; SE-HD: stem elongation to heading stages; HD-MA: heading to maturity stages.

3.4. Amylose and Protein Content

In both years, T2 reduced the amylose and the protein content of the grain of direct-seeding rice by 4.3–5.5% and 6.0–6.8%, respectively, when compared to T1. In terms of protein components, the content of albumin, globulin, gliadin, and glutenin all showed a decreasing tendency. The content of gliadin and glutenin was relatively low, decreasing by 6.7–8.0% and 9.6–10.6%, respectively. The amylose content of the grain in S2 was 5.1–6.2% higher than that in S1. However, a decreasing tendency of the protein content existed in S2 (Table 1).

Table 1. Influence of wheat straw return on the content of amylose, protein, and protein components of the grains in different direct-seeding rice production systems.

Year	Treatment	Amylose Content (%)	Protein Content (%)	Protein Component Content (mg g^{-1})			
				Albumin Content (mg g^{-1})	Globulin Content (mg g^{-1})	Gliadin Content (mg g^{-1})	Glutenin Content (mg g^{-1})
2019	T1S1	10.3 b [1]	9.00 a	4.40 a	6.07 a	10.0 a	58.7 a
	T1S2	10.9 a	8.79 a	4.29 a	5.90 ab	9.61 b	55.7 ab
	T2S1	9.79 c	8.42 b	4.23 a	5.88 ab	9.38 b	52.5 bc
	T2S2	10.3 b	8.26 b	4.16 a	5.75 b	8.92 c	50.4 c
2020	T1S1	10.9 bc	8.39 a	4.20 a	5.85 a	9.02 a	52.1 a
	T1S2	11.5 a	8.16 ab	4.14 ab	5.67 a	8.60 ab	50.2 ab
	T2S1	10.4 c	7.82 bc	4.12 ab	5.64 a	8.30 bc	47.0 bc
	T2S2	10.9 b	7.66 c	4.01 b	5.58 a	8.02 c	45.2 c

[1] Values followed by different lowercase letters were significantly different at the 0.05 probability level among different treatments.

3.5. Appearance Quality

In both years, after wheat straw return, the chalkiness area and chalkiness degree of the grain of direct-seeding rice increased by 2.5–6.3% and 5.7–7.4%, respectively. When compared to the chalkiness area and chalkiness degree of the grain in S1, after wheat straw return, those in S2 increased by 5.5–8.3% and 5.7–6.2%, respectively. There was no significant effect of wheat straw return on the length to width ratio; various direct-seeding methods led to no dramatic difference in the length to width ratio (Figure 4).

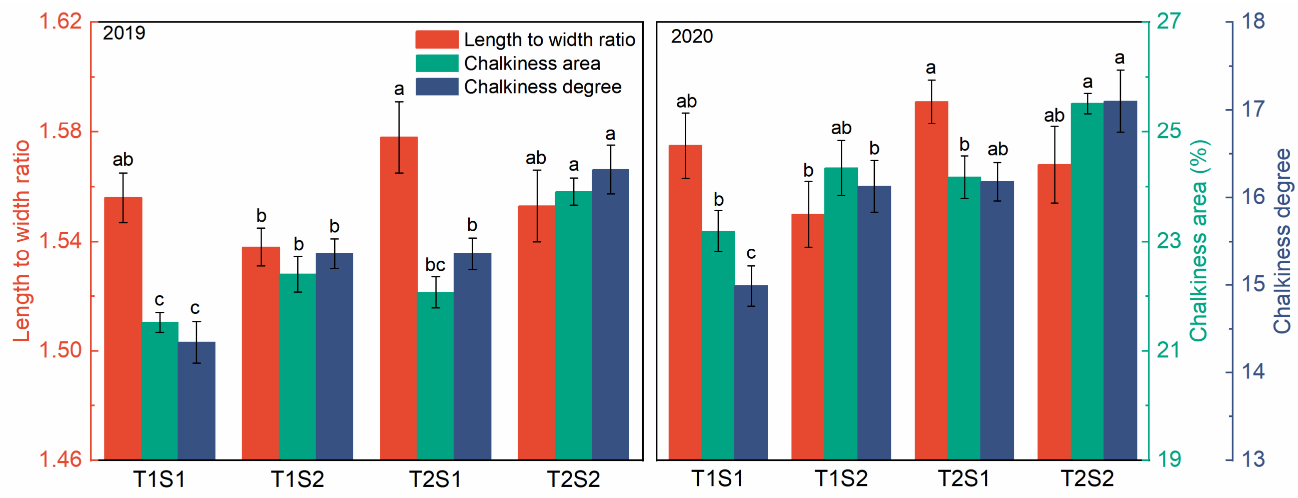

Figure 4. Influence of wheat straw return on length to width ratios, chalkiness areas, and chalkiness degrees in different direct-seeding rice production systems. Error bars show standard error of replicates (n = 3). Values followed by different lowercase letters were significantly different at the 0.05 probability level among different treatments.

3.6. Cooking Quality

In both years, T2 increased the taste value of the grain of the cooked direct-seeding rice by 5.3–5.9% when compared to T1. From the taste index of the cooked rice, the taste value was improved mainly because T2 increased the appearance and viscosity values by 4.1–5.3% and 4.5–5.3%, respectively, and reduced the hardness value by 3.5–5.4%. In addition, from the texture properties, T2 increased the spring and stickness of the cooked rice by 4.9–6.2% and 5.3–6.3%, respectively, and reduced the hardness by 6.0–7.2%. When compared with S1, after wheat straw return, S2 reduced the taste value of the cooked rice by 5.3–5.7%, mainly due to the decrease of 4.4–4.7% in appearance value and 5.2–5.7% in viscosity value, thus reducing the balance value of 5.9–7.1% (Table 2). In addition, from the texture properties, for the cooked rice in S2, the stickness decreased by 4.6–8.2%, and the hardness increased by 3.7–5.2% (Figure 5).

Table 2. Influence of wheat straw return on the taste scores of the cooked rice in different direct-seeding rice production systems.

Year	Treatment	Appearance Value	Hardness Value	Viscosity Value	Balance Value	Taste Value
2019	T1S1	6.67 ab [1]	6.91 a	7.02 b	6.56 b	69.8 b
	T1S2	6.53 b	6.76 ab	6.70 c	6.06 c	65.8 c
	T2S1	7.03 a	6.66 bc	7.36 a	7.03 a	73.6 a
	T2S2	6.71 ab	6.52 c	6.98 bc	6.53 b	69.7 b
2020	T1S1	6.59 b	6.50 a	6.80 b	6.27 b	66.9 b
	T1S2	6.35 b	6.38 a	6.48 c	5.96 b	63.1 c
	T2S1	6.97 a	6.26 ab	7.20 a	6.80 a	70.5 a
	T2S2	6.66 ab	6.04 b	6.78 b	6.40 ab	66.5 b

[1] Values followed by different lowercase letters were significantly different at the 0.05 probability level among different treatments.

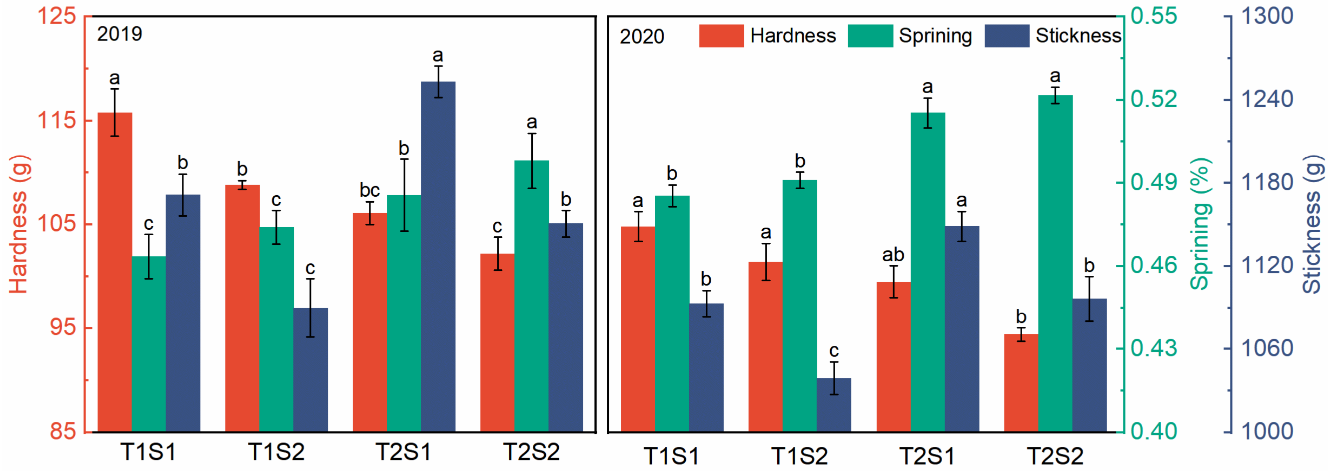

Figure 5. Influence of wheat straw return on the texture properties of the cooked rice in different direct-seeding rice production systems. Error bars show standard error of replicates (n = 3). Values followed by different lowercase letters were significantly different at the 0.05 probability level among different treatments.

3.7. RVA Parameters

In both years, the overall viscosity of rice flour was improved after wheat straw return. Regarding the RVA parameters, the peak viscosity, trough viscosity, and final viscosity increased by 4.9–7.2%, 5.5–6.2%, and 4.8–7.4%, respectively. The breakdown of rice flour after wheat straw return increased by 5.0–8.8%, and the setback decreased by 4.0–6.0%. After wheat straw return, although the peak viscosity, trough viscosity, and final viscosity of rice flour in S2 all increased, the breakdown in S2 decreased by 4.9–7.5%, and the setback in S2 increased by 6.4–7.5% when compared with those in S1 (Table 3).

Table 3. Influence of wheat straw return on the pasting properties of rice flour in different direct-seeding rice production systems.

Year	Treatment	Peak Viscosity (cP)	Trough Viscosity (cP)	Final Viscosity (cP)	Breakdown (cP)	Setback (cP)
2019	T1S1	2195 c [1]	1274 c	1882 d	921b c	−313 bc
	T1S2	2243 bc	1357 b	1958 c	886 c	−285 a
	T2S1	2327 ab	1349 b	2001 b	978 a	−325 c
	T2S2	2362 a	1432 a	2061 a	930 b	−301 ab
2020	T1S1	2126 c	1259 c	1845 d	867 b	−281 ab
	T1S2	2195 b	1346 b	1931 c	849 b	−264 a
	T2S1	2279 a	1336 b	1981 b	943 a	−298 b
	T2S2	2302 a	1430 a	2023 a	872 b	−279 a

[1] Values followed by different lowercase letters were significantly different at the 0.05 probability level among different treatments.

3.8. Correlation Analysis

Correlation analysis of the grain quality indexes indicated that the taste value of the cooked rice was significantly positively correlated with the appearance value, viscosity value, balance value, and stickness; it was significantly positively correlated with the breakdown of the RVA parameters and negatively correlated with the setback of the RVA parameters. The amylose content of the grain had a significantly positive correlation with the appearance value, viscosity value, balance value, and stickness of the cooked rice; it had a significantly negative correlation with the breakdown of the RVA parameters and significantly positively correlated with the setback of the RVA parameters. The chalkiness area and chalkiness degree of the grain were significantly negatively correlated with the content of protein and protein components (Figure 6).

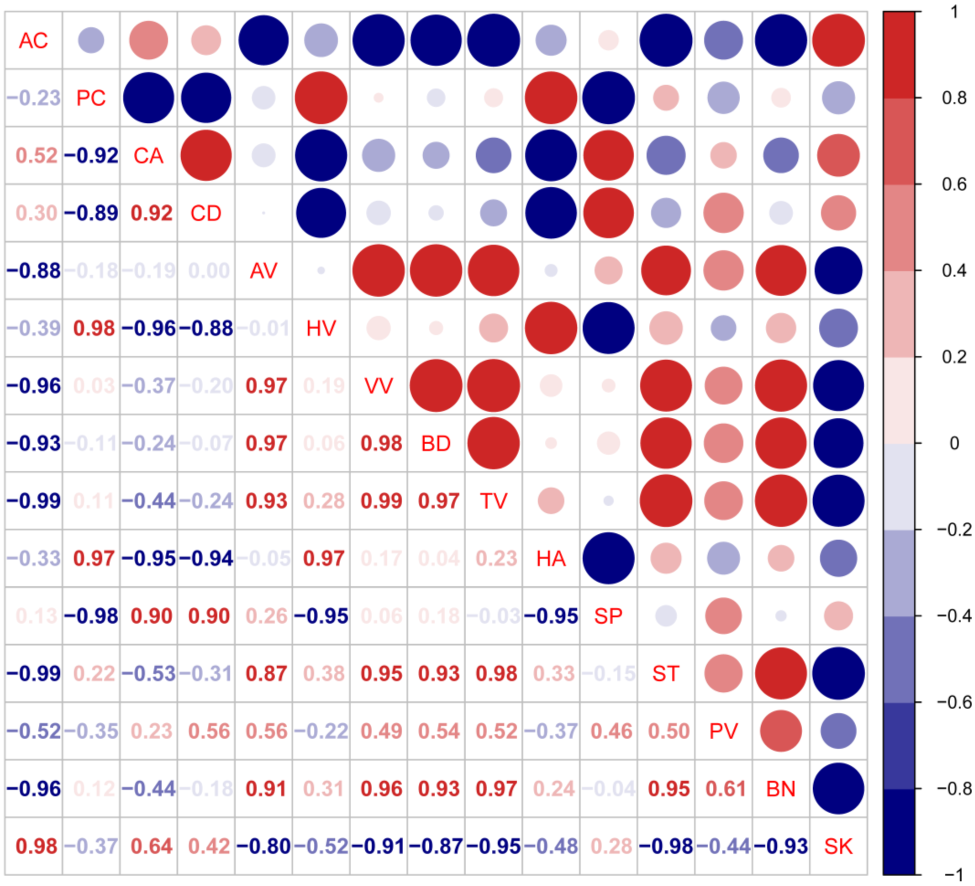

Figure 6. Correlation analysis of grain quality indexes ($R_{0.05}$ = 0.707, and $R_{0.01}$ = 0.834). AC: amylose content; PC: protein content; CA: chalkiness area; CD: chalkiness degree; AV: appearance value; HV: hardness value; VV: viscosity value; BD: balance degree; TV: taste value; HA: hardness; SP: spring; ST: stickness; PV: peak viscosity; BN: breakdown; SK: setback.

4. Discussion

4.1. Grain Yield

Wheat straw return had a significant effect on the yield of direct-seeding rice, which to some extent affected the uptake, utilization, and accumulation of soil nutrients by rice. Numerous studies were conducted on the effect of wheat straw return on rice yield, but the results were inconsistent. Some scholars concluded that wheat straw return increased rice yield by 5–10%. However, some studies showed that wheat straw return reduced rice yield [26]. In addition, some scholars believed that wheat straw return had no effect on rice yield [27]. The present study indicated that wheat straw return reduced the yield of direct-seeding rice. In terms of yield components, the insufficient panicle number was the main factor for yield reduction. The tiller number is the main determinant of the panicle number of rice, and the present study showed that wheat straw return decreased the panicle number of direct-seeding rice. We further concluded that the tillering capacity of the direct-seeding rice after wheat straw return dropped, resulting in a yield loss. This decrease in tillering capacity may be related to the strongly reducing soil environment formed after wheat straw return, the harmful substances produced by wheat straw decomposition [28], and the high consumption of soil nitrogen during wheat straw decomposition [29]. These factors restricted the development of the root systems of direct-seeding rice, thus limiting the normal growth and development of the rice seedlings and thus leading to a decrease in tillering capacity.

As a relatively stable harvest index, biomass accumulation at the maturity stage is a key determinant of rice yield. In particular, the biomass accumulation from the heading stage to the maturity stage is directly and positively correlated with the rice yield. The results of the present study showed that wheat straw return reduced biomass accumulation at the maturity stage. From the point of view of the biomass accumulation at each stage, wheat straw return reduced the biomass accumulation from the sowing stage to the stem elongation stage, from the stem elongation stage to the heading stage, and from the heading stage to the maturity stage. The loss of biomass accumulation from the sowing stage to the stem elongation stage was the most important factor, which may be related to the reduced tillering capacity of the direct-seeding rice after wheat straw return. Some scholars suggested that organic matter and nutrients provided by decomposing wheat straw could contribute to the increase in biomass accumulation of transplanted rice [30]. Unlike direct-seeding rice, transplanted rice has reached the four-leaf stage by the time it is planted into the main field, at which time it has some resistance to stress. However, direct-seeding rice is in a negative environment from seed germination to seedling growth, leading to biomass loss in direct-seeding rice [31]. Therefore, yield loss after wheat straw return is mainly due to insufficient biomass accumulation.

Using different direct-seeding methods after wheat straw return also affects the yield of direct-seeding rice. The present study showed that the yield potential in S2 was higher than that in S1 due to higher capacity in tiller and biomass accumulation. Similar conclusions were reached in previous studies on the effects of different direct-seeding methods on yield and biomass [32]. For example, Zhang et al. reported that, compared to using the dry direct-seeding method, using the wet direct-seeding method increased the proportion of effective tillers, the biomass accumulation at the post-flowering and maturity stages, the tiller number at the mid- and late-growth stages, the leaf area index, the crop growth rate, the leaf photosynthetic rate, and the root oxidation ability, thereby increasing the rice yield. In the present study, we considered two possible reasons for the higher advantage in S2 after wheat straw return. One is that using the wet direct-seeding method could moderate the negative effects of wheat straw return. As dry rotary tillage was performed in the soil in S1, the depth of rotation was only 0–15 cm. However, wet rotary tillage was performed in the soil in S2, contributing to increasing the depth of rotation, thus moderating the negative effects of wheat straw return. The other is that using the wet direct-seeding method resulted in a high relative content of soil nitrogen because S2 reduced ammonia volatilization and nitrogen runoff losses [33] when compared to S1.

4.2. Grain Quality

Nutritional quality is an important index for evaluating the grain quality of rice and can be measured by the content of amylose, protein, and protein components. Wheat straw return has an effect on the nutritional quality. In addition, different direct-seeding methods variably influence nutritional quality. The present study showed that wheat straw return reduced the amylose content of the grain of direct-seeding rice, which is consistent with previous studies. For example, Chen et al. reported a reduction in the amylose content of the rice grain after wheat straw return using two super rice varieties (indica Yangliangyou 6 and japonica Nanjing 45) [34]. However, this reduction could be increased by using the wet direct-seeding method, i.e., the amylose content of the grain in S2 was higher than that in S1 [35]. The results of the previous research on the effect of wheat straw return on protein content are inconsistent. Some studies showed that wheat straw return could increase the protein content in the grain because the nutrients released by the decomposition of the returned wheat straw increased soil fertility [17]. However, some studies concluded the opposite [36]. The present study showed that wheat straw return reduced the content of the protein and the protein components of the grain of direct-seeding rice, for which there are two possible reasons. One is that the returned wheat straw needed to consume nitrogen during decomposition, reducing soil available nitrogen. Nitrogen deficiency reduced the activities of related metabolic enzymes, thus hindering the synthesis of amino acids and proteins. The other is that the negative soil environment caused by the returned wheat straw resulted in a poor root system, leading to a poor nutrient uptake, stunted growth, and development of direct-seeding rice [37].

Appearance quality is also an important index for evaluating the grain quality of rice, with chalkiness area and chalkiness degree being the core measurements. Chalkiness adversely affects the milling, cooking, and appearance of rice grains and is a major problem in some rice production areas. Numerous spherical or elliptical amyloplasts in the endosperm of rice grains are not tightly arranged and cause pores in the endosperm starch cells, resulting in the scattering of the incident light, thus causing chalkiness [38]. Numerous studies have been conducted on the effect of wheat straw return on rice appearance quality, but the results are inconsistent. Some studies reported that, after wheat straw return, the chalkiness rate and chalkiness degree of the rice grain decreased significantly [39]. According to some studies, wheat straw return increased the length to width ratio of the rice grain and slenderized the grains, improving the appearance quality of the rice grain. Since the nutrients needed to fill the endosperm cells during grain filling are transported by the dorsal vascular bundle through the pearl epidermis and paste layer, a thinner rice grain reduces the distance of nutrient transport [34]. However, some studies believed that the chalkiness rate and chalkiness degree of the grain increased after wheat straw return. This was primarily because the returned wheat straw produced toxic gases, such as hydrogen sulfide, resulting in a strongly reducing soil environment [40]. Consequently, when compared to the rice roots without wheat straw return, those with returned wheat straw deteriorated severely, of which the nutrient uptake was reduced, and the vigor was weakened, leading to an increase in grain chalkiness. In the present study, we found that wheat straw return increased the chalkiness area and chalkiness degree of the grain of direct-seeding rice, thus deteriorating the appearance quality of the grain.

Different direct-seeding methods can lead to a difference in the appearance quality of the rice grain. When compared to the rice grain in S1, those in S2 had a smaller chalkiness area and lower chalkiness degree. Previous studies have shown similar results [35]. The present study indicated that the higher appearance quality of the rice grain after wheat straw return and the rice grain in S2 might be related to the protein content (Figure 6), which was negatively correlated with the chalkiness area and chalkiness degree of the rice grain [41]. The protein filled the gaps between the starch granules and reduced the refraction of light through those gaps, resulting in decreased chalkiness [38].

Cooking quality is the most important index in the current rice quality evaluation. It is a comprehensive evaluation index, mainly referring to the sensory characteristics of rice when eaten, such as appearance, hardness, viscosity, spring, and aroma [42]. Currently, the taste scores, the texture properties, and the RVA parameters are mainly used to evaluate the cooking quality of the rice grain. Taste scores are a simple and quick way to evaluate the taste of cooked rice and are highly consistent with human sensory scores. They can reflect the palatability of cooked rice to some extent [43]. Generally, cooked rice with a good appearance, low hardness, and high viscosity has a good taste. The present study showed that wheat straw return increased the appearance and viscosity values of the cooked rice and reduced the hardness value, thus improving the taste value. We measured the textural properties quantitatively by simulating the mechanical movement of the mouth in chewing using a texture analyzer to determine the hardness, spring, and stickness of the cooked rice. In general, the hardness of cooked rice is significantly negatively correlated with the taste score of cooked rice, while the stickness and spring are positively correlated with the taste score of cooked rice [44]. The present study showed that wheat straw return reduced the hardness of the cooked rice and improved the stickness and spring, thus increasing the taste score. The RVA parameters are related to the properties of the cooked rice. The peak viscosity reflects the stability of starch granules, the breakdown reflects the thermal stability and shear resistance of the starch granules during cooking, and the setback reflects the viscosity of starch during heating. Rice with high cooking quality tends to have a high breakdown and a lower setback. According to previous studies, the peak viscosity and breakdown of the cooked rice with wheat straw return increased, while the setback decreased, which makes the cooked rice softer and stickier, thereby improving the cooking quality of the rice effectively. The present study showed that the wheat straw return increased the breakdown and decreased the setback of the rice flour, thus improving the cooking quality of rice. In addition, various direct-seeding methods had different impacts on the cooking quality of rice. The results of the present study indicated that the rice in S2 had a lower appearance value, viscosity value, stickness, and breakdown and a higher hardness value and setback when compared to that in S1. Therefore, using the wet direct-seeding method after wheat straw return led to a decrease in the rice cooking quality. Both rice grains after wheat straw return and in S1 had a higher cooking quality, which may be related to the lower amylose content. The rice grain with a lower amylose content was often associated with a higher appearance value, viscosity value, stickness, and breakdown and a lower setback (Figure 6). Previous studies also indicated that rice grain with a lower amylose content was generally softer and had a better cooking quality [45].

5. Conclusions

The present study confirmed that wheat straw return reduced the yield of direct-seeding rice. The insufficient panicle number caused by reduced tillering capacity and a low biomass accumulation were the main reasons for the yield loss. However, wheat straw return improved the cooking quality and appearance quality of direct-seeding rice. Using the wet direct-seeding method improved the yield and appearance quality but reduced the cooking quality of the grain of direct-seeding rice. On balance, we recommend using the dry direct-seeding method in a rice–wheat rotation system. The reason is that the dry direct-seeding rice production system is more convenient and efficient and can result in rice with a higher cooking quality, compensating for the labor shortage and meeting the demand of people for cooking quality as their living standards improve. However, the yield in the dry direct-seeding rice production system needs to be improved by studying cultivation practices, such as increasing seedling density and the rotary tillage depth.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12123180/s1, Figure S1: daily mean temperature, sunshine hours, and precipitation during the rice growth season in 2019 and 2020. The 0 days after sowing is June 11 for both years.

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