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Case Report

The Improvement in Head Milled Rice Yield in Middle-Season Hybrid Rice: Evidence from a Case Study of Two Cultivars Released 18 Years Apart

Jialin Cao [1,†], Ruichun Zhang [2,†], Jiana Chen [1], Fangbo Cao [1], Longsheng Liu [2], Shengliang Fang [2], Ming Zhang [2] and Min Huang [1,*]

[1] Rice and Product Ecophysiology, Key Laboratory of Ministry for Crop Physiology and Molecular Biology, Hunan Agricultural University, Changsha 410128, China
[2] Hengyang Academy of Agricultural Sciences, Hengyang 421101, China
* Correspondence: mhuang@hunau.edu.cn
† These authors contributed equally to this work.

Abstract: Head milled rice is the main form of rice for sale and consumption. However, previous studies on the yield change due to the development of new cultivars in rice generally focus on grain yield but few on head milled rice yield. In this study, field experiments were conducted in two years (2019 and 2020) to compare head milled rice yield and associated traits (grain yield, milled recovery traits, and shape and chalkiness traits of rice grains) between two middle-season hybrid rice cultivars released 18 years apart, i.e., Jingliangyou 1468 (JLY1468), a recently-released cultivar with high eating quality, and Liangyoupeijiu (LYPJ), an old cultivar with high grain yield. JLY1468 had higher head milled rice yield than LYPJ by 30% in 2019 and by 33% in 2020. The higher head milled rice yield in JLY1468 than in LYPJ was attributable to improvements in both grain yield, and head milled rice rate (HMRR). The improvement in HMRR in JLY1468 compared to LYPJ was mainly attributable to a reduction in chalkiness degree, which was associated with a decrease in rice grain size. The results of this study provide evidence for the improvement in head milled rice yield in middle-season hybrid rice with the development of new cultivars in recent years.

Keywords: cultivar development; milling quality; head milled rice; hybrid rice; rice yield

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1. Introduction

Rice is one of the most important cereal crops in China, where nearly 70% of the population consumes rice as the staple food [1]. Chinese rice cropping systems are diverse [2], with middle- and double-season rice being the common ones [3]. In recent years, urbanization and economic growth have resulted in a shortage of labor for agricultural production in addition to the rising labor wages, which consequently caused a sharp increase in the middle-season rice planting area in the traditional planting region of double-season rice [4].

The commercial exploitation of hybrid rice has made a considerable contribution to ensuring national food security in China by increasing rice yield by 10–20% [5,6]. Along with the development in the economy and the improvement in livelihood and living standards, rice consumption is changing from quantity to quality in China [7], and the consumption of tasty rice has continuously increased in China in recent years [8]. To meet this change, many high-palatability hybrid rice cultivars, including some middle-season cultivars, have been released in China through great efforts of Chinese rice breeders [6].

Head milled rice is the main form of rice for sale and consumption, especially for the high eating quality rice that sells at a high price. Therefore, it is also important to focus on improving the head milled rice yield in developing new cultivars. Head milled rice yield is determined by grain yield and head milled rice rate (HMRR). Wang et al. [9] observed that an old middle-season hybrid rice cultivar Liangyoupeijiu (LYPJ, Peiai 64S × 9311, released in 1999) had higher head milled rice yield than an older middle-season hybrid rice cultivar Shanyou 63 (SY63, Zhenshan 97A × Minghui 63, released in 1984) mainly due to higher HMRR rather than higher grain yield. For the recently-released middle-season hybrid rice cultivars with high eating quality, it has been documented that they have good performance in grain yield [10], but there is limited information available on their HMRR.

HMRR is closely related to the shape and chalkiness traits of rice grains, and a high HMRR can be achieved from a high rice grain width (RGW) and/or a low occurrence of chalkiness [9,11]. Our recent study showed that both RGW and chalky grain rate (CGR) in middle-season hybrid rice have been significantly decreased with the year of cultivar release [12]. Based on such a finding, it is difficult to speculate whether HMRR and head milled rice yield in middle-season hybrid rice are improved due to the development of new cultivars.

To address the above uncertainty, this study compared head milled rice yield and associated traits between two middle-season hybrid rice cultivars released 18 years apart, i.e., a recently-released cultivar with high eating quality and an old cultivar with high grain yield.

2. Materials and Methods

2.1. Field Experiments

Two middle-season hybrid rice cultivars were chosen and used in the present study, i.e., LYPJ and Jingliangyou 1468 (JLY1468, Jing 4155S × R1468, released in 2017). LYPJ was a super rice cultivar approved by the Ministry of Agriculture of China in 2005 because of its high grain yield and large planting area. JLY1468 has first-grade quality according to the China's Agricultural Industry Standard of Edible Rice Quality and was selected as a recommended high-quality rice cultivar in the Hunan Province of China.

Two-year (2019 and 2020) field experiments were carried out in this study. The experimental field was located at Meihua Village, Xidu Town, Hengyang County, Hunan Province, China (26°53′ N, 112°28′ E, 71 m asl). The experimental soil was a clay with the following chemical properties at the 0–20 layer before transplanting in 2019: pH = 5.86, $KMnO_4$-oxidizable C content = 18.0 g kg^{-1}, $NaHCO_3$-extractable P content = 14.1 mg kg^{-1}, NH_4OAc-extractable K content = 187 mg kg^{-1}, and NaOH-hydrolyzable N content = 145 mg kg^{-1}.

To repeat the experiment under more environments, three sowing dates with a ten-day interval were employed each year, i.e., 25 May and 4 and 14 June. For each sowing date, two cultivars were arranged in a completely randomized block design and replicated three times. The plot size was 30 m^2. Average daily mean temperature during pre-heading and post-heading periods for each cultivar grown under each sowing date in each year are provided in Figure 1a–d, which were calculated using data recorded by an on-site automatic weather station (Vantage Pro 2, Davis Instruments, Hayward, California, USA). In brief, the average daily mean temperature during the pre-heading period was relatively stable (28.6–30.1 °C) across two cultivars grown under three sowing dates in two years, while the average daily mean temperature during the post-heading period was decreased with a delay in the sowing date for both cultivars in both years and decreased from 23.3–27.4 °C for the sowing date of 5 May to 19.0–23.4 °C for the sowing date of 14 June.

Rice seedlings were raised in a wet seedbed and were manually transplanted at twenty-five days after sowing. The transplanting was manually done at a hill spacing of 0.2 × 0.2 m with two seedlings per hill. The basal fertilizer was applied one day before transplanting with 75 kg N ha^{-1}, 75 kg P_2O_5 ha^{-1}, and 75 kg K_2O ha^{-1}. The first topdressing was applied seven days after transplanting with 45 kg N ha^{-1}. The second topdressing was applied at the panicle initiation stage with 30 kg N ha^{-1} and 75 kg K_2O ha^{-1}. A water depth of 5–10 cm was kept in all experimental plots from transplanting until seven days before maturity when plots were drained. Weeds, diseases, and insects were controlled intensively by spraying improved chemicals.

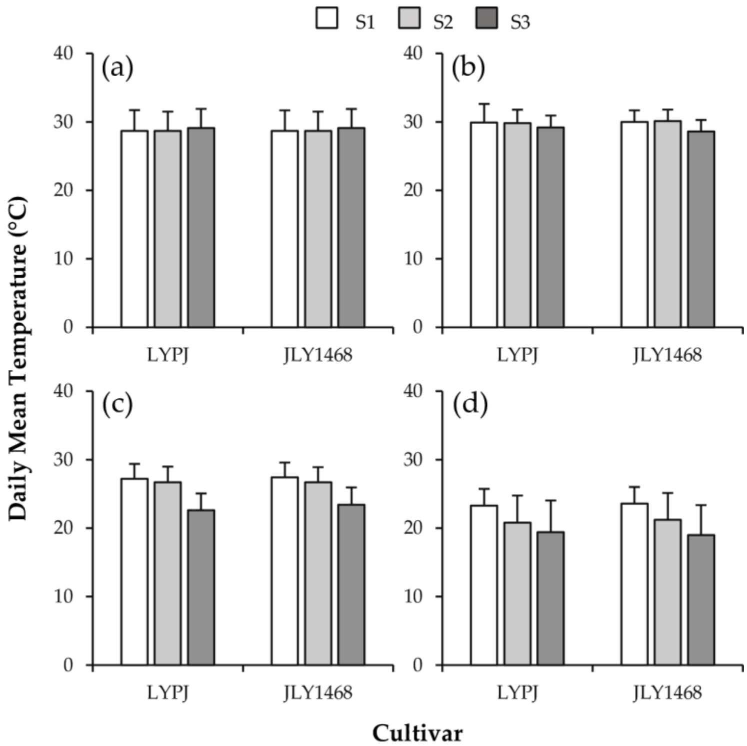

Figure 1. Average daily mean temperature during pre-heading (**a**,**b**) and post-heading periods (**c**,**d**) for two hybrid rice cultivars grown under three sowing dates in 2019 (**a**,**c**) and 2020 (**b**,**d**). Error bars are standard deviations. LYPJ and JLY1468 are hybrid rice cultivars Liangyoupeijiu and Jingliangyou 1468, respectively. S1, S2, and S3 represent the sowing dates of 25 May and 4 and 14 June, respectively.

2.2. Sampling and Measurements

Rice grains were collected from a 5 m^2 area in the middle of each plot. The collected rice grains were sun-dried for three days, and the moisture content of the sun-dried grains was determined by oven-drying (70 °C) a 50 g subsample of sun-dried rice grains to a constant weight. The moisture content of the sundried grains was adjusted to a standard moisture of 14% to calculate grain yield.

About 500 g of sundried rice grains were taken from each sample to store at room temperature for three months. Rice grain quality traits, including milling recovery traits (brown rice rate, BRR; milled rice rate, MRR; and head milled rice rate, HMRR), shape traits (rice grain length, RGL; rice grain width, RGW; and the ratio of rice grain length to width, RGL/RGW), and chalkiness traits (chalky grain rate, CGR; and chalkiness degree, CD) were measured according to Huang et al. [13]. The milling was carried out using a laboratory-scale milling machine (JGMJ8098, Shanghai Jiading Cereals and Oils Instrument Co., Ltd., Shanghai, China). Head milled rice yield was calculated as a product of grain yield and HMRR.

2.3. Statistical Analysis

Data were analyzed using analysis of variance (ANOVA), regression analysis, and Pearson's correlation analysis (Statistix 8.0, Analytical software, Tallahassee, FL, USA). The ANOVA was performed for each year on all measured traits, with the statistical model including replication, the main effects of cultivar and sowing date, and the interactive effect between cultivar and sowing date. The regression analysis was carried out between HMRR with shape and chalkiness traits of rice grains across two cultivars grown under three sowing dates in two years. Pearson's correlation analysis was performed between the shape and chalkiness traits of rice grains across two cultivars grown under three sowing dates in two years.

3. Results

3.1. Grain Yield, Milling Recovery Traits, and Head Milled Rice Yield

The main effect of cultivar on grain yield was significant in both 2019 and 2020 (Table 1). JLY1468 had higher grain yield than LYPJ by 13% in 2019 and by 17% in 2020. The main effect of sowing date and the interactive effect between cultivar and sowing date on grain yield were not significant in either 2019 or 2020.

Table 1. Grain yield, milling recovery traits, and head milled rice yield in two hybrid rice cultivars grown under three sowing dates in 2019 and 2020.

Cultivar (C) [a]	Sowing Date (S) [b]	Grain Yield ($t\ ha^{-1}$)	Milling Recovery Trait [c]			Head Milled Rice Yield ($t\ ha^{-1}$)
			BRR (%)	MRR (%)	HMRR (%)	
2019						
LYPJ	S1	9.86	82.1	73.9	58.6	5.78
	S2	9.28	81.7	73.4	57.0	5.29
	S3	8.56	81.9	74.1	61.8	5.29
	Mean	9.23	81.9	73.8	59.1	5.45
JLY1468	S1	10.64	81.2	73.4	68.4	7.28
	S2	10.04	81.4	73.7	68.8	6.91
	S3	10.56	81.3	73.9	67.1	7.09
	Mean	10.41	81.3	73.7	68.1	7.09
Analysis of variance (*F*-value)						
C		11.74 **	6.45 *	0.34 [NS]	48.86 **	51.74 **
S		1.57 [NS]	0.09 [NS]	1.05 [NS]	0.48 [NS]	1.38 [NS]
C × S		1.40 [NS]	0.38 [NS]	0.85 [NS]	2.22 [NS]	0.14 [NS]
2020						
LYPJ	S1	8.54	81.3	69.3	54.6	4.66
	S2	8.47	80.7	67.5	53.1	4.50
	S3	7.57	81.9	67.9	47.5	3.60
	Mean	8.19	81.3	68.2	51.7	4.25
JLY1468	S1	9.83	80.5	69.3	62.1	6.10
	S2	9.89	80.4	68.1	58.6	5.80
	S3	9.15	81.5	69.3	54.8	5.01
	Mean	9.62	80.8	68.9	58.5	5.64
Analysis of variance (*F*-value)						
C		27.10 **	9.31 *	4.14 [NS]	82.69 **	104.27 **
S		4.00 [NS]	18.60 **	6.35 *	32.20 **	23.50 **
C × S		0.09 [NS]	1.30 [NS]	1.45 [NS]	0.67 [NS]	0.10 [NS]

* and ** denote significance at $p < 0.05$ and $p < 0.01$, respectively; [NS] denotes non-significance at $p < 0.05$. [a] LYPJ and JLY1468 are Liangyoupeijiu and Jingliangyou 1468, respectively. [b] S1, S2, and S3 represent 25 May and 4 and 14 June, respectively. [c] BRR, brown rice rate; MRR, milled rice rate; HMRR, head milled rice rate.

The main effect of cultivar was significant for BRR and HMRR but was not significant for MRR (Table 1). BRR was slightly lower in JLY1468 than in LYPJ in both 2019 and 2020, whereas HMRR was significantly higher in JLY1468 than in LYPJ by 15% and 13% in 2019 and 2020, respectively. The main effects of sowing date on BRR, MRR, and HMRR were not consistent between two years, being not significant in 2019 but significant in 2020. The interactive effects between cultivar and sowing date on BRR, MRR, and HMRR were not significant in either 2019 or 2020.

The main effect of cultivar on head milled rice yield was significant in both 2019 and 2020 (Table 1). JLY1468 produced 30% and 33% higher head milled rice yield than LYPJ in 2019 and 2020, respectively. The main effect of sowing date on head milled rice yield was not consistent between two years, being not significant in 2019 but significant in 2020. The interactive effect between cultivar and sowing date on head milled rice yield was not significant in either 2019 or 2020.

3.2. Shape and Chalkiness Traits

The main effects of cultivar on RGL, RGW, and the ratio of RGL/RGW were significant in both 2019 and 2020 (Table 2). JLY1468 had 3% and 4% lower RGL but 7% and 8% lower RGW than LYPJ in 2019 and 2020, respectively. The ratio of RGL/RGW was 4% higher in JLY1468 than in LYPJ in both 2019 and 2020. The main effect of the sowing date was not consistent for RGL and RGW, being significant in only one of the two years. The main effect of the sowing date on the ratio of RGL/RGW was significant in both 2019 and 2020, but this effect was not consistent between the two years. The interactive effects between cultivar and sowing date on RGL and the ratio of RGL/RGW were not consistent, being not significant in 2019 but significant in 2020. The interactive effect between cultivar and sowing date on RGW was significant in both 2019 and 2020, but this effect was not consistent between the two years.

Table 2. Shape and chalkiness traits of rice grains in two hybrid rice cultivars grown under three sowing dates in 2019 and 2020.

Cultivar (C) [a]	Sowing Date (S) [b]	Shape Trait [c]			Chalkiness Trait [d]	
		RGL (mm)	RGW (mm)	RGL/RGW	CGR (%)	CD (%)
		2019				
LYPJ	S1	6.83	2.20	3.10	23.7	3.93
	S2	6.73	2.20	3.06	16.0	2.50
	S3	6.87	2.31	2.97	34.3	4.87
	Mean	6.81	2.24	3.04	24.7	3.77
JLY1468	S1	6.50	2.05	3.17	6.0	0.90
	S2	6.63	2.07	3.20	6.3	0.97
	S3	6.60	2.13	3.10	4.3	0.63
	Mean	6.58	2.08	3.16	5.5	0.83
		Analysis of variance (*F*-value)				
C		41.60 **	334.11 **	33.33 **	157.70 **	117.93 **
S		1.23 [NS]	54.16 **	12.00 **	9.63 **	4.91 *
C × S		3.68 [NS]	4.26 *	1.33 [NS]	15.10 **	8.36 **
		2020				
LYPJ	S1	6.77	2.26	3.00	12.7	2.23
	S2	6.83	2.28	3.00	9.0	2.13
	S3	6.70	2.23	3.00	23.0	4.77
	Mean	6.77	2.26	3.00	14.9	3.04
JLY1468	S1	6.30	2.05	3.07	2.0	0.33
	S2	6.57	2.05	3.20	6.3	1.23
	S3	6.57	2.10	3.13	9.7	2.40
	Mean	6.48	2.07	3.13	6.0	1.32
		Analysis of variance (*F*-value)				
C		96.57 **	294.30 **	80.00 *	44.69 **	38.43 **
S		10.86 **	0.32 [NS]	6.67 *	19.64 **	26.08 **
C × S		10.86 **	6.85 *	6.67 *	5.81 *	2.42 [NS]

* and ** denote significance at $p < 0.05$ and $p < 0.01$, respectively; [NS] denotes non-significance at $p < 0.05$. [a] LYPJ and JLY1468 are Liangyoupeijiu and Jingliangyou 1468, respectively. [b] S1, S2, and S3 represent 25 May and 4 and 14 June, respectively. [c] RGL, rice grain length; RGW, rice grain width. [d] CGR, chalky grain rate; CD, chalkiness degree.

The main effect of cultivar was significant for both CGR and CD (Table 2). JLY1468 had 78% and 60% lower CGR and 78% and 57% lower CD than LYPJ in 2019 and 2020, respectively. The main effects of the sowing date on CGR and CD were significant in both 2019 and 2020, but these effects were not consistent between the two years. The interactive effect between cultivar and sowing date on CGR was significant in both 2019 and 2020, but this effect was not consistent between the two years. The interactive effect between cultivar and sowing date on CD was not consistent, being significant in 2019 but not significant in 2020.

3.3. Relationships among HMRR, Shape Traits, and Chalkiness Traits

HMRR was not significantly related to shape traits of rice grains, including RGL, RGW, and the ratio of RGL/RGW, but was significantly related to chalkiness traits of rice grains, including CGR and CD (Table 3). CGR and CD explained approximately 77% of the variation in HMRR across two hybrid rice cultivars grown under three sowing dates in two years. CGR and CD were significantly positively related to RGL and RGW but significantly negatively related to the ratio of RGL/RGW (Table 4).

Table 3. Regression analysis between head milled rice rate (HMRR) with shape traits (RGL, rice grain length; RGW, rice grain width; RGL/RGW, the ratio of rice grain length to width) and chalkiness traits (CGR, chalky grain rate; CD, chalkiness degree) of rice grains across two hybrid rice cultivars grown under three sowing dates in two years (n = 12).

Variable	Regression Coefficient	Standard Error	*t*-Value	*p*-Value
Regression analysis using all variables				
Constant	–100.94	1097.58	–0.09	0.93
RGL	–15.09	–0.38	0.08	0.94
RGW	40.23	0.60	0.08	0.94
RGL/RGW	57.63	0.71	0.15	0.88
CGR	1.51	2.23	3.94	0.01
CD	–10.30	–2.45	4.38	0.00
Regression analysis using selected variables [a]				
Constant	65.65	1.83	35.79	0.00
CGR	1.47	2.18	4.01	0.00
CD	–11.20	–2.67	4.92	0.00
Regression equation based on selected variables				
HMRR = 65.65 + 1.47CGR − 11.20CD (r^2 = 0.77, p = 0.00)				

[a] Selected variables are those with $p < 0.05$ in the regression analysis using all variables.

Table 4. Pearson's correlation coefficients between shape traits (RGL, rice grain length; RGW, rice grain width; RGL/RGW, the ratio of rice grain length to width) and chalkiness traits (CGR, chalky grain rate; CD, chalkiness degree) of rice grains across two hybrid rice cultivars grown under three sowing dates in two years (n = 12).

Chalkiness Trait	Shape Trait		
	RGL	RGW	RGL/RGW
CGR	0.734 **	0.743 **	–0.591 *
CD	0.726 **	0.751 **	–0.613 *

* and ** denote significance at $p < 0.05$ and $p < 0.01$, respectively.

4. Discussion

Previous studies on the yield change due to the development of new cultivars in rice generally focus on grain yield [14–16], but few on head milled rice yield [9]. The present study compared head milled rice yield between two middle-season hybrid rice cultivars released 18 years apart, i.e., a recently-released cultivar with high eating quality (JLY1468, released in 2017) and an old cultivar with high grain yield (LYPJ, released in 1999) showing a considerable improvement (~30%) in head milled rice yield due to the cultivar development.

As head milled rice yield is a product of grain yield and HMRR, an increase in head milled rice yield can be achieved by increasing grain yield or HMRR or both. In this study, the improvement in head milled rice yield in JLY1468 compared to LYPJ was attributable to increases in both grain yield and HMRR. This finding is not in agreement with that of Wang et al. [9], who compared the old middle-season hybrid rice cultivar LYPJ with an older middle-season hybrid rice cultivar SY63 and found that LYPJ had higher head milled rice yield than SY63 mainly due to higher HMRR rather than higher grain yield. These indicate that new advances may have been achieved in the improvement of head milled rice yield in middle-season hybrid rice in recent years compared to earlier years. However, further investigations with more cultivars are required to obtain more conclusive results.

The reason for the higher grain yield in JLY1468 compared to LYPJ has been reported by Huang et al. [10]. Namely, JLY1468 has higher late-stage vigor (i.e., higher crop growth rate during the post-heading period) and consequently, higher harvest index, spikelet filling percentage, and grain yield than LYPJ. Although it has been well-documented that HMRR is closely associated with both shape and chalkiness traits of rice grains [9,11], the regression analysis in this study showed HMRR was only significantly associated with chalkiness traits of rice grains. From the regression equation between HMRR and chalkiness traits of rice grains (HMRR = 65.65 + 1.47CGR − 11.20CD), it can be speculated that the higher HMRR in JLY1468 than in LYPJ was mainly attributable to lower CD. This finding is not consistent with that of Wang et al. [9], who reported that lower CGR was responsible for the higher HMRR in LYPJ than in SY63. These again highlight that further investigations involving more cultivars are needed to obtain more conclusive results.

Rice grain chalkiness is a polygenic quantitative trait. Although many quantitative trait loci (QTLs) related to rice grain chalkiness have been detected [17], these QTLs cannot be directly used to explain the change in rice grain chalkiness with the development of new cultivars because they have not been practically applied in recent rice breeding programs [12]. From another point of view, rice grain chalkiness is related to some other rice grain traits, and hence the change in rice grain chalkiness can be explained by the changes in related rice grain traits [11,12,18]. Huang et al. [12] reported that the decrease in the occurrence of chalkiness in middle-season hybrid rice with the development of new cultivars in recent years (2006–2021) was related to a decrease in rice grain size. This was also partially responsible for the lower CD in JLY1468 than in LYPJ in this study.

In this study, we determined the difference in head milled rice yield between two middle-season hybrid rice cultivars released 18 years apart. However, the head milled rice yield does not only depend on the genotype but is also affected by many factors during the growing season (e.g., crop management practices) and during postharvest processing [19,20]. This highlights the need for further studies to obtain a more comprehensive understanding of the performance of head milled rice yield in recently-released middle-season hybrid rice cultivars.

5. Conclusions

JLY1468, a recently-released middle-season hybrid rice cultivar with high eating quality, had considerably higher (~30%) head milled rice yield compared to LYPJ, an old middle-season hybrid rice cultivar with high grain yield. Improvements in both grain yield and HMRR were responsible for the higher head milled rice yield in JLY1468 than in LYPJ. The improvement in HMRR in JLY1468 compared to LYPJ was mainly attributable to a reduction in CD, which was associated with a decrease in rice grain size. Based on these findings, the way for achieving high milled rice yield in JLY1468 is clarified and presented in Figure 2. This study provides evidence for the improvement in head milled rice yield in middle-season hybrid rice with the development of new cultivars in recent years and highlights the need for further investigations involving more cultivars to obtain more conclusive results.

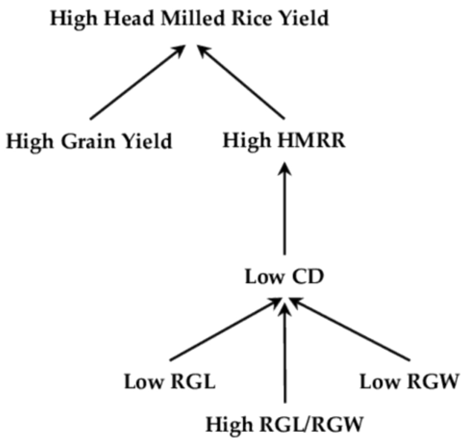

Figure 2. The way of achieving high milled rice yield in the recently-released middle-season hybrid rice cultivar Jingliangyou 1468. HMRR, head milled rice rate; CD, chalkiness degree; RGL, rice grain length; RGW, rice grain width; RGL/RGW, the ratio of rice grain length to width.

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