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Characteristics of Population Quality and Rice Quality of Semi-Waxy *japonica* Rice Varieties with Different Grain Yields

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Abstract: A primary focus of rice breeding and production is the optimization of yield and quality. Currently, semi-waxy *japonica* rice is widely planted in the middle and lower reaches of the Yangtze River due to its good eating quality and strong reputation among consumers. However, little information is yet available on grain yield formation and rice quality characteristics of these semi-waxy *japonica* rice varieties with different grain yields. In this study, three high-yielding (HGY) semi-waxy *japonica* rice varieties and three low-yielding (LGY) semi waxy *japonica* rice varieties were compared for population quality and rice quality in 2018 and 2019. The average values of spikelet per panicle, 1000-grain weight, and total spikelet number of the HGY varieties were significantly higher than those of the LGY varieties, while the panicle number and filled grain rate showed the opposite. Compared with the LGY varieties, the HGY varieties had a larger leaf area index at each growth stage, with a larger high efficient leaf area composed of a larger leaf length and width and smaller leaf angles of the top three leaves, as well as a greater single stem-sheath weight, more total dry matter accumulation, and longer growth duration from elongating to maturity. There were significant differences in rice quality between the HGY and LGY varieties. Compared with the LGY varieties, the head milled rice rate of the HGY varieties decreased significantly, and the chalky kernel rate and chalkiness degree increased significantly. Due to the low protein content, high peak viscosity, trough viscosity, and final viscosity and breakdown, as well as low setback, consistence, and pasting temperature of the HGY varieties, their taste values were significantly better than those of the LGY varieties. These results suggest that the HGY varieties could achieve a synergistic improvement of grain yield and eating quality, but the milling quality and appearance quality require further improvement.

Keywords: semi-waxy *japonica* rice; grain yield; rice quality; population quality

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1. Introduction

As the global population increases, demand for rice is expected to double by 2050 [1]. To ensure food security, high grain yield has long been the primary goal of rice breeding and cultivation [2,3]. With socioeconomic development and continuous improvements in standards of living, the demand for good quality rice is rapidly increasing [4]. Therefore, the realization of high grain yield and good rice quality in rice will not only meet the growing market demand; but also increase economic benefits due to its good rice quality and high price.

Historically, a large number of studies have examined the mechanisms generating high-yield rice and required cultivation practices, as well as the characteristics of high-yield rice varieties, such as greater total dry matter accumulation [5], larger sink capacity due to increased spikelet per panicle [6], higher leaf area and reduced decreasing rate of leaf area [7], improved canopy structure and root system [8], and more efficient use of temperature and light from elongating to maturity [9]. These findings have played a positive role in the breeding and cultivation of high-yield rice varieties, and the yield potential has significantly improved [10].

Rice quality traits dictate the market value and have a pivotal role in the adoption of new varieties. Rice quality traits include milling quality, appearance quality, nutritional quality, and cooking and eating quality. Previous studies have shown that rice quality traits are not only affected by cultivation techniques and the ecological environment, but there is also a close relationship with rice varieties [11–14]. Regarding the relationship between the grain yield and rice quality, some studies have indicated a deterioration in rice quality in the high-yield rice varieties [15], while other studies have also pointed out that grain yield and rice qualities, such as milling quality, appearance quality, and eating and cooking quality were significantly improved with the progress of breeding technology [16].

Semi-waxy *japonica* rice is a type of rice with an amylose content between 8% and 12% [17]. Due to the low amylose content being able to reduce the tendency of the starch granules to retrograde after cooling, cooked semi-waxy *japonica* rice is soft, elastic, and of moderate viscosity [18]. In recent years, these semi-waxy *japonica* varieties have attracted attention from breeders and rice physiologists, and as such, Nanjing46 and Nanjing9108 have been widely planted in the middle and lower reaches of the Yangtze River. Previous studies on semi-waxy *japonica* rice have mainly focused on the biological mechanisms driving its good eating quality [18] and the effects of related cultivation measures on its rice quality [11]. Similar to other types of rice, the grain yield of semi-waxy *japonica* rice showed significant differences across genotypes [12].

Until now, little information has been available on grain yield formation and the quality characteristics of these semi-waxy *japonica* rice varieties with different grain yields. It was hypothesized that the grain yield and rice quality of semi-waxy *japonica* rice varieties could be improved together. Therefore, we used semi-waxy *japonica* rice varieties with two different grain yield levels (with Nanjing5718, Nanjing9108, and Su1785 as the high-grain-yield rice varieties, and Songzaoxiang NO.1, Changruan07-5, and Suxiangjing NO.3 as the low-grain-yield rice varieties) to study the population characteristics and the differences in rice quality in this experiment. The objective of this study was to (a) clarify the high-yield formation pathway of semi-waxy *japonica* rice varieties, and (b) evaluate the rice quality of semi-waxy *japonica* rice with a high grain yield. Such a study should provide useful information for achieving a high-quality and high-yield rice production system with inputs from both agronomy and breeding.

2. Materials and Methods

2.1. Rice Varieties and Cultivation

Six semi-waxy japonica rice varieties with two different grain yield levels (with Nanjing5718, Nanjing9108, and Su1785 as the high-grain-yield rice varieties, and Songzaoxiang NO.1, Changruan07-5, and Suxiangjing NO.3 as the low-grain-yield rice varieties) were used in this experiment. Field experiments were conducted during the rice-growing season in 2018 and repeated in 2019 at Shengao Town, Jiangyan District, Taizhou City, Jiangsu Province, China. The field soil is sandy soil, containing 15.73 g/kg organic matter, 1.27 g/kg total N, 76.83 mg/kg alkali hydrolyzable N, 16.11 mg/kg available P, and 79.42 mg/kg available K in 2018. In 2019, the field soil contained 16.21 g/kg organic matter, 1.45 g/kg total N, 76.21 mg/kg alkali hydrolyzable N, 16.88 mg/kg available P, and 85.41 mg/kg available K.

In both years, all varieties (lines) were sown in seedbeds on 13 June and transplanted on 23 June into open fields with two seedlings per hill. The hill spacing was 25 cm row spacing with 6 cm plant spacing. The field experiments were arranged in a randomized block design with three replicates, and the size of each plot was 3 m × 5 m. Nutrient input included nitrogen (N), phosphorus (P), and potassium (K) fertilizers. A total of 270 kg/ha

N was applied as urea (46% N): 30% as basal fertilizer, 40% as tiller fertilizer, and 30% at the stage of panicle initiation. Urea was applied to all varieties at the same time. Calcium superphosphate (P_2O_5 content: 12%) was applied as a basal fertilizer at a rate of 135 kg P_2O_5 ha^{-1}. Similarly, potassium chloride (K_2O content: 60%) was split into two equal amounts (135 kg K_2O ha^{-1}) and applied around the emergence and booting stages. Field management followed established agronomic procedures.

2.2. Sampling and Measurements

2.2.1. Dates of Elongating, Heading, and Maturity

The date when the first internode length of more than 50% of the plants in the whole field reaches 2 cm is elongating stage. The period of more than 50% of the panicles extraction in the whole field is heading stage. Maturity refers to the date when more than 85% of the grains on a single panicle become hard and unbreakable, and more than 90% of the panicles in the whole field meet the above standards;

- Days before elongating (d) = elongating date − sowing date;
- Days form elongating to heading (d) = heading date − elongating date;
- Days form heading to maturity (d) = maturity date − heading date;
- Days total growth duration (d) = maturity date − sowing date.

2.2.2. Dry Matter Weight and Leaf Area Index (LAI)

Plants from three representative hills were uprooted from each plot at the elongating, heading, and maturity stages. Root portions were removed, and the remainder was separated into leaves, stems plus sheath, and panicles. LAI was measured with a portable leaf area meter (Li-3000A, LI-COR, Lincoln, Dearborn, MI, USA) at the elongating, heading, and maturity stages. The high effective leaf area (top 3 leaves area of effective tiller) was determined at the heading stage.

The high effective leaf area ratio (%) = (the top 3 leaves area of the effective tiller at heading/total green leaf area at heading) × 100.

Decreasing rate of leaf area (LAI d^{-1}) = (LAI at heading − LAI at maturity)/days from heading to maturity.

Each component of the plants was bagged and oven-dried separately at 105 °C for 30 min and then at 80 °C to a constant weight. Samples were then weighed to determine total dry matter weight.

2.2.3. Top 3 Leaves Morphology and Single Stem-Sheath Weight

At 10 days after heading, 15 representative single plants were randomly selected from each plot to determine leaf angle (the angle between leaf and stem) and length and width of the top 3 leaves. Then, all the stem-sheaths were bagged and oven-dried separately at 105 °C for 30 min and then at 80 °C to a constant weight. These stem-sheaths were then weighed to determine single stem-sheath weight.

2.2.4. Grain Yield and Its Components

At maturity, the number of panicles per m^2 was determined from three representative square meter regions that were randomly sampled from each plot. Five plants with average panicle number were sampled randomly from each plot to determine the yield components, including spikelet per panicle, filled grain rate, and 1000-grain weight. Grain yield was determined from a harvest area of 5 m^2 in the middle of each plot at maturity, and the grain yield was weighed. The final grain yield was adjusted to 14% moisture content.

- Harvest index = grain yield/total dry matter weight;
- Total spikelet number = panicle number × spikelet per panicle.

2.2.5. Rice Quality

A total of 1 kg of rice grains harvested from each tested variety was dried to a standard moisture content of 14% and stored for over 3 months. Characteristics of rice quality, including brown rice rate (BRR), milled rice rate (MRR), head milled rice rate (HMRR), chalky kernel rate (CKR), chalky area (CA), chalkiness degree (CD), and amylose content were measured according to GB/T17891-2017 [19]. To measure these traits, 100 g rice kernel samples were dehulled into brown rice by a laboratory dehuller (SY88-TH, BRIC, Korea), and the brown rice was processed into milled rice by a laboratory polisher (LTJM-2099, Hangzhou, China). After, the head milled rice was manually selected from the milled rice. A total of 10 g head milled rice was then scanned to analyze the CKR, CA, and CD by a rice appearance quality scanner (SC-E, Wanshen, Hangzhou, China). Amylose content was determined by iodine colorimetry at a wavelength of 620 nm, using a potato starch standard mixture. Protein content was measured using a grain analyzer (Infratec 1241, Foss, Copenhagen, Denmark).

The rice flour pasting properties were determined using a Rapid Visco Analyser (RVA, Super3, Newport Scientific, Sydney, Australia), following the procedure of the American Association of Cereal Chemists. A total of 3 g of flour sifted with 0.15 mm sieves was mixed with 25 g deionized water in the RVA sample can. The peak viscosity, trough viscosity, final viscosity in cP (centipoise) units and their derivative parameters breakdown (peak viscosity-trough viscosity), setback (final viscosity-peak viscosity), and consistency (final viscosity-trough viscosity) were recorded with matching Software of Thermal Cline for Windows.

Eating quality was evaluated with a rice taste analyzer (STA1A, Satake Co., Hiroshima, Japan), which converted various physicochemical parameters of the rice into "taste value" scores (a comprehensive reflection of the rice's eating quality) based on correlations between the near-infrared reflectance measurements of the key constituents and preference sensory scores.

2.3. Statistical Analysis

Analysis of variance was performed using SPSS version 22. The sources of variation included year, grain yield type, rice variety, and the interactions of year × grain yield type and year × rice variety. Means were tested using the least significant difference (LSD) test at $p = 0.05$. Tables were prepared using MS Excel 2013 for Windows.

3. Results

3.1. Days of Different Growth Stages

The total growth duration of the HGY varieties was 8 and 7 days longer than that of the LGY varieties in 2018 and 2019, respectively (Table 1). The duration from sowing to elongating stages and from heading to maturity stages was almost identical for the HGY and LGY varieties across both years, while the duration from elongating to heading stages of the HGY varieties was about 4 days longer than that of the LGY varieties.

3.2. Grain Yield and Its Components

There were significant genotypic differences in grain yield and its components across the HGY and LGY varieties (Table 2). Compared with the LGY varieties, the average grain yields of the HGY varieties were 29.39% higher in 2018 and 30.79% higher in 2019. The spikelet per panicle and 1000-grain weight of the HGY varieties were significantly higher than those of the LGY varieties, but the panicle number and filled grain rate were reduced. The average total spikelet number of the HGY varieties was 18.42% higher in 2018 and 22.28% higher in 2019, compared to the LGY varieties, likely due to increased numbers of spikelet per panicle.

Table 1. Dates of elongating, heading, and maturity of semi-waxy *japonica* rice varieties with different grain yields.

Type	Variety	Elongating	Heading	Maturity	Before Elongating (d)	Elongating to Heading (d)	Heading to Maturity (d)	Total Growth Duration (d)
2018								
HGY	Nanjing5718	5 Aug	2 Sep	26 Oct	53	28	54	135
	Nanjing9108	5 Aug	5 Sep	29 Oct	53	31	54	138
	Su1785	7 Aug	5 Sep	31 Oct	55	29	56	140
	Mean				54	29	55	138
LGY	Songzaoxiang NO.1	5 Aug	28 Aug	20 Oct	53	23	53	129
	Changruan07-5	4 Aug	1 Sep	23 Oct	52	28	52	129
	Suxiangjing NO.3	6 Aug	30 Aug	23 Oct	54	24	54	132
	Mean				53	25	53	130
2019								
HGY	Nanjing5718	5 Aug	2 Sep	26 Oct	53	28	54	135
	Nanjing9108	5 Aug	2 Sep	26 Oct	53	28	54	135
	Su1785	7 Aug	2 Sep	28 Oct	55	26	56	137
	Mean				54	27	55	136
LGY	Songzaoxiang NO.1	5 Aug	28 Aug	20 Oct	53	23	53	129
	Changruan07-5	5 Aug	29 Aug	20 Oct	53	24	52	129
	Suxiangjing NO.3	5 Aug	27 Aug	20 Oct	53	22	54	129
	Mean				53	23	53	129

HGY, high-yield varieties; LGY, low-yield varieties.

Table 2. Grain yield and yield components of semi-waxy *japonica* rice varieties with different grain yields.

Type	Variety	Panicle Number ($\times 10^4$ ha^{-1})	Spikelet per Panicle	Total Spikelet Number ($\times 10^6$ ha^{-1})	Filled-Grain Rate (%)	1000-Grain Weight (g)	Grain Yield (t ha^{-1})
2018							
HGY	Nanjing5718	286.46 f	123.33 a	353.31 d	96.98 a	30.17 a	10.18 a
	Nanjing9108	345.23 d	120.80 a	417.05 b	91.13 b	26.37 c	9.65 b
	Su1785	386.83 b	114.15 b	441.56 a	88.93 b	26.73 b	10.02 ab
	Mean	339.51	119.43	403.97	92.34	27.76	9.95
LGY	Songzaoxiang NO.1	371.79 c	87.44 d	325.10 e	94.82 a	25.93 d	7.57 c
	Changruan07-5	335.70 e	94.11 c	315.93 e	96.60 a	26.33 c	7.91 c
	Suxiangjing NO.3	456.36 a	83.78 d	382.34 c	96.22 a	20.93 e	7.58 c
	Mean	387.95	88.44	341.12	95.88	24.40	7.69
2019							
HGY	Nanjing5718	295.50 e	126.41 a	373.55 b	98.38 a	30.37 a	10.52 a
	Nanjing9108	352.35 c	118.03 b	415.87 a	90.88 b	26.70 c	9.84 b
	Su1785	373.05 b	117.43 b	438.07 a	86.20 c	27.07 b	9.97 b
	Mean	340.30	120.62	409.16	91.82	28.04	10.11
LGY	Songzaoxiang NO.1	343.80 c	92.89 cd	319.35 c	94.93 a	26.23 e	7.63 c
	Changruan07-5	327.08 d	98.00 c	320.53 c	96.93 a	26.60 d	7.85 c
	Suxiangjing NO.3	433.88 a	88.47 d	363.96 b	95.91 a	21.33 f	7.69 c
	Mean	368.25	93.12	334.61	95.92	24.72	7.73
Analysis of variance							
	Year (Y)	**	*	ns	ns	**	ns
	Type (T)	**	**	**	**	**	**
	Variety (V)	**	**	**	**	**	**
	Y × T	**	ns	ns	ns	ns	ns
	Y × V	*	ns	ns	ns	**	ns

HGY, high-yield varieties; LGY, low-yield varieties. Values within the same year followed by different letters are significantly different at the 0.05 probability level. * significant at the 0.05 probability level, ** significant at the 0.01 probability level, ns not significant at the 0.05 probability level.

3.3. Dry Matter Accumulation and Harvest Index

Compared with the LGY varieties, the dry matter accumulation of the HGY varieties was higher at each stage (Table 3). Before elongating, there was no significant difference in dry matter accumulation, but the dry matter accumulation ratio of the LGY varieties was significantly higher than that of HGY varieties in both years. During the period from elongating to heading, the average dry matter accumulation of the HGY varieties was 25.90% higher in 2018 and 28.95% higher in 2019 than that of the LGY varieties, while there was no significant difference in the dry matter accumulation ratio between the HGY and LGY varieties. At maturity, the total dry matter accumulation of the HGY varieties was more than 20 t ha^{-1}, and was 27.79% higher in 2018 and 29.04% higher in 2019 than that of the LGY varieties, and the dry matter accumulation ratio of the HGY varieties was significantly higher than that of the LGY varieties. There was no significant difference in the harvest index among the six tested varieties, while the average harvest index of the HGY varieties was significantly higher than that of the LGY varieties.

Table 3. Dry matter accumulation and harvest index of semi-waxy *japonica* rice varieties with different grain yields.

Type	Variety	Before Elongating		Elongating to Heading		Heading to Maturity		Total Dry Matter Accumulation (t ha^{-1})	Harvest Index
		Amount (t ha^{-1})	Ratio (%)	Amount (t ha^{-1})	Ratio (%)	Amount (t ha^{-1})	Ratio (%)		
2018									
HGY	Nanjing5718	3.32 a	15.64 b	8.86 a	41.76 a	9.05 a	42.61 a	21.23 a	0.480 a
	Nanjing9108	3.35 a	16.53 b	8.44 a	41.64 a	8.47 a	41.83 a	20.26 b	0.476 a
	Su1785	3.34 a	16.14 b	8.79 a	42.40 a	8.60 a	41.46 a	20.74 ab	0.483 a
	Mean	3.34	16.10	8.70	41.93	8.71	41.97	20.74	0.480
LGY	Songzaoxiang NO.1	3.18 a	19.39 a	6.94 b	41.73 a	6.37 b	38.88 b	16.38 cd	0.463 a
	Changruan07-5	3.17 a	19.00 a	7.16 b	42.84 a	6.38 b	38.16 b	16.71 c	0.474 a
	Suxiangjing NO.3	3.11 a	19.56 a	6.63 b	41.73 a	6.21 b	39.09 b	15.88 d	0.478 a
	Mean	3.10	19.31	6.91	41.97	6.32	38.71	16.32	0.471
2019									
HGY	Nanjing5718	3.39 a	15.80 b	9.05 a	42.15 a	9.03 a	42.05 a	21.48 a	0.489 a
	Nanjing9108	3.19 a	15.65 b	8.72 a	42.72 a	8.48 a	41.55 a	20.40 b	0.483 a
	Su1785	3.35 a	16.45 b	8.42 a	41.66 a	8.61 a	42.23 a	20.38 b	0.489 a
	Mean	3.31	15.97	8.73	42.09	8.70	41.94	20.75	0.487
LGY	Songzaoxiang NO.1	3.19 a	20.00 a	6.67 b	41.85 a	6.08 b	38.15 b	15.93 cd	0.479 a
	Changruan07-5	3.17 a	19.04 a	7.12 b	42.72 a	6.37 b	38.24 b	16.66 c	0.471 a
	Suxiangjing NO.3	3.14 a	20.07 a	6.52 b	41.66 a	5.99 b	38.27 b	15.65 d	0.492 a
	Mean	3.17	19.70	6.77	42.07	6.15	38.22	16.08	0.481
Analysis of variance									
Year (Y)		ns	ns	ns	ns	ns	ns	ns	ns
Type (T)		**	**	**	ns	**	**	**	*
Variety (V)		ns	*	**	ns	*	ns	**	ns
Y × T		ns	*	ns	ns	ns	ns	ns	ns
Y × V		ns	ns	ns	ns	ns	ns	ns	ns

HGY, high-yield varieties; LGY, low-yield varieties. Values within the same year followed by different letters are significantly different at the 0.05 probability level. * significant at the 0.05 probability level, ** significant at the 0.01 probability level, ns not significant at the 0.05 probability level.

3.4. Leaf Area Index (LAI)

The HGY varieties had increased LAI across different stages and years (Table 4). The average LAI of the HGY varieties was 25.89, 17.28, and 51.50% higher than that of the LGY varieties at the elongating, heading, and maturity stages, respectively, in 2018, and 20.72, 17.86, and 52.87% higher at those stages in 2019. The high effective LAI and high effective LAI ratio of the HGY varieties were both significantly higher than those of the LGY varieties in both years. The decreasing rate of leaf area of the HGY varieties was significantly lower than that of the LGY varieties in both years.

Table 4. LAI at the main growth stages of semi-waxy *japonica* rice varieties with different grain yields.

Type	Variety	Elongating	Heading			Maturity	Decreasing Rate of Leaf Area (LAI d^{-1})
			Total LAI	High Effective LAI	High Effective LAI Ratio (%)		
2018							
HGY	Nanjing5718	4.93 a	8.21 a	5.43 a	66.14 a	4.24 a	0.074 ab
	Nanjing9108	4.37 bc	7.64 b	5.19 b	67.87 a	3.83 b	0.071 b
	Su1785	4.55 b	8.18 a	5.50 a	67.19 a	4.01 ab	0.074 ab
	Mean	4.62	8.01	5.37	67.07	4.03	0.073
LGY	Songzaoxiang NO.1	3.34 d	6.82 c	4.36 cd	63.92 b	2.66 cd	0.078 ab
	Changruan07-5	4.11 c	6.99 c	4.50 c	64.39 b	2.94 c	0.078 ab
	Suxiangjing NO.3	3.55 d	6.69 c	4.21 d	63.03 b	2.39 d	0.080 a
	Mean	3.67	6.83	4.36	63.78	2.66	0.079
2019							
HGY	Nanjing5718	4.56 a	8.32 a	5.61 a	67.42 a	4.27 a	0.075 ab
	Nanjing9108	4.13 ab	7.85 b	5.28 b	67.28 a	3.90 b	0.073 b
	Su1785	4.43 ab	7.99 b	5.29 b	66.26 a	3.79 b	0.075 ab
	Mean	4.37	8.05	5.40	66.99	3.99	0.074
LGY	Songzaoxiang NO.1	3.37 c	6.90 c	4.38 c	63.51 b	2.75 c	0.078 ab
	Changruan07-5	3.99 b	6.86 c	4.39 c	64.09 b	2.77 c	0.079 ab
	Suxiangjing NO.3	3.48 c	6.73 c	4.33 c	64.30 b	2.31 d	0.082 a
	Mean	3.62	6.83	4.37	63.97	2.61	0.080
Analysis of variance							
Year (Y)		*	ns	ns	ns	ns	ns
Type (T)		**	**	**	**	**	**
Variety (V)		**	**	**	**	**	ns
Y × T		ns	ns	ns	ns	ns	ns
Y × V		ns	ns	*	**	ns	ns

HGY, high-yield varieties; LGY, low-yield varieties. Values within the same year followed by different letters are significantly different at the 0.05 probability level. * significant at the 0.05 probability level, ** significant at the 0.01 probability level, ns not significant at the 0.05 probability level.

3.5. Morphology of the Top Three Leaves and Single Stem-Sheath Weight

There were significant differences in the morphology of the top 3 leaves and single stem-sheath weight between the HGY and LGY varieties (Table 5). The single stem-sheath weight of the HGY varieties was significantly higher than that of the LGY varieties in both years, and the average single stem-sheath weight of the HGY varieties was 37.86% higher than that of the LGY varieties in 2018, and 38.19% higher in 2019. The average length and width of the top three leaves of the HGY varieties were significantly higher than those of the LGY varieties, while the leaf angle of the top 3 leaves was reduced.

3.6. Rice Quality

3.6.1. Milling Quality and Appearance Quality

Some metrics of milling quality and appearance quality varied across the varieties (Table 6). There was no detectable difference in brown rice rate (BRR) or milled rice rate (MRR) between the different grain yield types. The head milled rice rate (HMRR) of the LGY varieties was 7.04% higher than that of the HGY varieties in 2018, and 17.60% higher in 2019. Significant differences in appearance quality between the HGY and LGY varieties were observed: the average chalky kernel rate (CKR), chalky area (CA), and chalkiness degree (CD) of the HGY varieties were significantly higher than those of the LGY varieties.

3.6.2. Pasting Properties

There were significant differences in pasting properties among the varieties (Table 7). The average values of peak viscosity, trough viscosity, and final viscosity and breakdown of the HGY varieties were all significantly higher than those of the LGY varieties, while the average values of setback, consistence, and pasting temperature were all significantly lower than those of the LGY varieties.

Table 5. Single stem-sheath weight and morphology of the top three leaves of semi-waxy *japonica* rice varieties with different grain yields.

Type	Variety	Single Stem-Sheath Weight (g)	Flag Leaf			2nd Leaf			3nd Leaf		
			Length (cm)	Width (cm)	Leaf Angles (°)	Length (cm)	Width (cm)	Leaf Angles (°)	Length (cm)	Width (cm)	Leaf Angles (°)
2018											
HGY	Nanjing5718	2.31 a	29.18 a	2.22 a	10.36 c	39.50 a	1.68 a	17.06 c	39.54 a	1.40 a	22.44 b
	Nanjing9108	1.77 b	27.12 a	1.74 c	10.46 c	38.96 a	1.42 c	16.84 c	34.62 b	1.24 b	23.02 b
	Su1785	1.71 b	27.60 a	1.90 b	10.44 c	36.68 ab	1.54 b	16.50 c	35.82 b	1.44 a	23.24 b
	Mean	1.93	27.97	1.95	10.42	38.38	1.55	16.80	36.66	1.36	22.90
LGY	Songzaoxiang NO.1	1.45 d	30.34 a	1.64 c	14.18 a	34.84 ab	1.30 d	21.36 b	31.40 b	1.20 b	26.42 a
	Changruan07-5	1.62 c	24.48 a	1.60 c	12.74 b	34.20 ab	1.44 c	21.20 b	31.90 b	1.22 b	26.06 a
	Suxiangjing NO.3	1.13 e	24.48 a	1.40 d	14.14 a	31.94 b	1.14 e	22.04 a	31.64 b	1.04 c	26.00 a
	Mean	1.40	26.43	1.55	13.69	33.66	1.29	21.53	31.65	1.15	26.16
2019											
HGY	Nanjing5718	2.38 a	29.92 a	2.18 a	10.30 c	38.00 a	1.78 a	16.56 c	36.82 a	1.50 a	22.80 b
	Nanjing9108	1.83 b	27.30 a	1.72 c	10.44 c	35.46 a	1.44 bc	16.84 c	34.96 a	1.32 b	23.16 b
	Su1785	1.77 b	26.78 a	1.88 b	9.86 c	37.06 a	1.52 b	17.28 c	36.54 a	1.42 a	23.34 b
	Mean	1.99	28.00	1.93	10.20	36.84	1.58	16.89	36.11	1.41	23.10
LGY	Songzaoxiang NO.1	1.51 d	28.62 a	1.58 c	13.96 a	31.64 b	1.24 de	20.82 b	31.84 b	1.10 c	25.72 a
	Changruan07-5	1.63 c	21.82 a	1.58 c	12.12 b	30.06 b	1.36 cd	20.90 b	31.58 b	1.26 b	25.26 a
	Suxiangjing NO.3	1.17 e	22.56 a	1.38 d	14.12 a	28.08 b	1.14 e	21.66 a	29.08 b	1.04 c	25.54 a
	Mean	1.44	24.33	1.51	13.40	29.93	1.25	21.13	30.83	1.13	25.51
Analysis of variance											
Year (Y)		**	ns	ns	*	**	ns	ns	ns	ns	ns
Type (T)		**	*	**	**	**	**	**	**	**	**
Variety (V)		**	**	**	**	ns	**	**	*	**	*
Y × T		ns	ns	ns	ns	ns	ns	ns	ns	ns	**
Y × V		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

HGY, high-yield varieties; LGY, low-yield varieties. Values within the same year followed by different letters are significantly different at the 0.05 probability level. * significant at the 0.05 probability level, ** significant at the 0.01 probability level, ns not significant at the 0.05 probability level.

Table 6. Milling quality and appearance quality of semi-waxy *japonica* rice varieties with different grain yields.

Type	Variety	Milling Quality (%)			Appearance Quality (%)		
		BRR	MRR	HMRR	CKR	CA	CD
2018							
HGY	Nanjing5718	84.97 a	71.41 a	56.91 ab	35.50 a	27.68 a	9.82 a
	Nanjing9108	85.25 a	72.56 a	57.56 ab	33.01 a	23.98 c	7.92 b
	Su1785	83.53 a	72.43 a	54.30 b	36.93 a	25.29 abc	9.34 a
	Mean	84.59	72.13	56.26	35.14	25.65	9.03
LGY	Songzaoxiang NO.1	83.73 a	72.99 a	60.29 a	25.98 b	22.85 c	5.94 c
	Changruan07-5	85.79 a	72.18 a	59.35 a	24.87 b	24.64 bc	6.11 c
	Suxiangjing NO.3	85.54 a	73.59 a	61.03 a	23.42 b	27.14 ab	6.35 c
	Mean	85.02	72.92	60.22	24.75	24.88	6.13
2019							
HGY	Nanjing5718	84.21 a	72.24 a	56.59 c	35.71 a	30.92 a	11.04 a
	Nanjing9108	85.11 a	73.16 a	53.27 d	32.86 b	29.90 a	9.81 b
	Su1785	83.29 a	72.08 a	52.21 d	30.53 b	30.23 a	9.22 b
	Mean	84.20	72.49	54.03	33.03	30.35	10.02
LGY	Songzaoxiang NO.1	83.43 a	74.30 a	66.76 a	23.81 c	22.19 b	5.28 d
	Changruan07-5	85.04 a	72.37 a	59.39 b	23.23 c	23.89 b	5.55 d
	Suxiangjing NO.3	84.11 a	74.82 a	64.48 a	23.15 c	28.49 a	6.60 c
	Mean	84.19	73.83	63.54	23.40	24.86	5.81
Analysis of variance							
Year (Y)		ns	ns	ns	**	**	*
Type (T)		ns	ns	**	**	**	**
Variety (V)		ns	ns	**	ns	**	**
Y × T		ns	ns	**	ns	**	**
Y × V		ns	ns	**	*	ns	**

HGY, high-yield varieties; LGY, low-yield varieties. BRR, brown rice rate; MRR, milled rice rate; HMRR, head milled rice rate. CKR, chalky kernel rate; CA, chalky area; CD, chalkiness degree. Values within the same year followed by different letters are significantly different at the 0.05 probability level. * significant at the 0.05 probability level, ** significant at the 0.01 probability level, ns not significant at the 0.05 probability level.

Table 7. Pasting properties of semi-waxy *japonica* rice varieties with different grain yields.

Type	Variety	Peak Viscosity (cP)	Trough Viscosity (cP)	Final Viscosity (cP)	BREAKDOWN (cP)	Setback (cP)	Consistence (cP)	Pasting Temperature (°C)
2018								
HGY	Nanjing5718	3149 a	1620 a	2118 a	1529 a	−1031 c	499 c	72.38 a
	Nanjing9108	2612 d	1406 a	1987 a	1206 b	−625 ab	581 b	71.68 a
	Su1785	2733 b	1443 a	1959 a	1290 b	−774 b	516 c	71.28 a
	Mean	2831	1490	2021	1341	−810	532	71.78
LGY	Songzaoxiang NO.1	2682 c	1334 a	1900 a	1348 b	−782 b	566 b	72.00 a
	Changruan07-5	2740 b	1469 a	2091 a	1271 b	−650 ab	622 a	71.98 a
	Suxiangjing NO.3	2460 e	1342 a	1939 a	1118 b	−521 a	598 ab	73.23 a
	Mean	2627	1382	1977	1246	−651	595	72.40
2019								
HGY	Nanjing5718	3177 a	1755 a	2288 a	1423 a	−889 c	534 c	72.78 ab
	Nanjing9108	2549 b	1606 ab	2214 ab	943 c	−335 a	608 b	71.75 bc
	Su1785	2644 a	1596 ab	2158 ab	1048 c	−486 ab	562 c	71.15 c
	Mean	2790	1652	2187	1138	−603	535	71.89
LGY	Songzaoxiang NO.1	2528 b	1285 d	1891 c	1244 b	−638 b	606 b	72.38 ab
	Changruan07-5	2546 b	1492 bc	2139 ab	1054 c	−407 a	647 ab	72.78 ab
	Suxiangjing NO.3	2389 c	1393 cd	2063 b	996 c	−326 a	670 a	73.63 a
	Mean	2488	1390	2031	1098	−457	641	72.93
Analysis of variance								
	Year (Y)	**	**	**	**	**	**	ns
	Type (T)	**	**	**	**	*	**	**
	Variety (V)	**	**	**	**	**	**	**
	Y×T	**	*	*	ns	ns	ns	ns
	Y×V	*	ns	ns	ns	ns	ns	ns

HGY, high-yield varieties; LGY, low-yield varieties. Values within the same year followed by different letters are significantly different at the 0.05 probability level. * significant at the 0.05 probability level, ** significant at the 0.01 probability level, ns not significant at the 0.05 probability level.

3.6.3. Nutrition and Eating Quality

There was no significant difference in amylose content between the HGY and LGY varieties (Table 8). The protein content of the HGY varieties was significantly lower than that of the LGY varieties across both years: the average protein content of the LGY varieties was 22.55% higher in 2018 than that of the HGY varieties and 24.28% higher in 2019 than that of the HGY varieties. There were significant differences in eating quality between the HGY and LGY varieties. The average values of appearance, viscosity, and degree of balance of the HGY varieties were significantly higher than those of the LGY varieties, while hardness showed the opposite trend. The taste value of the HGY varieties was significantly higher than that of the LGY varieties across both years. The average taste value of the HGY varieties was 75.67 in 2018 and 74.50 in 2019, which was 10.92% and 11.48% higher than that of the LGY varieties.

Table 8. Nutrition and eating quality of semi-waxy *japonica* rice varieties with different grain yields.

Type	Variety	Amylose Content (%)	Protein Content (%)	Eating Quality				
				Appearance	Hardness	Viscosity	Degree of Balance	Taste Value
2018								
HGY	Nanjing5718	10.45 ab	7.12 c	6.37 b	6.67 a	6.77 ab	6.37 b	72.17 b
	Nanjing9108	10.04 b	6.20 d	7.90 a	5.80 c	7.87 a	7.97 a	78.40 a
	Su1785	8.92 c	6.25 d	7.47 a	6.23 b	8.03 a	7.63 a	76.43 a
	Mean	9.80	6.52	7.24	6.23	7.56	7.32	75.67
LGY	Songzaoxiang NO.1	9.80 b	8.28 a	6.53 b	6.73 a	6.53 ab	6.60 b	68.13 c
	Changruan07-5	10.85 a	7.61 b	6.07 b	6.60 a	6.50 ab	6.03 b	69.37 c
	Suxiangjing NO.3	8.72 c	8.10 a	6.07 b	6.77 a	6.10 b	6.00 b	67.17 c
	Mean	9.79	7.99	6.22	6.70	6.38	6.21	68.22
2019								
HGY	Nanjing5718	10.44 a	7.11 c	6.60 b	6.65 a	7.65 abc	6.80 b	70.50 b
	Nanjing9108	10.08 ab	6.33 d	7.40 a	6.25 a	7.95 ab	7.50 a	76.00 a
	Su1785	9.89 ab	6.46 d	7.60 a	6.20 a	8.25 a	7.75 a	77.00 a
	Mean	10.14	6.63	7.20	6.37	7.95	7.35	74.50

Table 8. *Cont.*

Type	Variety	Amylose Content (%)	Protein Content (%)	Eating Quality				
				Appearance	Hardness	Viscosity	Degree of Balance	Taste Value
LGY	Songzaoxiang NO.1	9.75 ab	8.53 a	6.15 b	7.15 a	6.85 cd	6.35 bc	66.50 c
	Changruan07-5	10.59 a	7.93 b	7.45 a	6.85 a	7.15 bcd	7.60 a	68.50 c
	Suxiangjing NO.3	9.34 b	8.26 a	5.95 b	7.00 a	6.25 d	5.90 c	65.50 c
	Mean	9.90	8.24	6.52	7.00	6.75	6.62	66.83
Analysis of variance								
Year (Y)		ns	**	ns	ns	*	ns	*
Type (T)		ns	**	**	**	**	**	**
Variety (V)		**	**	**	ns	*	**	**
Y × T		ns	ns	ns	ns	ns	ns	ns
Y × V		*	ns	**	ns	ns	**	ns

HGY, high-yield varieties; LGY, low-yield varieties. Values within the same year followed by different letters are significantly different at the 0.05 probability level. * significant at the 0.05 probability level, ** significant at the 0.01 probability level, ns not significant at the 0.05 probability level.

4. Discussion

4.1. Grain Yield Formation Characteristics of Semi-Waxy japonica Rice with a High Grain Yield

Good plant type traits, high dry matter accumulation, and sufficient total spikelet number were the important bases for achieving high rice grain yield [20–23]. Wu et al. [24] showed that to obtain a rice grain yield above 11.7 t hm^{-2}, the total spikelet number per square meter should be more than 45,000, the filled grain rate should be above 90%, and the 1000-grain weight should be above 26 g. In this study, the average total spikelet number of the HGY varieties was 18.42% higher in 2018 and 22.28% higher in 2019 than that of the LGY varieties, which resulted in the average grain yield of the HGY varieties being 29.39 and 30.79% higher than those of the LGY varieties in 2018 and 2019, respectively (Table 2). The total spikelet number was mainly determined by the effective panicle number and spikelet per panicle. Compared with the LGY varieties, the HGY varieties had a smaller effective panicle number per area, but more spikelet per panicle (Table 2), which indicated that more spikelet per panicle was the main reason for the observed higher total spikelet number of the HGY varieties [25,26]. In addition, we noted that the increase in the ratio of grain yield was greater than that of the total spikelet number, which may be related to the higher 1000-grain weight of the HGY varieties (Table 2). Therefore, we speculated that more spikelet per panicle and a larger 1000-grain weight are primary approaches for achieving a high yield with semi-waxy japonica rice, which is consistent with previous research [27].

To fill the huge sink formed by a great number of spikelets, the morphological and function of leaves, stems, and roots of high-yielding rice need to be better than those of low-yield rice. For the high-yield rice varieties, the leaf area index and the percentages of the highly effective leaf area were comparatively high [9], the decreasing rate of leaf area was low [28], and the top three leaves were upright and straight, with a lower leaf angle [29,30]. In addition, the longer the total growth period, especially from elongating to maturity, allows the amassing of more temperature and radiation resources, which is conducive to increased dry matter accumulation [5,9]. Our research also showed similar results: the leaf area indexes of the HGY varieties were significantly higher than those of the LGY varieties at the elongating, heading, and maturity stages in both years (Table 4). After heading, due to the larger length and width of the top three leaves of the HGY varieties (Table 5), the high effective leaf area and the ratio of the HGY varieties were significantly higher than those of the LGY varieties, and the average decreasing rate of the leaf area of the HGY varieties was lower than that of the LGY varieties (Table 4). The HGY varieties had a longer total growth duration, especially from elongating to maturity (Table 1). Moreover, the leaf angle of the top 3 leaves in the HGY varieties was smaller (Table 5), which was beneficial to increasing light energy capture and forming a high light efficiency population [31]. We hypothesized that the good morphology and function of leaves and stems, and longer growth duration, resulted in a high above-ground biomass accumulation of the HGY varieties. However, rice grain yield can also be expressed as the product of biomass accumulation and harvest index. Since there was no significant difference in harvest index between the HGY and

LGY varieties, we speculated that the difference in above-ground biomass accumulation was another major reason for the difference in rice yield, which was consistent with the results of previous studies [23,32].

The high-yield rice varieties with more grains per panicle generally have a low filled grain rate [33,34]. In this study, we also found that the average filled grain rate of the HGY varieties was significantly lower than that of the LGY varieties (Table 2), indicating that the assimilates of the high-yield varieties were not sufficient [35]. It should be noted that Nanjing5718 (a high-yield variety) not only had the highest grain yield, but also had an average filled grain rate of 97.68%, which did not differ significantly from that of the LGY varieties (Table 2). We speculated that the reasons for Nanjing5718 having a higher filled grain rate might be related to it having the highest single stem-sheath weight (Table 5). A Higher single stem-sheath weight can improve the filled grain rate because the assimilate accumulated in the stem-sheath at the heading stage can be translocated to support grain filling [34,36]. These findings indicate that the grain yield of the HGY varieties could be further improved by cultivating higher single stem-sheath weight.

4.2. Rice Quality Characteristics of Semi-Waxy japonica Rice with a High Grain Yield

Next to grain yield, rice quality is the most important factor in rice production as it is directly related to market value and thus influences farmer incomes. Rice quality is a complex and comprehensive metric, including milling quality, appearance quality, cooking and eating quality, etc.

The milling quality is an important index affecting the economic value of rice, including brown rice rate, milled rice rate, and head milled rice rate [37]. Previous studies showed a positive correlation between the milled rice rate and yield, but there was no significant correlation between the head milled rice rate and yield [38]. In this study, we found no significant difference in the brown rice rate and milled rice rate across different grain yield types, but the head milled rice rate of the HGY varieties was significantly lower than that of the LGY varieties (Table 6). The head milled rice rate is influenced by grain characteristics, such as chalkiness, grain shape, and grain moisture [39]. Previous studies have shown that larger grains are more likely trend to break during milling [40]. In this study, the 1000-grain weight of the HGY varieties was significantly higher than that of the LGY varieties (Table 2), indicating that the grain size of the HGY varieties was significantly larger than that of the LGY varieties, and it was easier to be broken during milling. Leesawatwong et al. [41] and Balindong et al. [42] reported that increasing the grain protein content can enhance the hardness of grains and reduce grain breakage during milling, thus increasing the head rice rate. Generally, protein content in rice grains is negatively correlated with grain yield and grain weight [43]. Our results also showed that the grain protein content of the HGY varieties was significantly lower than that of the LGY varieties (Table 8), which may be one of the reasons for the low head milled rice rate of the HGY varieties.

Chalkiness not only affects appearance quality but also milling quality, so it is a key determinant of the commercial value of milled rice. It has been well documented that chalkiness is controlled by polygenes, resulting from the loose packing of starch granules in the grain endosperm [44,45]. Cai et al. [38] suggested that ratoon rice with low grain yield had lower chalkiness than the main crop rice with a high grain yield. In this study, we also found that the average chalky kernel rate, chalky area, and chalkiness degree of the HGY varieties were significantly higher than those of the LGY varieties (Table 6). One reason for this result might be that the HGY varieties had a higher 1000-grain weight (Table 2), which tends to result in loose starch granules and higher chalkiness [15,46]. The high degree of chalkiness indicates that rice grains have lower starch density and are more easily broken during milling, so chalkiness is generally negatively correlated with processing quality [47]. This may be one of the reasons for the low head milled rice rate in HGY varieties.

Eating quality is the most important aspect of evaluating rice quality. The cooked rice texture, including hardness and stickiness, are important determinants of eating quality [48]. Previous studies have shown that the hardness and stickiness of cooked rice are closely related to amylose and protein contents, which can limit starch swelling and leaching during cooking [49–51]. Rice higher in amylose or protein has a harder, less-sticky texture after cooking, representing low eating quality [51,52]. Consistent with previous studies [12,52], there was no significant difference in amylose content between the HGY and LGY varieties (Table 8) in this study, indicating that there was no trade-off between amylose content and grain yield. Compared with the LGY varieties, the protein content of the HGY varieties was significantly lower (Table 8), which may be primarily due to the larger sink capacity of HGY varieties, which can dilute the grain protein content [53]. The results of our previous study showed that protein content was the main factor affecting the eating quality of semi-waxy japonica rice varieties [54]. Therefore, we speculated that the HGY varieties would have a higher appearance, viscosity, degree of balance, taste value, and lower hardness (Table 8) related to their lower grain protein content. In addition, the rice pasting properties revealed by RVA measurements reflected the swelling ability of starch granules, which predicts the texture of cooked rice [55]. Among the pasting property parameters, breakdown and setback values are considered important indexes in the evaluation of eating quality [56]. Generally, rice with good eating quality has a higher breakdown value and lower setback value [57]. In this study, we observed that the HGY varieties had a higher breakdown value and lower setback value (Table 7), which indicated that the HGY varieties had a better eating quality.

5. Conclusions

The grain yield superiority of the HGY varieties was mainly attributable to more spikelet per panicle and a larger 1000-grain weight. The underlying factors were a larger leaf area index at each growth stage, larger high efficient leaf area formed by the increased length and width of the top three leaves, smaller leaf angles of the top three leaves, greater single stem-sheath weight, more total dry matter accumulation, and longer growth duration from elongation to maturity. Due to the low protein content in grain, the HGY varieties had a better eating quality than the LGY varieties, and due to the low protein content and the high 1000-grain weight, the head milled rice rate and appearance quality of the HGY varieties were inferior to the LGY varieties. In conclusion, choosing the semi-waxy japonica varieties with more spikelet per panicle and higher 1000-grain weight can achieve the synergistic improvement of grain yield and eating quality, but how to improve the milling quality and appearance quality of high-yield semi-waxy japonica rice needs further research.

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