

## Research Paper

# Relationship between grain yield and quality in rice germplasms grown across different growing areas

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Rice grain yield and quality are two major foci of rice breeding. In this study, Chinese regional rice test data provide us the unique opportunity to analyze the relationship between yield and quality in rice, because China has an unusually wide range of rice cultivars. We analyzed the relationships between grain yield, yield components, and grain quality of 300 rice germplasms. *Japonica* was superior in both yield and quality compared with *indica*. A high setting rate improved the head rice ratio. A higher 1000 grain weight was negatively correlated with quality characteristics but had a positive correlation with yield. A high spikelet density (number of grains per centimeter on the panicle) not only benefits the yield but also the head rice ratio and chalkiness traits. According to our results, global rice production can be increased to at least 8500 kg/ha to meet projected demands in 2025 without sacrificing grain quality.

**Key Words:** relationship, yield, quality, rice breeding, different rice-growing areas.

## Introduction

Rice is the world's most important staple food crop and is a primary food source for about half the world's population. With continuing population growth and increasing competition for arable land between food and energy crops, food security is becoming a serious global problem. National and international rice breeding programs are emphasizing the improvement of crop productivity by selecting for grain yield components (Huang *et al.* 2009). Rice yields were greatly enhanced by the development of semi-dwarf cultivars in the 1960s (Peng *et al.* 1999). The exploitation of heterosis in hybrid rice boosted rice yields to even higher levels beginning in the 1970s (Virmani *et al.* 1982, Yuan 1998). The concept of an ideal plant type was subsequently proposed. In recent decades, the improvement of rice productivity by selection for superior yield components and ideal plant architecture has become an important focus of rice breeding research (Khush 1999, Peng *et al.* 2008).

In recent years, more and more scientists and breeders have focused on improving the quality of rice for different purposes and markets (Chen *et al.* 2012). Four main traits have been used to evaluate the quality of rice: milling prop-

erties, appearance, nutritional value, and cooking quality (Yu *et al.* 2008). Both the molecular genetic background and environment significantly affect the quality of rice (Adu-Kwarteng *et al.* 2003, Cameron and Wang 2005, Hakata *et al.* 2012, Kang *et al.* 2006, Li 2014, Li *et al.* 2014, Lyman *et al.* 2013).

However, few studies have been conducted to clarify the relationship between the yield and quality of rice. Moreover, it is difficult to design an experiment that can include a large range of rice cultivars in different cultivation locations. The latter is important since rice is commercially planted in a wide range of latitudes. In this study, Chinese regional rice test data present a unique opportunity to analyze the relationship between yield and quality because China has an unusually wide range of ecological zones and regional differences in grain type preferences. We investigated a wide range of improved *indica* and *japonica* germplasms grown in regions for two years, and we conducted a comparative relationship analysis between yield and quality among these germplasms. Moreover, the improved germplasms that were used in this study also indicated the breeding trends in recent decades.

## Materials and Methods

Over 300 germplasms that have been improved by breeders and scientists in recent decades were used in this study. As

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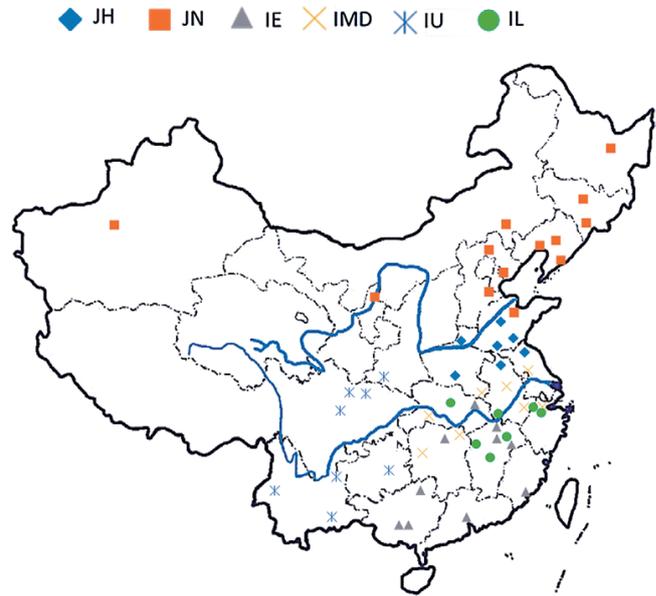
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China has an unusually wide cultivation region, both *indica* and *japonica* are widely cultivated. *Japonica* is mainly distributed in the middle and high latitude areas, while *indica* is usually cultivated in the low latitude areas. The *japonica* group, JN (*japonica* in northern area), is mainly distributed between latitudes 37°N and 45°N, while the JH (*japonica* in the Huanghuai area) group is located between 29°N and 37°N. The *indica* groups IU (*indica* in upstream regions of the Yangzi River) and IMD (*indica* in midstream and downstream regions of the Yangzi River) shared the latitudes between 22°N and 37°N, but IU was distributed in upstream regions of the Yangzi River, while IMD was distributed in downstream regions of the Yangzi River. Because there were two growth seasons in some regions of the low latitude area, we also established the IE (*indica* early) and IL (*indica* late) groups for the early and late growth season germplasm, respectively. The number of research locations and number of test lines for each group are listed in Table 1, and the research locations are shown in Fig. 1. The test lines were evaluated in a randomized complete block design with at least three replications and each block was ~13–14 m<sup>2</sup>. Seeds were sown in a seedling nursery and transplanted into the block. The planting densities and fertilizer protocols were based on local conventional methods.

Rough rice samples for quality evaluation were obtained from the center of each block at the maturing stage. After counting the number of panicles, they were hand threshed and put into water. The filled grains that sank were separated from the floating unfilled grains. The number of grains per panicle, 1000 grain weight, and setting rate were calculated. After drying, the rough rice from each block was dehulled and the percent hulled was determined. Brown rice samples from each block were milled and the yield of head rice was calculated. The grains with chalkiness were counted, and the percentage of chalky grains was calculated as the chalkiness rate (CR). For chalkiness area (CA), 30 grains with chalkiness were randomly selected, and the ratio of the CA to the whole kernel square was evaluated by visual assessment. The spikelet density was calculated as the average number of seeds per centimeter on a panicle. Each data set was collected by three replications over 2 years, and the average value was used in comparative analysis. Correlation analysis and Student's test were performed using Excel 2013 (Microsoft, USA), and Duncan's

**Table 1.** Number of test locations for each group and number of test lines for each test location

Group	Test locations	No. of test lines	
		2011	2012
JH	20	38	38
JN	33	44	48
IE	43	44	47
IU	17	47	48
IMD	15	72	75
IL	35	59	59
Total	163	304	315



**Fig. 1.** The main locations of the Chinese national rice regional tests for the six rice groups.

new multiple range method was used for statistical analysis between groups using DPS 7.05 (Data Processing System) software (China).

## Results

### Varietal differences in grain yield and yield components

The grain yields of the six groups were ranked as follows: JN > JH > IU > IMD > IL > IE, with only a slight difference between the 2 years (Table 2). No significant differences among yield components or quality traits were observed between the two test years (data not show), so the average of the data from the 2 years was used in the following analyses. There was no significant difference in the yields between JN, JH, IU, and IMD, but the yields of these four groups were significantly higher than those of IL and IE. The increase in grain yield in JN and JH mainly resulted from an increase in the number of panicles and a higher setting rate. Although IU and IMD had fewer panicles than the other four groups, an increase in the 1000 grain weight resulted in higher yields from IU and IMD than from IL and IE. The low yields of IL and IE were due to decreases in the number of grains per panicle and 1000 grain weights.

To elucidate which yield components had the most effect on grain yield, a correlation analysis was conducted. We first analyzed the six groups combined, and the effect of each yield component was ranked as follows: number of grains per panicle > setting rate > 1000 grain weight > number of panicles. However, different results were observed within each group. The yields of JH, JN, IMD, and IL were mainly determined by the number of panicles, while the setting rate was the main factor affecting the yields of IU and IE (Table 3).

**Table 2.** Grain yield and its yield components

Group	Grain yield				No. of panicles	No. of grains per panicle	Setting rate	1000 grain weight
	2011	2012	Average	<i>t</i> -statistic				
JH	591.36 b	642.85 a	617.10 a	0.00	19.91 b	148.20 c	85.79 a	26.07 c
JN	615.65 a	638.40 a	627.02 a	0.00	23.89 a	134.41 d	85.18 a	25.09 d
IE	487.91 d	488.47 e	487.86 b	0.26	19.48 bc	129.04 d	83.06 b	26.09 c
IU	593.79 b	586.98 c	590.39 a	2.20	15.00 e	177.11 b	80.86 c	29.22 a
IMD	588.88 b	603.10 b	595.99 a	0.00	16.42 d	181.63 a	80.96 c	27.35 b
IL	500.63 c	523.56 d	512.10 b	0.00	18.95 c	148.99 c	79.22 d	25.85 c

Letter difference means significant at 5% probability levels by Duncan's new multiple range method.

**Table 3.** Relationships between grain yield and yield components

Group	No. of panicles	No. of grains per panicle	Setting rate	1000 grain weigh
JH	0.324*	-0.052	0.184	-0.054
JN	0.340*	0.016	0.289	0.302*
IE	-0.045	0.031	0.292	0.303*
IU	0.057	0.147	-0.329*	0.379*
IMD	0.279*	0.176	0.269*	-0.230
IL	0.646*	-0.236	0.255	0.110
Entirety	0.103	0.349*	0.251*	0.240*

\* Significant at  $p = 0.05$ .

**Table 4.** Varietal differences of main quality traits in the six groups

Group	Brown rice ratio (%)	Head rice ratio (%)	CR (%)	CA
JH	84.38 a	68.55 a	35.30 cd	4.27 d
JN	83.37 b	66.65 a	29.07 d	3.02 e
IE	81.50 cd	49.10 c	58.11 a	10.50 a
IU	81.19 cd	57.02 b	46.50 b	7.70 b
IMD	80.81 cd	58.23 b	36.68 cd	6.22 c
IL	81.83 c	57.81 b	39.05 bc	6.09 c

Letter difference means significant at 5% probability levels by Duncan's new multiple range method.

### Varietal differences in quality traits

There were significant differences in quality traits between the six groups (Table 4). The two *japonica* groups showed an increase in the brown rice and head rice ratios, and a decrease in CA and CR. Between the two *japonica* groups, JH showed slightly greater brown rice and head rice ratios compared with JN, along with higher CR and CA values. Among the four *indica* groups, IE had a low head rice ratio, and IE had the highest CR value. The CR of IL was higher than that of IMD, but the CA of IL was lower than that of IMD, although the difference was not significant.

### The relationship between grain yield and quality

Grain yield and grain quality are two major foci of rice breeding. We first investigated the relationship between grain yield and quality in all of the groups combined (Table 5). The results showed that grain yield had a significant positive correlation with the brown rice and head rice ratios, and a significant negative correlation with CR and CA. We subsequently analyzed the correlations of different yield components with grain quality (Table 5). The number of panicles had a significant positive correlation with the

**Table 5.** Relationships of quality traits with grain yield and its yield components

Group	Traits	Brown rice rate (%)	Head rice rate (%)	CA (%)	CR
JH	Yield	0.085	-0.093	-0.244	-0.242
	No. of grains per panicle	-0.548*	0.455*	0.312	0.179
	No. of panicles	0.545*	-0.508*	-0.447*	-0.283
	1000 grain weight	-0.154	0.381*	0.500*	0.387*
	Setting rate	0.106	0.297	0.039	-0.175
JN	Yield	0.221	0.312*	0.069	0.113
	No. of grains per panicle	-0.244	-0.271	0.353*	0.193
	No. of panicles	0.147	0.141	-0.049	0.076
	1000 grain weight	0.201	0.192	0.041	0.066
	Setting rate	0.627*	0.461*	-0.448*	-0.383*
IE	Yield	0.562*	-0.003	0.264	0.219
	No. of grains per panicle	-0.006	0.020	-0.378*	-0.397*
	No. of panicles	-0.112	0.056	0.190	0.220
	1000 grain weight	0.482*	-0.449*	0.579*	0.564*
	Setting rate	-0.014	0.458*	0.126	0.124
IU	Yield	0.063	-0.287*	-0.026	-0.011
	No. of grains per panicle	0.027	0.084	-0.104	-0.034
	No. of panicles	-0.465*	0.120	-0.288*	-0.311*
	1000 grain weight	0.306*	-0.525*	0.168	0.217
	Setting rate	-0.117	0.313*	0.062	-0.047
IMD	Yield	-0.028	0.242*	-0.114	-0.080
	No. of grains per panicle	0.214	0.367*	-0.345*	-0.280*
	No. of panicles	-0.182	0.145	-0.078	-0.109
	1000 grain weight	0.123	-0.336*	0.219	0.266*
	Setting rate	-0.254*	0.018	0.374*	0.260*
IL	Yield	-0.229	-0.276*	0.159	0.175
	No. of grains per panicle	0.273*	0.449*	-0.015	-0.032
	No. of panicles	-0.248	-0.171	-0.136	-0.164
	1000 grain weight	-0.248	-0.773*	0.438*	0.450*
	Setting rate	-0.152	0.175	0.115	0.124
Entirety	Yield	0.243*	0.408*	-0.203*	-0.267*
	No. of grains per panicle	-0.305*	0.022	-0.039	-0.060
	No. of panicles	0.418*	0.303*	-0.236*	-0.170*
	1000 grain weight	-0.260*	-0.395*	0.313*	0.309*
	Setting rate	0.326*	0.325*	-0.053	-0.084

\* Significant at  $p = 0.05$ .

brown rice and head rice ratios, and a significant negative correlation with CR and CA. The number of grains per panicle had a significant negative correlation with brown rice ratio, and setting rate had a significant positive correlation with the brown rice and head rice ratios. The 1000 grain weight had a significant negative correlation with the brown rice and head rice ratios, and there was a significant positive correlation between CR and CA.

To clarify the differences within each group, subsequent group analyses were conducted (Table 5). The yield had a significant positive correlation with the head rice ratio in the

**Table 6.** Relationships of aspect ratio with grain yield and quality

	Aspect ratio	Grain yield	No. of panicles	No. of grains per panicle	Setting rate	1000 grain weight	Brown rice ratio (%)	Head rice ratio (%)	CA (%)	CR
JH	1.85 c	0.057	-0.344*	0.448	-0.042	-0.110	-0.566*	0.162	-0.214	-0.104
JN	1.93 c	0.046	-0.100	0.206	-0.091	0.165	-0.286	-0.050	-0.239	-0.068
IE	2.90 ab	-0.344*	-0.007	0.089	-0.239	-0.230	-0.220	0.119	-0.651*	-0.664*
IU	2.75 b	0.212	0.183	0.034	-0.443*	0.204	0.092	-0.285	-0.282	-0.436*
IMD	3.16 a	0.037	0.184	0.108	-0.357*	-0.144	-0.042	-0.024	-0.701*	-0.745*
IL	3.08 a	0.338*	0.400*	-0.239	-0.200	0.251	-0.064	-0.405*	-0.189	-0.152
Entirety	2.64	0.476*	0.386*	0.172*	-0.438*	0.200*	-0.650*	-0.592*	0.044	0.142*

Letter difference means significant at 5% probability levels by Duncan’s new multiple range method.

\* Significant at p = 0.05.

JN and IMD groups, and a significant positive correlation with the brown rice ratio in IE. The coefficient between the yield and chalkiness was not significant in any group. The number of grains per panicle had a positive correlation with the head rice ratio in all of the groups except in JN. The number of grains per panicle had a negative correlation with the brown rice ratio in both *japonica* groups and in the IE group, but the correlation was positive in the other *indica* groups. The number of grains had a positive correlation with CA and CR in both *japonica* groups, but the correlation was negative in all four *indica* groups. The number of panicles significantly affects the milling and appearance qualities in JH and IU, but only slightly affects the milling and appearance qualities in the other groups. The 1000 grain weight had a positive correlation with the head rice ratio in both two *japonica* groups, but the correlation was negative in all four *indica* groups. The setting rate had a positive correlation with the brown rice ratio in the JN and JH groups, but the correlation was negative in all four *indica* groups. The setting rate also had a positive correlation with the head rice ratio in all six groups.

**The relationships of grain aspect ratio (shape) with yield and quality**

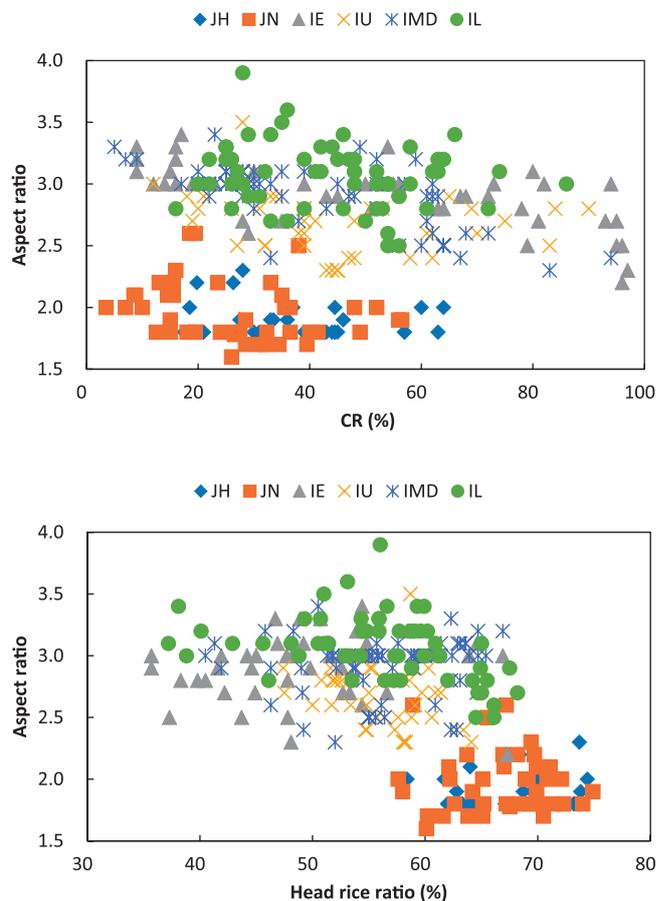
The grain aspect ratios of the four *indica* groups were significantly higher than those of the two *japonica* groups (Table 6). No difference was observed between the two *japonica* groups, and the grain aspect ratios of the four *indica* groups also showed little change. In all of the groups combined, the grain aspect ratio had a significant negative correlation with the yield, number of panicles, and setting rate, and a significant positive correlation with the number of grains per panicle and the 1000 grain weight. The aspect ratio also affects quality traits, showing significant negative correlations with the brown rice and head rice ratios.

Within-group analyses revealed that the grain aspect ratio had a significant negative correlation with yield in IE, but a significant positive correlation with yield in IL. The grain aspect ratio had a significant negative correlation with the number of panicles in JH, but a significant positive correlation with the number of panicles in IL. The grain aspect ratio barely affected the setting rates and 1000 grain weights in all of the groups (Table 6).

The aspect ratio had a significant correlation with CR in each group, but the correlation was not significant when the groups were combined. However, the aspect ratio had a significant correlation with the milling quality when the groups were combined, but it was not significant in the individual groups (Fig. 2).

**The relationships of spikelet density with yield and quality**

JH showed a significantly higher spikelet density compared with JN, and both JN and JH had a significantly higher



**Fig. 2.** The relationships between the aspect ratios and chalkiness rates (CRs) (A), and the relationships between the aspect ratios and head rice ratios (B) for the six rice groups.

spikelet density than the four *indica* groups (Table 7). Although the spikelet density had a significant positive correlation with yield when the groups were combined, diversity was observed inside each group and the correlation coefficient was not significant in any group. The spikelet density had a negative correlation with setting rate and a positive correlation with the number of grains per panicle in all of the groups. When all of the groups were combined, the spikelet density had a significant positive correlation with the brown rice and head rice ratios. The within-group analyses revealed that the spikelet density of JN had a significant negative correlation with the brown rice and head rice ratios. Contrary to JN, a significant positive correlation of spikelet density with the brown rice and head rice ratios was found in the IE group. The spikelet densities in all of the *indica* groups showed negative correlations with CR and CA, but the reverse results were obtained in both *japonica* groups.

## Discussion

### The relationship between yield and quality

While soybean and maize quality is directly related to fat and protein, the grain quality of rice is mainly determined by the starch type and contents (Williams *et al.* 1958), suggesting that it is easier to mediate the relationship between grain yield and grain quality in rice than in soybean and maize. Among the yield components, the 1000 grain weight had a positive correlation with the appearance quality in all of the rice groups and a negative correlation with the head rice ratio in the four *indica* groups. Because the head rice ratio is an important factor in the market price, which values complete grains more highly than broken grains, a greater 1000 grain weight was not an ideal selective indicator for both yield and quality, especially for *indica*. Consequently, the 1000 grain weight may be a main factor behind the difficulty in balancing grain yield and quality. However, the number of grains per panicle had a positive correlation to the head rice ratio and a negative correlation to CA and CR in all of the rice groups, which indicates that enhancing the number of grains per panicle is a feasible strategy for improving rice yield and quality in both *indica* and *japonica*. No significant correlation was found between yield and the

appearance qualities in any of the six groups, indicating that there was no serious conflict between increasing the grain yield and maintaining the grain appearance quality. A negative correlation between yield and milling quality was only observed in the IL and IU groups. In this study, the average yield of the Chinese regional rice tests reached 8576 kg/ha, and the increase in the yield did not negatively affect the milling or appearance qualities. Global rice production must reach 8500 kg/ha by 2025 to meet the projected demand (Peng *et al.* 1999), and, according to our results, the grain yield can reach this goal without sacrificing grain quality.

### The differences in quality traits between *indica* and *japonica*

According to a 2004 study (Zhu *et al.* 2004), the brown rice ratios of *japonica* and *indica* in China were 83.6% and 80.5%, respectively, while the head rice ratios of *japonica* and *indica* were 67.8% and 49.4%, respectively. Additionally, the CRs of *japonica* and *indica* were 38.0% and 50.3%, respectively. In this study, the brown rice ratio of *japonica* (83.88%) was 2.55% higher than that of *indica* (81.33%), and the head rice ratio of *japonica* (67.60%) was 12.06% higher than that of *indica* (55.54%). The CR of *japonica* (32.04%) was 13.5% lower than that of *indica* (45.09%). Although the milling and appearance qualities of *indica* have been dramatically improved by recent breeding projects, the gap between *indica* and *japonica* was still obvious.

This study was conducted throughout the rice cultivation regions of China, and thus, the results may be affected by genetics and various ecological conditions. There were obvious differences in the milling and appearance qualities in inter-subspecies, but the differences in intra-subspecies were subtle. A previous study demonstrated that large differences are observed between *japonica* and *indica* in the midstream and downstream regions of the Yangtze River (Zhang *et al.* 2013). Thus, we concluded that the gaps in the milling and appearance qualities between *japonica* and *indica* were mainly from differences in the subspecies' genetic backgrounds.

### The relationships of spikelet density with yield and quality

Plant architecture is an important agronomic trait that affects both grain yield and quality. Culm- and leaf-related

**Table 7.** Relationships of spikelet density with grain yield and quality

	Spikelet density	Grain yield	No. of panicles	No. of grains per panicle	Setting rate	1000 grain weight	Brown rice ratio (%)	Head rice ratio (%)	CA (%)	CR
JH	8.65 a	0.089	-0.438*	0.517*	-0.023	0.045	-0.004	0.312	0.140	0.152
JN	7.45 b	-0.015	-0.596*	0.887*	-0.226	-0.244	-0.268	-0.324*	0.245	0.349*
IE	6.20 e	0.167	-0.630*	0.768*	-0.117	-0.334*	-0.109	0.293	-0.381*	-0.383*
IU	7.08 c	0.107	-0.035	0.854*	-0.253	-0.666*	-0.107	0.233	-0.124	-0.158
IMD	7.27 bc	0.107	-0.220	0.834*	-0.356*	-0.347*	0.105	0.204	-0.234*	-0.307*
IL	6.58 d	-0.241	-0.479*	0.897*	-0.128	-0.615*	0.379*	0.590*	-0.147	-0.147
Entirety	7.11	0.435*	-0.238*	0.562*	0.006	-0.170*	0.311*	0.443*	-0.187*	-0.261*

Letter difference means significant at 5% probability levels by Duncan's new multiple range method.

\* Significant at p = 0.05.

traits have been extensively researched, and panicle-related traits have become a recent research focus. High spikelet density, which is directly related to the number of grains per panicle, was considered to be a high yield characteristic. Since the first north *japonica* erect panicle variety, LiaoJing 5, was released in the early 1980s, grain yield has significantly improved because the erect panicle enhanced the spikelet density. However, the poor setting rate and grain quality of LiaoJing 5 limited the further extension of the erect panicle variety. At present, the milling and appearance qualities of erect panicle varieties have been dramatically improved, and are even better than those of the curved panicle varieties (Xu *et al.* 2013). In this study, spikelet density had a significant positive correlation with grain yield in the combined rice groups; however, the correlation coefficient was not significant within any of the individual groups. The correlation coefficient between spikelet density and setting rate was not significant, except in JMD. These results suggest that the negative impact of high spikelet density on setting rate was successfully reduced in the improved germplasms. Moreover, the advantages of a high spikelet density variety in the number of grains per panicle, brown rice ratio, head rice ratio, and chalkiness traits have partly eliminated the disadvantages in the number of panicles and 1000 grain weight. Thus, we believe that a breeding strategy that enhances spikelet density is favorable, and having an erect panicle is an effective way to enhance the spikelet density.

### The relationships of grain aspect ratio with yield and quality

The grain aspect ratio is a main difference between *japonica* and *indica*, and a high aspect ratio is positively correlated with appearance quality but negatively correlated with milling quality (Luo *et al.* 2004, Zhu *et al.* 2004). In this study, the aspect ratio had a significant negative correlation with the brown rice and head rice ratios, and correlations with CR and CA were not apparent when the groups were combined. However, within each group, the aspect ratio showed a significant or near-significant negative correlation with CR and CA, and the correlation coefficient was higher in *indica* than in *japonica*.

These results, which are shown in Fig. 2, indicate that the relationships between the aspect ratio and chalkiness-related traits were mainly controlled by genetic factors, and the relationship between the aspect ratio and milling quality was controlled by both genetic factors and environmental conditions. With the development of molecular genetic technologies, several grain shape-related genes have been identified, such as *GS3*, *qSW5*, and *GW2* (Fan *et al.* 2006, Shomura *et al.* 2008, Song *et al.* 2007). It would be interesting to investigate the effects of these genes under different ecological conditions. Moreover, using these genes to modulate the aspect ratio of *indica* and *japonica* may help breeders and scientists improve rice appearance and milling qualities.

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