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Integrative Effect of Reduced Tillage and Shading Enhanced Yield and Grain Quality of Fragrant Rice

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Abstract: The major challenge in fragrant rice production is to improve both yield and grain quality in fragrant rice. Reducing tillage has been singled out as an effective impact to improve grain yield. However, information on the improvement of grain yield and grain quality and their relationship is sparse. This study aimed to assess the influence of different tillage methods on rice growth during the booting stage under shading conditions. The experiments were conducted with rotary tillage and no-shading (RTNS), rotary tillage and shading (RTS), reduced tillage and no-shading (LTNS), reduced tillage and shading (LTS), no-tillage and no-shading (NTNS) and no-tillage and shading (NTS), using two fragrant rice varieties, Meixiangzhan 2 (MXZ2) and Xiangyaxiangzhan (XYXZ). Grain yield, grain quality, Malondialdehyde (MDA) content and antioxidant activities were all investigated. Our results showed that grain yield of reduced tillage and no-tillage were 27.9% and 27.0% higher than rotary tillage, respectively. In addition, with shading applied, grain yield significantly decreased. Moreover, with the application of a shading treatment, the brown rice rate, chalkiness degree and chalk grain rate decreased, while the milled rice rate, amylose content and protein content increased. The results of this study revealed that shading improves the grain quality of fragrant rice but has a negative impact on its yield while reducing tillage effectively makes up for the yield loss resulting from shading and improves rice quality.

Keywords: fragrant rice; reducing tillage; shading; grain quality; antioxidant; grain yield

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1. Introduction

Rice is indeed one of the most vital food crops in China, occupying the second largest planted area globally and achieving the highest total yield, and it occupies an important position in China's food production and national economic construction [1]. As people's living standards improve, the demand for rice quality, particularly in terms of palatability, has significantly increased [2]. Fragrant rice is a distinct variety of rice that commands a premium price in the global market due to its distinctive aroma [3]. However, there are limitations in the improvement of grain yield and taste quality in fragrant rice, as well as its resistance to biological and abiotic stresses [4]. To tackle these challenges, researchers are engaged in screening and developing new fragrant rice cultivars and exploring techniques to improve their quality and stress resistance. The ultimate goal is to meet the increasing demand for high-quality fragrant rice while ensuring its sustainable production [5].

Tillage methods and light conditions are important factors which can affect rice yield and rice quality. The growth and development of crops play a crucial role in determining their yield, and improving yield requires accumulating as much dry matter as possible. Some studies suggest that the stronger the rice tillering ability, the larger the effective photosynthetic area in the later stage, which can effectively ensure the accumulation of dry matter. Hu et al. [6] found that the number of years of continuous no-tillage has a remarkable impact on the growth of rice. Compared with traditional cultivation, rice, after 1–5 years of no-tillage, generally has a stronger tillering ability. After 6 years of no-tillage, the tillering ability slightly decreases, and after 7 years, the tillering ability of rice in paddy fields decreases significantly. In recent years, numerous researchers have studied the impacts of various soil tillage methods on the physicochemical properties of paddy soil, the growth, physiological, and biological characteristics of rice plants, as well as the rice yield. Wu et al. [7] found that compared with rotary tillage, plowing reduced soil bulk density by 10–20 cm but increased soil organic matter and nutrient content. Xu et al. [8] found that no-tillage was beneficial to improving the soil quality of double-cropping paddy fields. Quan et al. [9] found that ridge cultivation increased the protective enzyme activity and photosynthetic rate of rice compared with traditional cultivation, thereby promoting rice yield. However, the results of the effect of minimal tillage or no-tillage on yield are still inconclusive and need further exploration.

The rainy and cloudy weather during the grain-filling period leads to a decrease in rice yield and a decline in quality. Many researchers have employed shading techniques to simulate the impact of low light conditions on rice growth, photosynthesis, yield and quality in numerous studies. Ren et al. [10] found that after application of shading treatment resulted in a significant or extremely significant decrease in indicators such as rudimentary rice rate, milled rice rate, whole-grain rate, transparency and stickiness. Conversely, there was a significant or extremely significant increase in indicators such as chalky rice rate and chalkiness. And the amylose content decreased significantly, while the protein content increased significantly. Loc et al. [11] conducted shading experiments on 14 Vietnamese rice varieties and found that shading increased the green seedling rate and chalkiness rate. In addition, Wang et al. [12] found that insufficient light during the flowering and grain-setting period of early rice would reduce the setting rate, mainly due to the increase in empty grain rate. Low light reduces the production of assimilates, resulting in fewer assimilates in the rice panicle, which affects the development and fertilization of weak flowers. The sensitive period of panicle shading treatment for rice is from panicle initiation to the bending stage. The panicle shading not only affects the total accumulation of assimilates in rice plants but also affects the distribution of photosynthates to rice grains. The effect on the distribution of photosynthates is more significant than that on the cultivation pattern of upright panicles, compared with that of the bent panicles [13]. Li et al. [14] believed that changes in light conditions within a certain range did not have a significant effect on the yield per plant, biological yield, grain weight and setting rate. However, when the light intensity decreased by more than 20% of natural light, both biological yield and rice grain yield decreased, and when the light intensity dropped to 60% of the control, plant growth almost stopped. Tohru et al. [15] found that shading treatments for 30 days after rice heading in 2011 and 2012 caused a significant decrease in spike-filling rate and grain weight in five selected rice varieties, resulting in a decrease in yield. However, there is a limited amount of research available on the yield and grain quality of fragrant rice under different tillage methods in shading conditions.

Previous studies have primarily focused on evaluating the individual effects of reduced tillage or shading treatment on rice. However, limited research has been conducted to examine their combined effects. Therefore, the objective of the present study was the following: (1) to investigate the interactive effects of different tillage methods and shading conditions on rice grain yield, grain quality and antioxidant activities of fragrant rice and (2) to explore the potential of reduced tillage to offset the detrimental effects of low light conditions on rice yield, enhance rice quality and improve stress resistance.

2. Materials and Methods

2.1. Field Experimental Details

Two rice cultivars, Meixiangzhan-2 (MXZ2) and Xiangyaxiangzhan (XYXZ), were used in the experiment. These cultivars, having similar growth periods, are widely cultivated in Southern China.

The field experiments were conducted in the late season of 2021 and 2022 at the Experimental Research Farm, College of Agriculture, South China Agricultural University, Guangzhou, China (23°130 N, 113°810 E, altitude 11 m). The soil in the experimental field was identified as sandy loam, with the following nutrient composition: 985 mg kg^{-1} total N, 1001 mg kg^{-1} total P, 20,073 mg kg^{-1} total K, 54.3 mg kg^{-1} available P, 91 mg kg^{-1} available K and 19,517 mg kg^{-1} organic matter.

Treatments were arranged in a split-plot design with tillage method as the main plots and light treatments as the subplots. The experiment had three duplications, and the subplot size was 80 m^2. Pre-germinated seeds were sown in a seedbed at 25 g m^2. About 16 days after sowing, seedlings at three leaves stage were transplanted to field plots with 20 × 30 cm hill spacings and two seedlings per hill. There are six treatments in the study, which were rotary tillage and no-shading (RTNS); rotary tillage and shading (RTS); reduced tillage and no-shading (LTNS); reduced tillage and shading (LTS); no-tillage and no-shading (NTNS); and no-tillage and shading (NTS)—the shading treatments were all applied during the booting stage. In rotary tillage, rotary tillage (with a till depth of about 10–15 cm) was carried out twice before transplanting. Under the rotary tillage and reduced tillage methods, all rice residues were incorporated into the field, while under the no-tillage method, the residues were mulched on the soil surface. Shading treatment employed one layer of black netting, which can offer a shading level equivalent to a 67% reduction of full natural light (as measured by a Luxmeter, model ZDS-10, Hangzhou, China). The soil remained undisturbed from harvest to the subsequent sowing period under the no-tillage management. Fertilizers were applied as 1500 kg ha^{-1} (total nitrogen contents TN = 15%, N: P_2O_5: K_2O = 15%:15%:15%) in two splits as 900 kg ha^{-1} and 600 kg ha^{-1} at the basal and panicle initiation stages, respectively. Crop management followed standard cultural practices. Insects were intensively controlled with chemicals to avoid biomass and yield losses. The differences in daily temperature and daily solar radiation between the two years were negligible (Figure 1).

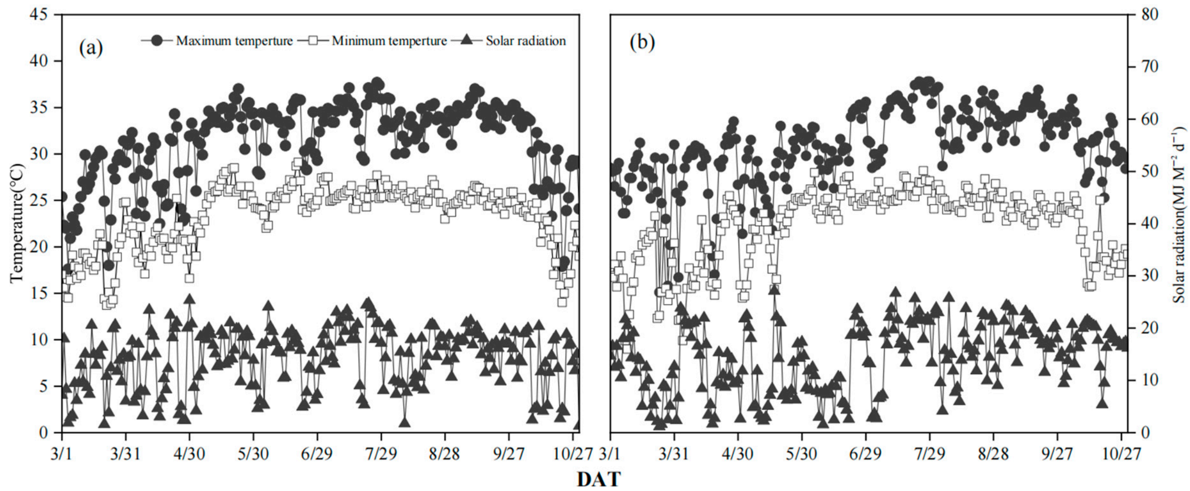

Figure 1. Daily maximum temperature (Tmax), daily minimum temperature (Tmin) and solar radiation from transplanting to maturity in 2021 (**a**) and 2022 (**b**) in Guangzhou, Guangdong Province, China.

2.2. Sampling and Measurements

2.2.1. Measurement of Grain Yield and Yield Components

A sample was taken at maturity from 8 randomly selected hills within a 5-m^2 harvest area to assess the yield components and harvest index (HI). The number of panicles was counted on each hill to determine the panicle number per m^2. The plants were then separated into straw and panicles. The panicles were manually threshed, and the filled spikelets were separated from the unfilled spikelets by submerging them in tap water. To further analyze the data, three subsamples weighing 30 g each were taken from the filled spikelets, while three subsamples weighing 3 g each were taken from the unfilled spikelets. The number of spikelets was counted in each subsample. The dry weights of the rachis, filled spikelets and unfilled spikelets were determined by oven-drying them at 80 °C until a constant weight was achieved. Using the above data, spikelet per panicle and grain-filling percentage (calculated as 100 × filled spikelet number/total spikelet number) were determined. Grain yield was calculated by measuring the yield from a 5-m^2 area in each plot and adjusting it to the standard moisture content of 0.14 g H_2O g^{-1}.

2.2.2. Measurement of Grain Quality

After harvesting, the mature grains were collected from three different parts of each plot, with an area of 2 m^2 each. The moisture content of the harvested grains was adjusted to 14% for further analysis. The grain-quality measurements were conducted after the sun drying process and storing the grains at room temperature for three months. The brown rice rate, milled rice rate and head rice rate were determined following the method outlined by Mo et al. [16]. Furthermore, the protein content and amylose content of the rice were determined using the FOSS Corporation's Danish Near-Infrared Grain Analyzer (INFRATEC-1241). This analyzer utilizes near-infrared spectroscopy to measure the protein and amylose content in the rice samples. To evaluate the chalkiness degree and chalky rice rate, a rice appearance quality analyzer (SC-E, produced by Hangzhou Wanshen Corporation in Hangzhou, China) was employed.

2.2.3. Measurement of Antioxidant Activities

The fresh flag leaf samples were homogenized by grinding with liquid nitrogen. Next, 9 mL of 50 mM sodium phosphate buffer (pH 7.8) was added to the homogenate, followed by centrifugation at 8000 rpm for 15 min at 4 °C. Subsequently, the supernatant was utilized for assessing the activities of superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT), as well as the measurement of malondialdehyde (MDA) content, according to the method described by Huang et al. [17]. SOD activity was determined by measuring the enzyme's ability to inhibit the initial rate of nitroblue tetrazolium reduction at 560 nm, causing a 50% reduction. The POD assay mixture consists of 1 mL of sodium phosphate buffer (pH 7.8), 0.95 mL of 0.2% guaiacol, 1 mL of 0.3% H_2O_2 and 0.05 mL aliquot of the enzyme extract. Absorbance was recorded at 470 nm for 90 s at 30 s intervals. One unit of POD activity was defined as the enzyme amount that decomposed 1 mg of substrate at 470 nm. The CAT assay mixture consisted of 1 mL of 1.95 mL distilled water, 1 mL of 0.3% H_2O_2, and 0.05 mL of the enzyme extract. Absorbance was recorded at 470 nm for 90 s at 30 s intervals. One unit of CAT activity was defined as the decomposition of 1 M H_2O_2 at A240 within 1 min in 1 g of fresh leaf samples. To determine the MDA content, a 1.5 mL enzyme extract was mixed with a 0.5 mL solution of thiobarbituric acid prepared in 5% trichloroacetic acid. The mixture was boiled at 100 °C for 30 min and then centrifuged at 3000 rpm for 15 min after cooling. The absorbance was read at 450 nm, 532 nm and 600 nm. MDA contents were calculated using the formula: MDA content = 6.45(OD532 − OD600) − 0.599OD450.

2.3. Statistical Analysis

The data collected from the experiments were analyzed using a three-way analysis of variance (ANOVA) in R version 4.3.1, an analytical software package from Tallahassee, FL, USA. The means were compared using the least significant difference (LSD) test at a

0.05 probability level to determine the significance of differences between treatments and rice cultivars.

3. Results

3.1. Yield and Yield Components

Grain yield in the LTNS, LTS, NTNS and NTS was significantly ($p < 0.05$) higher than RTNS and RTS of different tillage methods and shading treatments in both 2021 and 2022 (Figure 2). The grain yields of LT and NT were 27.9% and 27.0% higher than RT, respectively. Comparably, RTS, LTS and NTS grain yields were 14.12%, 3.81% and 4.73% higher in the RTNS, LTNS and NTNS. The differences in grain yield between LTNS and LTS were negligible.

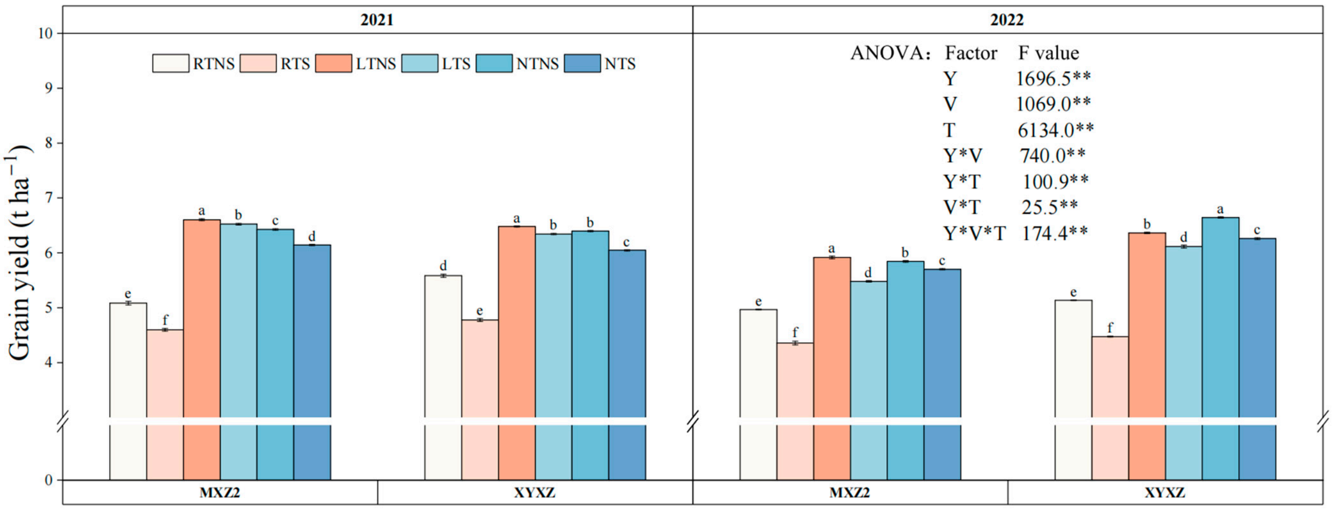

Figure 2. Grain yield of two rice varieties under different tillage methods and shading treatments in 2021 and 2022. Vertical bars indicate standard errors ($n = 3$); **: significant at $p < 0.01$ level; different lowercase letters indicate statistical differences among treatments at $p < 0.05$.

Panicle number, spikelet per panicle and grain filling were significantly affected by different tillage methods and shadings (Figure 3). Panicle numbers of NS were 37%, 36.6% and 29.5% higher than RTS, LTS and NTS, respectively. Compared with RT, panicle numbers were 5.5% and 7.0% higher in LT and NT treatments. RTNS, LTNS and NTNS had higher spikelets per panicle and 1000-grain weight. Spikelets per panicle were 10.30%, 13.17% and 9.41% higher than RTS, LTS and NTS, respectively, and 15.3%, 16.6% and 16.9% higher in the 1000-grain weight. Spikelet per panicle of LT and NT were 7.6% and 30.8% higher than RT, respectively.

3.2. Grain Quality

Brown rice rate, milled rice rate, chalkiness degree, chalk grain rate, amylose content and protein content were significantly ($p < 0.05$) different under the tillage methods and shading treatments (Table 1). In both 2021 and 2022, the NTNS exhibited the highest brown rice rate of the two varieties. Moreover, RTNS showed a higher chalkiness degree and chalk grain rate compared to other treatments. Compared with the shading treatment, the brown rice rate was 4.2% higher in the no-shading treatment, 60.8% in the chalkiness degree and 50.5% in the chalk grain rate, while the shading treatment had the higher milled rice rate, amylose content and protein content than the no-shading treatment, which was 0.8% higher in the milled rice rate, 3.1% in the amylose content and 7.3% in the protein content. Brown rice rate, chalkiness degree, chalk grain rate and protein content were significantly ($p < 0.05$) different in the two varieties. MXZ2 has a higher brown rice rate, chalkiness degree, amylose content and protein content than XYXZ.

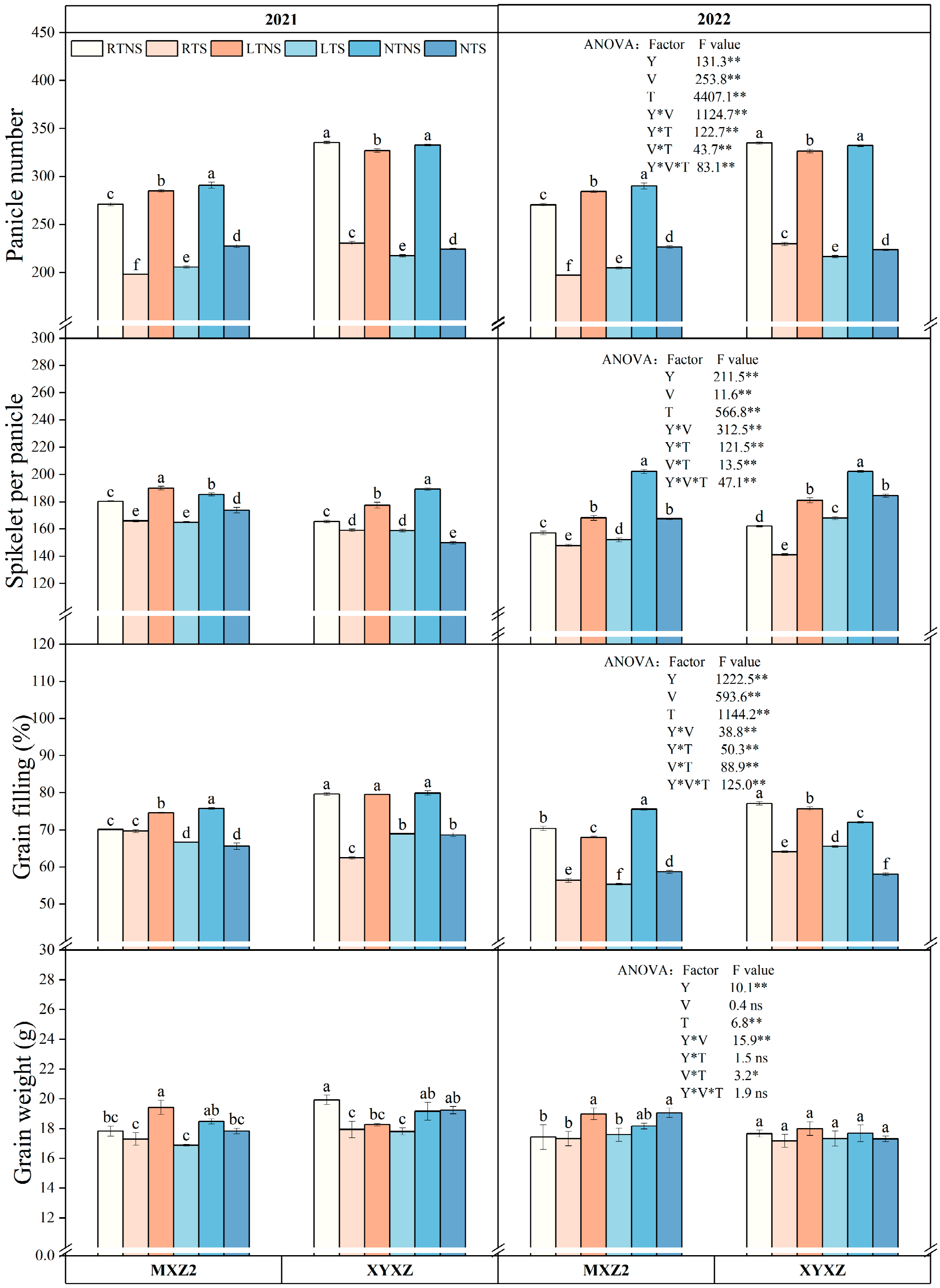

Figure 3. Yield components of two rice varieties under different tillage methods and shading treatments in 2021 and 2022. Vertical bars indicate standard errors ($n = 3$); *: significant at $p < 0.05$ level; **: significant at $p < 0.01$ level; different lowercase letters indicate statistical differences among treatments at $p < 0.05$.

Table 1. Effects of different tillage methods and shading treatments on the quality of the two rice varieties from 2021–2022 (n = 3).

Year	Variety	Treat	Brown Rice Rate	Milled Rice Rate	Chalkiness Degree	Chalk Grain Rate	Amylose Content	Protein Content
			(%)	(%)	(%)	(%)	(%)	(%)
2021	MXZ2	RTNS	75.47abc	68.34c	17.46a	27.16a	16.85b	7.42e
		RTS	74.91c	68.69bc	10.23c	16.21d	17.38ab	8.25d
		LTNS	78.96ab	72.15abc	14.87b	21.41b	18.18ab	8.71c
		LTS	75.62abc	73.25a	9.15cd	14.69e	18.87a	9.53b
		NTNS	79.56a	71.07ab	13.49b	19.94c	20.03a	10.07a
		NTS	76.32bc	72.26ab	8.39d	13.25f	18.73a	10.25a
		Mean	76.81	70.96	12.27	18.78	18.34	9.04
	XYXZ	RTNS	73.17ab	67.7c	15.25a	26.59a	18.06bc	7.71e
		RTS	71.45b	67.93bc	9.68cd	15.17c	18.27ab	7.97d
		LTNS	74.05ab	70.24bc	12.17b	20.26b	17.03c	8.45c
		LTS	72.64b	70.35ab	8.25de	13.89c	19.03a	8.31c
		NTNS	76.34a	71.47ab	10.39bc	20.72b	18.36ab	9.56b
		NTS	73.96ab	72.02a	6.49e	14.23c	17.92bc	10.05a
		Mean	73.60	69.95	10.37	18.48	18.11	8.68
2022	MXZ2	RTNS	79.73ab	69.75a	14.19a	23.17a	17.93a	7.54f
		RTS	76.25c	70.24a	8.56b	16.47c	18.56a	7.89e
		LTNS	80.76a	72.24a	12.178a	20.36b	17.65a	8.34d
		LTS	78.47b	72.51a	7.16bc	15.23c	17.51a	8.65c
		NTNS	81.57ab	71.37a	9.25b	21.09b	16.75a	10.27b
		NTS	77.38b	72.05a	6.23c	16.25c	17.21a	11.05a
		Mean	79.03	71.36	9.59	18.76	17.60	8.96
	XYXZ	RTNS	76.83bc	68.56a	11.87a	26.55a	17.14a	8.05c
		RTS	74.16d	69.13a	7.33bc	13.25d	17.39a	8.23c
		LTNS	79.28abc	71.23a	8.19b	19.15b	17.97a	9.45b
		LTS	76.16cd	71.95a	6.14cd	14.68d	18.36a	10.34a
		NTNS	81.24a	72.49a	5.38d	17.51c	17.03a	10.59a
		NTS	80.08ab	73.08a	3.47e	13.07d	17.39a	10.51a
		Mean	77.96	71.07	7.06	17.37	17.55	9.53
	ANOVA	Y	89.9 **	11.1 **	328.7 **	7.1 *	6.9 *	295.2 **
		V	51.8 **	1.9 ns	211.9 **	28.0 **	0.1 ns	21.9 **
		T	41.3 **	17.2 **	234.6 **	807.8 **	4.1 **	1903.0 **
		Y × V	5.5 *	0.1 ns	11.3 **	18.0 **	0.9 ns	491.9 **
		Y × T	2.5 *	0.9 ns	5.2 **	9.3 **	6.2 **	18.3 **
		V × T	4.0 **	1.6 ns	4.2 **	21.7 **	1.5 ns	34.1 **
		Y × V × T	1.5 ns	0.7 ns	0.6 ns	18.1 **	5.0 **	132.8 **

Within each column, means followed by the same letters are not significantly different according to LSD (0.05). RTNS, rotary tillage and no-shading; RTS, rotary tillage and shading; LTNS, reduced tillage and no-shading; LTS, reduced tillage and shading; NTNS, no-tillage and no-shading; NTS, no-tillage and shading; *: significant at $p < 0.05$ level; **: significant at $p < 0.01$ level.

3.3. MDA Content and Activities of SOD, CAT and POD

Shading significantly increased the activities of POD, CAT and MDA content by 6.2%, 5.1% and 2.9, respectively, and declined the activities of SOD by 4.2% (Figure 4). However, the reduction of tillage increased the activities of SOD, CAT, POD and MDA content. Compared with rotary tillage, the LT and NT had the higher SOD, CAT, POD and MDA content, which was 4.2% and 11.7% in the SOD, respectively, 2.1% and 29.4% in the POD, 16.2% and 30.5% in the CAT, 12.8% and 17.9% in the MDA content, respectively. The NT treatment had the highest activities of SOD, POD, CAT and MDA content.

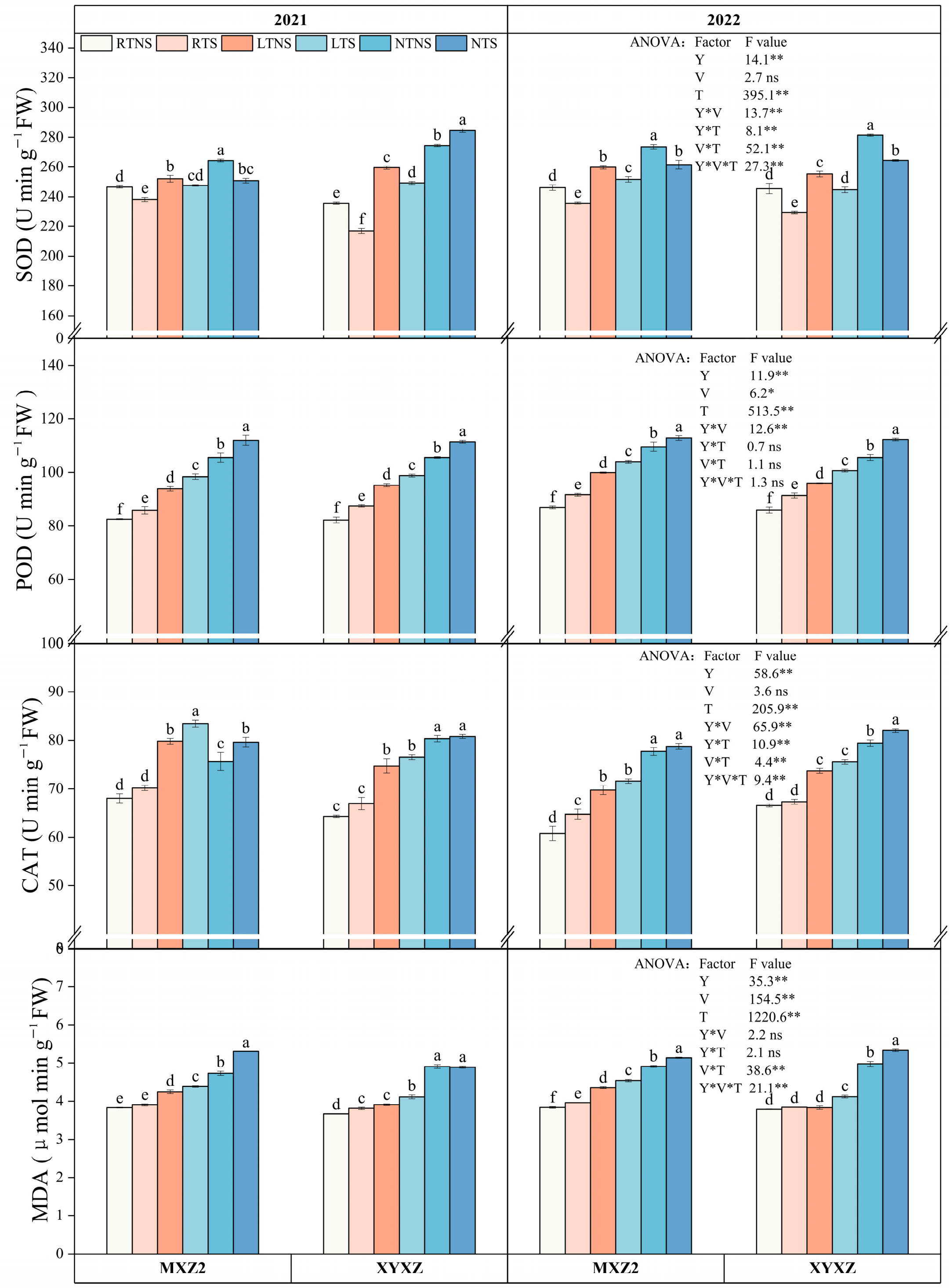

Figure 4. Activities of superoxide dismutase (SOD), peroxidase (POD), catalase (CAT) and malondialdehyde (MDA) content in leaves of rice under different tillage methods and shading treatments from 2021 to 2022; *: significant at $p < 0.05$ level; **: significant at $p < 0.01$ level; different lowercase letters indicate statistical differences among treatments at $p < 0.05$($n = 3$).

3.4. Correlation Analyses of Grain Yield and Population Growth Parameters

Correlation matrices among the various grain yield components and population growth parameters are shown in Figure 5. Grain yield significantly ($p < 0.01$) and positively correlated with GF, MR, POD, PC, MDA, CAT, SOD and GN. Additionally, CGR were significantly ($p < 0.01$) positively correlated with CD and PN, but CGR and CD had the contract significantly ($p < 0.01$) positively correlated with MR, POD, PC, MDA and CAT. Moreover, PC were significantly ($p < 0.01$) positively correlated with MDA, CAT, SOD, POD and MR, but the contract significantly ($p < 0.01$) positively correlated with CGR and CD.

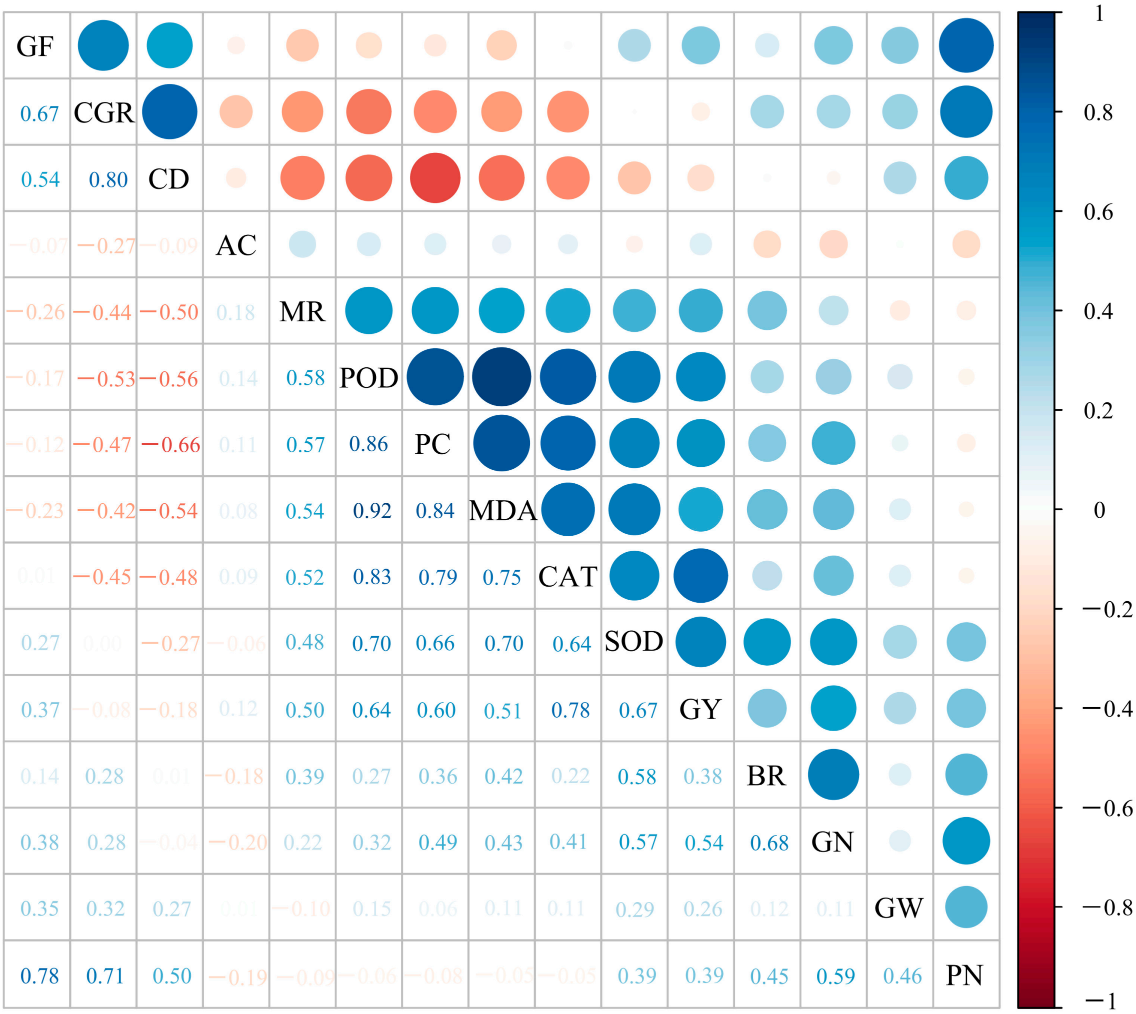

Figure 5. Correlation matrix of various grain yield and population growth parameters ($n = 72$). GY, grain yield; PN, panicle number; GN, spikelet per panicle; GF, grain filling; GW, 1000-grain weight; BR, brown rice rate; MR, milled rice rate; CD, chalkiness degree; CGR, chalk grain rate; AC, amylose content; PC, protein content; SOD, superoxide dismutase; POD, peroxidase; CAT, catalase; MDA, malondialdehyde.

3.5. Principal Components Analysis

Principal component 1 is mainly the change of protein content, MDA content and antioxidant activities; principal component 2 is the yield and chalkiness components. Tillage methods and shading treatments are significantly different in principal components 1 and 2. The high level of antioxidant activities and MDA content contribute to the accumulation of protein content (Figure 6).

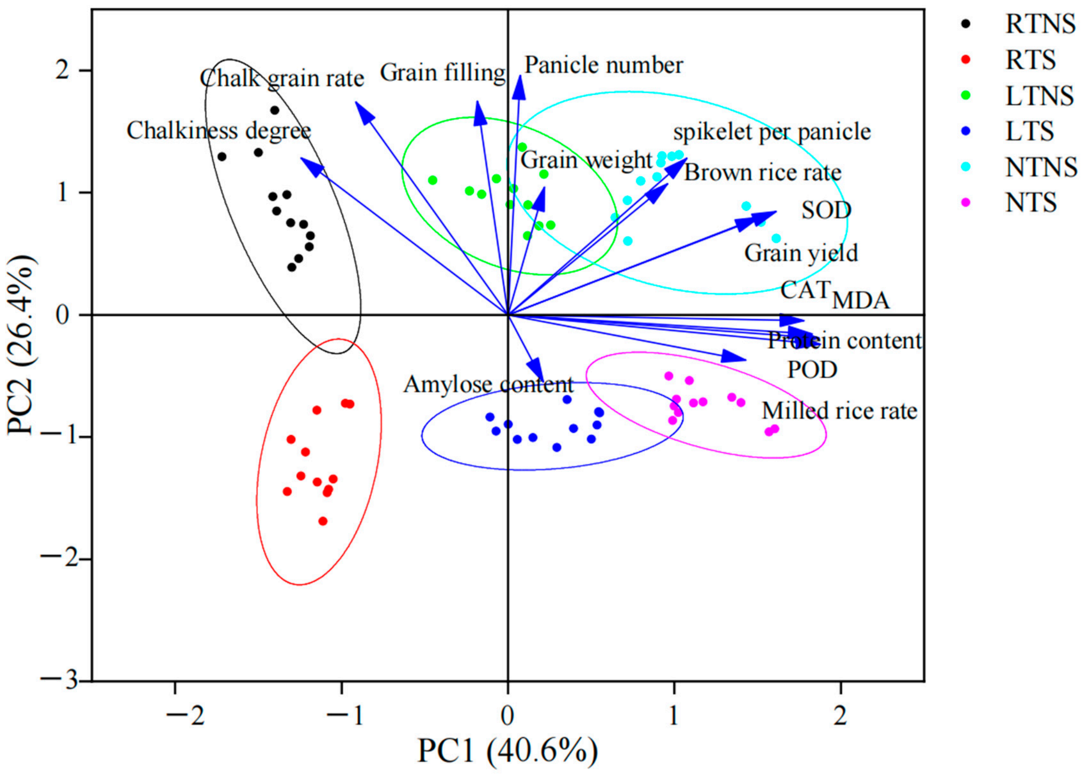

Figure 6. Principal components analysis (PCA) of different tillage methods and shading treatments on the various grain yield and population growth parameters from 2021 to 2022.

4. Discussion

4.1. Grain Yield and Yield Components

This study investigated the effects of different soil cultivation methods and shading conditions on two types of fragrant rice. The results showed that the soil cultivation methods had significant impacts on soil physical and chemical properties, as well as rice yield and yield components. The yield under the rotary tillage was the lowest, which may have been caused by the decrease in the rice LAI during the later growth stage [18]. The yields of the reduced tillage and no-tillage treatments were significantly higher than that of the rotary tillage. Chen et al. [19] found that no-tillage was beneficial to the improvement of rice yield components, which in turn increased the rice yield. Yi et al. [20] reported that compared with no-tillage, tillage had a higher rice yield, consistent with our findings. Tang et al. [21] showed that the yield of conventional tillage was higher than that of rotary tillage, but both were higher than that of no-tillage; Li et al. [22] also believed that no-tillage reduced rice yield, which may have been related to the soil nutrient characteristics. Our study demonstrated that the main reason for the increased yield by reduced tillage and no-tillage was the significant improvement in panicle number and spikelet per panicle compared with rotary tillage. Wen et al. [23] found that no-tillage decreased the number of panicle number in rice but increased the total number of spikelets per panicle, the number of filled spikelets per panicle and the grain weight, while the panicle number of conventional tillage more. Chen [24] believed that in the case of a straw return, conventional tillage could effectively increase the number of spikelets per panicle to achieve a higher yield, while no-tillage could increase the number of panicles of rice but reduce the number of spikelets per panicle. Some studies have also demonstrated that no-tillage can reduce rice yield by affecting the number of panicles, grain weight and other factors [21,25], which may be related to the increase in soil volume and too compact soil in the middle layer, which suppresses rice growth [26].

Our study found that shading during grain filling resulted in a significant reduction in rice yield by reducing the number of panicles, grain number, grain-filling rate and grain weight. Shading has a negative effect on rice yield, which varies in different growth stages of rice. Early shading has a smaller impact on rice yield [15,27]. Song et al. [28] found that the yield reduction under shading during the grain-filling stage was much greater than that during the booting or tillering stage. The reason for the yield reduction under shading during the grain-filling stage is the decrease in dry matter accumulation, grain-filling rate or hindrance of pollination and fertilization processes, which significantly reduces the filling ratio [14,16,29]. Mu et al. [30] found that the reason for the yield reduction under shading was the decrease in the grain number and grain weight, while Jia et al. [31] believed that the yield reduction was closely related to the decrease in filling ratio and grain weight. Wang et al. [14] observed that shading stress inhibited the process from tillering to the formation of effective panicles and reduced the number of effective panicles.

Our study showed that although shading treatment reduced rice yield, reduced tillage or no-tillage methods could compensate for the yield decrease by increasing the panicle number and spikelet per panicle.

4.2. Grain Quality

Crop yield and quality can be negatively affected by cloudy and rainy weather during the growth period [32]. In all the growth stages, the grain-filling period is the most heavily affected by shading [28,33]. In this study, shading during the grain-filling period was found to significantly reduce rice grain yield, chalkiness degree and chalk grain rate while increasing milled rice rate, amylose content and protein content. Similarly, Mo et al. [16] found that shading has significant effects on most rice grain-quality traits, such as increasing grain protein content and decreasing average chalk grain rate and chalkiness degree, which is consistent with our findings. However, Deng et al. [34] found that, although shading increased rice protein content, it decreased amylose content while chalk grain rate and chalkiness degree increased. Deng et al. [29] also found that shading increased chalk grain rate while reducing head rice rate and taste value. Rice quality is affected by multiple factors, with temperature during the growth period having a larger effect on quality. The average temperature in the first 30 days after heading has a significant and strong impact on rice grain quality [35]. High temperature during the grain-filling period can interfere with grain plant hormone metabolism, reduce key enzyme activity, inhibit grain filling, increase chalkiness degree and reduce whole-milled rice rate and taste value. Temperatures above 38 °C for 3–5 days during the booting stage can cause a significant decrease in spikelet fertility [36]. Therefore, it is speculated that the continuous high temperature in the Guangzhou region may have led to obstruction of grain-filling in rice and a reduction in rice quality, and shading may effectively mitigate this phenomenon.

Different tillage methods also have a significant impact on rice quality. The results of this study found that both reduced tillage and no-tillage significantly increased rice brown rice yield, milled rice yield and protein content and significantly reduced chalk grain rate and chalkiness degree, with no-tillage having a more significant effect than reduced tillage. Liu et al. [37] found that no-tillage improved rice quality by significantly reducing the chalk grain rate, chalkiness degree and protein content while improving the taste value, which is consistent with our findings. However, some studies have indicated that no-tillage is not conducive to improving rice processing quality, appearance quality and palatability [38]; Yi et al. [20] found a trend that no-tillage had significantly higher chalk grain rate and chalkiness degree than conventional tillage.

4.3. Antioxidant Responses

Superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT) are important antioxidant enzyme systems that work together to clear reactive oxygen species and free radicals in plant cells to maintain a stable membrane system [39]. Malondialdehyde (MDA) is the final product of lipid peroxidation and is usually an important indicator of plant stress. Sun et al. [40] found that during the booting stage, shading in hybrid rice increased the content of MDA, and the activity of SOD, POD and CAT increased to varying degrees with increasing shading intensity in leaves. Xu et al. [41] found that an increase in shading intensity resulted in an increase in MDA content but a slight increase in SOD and POD activity, followed by a significant decrease in activity. Jiang et al. [42] found that shading increased MDA content and reduced antioxidant enzyme activity. In this study, we found that shading increased the activity of POD and CAT and the content of MDA but decreased the activity of SOD. This might be due to the decrease in metal ion concentration caused by decreased energy metabolism under low-light conditions. Furthermore, we found that reduced and no-tillage, especially no-tillage, significantly increased the activity of SOD, POD and CAT, as well as the content of MDA, which is different from some previous studies that suggested that no-tillage would reduce the protective enzyme activity in rice plant leaves [9,43,44]. The higher content of MDA in no-tillage and reduced tillage might be due to the effect of no-tillage on soil structure. No-tillage reduces the total porosity, non-capillary porosity, soil microbial activity and nutrient content of lower soil layers, causing mild stress [22,45]. Previous studies have shown that no-tillage is beneficial for the accumulation of nitrogen in the surface soil [46,47]. No-tillage soil has a higher mineralization rate of nitrogen than conventional tillage but a lower nitrification rate than conventional tillage [48], all indicating that no-tillage is conducive to the absorption and utilization of nitrogen in rice. An increase in nitrogen has a positive effect on increasing antioxidant enzyme activity [42,49,50], which may be the reason for the increased antioxidant enzyme activity in no-tillage and reduced tillage in this study.

In summary, in this study, reducing tillage can effectively improve rice quality and increase rice antioxidant enzyme activities, while shading can further increase milled rice rate and protein content, reduce chalk grain rate and chalkiness degree, and increase the activity of POD and CAT. Reduced tillage can also compensate for yield loss caused by shading.

5. Conclusions

In this study, we present the potential of reduced tillage as a compensation strategy for mitigating the effects of shading on rice yield and grain quality for the first time. Additionally, we explore the impact of reduced tillage under shading conditions on improving antioxidant activities in rice. Grain yield significantly decreased under the shading treatment because of the reduction of PN, GN, GF and GW but increased with the reduction of tillage as a result of the increase in PN and GN. With the application of a shading treatment, the brown rice rate, chalkiness degree and chalk grain rate decreased, while the milled rice rate, amylose content and protein content increased. Moreover, we found that both reduced tillage and shading treatment can improve antioxidant activities. We can speculate that by optimizing the mode of reduced tillage and shading, rice canopy and grain filling can be improved. The findings from this investigation offer novel insights into the factors that contribute to the yield and grain quality of aromatic rice.

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