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Changes in the Grain Yield and Quality of Early *Indica* Rice from 2000 to 2020 in Southern China

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Abstract: The double-season rice system plays an important role in ensuring food security in China. However, changes in the grain yield and quality of recently released rice varieties are still not fully understood, especially early *indica* rice (*Oryza sativa*). In this study, we collected the yield and quality traits of 224 early *indica* rice varieties released in China's Hunan and Jiangxi provinces from 2000 to 2020. The results showed that rice grain yield, but not quality, was significantly improved in early *indica* rice from 2000 to 2020, and the improvement in grain yield was mainly the result of an increased spikelet number per panicle. Quality traits such as head rice rate, chalky rice rate, and amylose content remained stable while the milled rice rate and degree of chalkiness showed adverse changes during early *indica* rice breeding. These results suggested that improving grain yield, but not quality, has been prioritized during early *indica* rice breeding in the past few decades. Further analysis showed that the degree of chalkiness had the largest coefficient of variation among the studied quality traits in the 224 early *indica* rice varieties, indicating that there is still great potential to decrease the degree of chalkiness through rice breeding. Interestingly, the results showed that lower degrees of chalkiness were associated with lower amylose contents and chalky rice rates but with a higher length-to-width ratios and a gel consistency. Therefore, focusing on the degree of chalkiness seems a promising strategy to synergistically improve the quality traits of early *indica* rice. Overall, our results have value for guiding future research on high-yield and high-quality breeding in early *indica* rice.

Keywords: early *indica* rice; yield; quality; breeding; chalkiness degree; *Oryza sativa*

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1. Introduction

Rice (*Oryza sativa* L.) is one of the most important staple foods in the world, feeding more than half of the global population and over 60% of China's population [1]. A continuous increase in rice yield is necessary to meet the increasing food consumption needs of growing populations worldwide [2,3]. In China, with the utilization of heterosis (i.e., the development hybrid and "super" rice varieties) and the development of modern cultivation management strategies, the rice yield has increased by 68% since 1976 despite a 17% reduction in rice production area [4].

Rice cropping systems are generally single- or double-season rice systems in China (early- and late-season rice) and other southeast Asian countries (wet- and dry-season rice) [5,6], in which the double-season rice system dominates in the warm climates of central and southern China and is considered an efficient approach to increase both the multiple cropping index and rice yield [6]. At present, the double-season rice planting area accounts for 33% of the national total rice production area, and its yield comprises 27% of the total national yield [7]. Although these percentages have declined substantially since 1980 due to rapid urbanization and increased labor costs, as well as low returns, the double-season rice system has continued to make a considerable contribution to rice self-sufficiency and food security in China [6,8].

As the two largest double-season rice-producing provinces, Jiangxi and Hunan, located in the middle reaches of the Yangtze River, together account for nearly 51% of the national double-season rice production area and produce 51% of the national double-season rice yield [7,8]. In general, early-season rice and late-season rice are continuously grown annually from March to July and from June to November, respectively, in these provinces. However, early-season rice is often affected by lower temperatures in the tillering stage and by higher temperatures in the grain-filling stage, which, respectively, decrease crop growth rates during the vegetable phase and shorten the grain-filling duration, resulting in a 6–12% lower yield per unit area compared with late-season rice [8–10]. Therefore, to close the yield gap between early-season rice and late-season rice, the priority should be to develop climate-smart and higher-yield-potential varieties of early-season rice.

Although improving grain yield should be a permanent goal of rice breeders, grain quality has received increasing attention in recent years because the eating and living habits of people have changed [11–15]. However, there can be a trade-off between grain yield and quality, which is more likely to appear in early-season rice than in single- and late-season rice. To date, few early-season rice varieties released by provincial and state authorities have met the Grade III national and ministerial standards of rice quality: GB/T17891-1999 (1999) [16] and NY/T593-2002) (2002) [17], respectively. In contrast, in Jiangxi and Hunan provinces, over 60% of mid- and late-season rice varieties have met these standards [18,19]. Today, it is still difficult to breed rice varieties that are both high yield and high quality, especially in early-season rice. Moreover, due to global warming, increased temperatures during the grain filling stage of growing early-season rice will have profound adverse effects on grain quality, such as effects on the degree of chalkiness, as has been shown in previous studies [20,21].

Although some studies have investigated changes in grain yield and quality in rice varieties released in different years [11,13,14,22,23], no previous study has systematically investigated the relationships among yield components and grain quality traits, especially in early *indica* rice, which may hinder the improvement of both grain yield and quality from the perspective of variety selection. Therefore, the objectives of this study were to (1) compare changes in yield and quality traits in 224 early *indica* rice varieties from 2000 to 2020 and (2) explore the possibility of synergistically improving grain yield and quality in early *indica* rice.

2. Materials and Methods

2.1. Data Collection

We explored the yield and quality traits of 224 early *indica* rice varieties released in the Chinese provinces of Hunan and Jiangxi from 2000 to 2020 (Table S1). These provinces comprise the main production area of double-season rice in southern China [8]. The yield and quality traits were examined and approved by the provincial crop variety assessment committee (PCVAC) at the China Rice Data Center (https://www.ricedata.cn/index.htm, accessed on 12 December 2020). The selected rice varieties were subjectively divided into 4 release periods (2000–2005, 2006–2010, 2011–2015, and 2016–2020) to examine changes in yield and quality during early *indica* rice breeding. The yield traits, including grain yield per area (GY), panicle number (PN), spikelet number per panicle (SN), seed-set rate (SSR), and 1000-grain weight (TGW), and quality traits, including brown rice rate (BRR), milled rice rate (MRR), head rice rate (HRR), length-to-width ratio (LWR), chalky rice rate (CRR), chalkiness degree (CD), gel consistency (GC), and amylose content (AC), were obtained directly from the China Rice Data Center. Only rice varieties in which all the yield and quality traits were determined were included in our dataset. The planting locations in Jiangxi and Hunan provinces had adequate temperature, light, and water resources.

2.2. Statistical Analysis

Normal distribution and homogeneity of variance were evaluated using the Shapiro–Wilk test and Levene test, respectively. For data conforming to both assumptions, one-way analysis of variance (ANOVA) was performed, followed by the Tukey HSD test using SPSS 26. If the data violated these prerequisites, then a Kruskal–Wallis test was conducted for multiple comparisons using SPSS 26. The R packages factoMineR and factoextra were used to perform a principal components analysis (PCA). During a PCA, the data are often standardized to ensure that the variables are comparable, especially when they are measured at different scales. The first five principal components (dimensions, Dim) of grain components and quality traits had eigenvalues greater than 1 and were retained for further analysis according to Kaiser's rule [24]. For each trait, factor loadings greater than 0.5 in absolute value were considered important, following our previous study [25].

3. Results

3.1. Changes in Grain Yield, Yield Components, and Grain Quality Traits in Early Indica Rice from 2000 to 2020

During the studied periods, grain yield and spikelet number per panicle both significantly increased from 2000 to 2020, while panicle number, seed-set rate, and 1000-grain weight did not show consistent trends across the periods (Table 1). Milled rice rates showed a slight but significantly decreasing trend (Table 2). Although the degree of chalkiness did not change in the first three periods, it significantly increased in rice varieties released during 2016 to 2020 (Table 2). There were significant differences in brown rice rate, length-to-width ratio, and gel consistency among the study periods. However, no consistent change in these traits was found from 2000 to 2020 (Table 2). Additionally, we did not observe any significant variation in head rice rate, chalky rice rate, or amylose content among the study periods (Table 2). It should be noted that all coefficients of variation in grain yield, panicle number, spikelet number per panicle, seed-set rate, 1000-grain weight, brown rice rate, milled rice rate, head rice rate, length-to-width ratio, and amylose content were lower than 20%, while the chalky rice rate, degree of chalkiness, and gel consistency showed large variations among the 224 early *indica* rice varieties, the CVs of which were 39%, 73%, and 30%, respectively (Figure 1).

Table 1. Means ± SD of yield-related traits in early *indica* rice varieties released from 2000 to 2020.

Released Years	Number of Rice Varieties	Grain Yield (t ha^{-1})	Panicle Number (m^{-2})	Spikelet Number per Panicle	Seed-Set Rate (%)	1000-Grain Weight (g)
2000–2005	14	6.90 ± 0.49 c	351.9 ± 27.7 a	106.0 ± 8.7 c	79.5 ± 4.8 c	26.0 ± 1.6 ab
2006–2010	98	7.45 ± 0.38 b	333.1 ± 22.8 ab	107.7 ± 11.9 c	83.1 ± 3.6 a	26.9 ± 1.4 a
2011–2015	60	7.48 ± 0.31 b	331.1 ± 20.6 b	116.5 ± 9.8 b	82.9 ± 3.7 ab	26.5 ± 1.4 a
2016–2020	52	7.90 ± 0.36 a	336.4 ± 22.2 ab	125.1 ± 12.7 a	81.1 ± 2.5 c	25.8 ± 1.1 b

Note. Lowercase letters following a value indicate significant differences at the 0.05 probability level.

Table 2. Means ± SD of grain quality traits in early *indica* rice varieties released from 2000 to 2020.

Released Years	Number of Rice Varieties	Brown Rice Rate (%)	Milled Rice Rate (%)	Head Rice Rate (%)	Length-to-Width Ratio	Chalky Rice Rate (%)	Chalkiness Degree (%)	Gel Consistency (mm)	Amylose Content (%)
2000–2005	14	81.8 ± 0.8 a	71.5 ± 2.9 a	49.0 ± 12.1 a	2.96 ± 0.20 abc	57.9 ± 27.6 a	12.2 ± 8.2 b	57.6 ± 18.5 ab	21.3 ± 4.6 a
2006–2010	98	80.9 ± 1.8 b	70.5 ± 3.1 ab	55.1 ± 11.1 a	2.99 ± 0.25 a	65.6 ± 27.3 a	10.6 ± 7.3 b	64.5 ± 13.3 a	20.2 ± 3.4 a
2011–2015	60	80.1 ± 2.2 c	69.9 ± 2.3 bc	53.7 ± 7.9 a	2.90 ± 0.30 ab	67.3 ± 25.4 a	9.8 ± 5.7 b	59.9 ± 19.4 a	19.6 ± 4.3 a
2016–2020	52	81.0 ± 1.8 ab	69.1 ± 3.4 c	55.8 ± 6.7 a	2.71 ± 0.42 c	68.6 ± 23.6 a	22.2 ± 11.7 a	48.3 ± 17.3 bc	19.2 ± 3.6 a

Note. Lowercase letters following a value indicate significant differences at the 0.05 probability level.

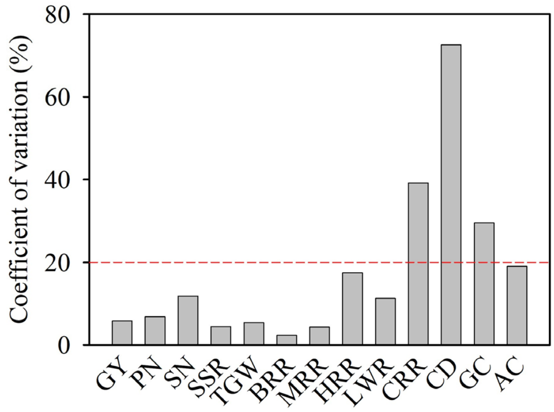

Figure 1. Coefficient of variation in the studied yield and quality traits among 224 early *indica* rice varieties. GY, grain yield; PN, panicle number; SN, spikelet number per panicle; SSR, seed-set rate; TGW, 1000-grain weight; BRR, brown rice rate; MRR, milled rice rate; HRR, head rice rate; LWR, length-to-width ratio of rice grain; CRR, chalkiness rice rate; CD, chalkiness degree; GC, gel consistency; and AC, amylose content. Red dotted line represents CV at 20%.

3.2. Relationships among Grain Yield, Yield Components, and Grain Quality Traits in Early Indica Rice

The results showed that grain yield was positively correlated with spikelet number per panicle, while no significant relationship was found between grain yield and the remaining yield components (Figure 2). The panicle number was positively correlated only with the length-to-width ratio, while it was not correlated with the other grain quality traits (Figure 3). Meanwhile, the spikelet number per panicle was positively correlated with both the degree of chalkiness and head rice rate but negatively correlated with length-to-width ratio and gel consistency. Interestingly, we found that the seed-set rate was not correlated with any grain quality traits among the different early *indica* rice varieties (Figure 3). In addition, positive relationships between 1000-grain weight and amylose content, chalky rice rate, and length-to-width ratio were observed, while negative association between 1000-grain weight and head rice rate was found (Figure 3). Importantly, our results suggested that though there was a positive relationship between grain yield and the degree of chalkiness among the 224 early *indica* rice varieties (Figure 3), it was still possible to achieve both a high grain yield and low degree of chalkiness through rice breeding, as shown in Figure 4. However, it should be noted that the inherent connections and causal relationships between the paired traits shown in Figure 3 are mostly still unknown, and further research is warranted.

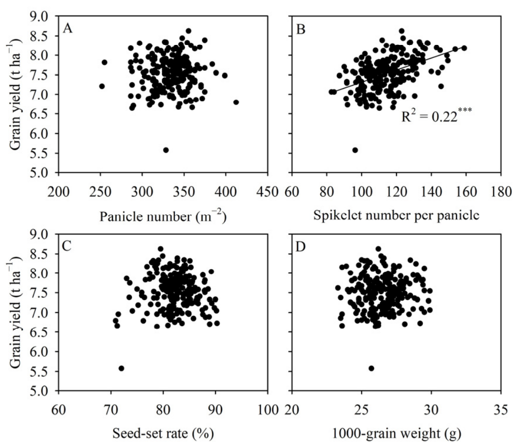

Figure 2. Relationships between grain yield and panicle number (**A**), spikelet number per panicle (**B**), seed-set rate (**C**) and 1000-grain weight (**D**), respectively, among 224 early *indica* rice varieties. *** represents significance at $p < 0.001$.

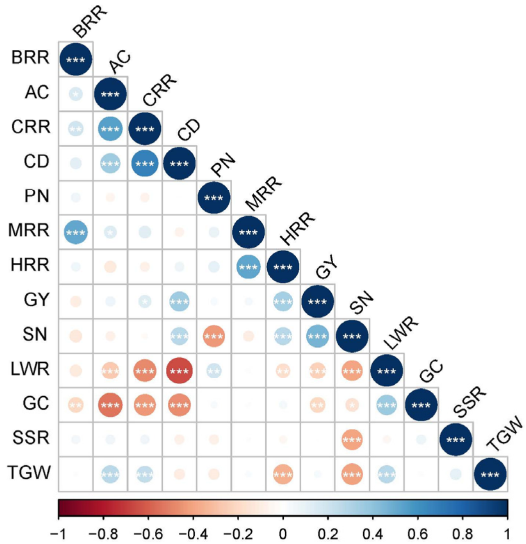

Figure 3. Pearson's correlations of yield components and grain quality traits in 224 early *indica* rice varieties. BRR, brown rice rate; AC, amylose content; CRR, chalkiness rice rate; CD, chalkiness degree; PN, panicle number; MRR, milled rice rate; HRR, head rice rate; GY, grain yield; SN, spikelet number per panicle; LWR, length-to-width ratio of rice grain; GC, gel consistency; SSR, seed-set rate; and TGW, 1000-grain weight. ***, **, and * represent significance at $p < 0.001$, $p < 0.01$, and $p < 0.05$, respectively.

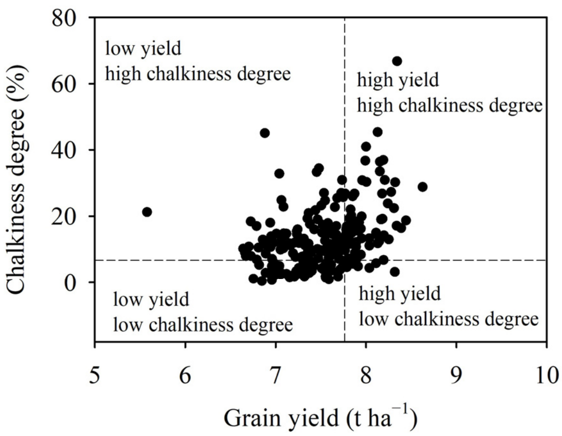

Figure 4. Analysis of the degrees of chalkiness and grain yields in 224 early *indica* rice varieties. Short dashed lines represent 10% of maximum chalkiness degree and 90% of maximum grain yield, respectively.

3.3. Coordination between Yield Components and Grain Quality Traits: Principal Component Analysis

Principal component analysis was performed to evaluate the covariations among yield components and grain quality traits. The first five axes with eigenvalues ≥ 1 were further analyzed (Table 3). The first two major axes (Dim1 and Dim2) are presented in Figure 5. Dim1 explained 25.6% of the total variation, and it was positively correlated with the chalky rice rate, degree of chalkiness, and amylose content (Figure 5, Table 3). In contrast, Dim1 was negatively correlated with length-to-width ratio and gel consistency (Figure 5, Table 3). Therefore, Dim1 tended to differentiate the studied early *indica* rice varieties based on their grain quality. Dim2 explained approximately 17.7% of the total variation and was positively correlated with 1000-grain weight, while it was negatively correlated with spikelet number per panicle and head rice rate (Figure 5, Table 3). Thus, Dim2 indicated the trade-off between yield components and grain quality. Dim3 explained 15.1% of the total variation, which was positively correlated with brown rice rate, milled rice rate, and head rice rate (Table 3). Dim4 and Dim5 explained 9.4% and 8.9%, respectively, of the total variation, which was negatively and positively correlated with panicle number and seed-set rate, respectively (Table 3).

Table 3. Component loadings of grain yield and quality traits in this study.

	Dim1	Dim2	Dim3	Dim4	Dim5
Eigenvalue	3.07	2.13	1.81	1.13	1.06
Total variance explained (%)	25.6	43.3	58.4	67.8	76.7
PN	−0.17	0.19	0.39	**−0.85**	0.11
SN	0.31	**−0.79**	−0.23	0.21	−0.24
SSR	−0.04	0.4	0.06	0.35	**0.8**
TGW	−0.02	**0.75**	−0.15	0.25	−0.31
BRR	0.3	0.21	**0.62**	0.14	−0.12
MRR	0.15	0.04	**0.87**	0.25	−0.18
HRR	0.1	**−0.52**	**0.64**	0.07	0.11
LWR	**−0.76**	0.32	0.07	−0.04	−0.33
CRR	**0.8**	0.32	−0.03	−0.02	0.06
CD	**0.83**	−0.11	−0.13	−0.24	0.16
GC	**−0.71**	−0.12	0.07	0.16	0.2
AC	**0.65**	0.44	−0.03	0.04	−0.17

PN, panicle number; SN, spikelet number per panicle; SSR, seed-set rate; TGW, 1000-grain weight; BRR, brown rice rate; MRR, milled rice rate; HRR, head rice rate; LWR, length-to-width ratio; CRR, chalky rice rate; CD, chalkiness degree; GC, gel consistency; and AC, amylose content. Factor loadings greater than 0.5 in absolute value were bold.

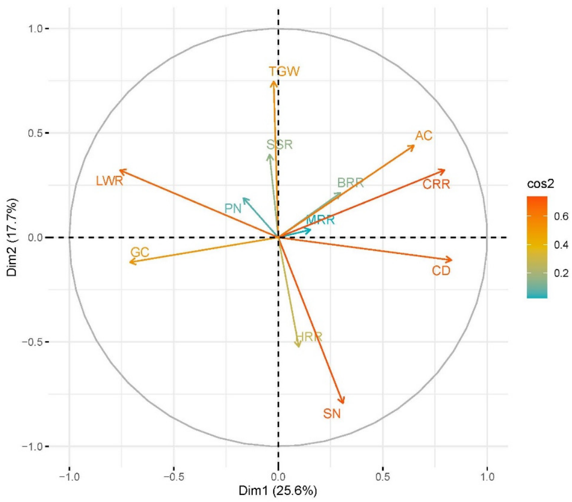

Figure 5. PCA biplot showing major axes of variations in yield and quality traits among 224 early *indica* rice varieties. Eigenvalues and factor loadings for the first four principal components (Dim) are shown in Table 3. The arrows are vectors showing the correlation between a trait and the Dims, and the quality of representation of the variables on the factor map (cos2) is indicated in different colors. A higher cos2 indicates a good representation of the variable on the principal component. BRR, brown rice rate; AC, amylose content; CRR, chalkiness rice rate; CD, chalkiness degree; PN, panicle number; MRR, milled rice rate; HRR, head rice rate; SN, spikelet number per panicle; LWR, length-to-width ratio of rice grain; GC, gel consistency; SSR, seed-set rate; and TGW, 1000-grain weight.

4. Discussion

4.1. Grain Yield, but Not Quality, Was Improved during Early Indica Rice Breeding

The results of this study showed that grain yield continued to increase from 2000 to 2020 (Table 1), while head rice rate, chalky rice rate, and amylose content remained stable. More importantly, the milled rice rate and degree of chalkiness showed adverse changes during early *indica* rice breeding (Table 2). These results indicate that improving grain yield, but not quality, has been prioritized during early *indica* rice breeding in the past few decades. It was also observed that when the yield was below 7.48 t ha^{-1}, the degree of chalkiness remained unchanged during early *indica* rice breeding from 2000 to 2015; however, when the yield reached 7.90 t ha^{-1}, the degree of chalkiness significantly increased (Tables 1 and 2), which may imply that at a certain yield level, the coordination of yield and degree of chalkiness could be achieved, but increasing the yield while maintaining a low degree of chalkiness would be difficult. Furthermore, temperature differences during the study periods and between the sites may have been responsible for the significantly increased amylose content from 2016 to 2020.

The provinces of Hunan and Jiangxi are the main production areas of double-season rice in China. Their planting area was reported as having decreased between 2017 and 2019 [8]. However, the total rice production from 2017 to 2019, although it showed a decreasing trend, was higher than that between 2011 and 2016 [8]. This could be explained, at least partly, by the results of this study, which showed that grain yield per area significantly increased in early *indica* rice from 2000 to 2020. In line with this study, Wang et al. [22] found significant increases in the grain yield of high-quality *indica* rice varieties released from 2000 to 2017 in southern China. The authors suggested that an increased spikelet number per panicle and seed-set rate contributed to the observed improvement in the yield of *indica* hybrid rice [22], which was in line with our results showing that an increased spikelet number per panicle was also observed over the studied years in early *indica* rice (Table 1). Most early *indica* rice is not part of the high-quality rice population, but our main data source was *indica* hybrid rice (Table S1). In this case, we did not observe a consistent change trend in seed-set rate (Table 1), suggesting that the improved grain yield might have been due to several traits of early and high-quality *indica* rice.

In this study, a positive relationship was observed only between grain yield and spikelet number per panicle (Figure 1), which suggested that spikelet number per panicle is the most important factor determining early *indica* rice yield. These results were in line with previous studies that showed larger amounts of spikelet were usually associated with higher grain yields of rice [12,14]. For instance, in one study, the application of allele mining could improve the yield of elite *indica* rice through increased spikelet number per panicle [26]. Therefore, attention should be paid to improving the spikelet number per panicle in early *indica* rice breeding. Meanwhile, we did not observe any correlation between grain yield and 1000-grain weight, which was consistent with previous findings that grain yield was independent of grain weight in *indica* rice [15,22]. These results suggest that, during *indica* rice breeding, the contribution of grain weight to yield improvement may be negligible.

In this study, we found that the grain quality of early *indica* rice did not change from 2000 to 2020. However, milled rice rate and the degree of chalkiness showed adverse changes in the more recent years (Table 1). On the contrary, Feng et al. [11] and Zeng et al. [13] found that grain quality traits including the degree of chalkiness, amylose content, and gel consistency were improved during *indica* hybrid rice breeding. These inconsistent findings indicate that, to date, only the grain quality of mid- and/or late-season *indica* rice has been improved during rice breeding, as evidenced by Zhang et al. [14]. These results could be expected because most high-quality rice varieties are cultivated mid- and/or late-season [18,19]. Due to the growth period of early-season rice in southern China (from March to July), early rice is highly susceptible to high temperatures during the grain-filling period and thus has a low grain quality compared with mid- and late-season rice. Similar results were found in Taiwan, showing that the grain quality of early rice was lower than that of late rice due to the higher temperature during the grain-filling period for early rice [27]. Therefore, more research is needed to improve grain quality during early *indica* rice breeding, especially considering the improvements in the economic and living standards of Chinese people, which raise their demand for higher-quality food [28,29].

Interestingly, the amylose content of early *indica* rice (~20%) found in this study (Table 2) was higher than that in high-quality rice (~17%) reported by Zeng et al. [13]. This finding may due to the fact that early *indica* rice is usually used to make rice noodles rather than being consumed in its original rice form [30].

4.2. Can Both High Yield and High Quality Be Achieved through Breeding Early Indica Rice?

In the present study, we found that both the length-to-width ratio and gel consistency were negatively correlated with Dim1, whereas amylose content, chalky rice rate, and degree of chalkiness were positively correlated with Dim1, which indicate that a lower degree of chalkiness is associated with larger length-to-width ratios and increased gel consistency but with lower amylose contents and degrees of chalkiness (Figure 3). Accordingly, it seems that breeding rice varieties with lower degrees of chalkiness is a promising approach to achieving a high grain quality in early *indica* rice. Furthermore, our present results demonstrated that the degree of chalkiness had the largest coefficient of variation among the studied quality traits (Figure 1). This finding indicates that there is still great potential to improve the degree of chalkiness through rice breeding. Consistent with this, we also found that a high grain yield and low degree of chalkiness could be achieved simultaneously through breeding early *indica* rice (Figure 4).

Wang et al. [22] analyzed the relationships between yield components and grain quality traits among different high-quality rice varieties, and they found that grain yield was positively correlated with the chalky rice rate, which was consistent with the results of this study (Figure 2). However, Wang et al. [22], did not investigate relationships among grain quality traits, which are expected to hinder the collaborative improvement of grain quality traits. The results of this study indicate that a network of grain quality traits should be established to achieve the simultaneous improvement of multiple traits.

Wang and Peng [31] suggested that rice yield improvement was associated with increased nitrogen consumption for fertilizers in China from 1961 to 2013. However, although increased nitrogen fertilization may enhance grain yield, grain quality is worsened. Zhu et al. [12] found that grain yield in japonica soft super rice improved with increased nitrogen application before reaching the optimal nitrogen rate. However, while the increased nitrogen supply improved milling quality, it also significantly increased the chalky rice rate, degree of chalkiness, and protein content; moreover, gel consistency significantly decreased at high rates of nitrogen application [12]. Therefore, a trade-off between grain yield and quality might have resulted from the high rate of nitrogen application in current farming systems.

5. Conclusions

The results of this study showed that although grain yield in early *indica* rice increased from 2000 to 2020, grain quality worsened. The improvement of grain yield in early *indica* rice was largely due to the increased spikelet number per panicle. Thus, improving the spikelet number per panicle could offer a promising approach to further enhance early *indica* rice yield. More importantly, we found that among the quality traits of early *indica* rice, the degree of chalkiness showed the greatest potential for improvement. Therefore, we recommend that future research should focus on improving the degree of chalkiness in order to synergistically improve the quality traits of early *indica* rice, including amylose content, chalkiness rice rate, length-to-width ratio, and gel consistency. The results also suggest that both a high yield and low degree of chalkiness may be achieved in early *indica* rice through breeding. Therefore, this study has important implications for future high-yield and high-quality breeding in early *indica* rice.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14020295/s1, Table S1: Grain yield and quality traits in 224 early *indica* rice varieties.

Author Contributions: Conceptualization, X.X. and G.H.; methodology, G.H.; software, G.H.; validation, G.H., L.G. and X.X.; formal analysis, G.H. and X.X.; writing—original draft preparation, G.H. and L.G.; writing—review and editing, Y.Z. (Yanhua Zeng), S.H. and Y.Z. (Yongjun Zeng); visualization, G.H.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Z. (Yongjun Zeng). All authors have read and agreed to the published version of the manuscript.

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