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Greater Propensity to Photosynthesize Enables Superior Grain Quality of *Indica–japonica* Hybrid Rice under Shading

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Abstract: *Indica–japonica* hybrid rice (I–JR) typically has greater grain yield than that of *Indica* hybrid rice (IR) under prolific shading, but it is not known how shading impacts on physiological characteristics underpinning grain quality. Here, we conducted a two-year field experiment in the mid-reaches of the Yangtze River region using I–JR (genotypes Yongyou 1540 and Yongyou 538) and IR (genotypes Y-liangyou 900 and Quanyouhuazhan). We found that shading reduced grain appearance and quality, particularly milling and heading rates, and chalkiness. Shading disrupted carbon and nitrogen metabolism, impacting traits influencing the human perception of the taste of the grain, such that amylose decreased by 5.9% (I–JR) and 12.9% (IR); grain protein significantly increased, with lesser effects in I–JR than IR under shading. Shading also reduced peak, hot, and final viscosities, and breakdown value. I–JR had improved rice quality compared with that of IR due to the greater propensity of the former to photosynthesize under shading, leading to the improved functioning of carbon and nitrogen metabolism.

Keywords: *Indica–japonica* rice; irrigation; shading; stress; rice quality; grain yield

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1. Introduction

In two subspecies of rice, *indica* rice (IR) and hybrid rice (JR), the use of heterosis between them is considered an important way to increase rice yield. Compared with IR, *Indica–japonica* hybrid rice (I–JR) is able to utilize light and temperature resources more efficiently and fully, which gives I–JR a longer grain filling period than that of IR [1–3]. However, the longer time to maturity may extend the growing season into unfavorable weather of suboptimal temperature [4] and low light during the rice growth stage, especially in the panicle differentiation stage and the grain filling stage. Continuous rainy weather causes significant reductions in rice grain yield [5,6], even though waterlogged soils do not impact rice to the extent that they do other staple cereals, such as wheat and maize [7].

Similar to grain yield, grain quality as a trait reflects the cumulation of effects over the growing season, encompassing management, weather, nutrition, biotic controls, and their interaction [8–12]. Weather impacts rice quality through the development of the grain endosperm, and associated physiological and biochemical processes [13,14]. The impact of light (duration and intensity) is one of the most critical determinants of grain quality [15,16]. Science has progressed in our understanding of the influence of shading on rice quality. Some studies theorized that shading from heading to maturity could increase the head rice rate and reduce the chalkiness of rice [17]. However, some studies showed that shading stress significantly increased chalkiness rate and degree, resulting in a lower milled-rice rate, deteriorating the appearance and processing quality [18,19]. Compared with ambient light conditions, shading at 50% reduced the heading rate, penalizing processing quality [20,21].

Starch is the main component of rice grain, primarily consisting of amylose and amylopectin. Among these constituents, amylose content has the greatest impact on rice quality [22]. The correlation between amylose content in rice and light intensity is often strongly positive, such that shading significantly increases amylose content [23]. Protein content determines nutritional quality, having a negative impact on amylose content and chalkiness rate [24,25]. In addition, studies on shading offer an advanced contemporary understanding of how nitrogen metabolism and inhibited carbon metabolism impact nitrogen and protein concentration in grains [26,27].

Our prior study showed that I–JR had greater photosynthetic capacity and yield than that of IR under shading stress [28]. To further study the effects of shading after flowering on the quality of I–JR, we conducted a two-year field experiment and systematically analyzed the experimental data. I–JR cultivars Yongyou 1540 and Yongyou 538 were used as treatment cultivars, while IR cultivars Y-Liangyou 900 and Quanyouhuazhan were used as controls, given their popularity in the middle reaches of the Yangtze River. By establishing shading experiments in the field, we simulated shading under real solar radiation that I–JR after flowering was likely to encounter in the middle reaches of the Yangtze River. Our aims were to (1) compare the grain quality between I–JR and IR under shading stress. and (2) analyze the quality adaptability of I–JR in the middle reaches of the Yangtze River.

2. Methods and Materials

2.1. Field Experimental Details

Field experimentation was conducted in the paddy fields of Yangtze University (Jingzhou, 32°21′ N, 112°31′ E, 34 m asl) during 2020–2021. The experimental site is located in the middle reaches of the Yangtze River, China. The soil was clay loam with the following properties: pH 6.7, 18.7 g kg^{-1} organic matter, 136.3 mg kg^{-1} hydrolyzable N, 30.2 mg kg^{-1} available *p*, and 121.5 mg kg^{-1} available K. Data for the soil properties were means across the two years. Soil samples taken from the upper 20 cm of the soil were used to test soil properties.

Four hybrid rice varieties were chosen as the experimental materials, which they had been widely grown in China. Genotypic and growth period details are shown in Tables 1 and 2. Pregerminated seeds were sown in a seedbed at 25 g m^{-2} seedlings were manually transplanted at 30 to 32 days old to field plots, with 20 × 30 cm hill spacings and two seedlings per hill.

The experiments were performed in a split-plot design. The main plots were four rice cultivars, and the subplots consisted of two shading treatments: no shading (Normal) and 40% shading (Shading). When the rice plants were at the full-heading stage, a shading net was used at 2.5 m above the ground to reduce 40% of the natural light intensity from the flowering to the maturity stage. The plot size was 32 m^2 with three replications. N fertilizer was applied at the basal, tillering, and panicle initiation stages in a ratio of 5:2:3: 90, 36, and 54 kg N ha^{-1} respectively. Phosphorus (100 kg ha^{-1}) was applied and incorporated into all subplots on the day before transplantation. Potassium (180 kg ha^{-1}) was split equally between the basal and panicle initiation stages. The N, P, and K sources were urea, calcium superphosphate, and potassiumchloride, respectively. Crop management followed the standard cultural practices.

Table 1. Pedigrees and year of release of genotypes used in these experiments.

Variety	Type	Year of Release	Female Parent	Male Parent
Y-liangyou 900	*Indica*	2015	Y 58S	R 900
Quanyouhuazhan	*Indica*	2017	Quan 9311A	Huazhan
Yongyou 1540	*Indica–japonica*	2017	Yongjing 15A	F 7540
Yongyou 538	*Indica–japonica*	2013	Yongjing 3A	F 7538

Table 2. Typical crop husbandry associated with the genotypes used here.

Variety	Seeding Date	Transplanting Date	Full Heading Date	Mature Date
		2020		
Y-liangyou 900	12 May	12 June	21 August	1 October
Quanyouhuazhan	12 May	12 June	14 August	23 September
Yongyou 1540	12 May	12 June	23 August	13 October
Yongyou 538	12 May	12 June	25 August	20 October
		2021		
Y-liangyou 900	9 May	4 June	15 August	20 September
Quanyouhuazhan	9 May	4 June	13 August	21 September
Yongyou 1540	9 May	4 June	20 August	12 October
Yongyou 538	9 May	4 June	24 August	14 October

2.2. Plants Sampling and Measurements

At maturity stage (MA), a diagonal 5 m^2 area was harvested to determine grain yield. The panicle number was recorded from those 12 hills. Plant samples were separated into straw and panicles. The dry weight of straw was determined after oven drying at 70 °C to constant weight. The panicles were hand-threshed, and the filled spikelets were separated from the unfilled spikelets by submerging them in tap water. Three 30 g subsamples of filled spikelets and three 3 g subsamples of unfilled spikelets were assessed to determine the number of spikelets. The dry weights of rachis, and filled and unfilled spikelets were determined after oven drying at 70 °C to constant weight. The total dry weight of straw, rachis, and filled and unfilled spikelets was considered the above-ground weight. Spikelets per panicle and grain filling percentage were calculated. Grain yield was determined from a 5 m^2 area in each plot and adjusted to the standard moisture content of 0.14 g H_2O g^{-1}.

2.3. Rice Quality

2.3.1. Rice Processing and Appearance Quality

The rice was harvested at the mature stage. Three biological replicates of each rice variety were collected, threshed, naturally dried, and stored for three months. The national standard of the People's Republic of China (GB/T17891-2017) was used to determine the brown rice rate (BR), milled rice rate (MR), head rice rate (HR), chalkiness rate (CR), chalkiness degree (CD).

2.3.2. Amylose Content

The rice was pulverized by a plant pulverizer and passed through a 100-mesh sieve after pulverization. Referring to the method of Xu Dong, the amylose content was determined via iodine colorimetry [29].

2.3.3. Protein Components

The rice was pulverized with a plant pulverizer and passed through a 100-mesh sieve after pulverization. Referring to the method of Fen zhiming, the protein components were determined via BCA [30].

2.3.4. RVA Profile Characteristics

The rice was pulverized with a plant pulverizer and passed through a 100-mesh sieve after pulverization. The RVA4500 rapid viscosity-measuring instrument of PERTEN Company was used for testing, and matching software TWC was used for analysis. The characteristic values of the RVA spectrum include peak viscosity (PV), hot viscosity (HV), final viscosity (FV), breakdown value (BKV), setback (SB), peak viscosity time (PVT), and gelatinization temperature (GT).

2.3.5. Taste Value

Cooked Rice Taste Analyzer STA1A (Satake Co., Ltd., Hiroshima, Japan) was used to measure the taste value of rice grains. The taste value is a comprehensive evaluation of cooked grain that consists of appearance, hardness, viscosity, and the degree of balance [31].

2.4. Statistical Analysis

Data were analysed using two-way analysis of variance with SAS 9.2 (SAS Institute, Cary, NC, USA). The means were compared with the least-significant-difference (LSD) test at the 0.05 probability level.

3. Results

3.1. Climate Conditions

As shown in Figure 1, compared with 2020, the temperature in the rice growth stage (June–October) in 2021 was more conducive to the growth and development of rice. The lowest temperature in Jingzhou was 21.5 °C in 2020 and 22.3 °C in 2021. The average daily radiation during the grain filling period (mid-August to mid-October) in 2020 was 15.1 and 15.5 MJ m^{-2} d^{-1} in 2020 and 2021, respectively.

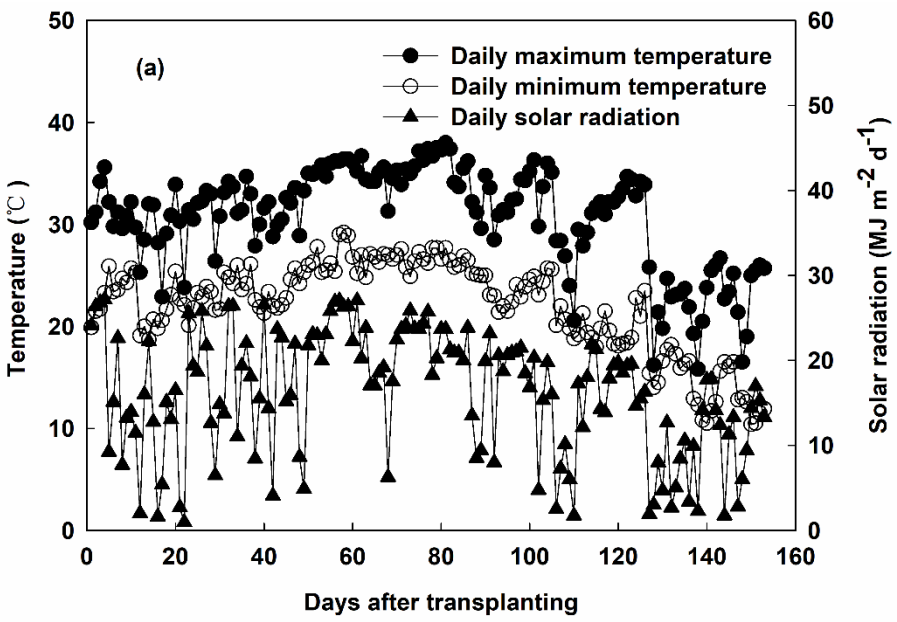


Figure 1. *Cont.*

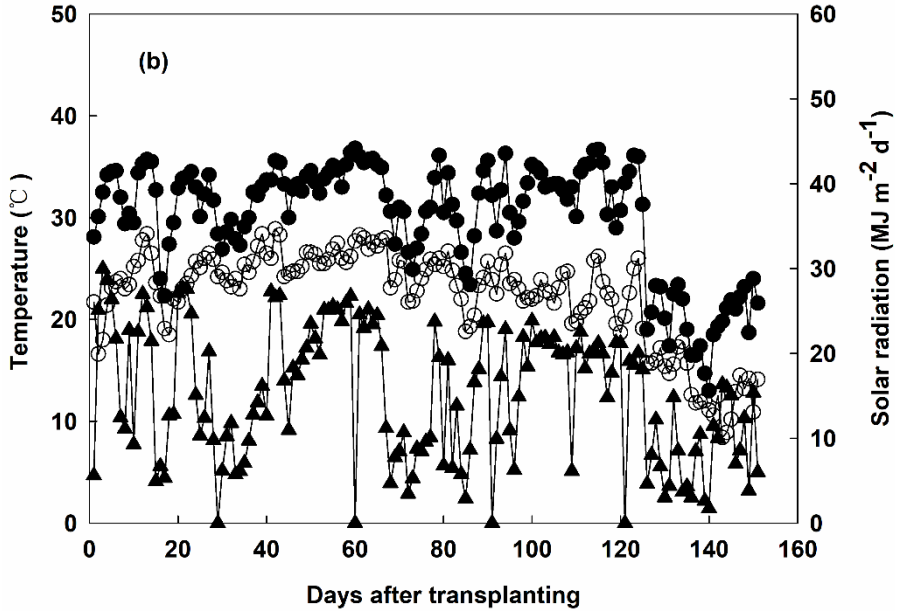


Figure 1. Daily maximal and minimal temperatures, and solar radiation during rice-growing season in Jingzhou in (**a**) 2020 and (**b**) 2021.

3.2. Grain Yield

Shading significantly reduced the grain yield of all cultivars (Figure 2). In normal conditions, the average grain yield of I–JR and IR was 9.7 and 8.9 t ha^{-1} across two years, and I–JR had a 9.5% yield advantage over the IR. Under shading stress, the two-year average grain yield of I–JR was 5.4 t ha^{-1}, while that of IR was 3.8 t ha^{-1}. Compared with normal conditions, the grain yield of IR under shading in 2020 decreased by 60.0%, which was significantly greater than that of I–JR (47.2%); in 2021, the grain yield of I–JR decreased by 41.9%, and the decline of IR was 54.7%.

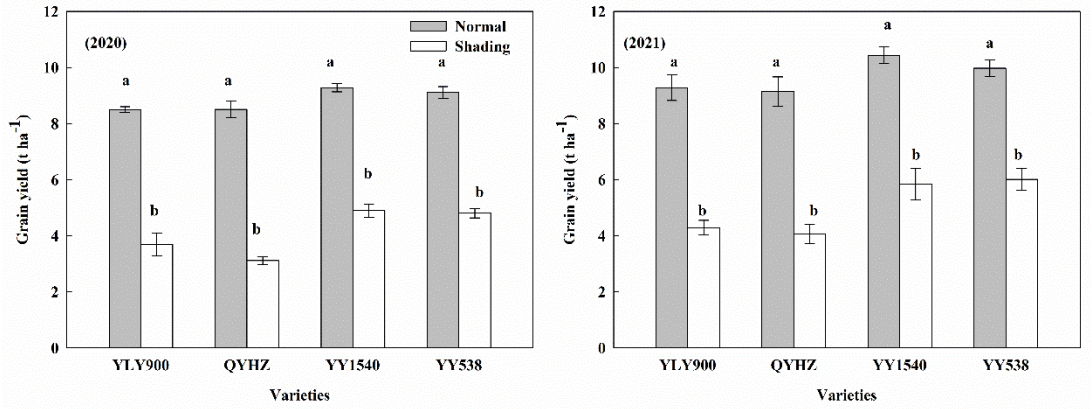


Figure 2. Grain yield of different rice varieties under shading after flowering in 2020–2021. YLY900 (Y-liangyou 900); QYHZ (Quanyouhuazhan); YY1540 (Yongyou 1540); YY538 (Yongyou 538). Different lowercase letters indicate significant differences at $p < 0.05$ between Normal and shading according to LSD at 0.05 level.

3.3. Rice Processing and Appearance Quality

Shading stress decreased the MR and HR of all cultivars, and the HR was the most affected by shading (Table 3). Compared with normal conditions, the MR and HR of IR decreased by 6% and 14% respectively across two years, while I–JR decreased by 4.5% and 9%. Shading also increased the CR and CD of all cultivates. The CR and CR of I–JR increased by 65% and 124% in 2020–2021, which were lower than that of IR (78% in CR and 162% in CD).

Table 3. Processing and appearance quality of different rice varieties under shading after flowering in 2020–2021.

Variety	Treatment	Brown Rice Rate	Milled Rice Rate	Head Rice Rate	Chalkiness Rate	Chalkiness Degree
		%				
2020						
Y-liangyou 900	Normal	80.1 a	72.6 a	64.5 a	13.7 b	5.3 b
	Shading	79.4 a	66.4 a	56.4 a	23.4 a	13.0 a
Quanyouhuazhan	Normal	80.1 a	70.2 a	63.2 a	14.1 b	5.7 b
	Shading	78.3 b	64.9 b	52.9 b	26.4 a	15.6 a
Yongyou 1540	Normal	80.1 a	73.2 a	67.3 a	10.4 b	4.5 b
	Shading	79.9 a	69.2 b	60.4 b	18.8 a	10.5 a
Yongyou 538	Normal	80.4 a	75.0 a	69.3 a	13.1 b	5.6 b
	Shading	79.9 a	72.2 a	63.0 b	19.4 a	12.5 a
2021						
Y-liangyou 900	Normal	80.4 a	70.5 a	65.5 a	13.8 b	5.1 b
	Shading	79.6 a	69.0 b	58.9 b	23.5 a	12.7 a
Quanyouhuazhan	Normal	80.2 a	70.7 a	64.4 a	14.1 b	5.7 b
	Shading	78.4 b	65.8 b	52.7 b	26.1 a	16.0 a
Yongyou 1540	Normal	80.7 a	74.3 a	68.6 a	10.2 b	4.8 b
	Shading	80.2 a	71.1 b	62.8 b	18.5 a	10.5 a
Yongyou 538	Normal	80.4 a	75.1 a	69.5 a	12.8 b	5.6 b
	Shading	80.0 a	71.8 b	62.7 b	19.1 a	12.3 a

Different lowercase letters indicate significant differences at $p < 0.05$ between normal and shading according to LSD at 0.05 level.

Shading after flowering had different effects on rice processing and appearance quality (Table 4). Shading reduced the BR, but it did not reach a significant level. In 2020, the CR was most significantly affected by the treatments, followed by CD, HR, and MR; in 2021, the performance was CR > HR > CD > MR. In 2020, only CR and CD had an interaction effect between varieties and treatments; in 2021, all indicators were affected by the interaction effects between varieties and treatments.

Table 4. Variance analysis of processing and appearance quality of different rice varieties under shading after flowering in 2020–2021.

Source of Variation	*F* Value				
	Brown Rice Rate	Milled Rice Rate	Head Rice Rate	Chalkiness Rate	Chalkiness Degree
2020					
Variety (V)	1.7 ns	9.3 **	12.6 **	39.1 **	9.8 **
Treatment (T)	4.6 ns	14.6 **	60.7 **	527.2 **	342.9 **
V × T	1.0 ns	1.1 ns	0.7 ns	9.8 **	3.9 *
2021					
Variety (V)	2.0 ns	68.7 **	74.6 **	36.2 **	8.1 **
Treatment (T)	6.5 *	117.0 **	355.6 **	442.4 **	270.5 **
V × T	0.9 ns	5.5 *	10.7 *	7.6 **	4.6 *

* $p < 0.05$. ** $p < 0.01$. ns, not significant.

3.4. Amylose Content

The amylose content was positively correlated with light intensity, and there were significant differences among different types of varieties (Figure 3). In 2020, the amylose of IR decreased by 12.2% under shading, while I–JR only decreased by 5.8%; in 2021, the amylose of I–JR decreased by 6.0%, which was significantly lower than that of IR (13.4%). Obviously, the amylose content of I–JR was less affected by shading than IR was.

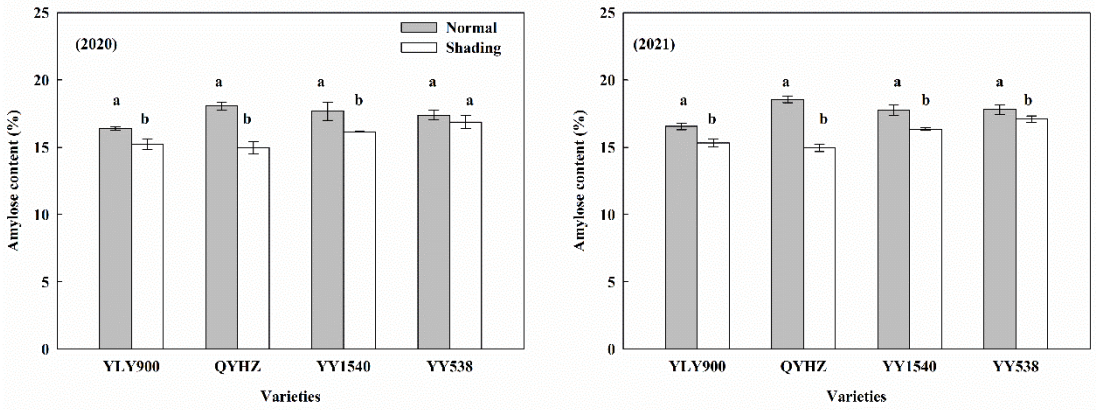


Figure 3. Amylose content of different rice varieties under shading after flowering in 2020–2021. YLY900 (Y-liangyou 900); QYHZ (Quanyouhuazhan); YY1540 (Yongyou 1540); YY538 (Yongyou 538). Different lowercase letters indicate significant differences at $p < 0.05$ between normal and shading according to LSD at 0.05 level.

3.5. Protein Component Content

In normal conditions, there was more albumin and globulin in I–JR, while the opposite was true for gliadin and glutenin (Table 5). With the decline in light intensity, the protein content in the grains of all cultivars increased significantly, in which gliadin had the largest increase. In 2020 and 2021, the gliadin of IR increased by 162.9% and 166.0%, while I–JR increased by 115.1% and 111.3%, respectively. The protein component with the smallest increase was glutelin. In 2020, I–JR and IR increased by 13.4% and 24.0%, respectively. In 2021, I–JR and IR increased by 13.0% and 22.8% respectively. Overall, the effects of shading on grain protein components were significantly different among cultivars, and I–JR were less affected by shading.

Table 5. Protein components of different rice varieties under shading after flowering in 2020–2021.

Variety	Treatment	Albumin mg g^{-1}	Globulin mg g^{-1}	Gliadin mg g^{-1}	Gluten mg g^{-1}
2020					
Y-liangyou 900	Normal	3.5 b	2.7 b	1.3 b	35.2 b
	Shading	4.3 a	5.5 a	2.9 a	41.6 a
Quanyouhuazhan	Normal	2.5 b	2.9 b	1.3 b	37.9 b
	Shading	4.3 a	5.1 a	4.0 a	49.2 a
Yongyou 1540	Normal	3.3 b	4.7 b	0.6 b	35.9 b
	Shading	4.2 a	5.2 a	1.6 a	39.6 a
Yongyou 538	Normal	4.7 b	3.9 b	0.9 b	32.3 b
	Shading	5.4 a	4.9 a	1.2 a	37.6 a
Mean		***4.0 A***	***4.4 A***	***1.7 A***	***38.7 A***

Table 5. *Cont.*

Variety	Treatment	Albumin mg g^{-1}	Globulin mg g^{-1}	Gliadin mg g^{-1}	Gluten mg g^{-1}
2021					
Y-liangyou 900	Normal	3.4 b	2.5 b	1.2 b	36.8 b
	Shading	4.4 a	5.4 a	2.8 a	41.2 a
Quanyouhuazhan	Normal	2.3 b	2.9 b	1.4 b	37.3 b
	Shading	4.3a	5.0 a	4.1 a	48.8 a
Yongyou 1540	Normal	3.5 b	4.8 b	0.6 b	35.7b
	Shading	3.9 a	5.2 a	1.5 a	39.2 a
Yongyou 538	Normal	4.6 b	3.8 b	0.7 b	32.1 b
	Shading	5.4 a	4.8 a	1.2 a	37.3 a
Mean		***4.0 A***	***4.3 A***	***1.7 A***	***38.6 A***
Analysis of variance	Variety (V)	**	**	**	**
	Treatment (T)	**	**	**	**
	V × T	**	**	**	*

Different lowercase letters indicate significant differences at p <0.05 between Normal and shading according to LSD at 0.05 level. * $p < 0.05$. ** $p < 0.01$.

3.6. RVA Profile Characteristics

In 2020, the RVA profile characteristics of different types of rice changed to varying degrees under shading (Table 6). Except for PVT, other RVA profile characteristics were significantly affected by shading. In normal conditions, the PV and BKV were significantly higher than those under shading. In normal conditions, the SB of I–JR was significantly lower than that of IR. Shading significantly increased the SB of all cultivars, and showed the IR was more affected by shading. In addition, the BKV and SB of I–JR were significantly less affected by shading than that of IR. PVT was not significantly affected by treatment, but was significantly affected by varieties. Compared with IR, I–JR had higher GT under all treatments. Overall, the I–JR had a more stable RVA profile characteristics than those of IR under shading.

Table 6. RVA profile characteristics of different rice varieties under shading after flowering in 2020.

Variety	Treatment	PV cP	HV cP	FV cP	BKV cP	SB cP	GT s	PVT °C
Y-liangyou 900	Normal	2728.3 a	1495.0 a	2801.3 a	1233.3 a	73.0 b	84.0 a	5.9 a
	Shading	2402.3 b	1408.7 b	2552.0 b	993.7 b	149.7 a	82.8 b	5.9 a
Quanyouhuazhan	Normal	2634.0 a	1389.0 a	2722.7 a	1245.0 a	88.7 b	85.1 a	5.7 a
	Shading	2080.7 b	1264.7 b	2361.3 b	816.0 b	280.7 a	84.2 a	5.8 a
Yongyou 1540	Normal	2833.3 a	1588.0 a	3109.3 a	1245.3 a	−24.0 a	88.0 a	6.1 a
	Shading	2467.7 b	1446.3 b	2723.3 b	1021.3 b	−44.3 a	86.4 b	5.9 b
Yongyou 538	Normal	2743.3 a	1521.0 a	3049.0 a	1222.3 a	5.7 a	87.1 a	6.0 a
	Shading	2612.3 b	1460.3 a	2916.7 b	1152.0 a	4.3 a	85.8 b	6.0 a
Analysis of variance	Variety (V)	**	**	**	*	**	**	**
	Treatment (T)	**	**	**	**	**	**	ns
	V × T	**	ns	**	*	**	ns	**

Different lowercase letters indicate significant differences at $p < 0.05$ between Normal and shading according to LSD at 0.05 level. * $p < 0.05$. ** $p < 0.01$. ns, not significant. Peak viscosity (PV), hot viscosity (HV), final viscosity (FV), breakdown value (BKV), setback (SB), peak viscosity time (PVT), and gelatinization temperature (GT).

3.7. Taste Value

In normal conditions, the taste value of I–JR was 74.9 across two years, which was slightly higher than that of IR (Figure 4). Shading significantly reduced the taste value of

all cultivars. Under shading stress, I–JR had a better and more stable taste value than that of IR. In 2020, the taste value of I–JR decreased by 8.9%, which was lower than that of IR (15.8%); in 2021, the taste value of I–JR decreased by 7.2%, and the IR decreased by 14.5%.

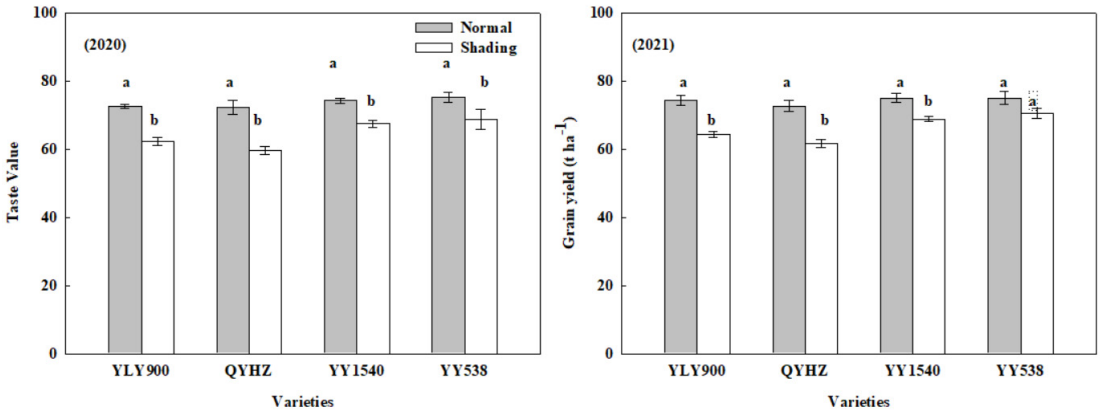


Figure 4. Taste values of different rice varieties under shading after flowering in 2020–2021. YLY900 (Y-liangyou 900); QYHZ (Quanyouhuazhan); YY1540 (Yongyou 1540); YY538 (Yongyou 538). Different lowercase letters indicate significant differences at $p < 0.05$ between normal and shading according to LSD at 0.05 level.

3.8. Relationships among Taste Value and HR, CR, Protein Component Content, and Amylose Content

There were significant differences in the effects of shading on the correlation between rice taste value and rice quality of different types of rice varieties (Figure 5). For I–JR, there was a significant positive correlation between amylose content and taste value ($R^2 = 0.72$), which was significantly higher than that of IR ($R^2 = 0.39$). The correlation between protein components and taste value was the opposite, showing significant negative correlation. The correlation of I–JR was $R^2 = 0.74$, and that of IR was $R^2 = 0.78$. There was a positive correlation between the taste value and the HR of the two types of rice cultivars. For IR, there was a significant negative correlation between CR and taste value, but this relationship was not significant for I–JR.

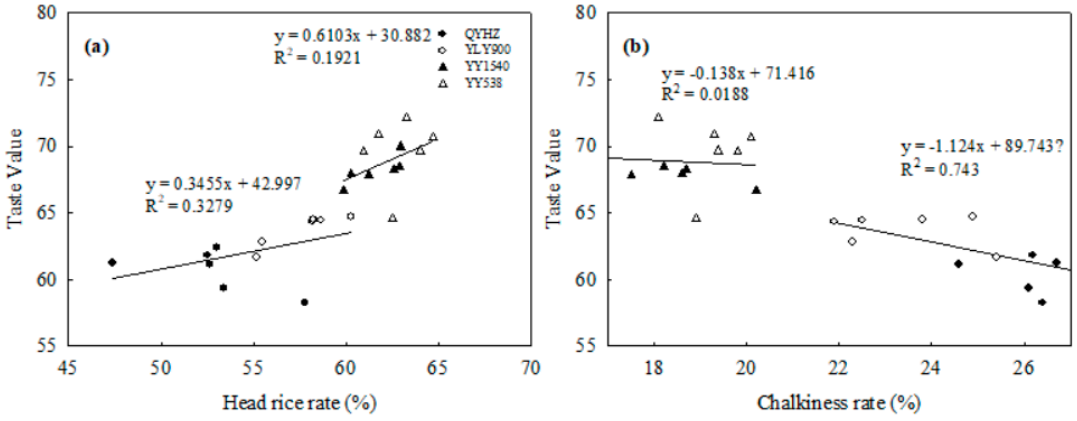


Figure 5. *Cont.*

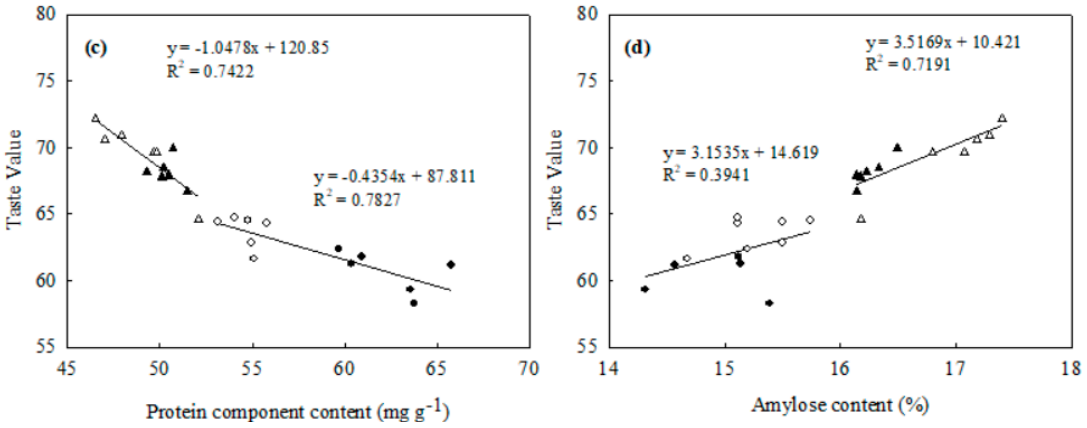


Figure 5. Correlation analysis of taste value and head rice rate (**a**), chalkiness rate (**b**), protein component content (**c**) and amylose content (**d**) of different rice varieties under shading after flowering in 2020–2021. YLY900 (Y-liangyou 900); QYHZ (Quanyouhuazhan); YY1540 (Yongyou 1540); YY538 (Yongyou 538).

4. Discussion

Grain production is one of the most important issues in agricultural production. There are many studies on the impact of shading stress on rice [32]. Shading stress at different growth stages could lead to stunted growth and development, reduce dry matter accumulation and the rate of assimilation of photosynthetic matter, and ultimately lead to a substantial reduction in rice yield [33,34]. For each growth stage, shading after flowering has the greatest impact on rice grain yield [35]. In this experiment, shading after flowering significantly reduced the grain yield of the two types of rice cultivars, and I–JR had better grain yield adaptability than that of IR under shading. In our previous study, we found that shading significantly reduced the grain filling percentage, which was the main reason for crop failure. Due to the inhibition of photosynthesis under shading stress, the "source" could not provide enough assimilates to meet grain growth, and the rice grain filling was insufficient, forming a large number of empty and half-filled grains, which greatly limited the grain yield potential [36,37]. In addition to the effect on the accumulation of photosynthetic substances, the shading stress after flowering also changed the transport and distribution ratio of photosynthetic substances. The decline in photosynthetic matter production capacity made grain filling rely on the output of assimilates accumulated in the stem and leaf before flowering, which significantly increased the dry matter output and output rate of stem and leaf. However, this increase in output could not completely offset the loss caused by the decrease in photosynthetic material accumulation, which led to a significant decrease in the amount of dry matter allocated to the rice panicles [38].

Crop quality and grain yield rely on the synthesis and distribution of assimilates during the growth stages of crops, which are regulated by genetic factors and the environment [39,40]. On the basis of the inhibitory effects of shading stress on rice material accumulation after full heading, the reduction in rice quality under shading became inevitable. In this experiment, the effect of shading stress on BR was not significant, but the MR and HR of all cultivars were significantly reduced under shading. With the decrease in accumulated substances in the grain, the number of empty grains increased, which made the MR and the HR decline. This study found that shading after flowering could lead to a significant increase in CR and CD, which is consistent with previous studies [41,42]. Compared with IR, the MR, HR, CD, and CR of I–JR were less affected by shading stress. Overall, the processing and appearance quality of I–JR were more stable than those of IR, which was mainly from I–JR having a higher grain filling percentage and grain weight under shading.

Rice cooking quality is a complex rice quality trait. Shading significantly reduced the amylose content, and the degree of amylose reduction was more significant as the light intensity decreased [43]. However, some studies found that shading caused an increase in rice amylose content, and this increase was different among different cultivars [44,45]. In

this experiment, the amylose content of all tested cultivars under shading was lower than that under normal conditions. This was mainly caused by shading significantly reducing photosynthesis and the production of sugar sources, resulting in a significant decrease in amylose content. The decrease in amylose content in I–JR under shading was smaller than that in IR, which indicated that the *Indica–japonica* hybrid rice could greatly manufacture and transport sugar-derived substances even under shading stress.

In addition, shading stress increased the content of each protein component in this experiment. The reason for this phenomenon might be that shading led to an imbalance in the carbon and nitrogen ratio of rice plants [18]. Under shading, rice had a higher nitrogen assimilation capacity, and the metabolism of rice was shifted from carbon metabolism to nitrogen metabolism, which led to an increase in the nitrogen content rate of rice plant tissue. Moreover, shading after flowering reduced the relative distribution rate of carbon and nitrogen elements in rice organs [27]. Compared with normal conditions, the content of produced and transported nitrogenous compounds increased under shading, which reduced the production and transport capacity of the carbohydrates, and lastly led to a significant increase in protein content in grains. The increased rice grain protein content improved the nutritional quality of rice, but reduced the taste value [46]. This also verified our previous research that shading reduces the activities of sucrose synthase and sucrose phosphate synthase in rice leaves, and increases the activity of glutamate synthase. Due to the more stable carbon and nitrogen metabolism enzyme activity, I–JR could maintain a relatively stable level of carbon and nitrogen metabolism, even under shading [47]. Combining the relationship between the taste value and the rice quality, the amylose content and protein component significantly affected on the taste value of I–JR. So, maintaining the stability of carbon and nitrogen metabolism in I–JR under shading is the most critical factor to maintain the taste value.

As an important characteristic of rice quality, RVA profile characteristics were not only affected by genetic factors, but also restricted by environmental factors [48]. This study found that shading significantly reduced PV, HV, FV, BKV, and GT, and significantly increased SB, which is consistent with previous studies [49]. Lim found that PV, HV, FV, and BKV were positively correlated with rice taste, and FV and SB were negatively correlated with rice taste [50]. It is generally believed that rice with high PV and BKV, low FV and SB (absolute value) has better eating quality [51]. In this experiment, under normal conditions, I–JR had higher PV, and smaller FV and SB than those of IR. Under shading, I–JR also had higher PV, larger BKV, and smaller SB than those of IR.

5. Conclusions

Shading after anthesis has a great negative impact on grain yield and rice quality. Under shading stress, the production and accumulation of photosynthetic characters in all rice cultivars were significantly inhibited, which reduced grain yield. Shading stress caused a lot of empty grains, which decreased HR and MR, but increased the chalkiness rate and degree. Shading caused carbon and nitrogen metabolism disorders, decreased amylose content, and increased protein components, leading to a decline in rice taste quality and an increase in nutritional quality. Overall, shading after flowering reduced rice quality, and there were significant differences among cultivars, showing that I–JR had a more stable rice quality than that of IR. Combined with our previous experimental results, the better rice quality of I–JR was mainly from it having better photosynthetic production capacity, and a more stable carbon and nitrogen metabolism.

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