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Variations of Rice Yield and Quality in Response to Different Establishment Methods at Farmers' Field

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Abstract: Mechanized production plays an important role in fulfilling food security demands during the period of labor shortage. Despite its benefits, the mechanical transplanted method (MET) has not been widely adopted due to a lack of awareness. Thus, this study aimed to evaluate the effect of the MET, the manual transplanted method (MAT), and the directed seeded method (DS) on rice yield and quality in farmers' fields. A two-years field experiment (2016 and 2017) and a one-year survey (2020) were conducted to compare rice yield and quality among the MAT, MET, and DS methods. MET exhibited a higher-yielding population, increased biomass production, enhanced yield, and improved grain quality, compared with MAT. Moreover, japonica rice in MET (MET-JR) produced the maximum yield, 0.6 t hm^{-2} to 3.1 t hm^{-2} higher than in other treatments. However, japonica rice showed a poorer appearance quality than indica rice, as well as large panicle size (grains number per panicle $\geq$ 190); hybrid indica rice (HIR) also presented a high yield with poor appearance quality. These results confirmed that the application of MET could be useful in attaining high panicles per m^2, high biomass production, high rice yield, and considerably improved rice quality in farmers' fields under labor shortage circumstances. Furthermore, it is also imperative to consider balancing the yield and quality of japonica rice and large panicle HIR and employing MET at a broader scale in China, as well as other developing countries having rice–based cropping systems.

Keywords: rice yield; grain quality; cultivars; establishment methods

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1. Introduction

Rice (*Oryza sativa* L.) is a staple food that fulfills the dietary and nutritional needs of about half of the world's population [1], and plays a central role in food security and economic growth in China. It was predicted that 41 million t (Mt) more rice needs to be produced in China by the end of 2030 [2]. In addition, people have higher and higher requirements for grain quality with increasing living standards [3,4]. However, future increases in rice production must come from greater yields, rather than expanding croplands, because of limited cropland resources [5]. Additionally, a huge challenge also occurs with reagrds to rice production, due to the labor shortage, and increasing wages for agricultural production in recent years [6]. Obviously, these changes present a great challenge for food security. The manual transplanted method (MAT) is the traditional establishment method in China. However, this method requires a large amount of labor (about 400 man-hours ha^{-1}) and the operation is very laborious, involving working in a stooping posture and moving through a muddy field [7]. In recent years, the transfer of labor forced into the non-agricultural sector had led to a shortage of farmers and reduced the potential labor supply of farmers for agricultural production. Under the condition that the rural labor market was not perfect, and agricultural production employees were difficult to supervise, the shortage of farmers reduced the growth rate of agricultural output and had a certain negative impact on agricultural production. As a result, the mechanical transplanted method (MET) and the directed seeded method (DS) were developed in China [8].

Numerous studies have stated that MET and DS displayed better performance with high yield, profit, and labor productivity [9–12]. Compared with conventional artificial planting, a key feature of rice machine transplanting is maintaining higher planting density, which is also the premise of ensuring a sufficient number of seedlings and a low leak-stump rate in the field after transplanting. This technology has higher requirements for field, climate, seedling quality, machinery, and operation quality. In addition, other operations can be carried out simultaneously in the process of machine insertion, such as fertilization, comprehensive shallow tillage, etc., which saves time and labor. Folding and unmanned rice transplanters have also been developed to meet the particular requirements of different rice-producing regions. In direct seeding rice cultivation, seeds are directly planted in the field without separately raising seedlings and then transplanting; it significantly shortens the growth cycle and solves the problems of labor shortage, high-cost wages for transplanting, and the waste of water resources. However, weed infestation is a severe issue in direct seeding rice cultivation, and their complete elimination from the rice fields is a tough ask, which in turn declines rice productivity. In spite of numerous studies suggested that MET was of benefit for attaining high biomass and yield, the planting area of MET and DS showed a slow growth rate in China [2], and in other developing countries with rice–based cropping systems [12]. It is important to know that MET and DS have not been widely tested and verified in farmers' fields, which causes a lack of awareness about their advantages [12,13], especially the significant augmentations in the yield.

Furthermore, since rapid progress has been made in rice breeding, more and more cultivars with high yield potential were bred and spread [14]. It has been evaluated that cultivars renewal contributed to rice grain yield change by 19.3–27.2% in the past three decades [15]. Moreover, breeding high-quality rice cultivars has become a trend in recent decades [3,16]. Statistical data displayed that a total of 10,628 rice cultivars were approved from 1977 to 2018 in China. Since 2005, the number of approved cultivars has exceeded 400 each year. It contains hybrid *indica*, inbred *indica*, hybrid *japonica*, and inbred *japonica* rice cultivars [17]. Besides, it was reported that there was a significant increase in grain number per panicle of approved cultivars [18]. These indicated that more and more cultivars (different subspecies and panicle size) could be introduced yearly for planting at farmers' fields in major rice-producing regions. However, the interaction between cultivars and establishment methods has rarely been tested in farmers' fields.

In addition, the phenomenon of labor shortage caused by the large transfer of the agricultural population was becoming more and more serious in practice. However, previous studies were carried out under the condition of sufficient labor, which hardly represents the facts in the current situation, namely, labor shortage. Therefore, it is necessary to study the effect of the establishment methods on rice yield in farmers' fields. The middle and lower reaches of the Yangtze river are known as China's largest rice production region, practicing MET, DS, and MAT cultivation methods. Moreover, MET and DS has progressed considerably in this region [19]. It showcases natural and reliable samples to evaluate: 1. the impacts of the establishment methods on rice yield and grain quality at the farmers' field; and 2. the interaction between the establishment methods and cultivars on rice yield and grain quality.

2. Materials and Methods

2.1. Field Experiments Design

Two years of field experiments were conducted in 2016 and 2017. The yield differences in MET and MAT were examined in detail by investigations at Zaoyang (2016) and Hefei (2017). Zaoyang (32.0° N, 112.8° E) and Hefei (31.0° N, 117.3° E) are located at the middle and lower reaches of the Yangtze River. It is a typical transitional region between a warm temperate zone and a subtropical zone. Twelve farmers' fields were selected, and the same cultivars were sown under MET and MAT. Six regional commercial rice cultivars were employed, namely Yongyou 4949 (YY4949), Yongyou 4149 (YY4149), Yongyou 1540 (YY1540), C liangyouhuazhan (CLYHZ), Huiliangyou858 (HLY858) and Hui liangyou898 (HLY898). Air temperature, sunshine-shine hours, and precipitations are shown in Figure 1. The main growth periods were showed in Table 1. The properties of soil in Zaoyang and Hefei determined from the upper 20 cm layer were: pH = 6.4 and 6.1, organic matter = 34.3 and 25.6 g kg^{-1}, total N = 1.58 and 1.12 g kg^{-1}, available P = 8.8 and 11.2 mg kg^{-1} and available K = 56.6 and 50.9 mg kg^{-1}. The carpet seedlings machine was used in MET, and upland rice seedling was used in MAT. The 20 d seedlings were transplanted with a space of 30 cm × 13 cm. All experiments were performed according to the recommended farmer's practice. The N, P, and K fertilizers were applied at the rate of 225 kg hm^{-2}, 90 kg km^{-2} and 180 kg hm^{-2}. After the five-leaf stage, the water level was allowed to fluctuate between 5 and 10 cm during the whole rice-growing season. Insects, diseases, and weeds were controlled by spraying pesticides to avoid loss of biomass and grain yield. At maturity, 0.5 m^2 plants were sampled to determine yield components and total aboveground biomass according to the methods of Liu et al. [11]. Grain yield was determined from a 5 m^2 area in each plot and adjusted to the standard moisture content of 0.14 g H_2O g^{-1} fresh weight.

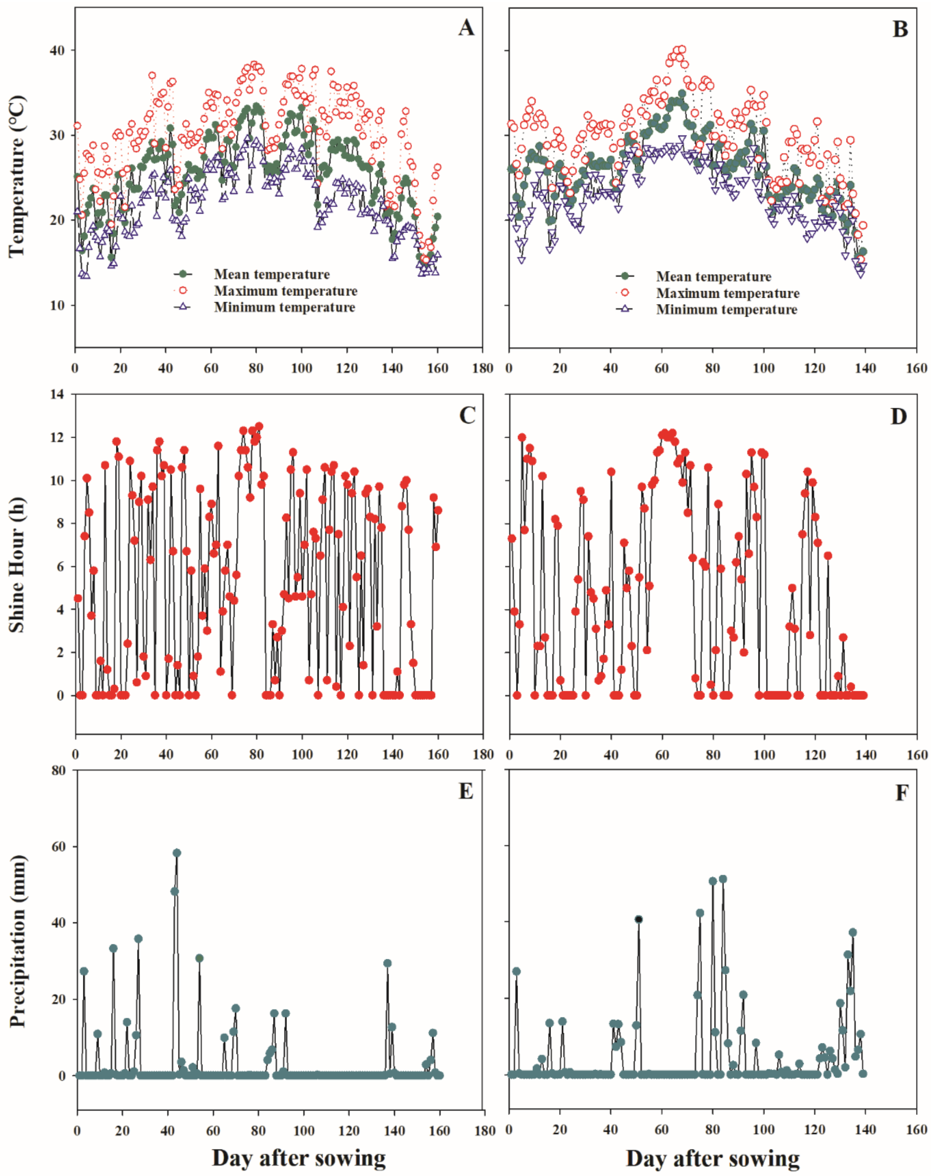

Figure 1. Air temperature, sunshine hours, and precipitation during the rice growing season in 2016 (**A**,**C**,**E**) and 2017 (**B**,**D**,**F**).

Table 1. The rice growth period in 2016 and 2017.

Years	Variety	Treatment	Sowing Date	Heading Date	Harvest Date
2016	YY4949	MET	12 May	15 August	6 October
		MAT	12 May	13 August	5 October
	YY4149	MET	12 May	18 August	9 October
		MAT	12 May	14 August	7 October
	YY1540	MET	12 May	5 September	17 October
		MAT	12 May	4 September	17 October
	CLYHZ	MET	12 May	20 August	2 October
		MAT	12 May	18 August	2 October
2017	HLY858	MET	21 May	17 August	29 September
		MAT	21 May	17 August	29 September
		DS	21 May	12 August	21 September
	HLY898	MET	21 May	16 August	27 September
		MAT	21 May	15 August	27 September
		DS	21 May	9 August	18 September

Data were pooled from examinations conducted in Zaoyang (2016) and Hefei (2017). MET and MAT represent mechanical transplanted method and manual transplanted method, respectively. YY4949, YY4149, YY1540, ClYHZ, HLY858, and HLY898 represented Yongyou 4949 (YY4949), Yongyou 4149, Yongyou 1540, C liangyouhuazhan, Hui liangyou 858 and Hui liangyou 898, respectively.

2.2. Survey Study Design

In 2020, a survey study was conducted to investigate and compare the yield and quality under MET, MAT, and DS. The examinations were conducted at farmers' fields in the middle and lower reaches of the Yangtze River, including 11 areas from 29.4° N to 34.6° N and 114.9° E to 119.6° E (Table 2). These areas were typical transitional regions between warm temperate and subtropical zones. In this zone, the mean temperature, mean maximum temperature, and mean minimum temperature of rice growth season ranged from 22.5 °C to 24.5 °C, 27.0 °C to 30.0 °C, and 18.5 °C to 20.5 °C, respectively. The average rainfall in the rice growing season is more than 750 mm. Moreover, according to the report by Deng et al. [20] (2015), the mean temperature in this region ranged from 22.4 °C to 29.1 °C in the vegetative stage, from 26.2 °C to 31.8 °C in the reproductive stage, and from 21.6 °C to 30.6 °C in grain filling stage in this zone. In addition, fertility quality is generally at a good level. The properties of soil in this region were: pH 5.0~6.5, organic matter 13.3 g kg^{-1}~35.8 g kg^{-1}, total N 0.8 g kg^{-1}~2.2 g kg^{-1}, available Olsen-P 4.5 mg kg^{-1}~35.0 mg kg^{-1}, and exchangeable K 47.5 mg kg^{-1}~165.0 mg kg^{-1} [21]. The middle rice system is the primary cropping system in this region. In this system, the preceding dryland crops are harvested by the end of May or the land is left fallow until then; rice plants are transplanted or direct-seeded in June and harvested in October [22].

Table 2. The distribution of sampled paddy plots in the present study.

Region	Number of MAT	Number of MET	Number of DS	Total Number of Sampled Paddy Plot
Anqing	6	5	21	32
Chizhou	2	7	14	23
Chuzhou	2	16	10	28
Fuyang	4	7	2	13
Hefei	10	17	6	33
Huainan	7	17	5	29
Huangshan	3	6	3	12
Lu'an	4	14	9	27
Maanshan	2	18	6	26
Wuhu	6	7	9	22
Xuanchen	4	7	17	28

Two hundred eighty-three paddy plots were randomly selected for data collection in 11 rice-planted regions. The number of sampled paddy plots in each region depends on the size of the rice planting area in the region (Table 2). The establishment methods, cultivars, sowing dates, and harvesting dates of each paddy plot were recorded. The sampled paddy plots contained 102 DS plots, 121 MET plots, 50 MAT plots and 10 seeding-broadcasted plots. The DS, MET, and MAT are this region's three main establishment methods. Thus, the results of seeding-broadcasted plots were no longer stated in the following part. Moreover, the samples covered 130 cultivars, including hybrid *indica* rice (HIR), inbred *indica* rice (IIR), hybrid *japonica* rice (HJR), and inbred *japonica* rice (IJR).

2.3. Determination of Rice Yield and Quality

At the maturity stage, plants from an area of 5 m^2 in the center of the plot were harvested, and subsequently, the grain yield was adjusted to 14.0% moisture content in 2016 and 2017. For 2020, plants from an area of 666.67 m^2 in the field plot were harvested, and the grain yield was calculated after adjusting to the standard moisture content of 14% fresh weight. In three years, mature rice was threshed after harvest, air-dried, and stored at room temperature for three months until testing rice quality. A rubber roller sheller (BLH-3250, Zhejiang Bethlehem Aparatus Co., Ltd., Zhejiang China) was used to shell, and the brown rice rate was measured. The brown rice was milled with a rice polishing machine (Kett, Tokyo, Japan), and the head rice rate was measured. In addition, the appearance quality of the milled rice was determined using a rice-grain appearance analysis system MRS-9600TFU2L (Wseen, Zhejiang, China).

2.4. Statistical Analysis

The differences among the treatments were calculated and statistically analyzed using the variance and the least-significant-difference multiple-range test (LSD, $p < 0.05$). The statistical package for SigmaPlot 14.0 and SPSS 21 was used for the statistical analysis. In order to identify the response of rice yield to establishment methods change, the differences in properties among cultivars were minimized by using the average and standardized management [1,20]. The standardized data were defined as "relative data" and calculated as follows: relative grain yield = the grain yield of a given cultivar on one establishment method/average grain yield of this cultivar on two establishment methods (MET and MAT). The other relative parameters were calculated according to the calculation formula of relative grain yield described above, such as relative panicles and relative total dry weight.

3. Results

3.1. Differences in Rice Grain Yields among Different Establishment Methods

In the survey study, there were significant differences in rice grain yield across different establishment methods and cultivars of rice (Figure 2A). Among different establishment methods, the mean grain yield of MET was 0.3 t hm^{-2} higher than that of DS, and 0.6 t hm^{-2} greater than that of MAT. Similarly, the results also demonstrated that the rice yield of MET was significantly higher than that of MAT in field experiments (Figure 3A). The result showed that there was an interaction between them on yield, yield components, and total dry weight (Table 3). In addition, there were significant differences in yield components (panicles per m^2, spikelets per panicle and total dry weight) between MET and MAT. Rice yields positively correlated with panicles per m^2 and total dry weight (Figure 3B,C).

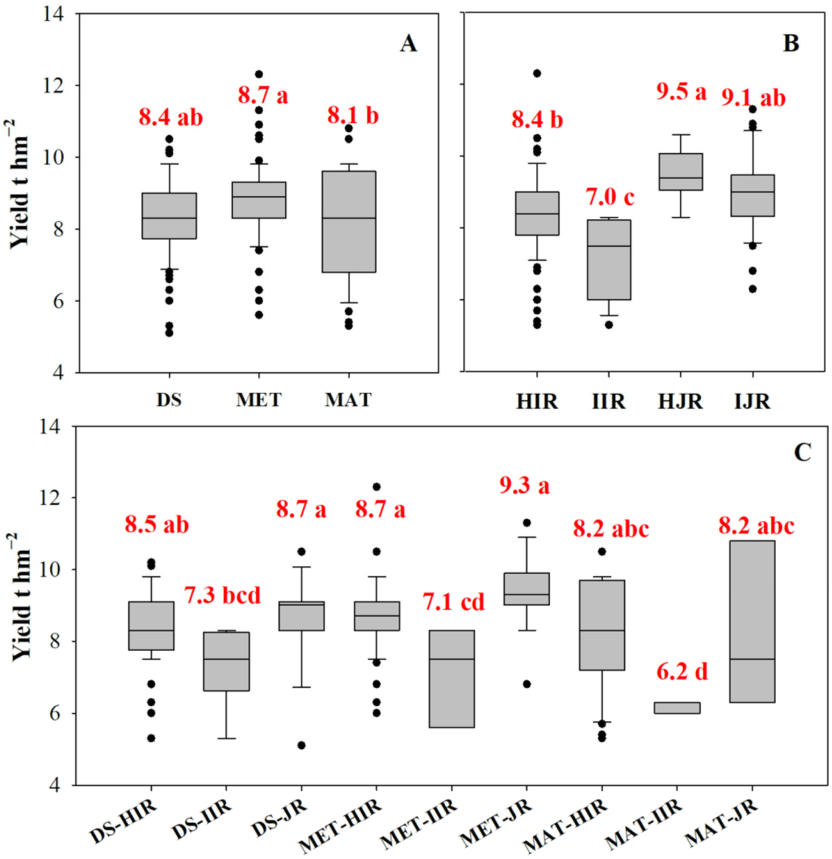

Figure 2. Differences in rice grain yield across different establishment methods (**A**), different types of rice (**B**), and their interactions (**C**). DS, MET, and MAT represent directed seeded method, mechanical transplanted method, and manual transplanted method, respectively. HIR, IIR, HJR, and IJR represent hybrid *indica* rice, inbred *indica* rice, hybrid *japonica* rice, and inbred *japonica* rice, respectively. JR represents *japonica* rice (including hybrid *japonica* rice and inbred *japonica* rice). The red data is the average grain yield of each series. The same letter are not significantly different at p = 0.05. Data were pooled from examinations conducted in 2020.

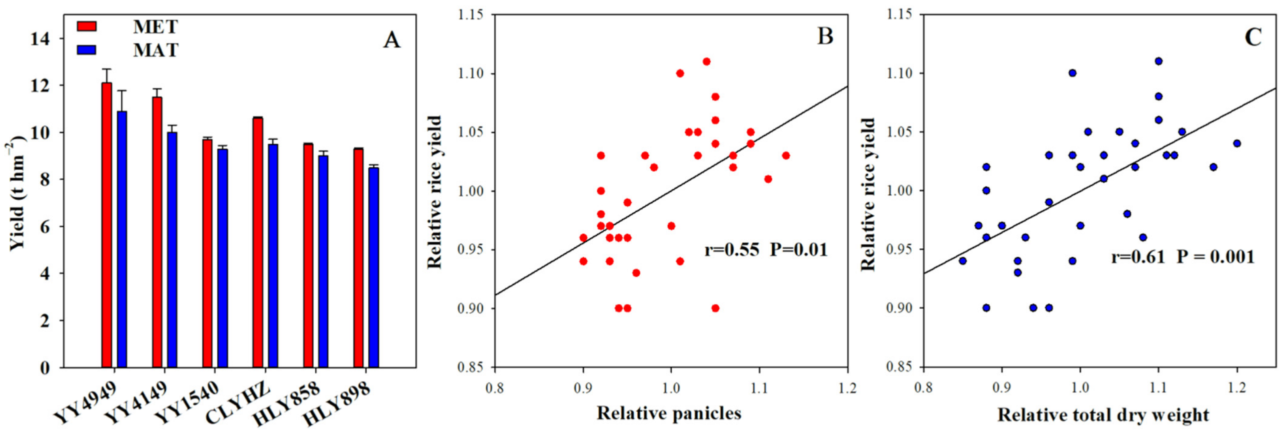

Figure 3. The rice yield in different establishment methods (**A**), and the relationship of relative rice yield with relative panicles (**B**) and relative total dry weight (aboveground biomass) (**C**) at maturity. Data were pooled from examinations conducted in Zaoyang (2016) and Hefei (2017). MET and MAT represent mechanical transplanted method and manual transplanted method, respectively. YY4949, YY4149, YY1540, ClYHZ, HLY858, and HLY898 represented Yongyou 4949 (YY4949), Yongyou 4149, Yongyou 1540, C liangyouhuazhan, Hui liangyou 858 and Hui liangyou 898, respectively.

Table 3. Analysis of variance (ANOVA) for yield and yield-related traits.

Treatment	Panicles per m^{-2}	Spikelets per Panicle	Percentage of Filled Grains	1000-Grain Weight	Grain Yield	Total Dry Weight
Variety (V)	**	**	ns	**	**	**
Establishment method (E)	**	ns	ns	ns	**	**
E × V	ns	ns	ns	ns	ns	ns

Data were pooled from examinations conducted in Zaoyang (2016) and Hefei (2017). MET, and MAT represent mechanical transplanted method and manual transplanted method, respectively. Here, ns represents not significantly different at p = 0.05. ** represent significant difference b at level of $p < 0.01$.

3.2. Differences of Grain Yields among Different Rice Types

In the survey study, the significant yield gaps among different rice types reached 0.4 t hm^{-2}–2.5 t hm^{-2}. *Japonica* rice (JR, including HJR and IJR) had the highest grain yield, followed by HIR and IIR (Figure 2B,C). Regardless of establishment methods, MET-JR obtained the highest grain yield, and there were 0.6 t hm^{-2}, 0.6 t hm^{-2}, 0.8 t hm^{-2}, 1.1 t hm^{-2}, 1.1 t hm^{-2}, 2.0 t hm^{-2}, 2.2 t hm^{-2}, and 3.1 t hm^{-2} higher than MET-HIR, DS-JR, DS-HIR, MAT-JR, MAT-HIR, DS-IIR, MET-IIR, and MAT-IIR. There were also some differences in grain yields among different panicle size cultivars (Table 4). In DS, the cultivars with large panicle size (grains number per panicle ≥ 190) obtained high grain yields, and the grain yields also had low variation. Similarly, compared with the medium panicle-size cultivars, the large panicle sizes cultivars showed comparable yield performance and lower yield variation in MET, which were better than that those of DS and MAT. While cultivars with medium panicle size (155 < grains number per panicle < 190) reached high grain yield and showed low yield variation under MAT. Similarly, there were also significant differences in grain yields among cultivars in field experiments (Table 3 and Figure 3A).

Table 4. Variations of rice grain yield for hybrid indica rice (HIR) with different panicle sizes (grain number per panicle) in different establishment methods. DS, MET, and MAT represent directed seeded method, mechanical transplanted method, and manual transplanted method, respectively.

Rice Establishment Methods	Panicle Size (Grains $Panicle^{-1}$)	Rice Yield (t hm^{-2})			Cv (%)
		Maximum	Minimum	Mean	
DS	≥190	10.2	7.5	8.6	9.4
	155–190	9.8	6.0	8.3	10.6
	≤155	10.1	5.3	8.4	17.2
MET	≥190	10.5	6.3	8.7	9.2
	155–190	12.3	6.0	8.9	14.3
	≤155	9.8	5.6	8.5	10.7
MAT	≥190	9.8	5.3	8.1	20.0
	155–190	10.5	6.8	8.7	12.3
	≤155	9.8	5.7	7.7	19.5

Data were pooled from examinations conducted in 2020.

3.3. Difference in Grain Quality among Different Establishment Methods and Rice Types

In the survey study, a higher head rice rate was observed in MET than in other establishment methods, but there were no significant differences. The grain chalkiness (chalky grain rate and chalkiness level) of DS was significantly higher than those of MET and MAT. At the same time, there were no significant differences between MET and MAT (Figure 4A–C). The grain appearance also showed varietal variations. The IJR had the highest head rice rate (66.7%), followed by HJR (66.0%), HIR (59.7%), and IIR (51.7%). For chalkiness (chalky grain rate and chalkiness level), *indica* rice (IR, including IIR and HIR) performed better than JR.

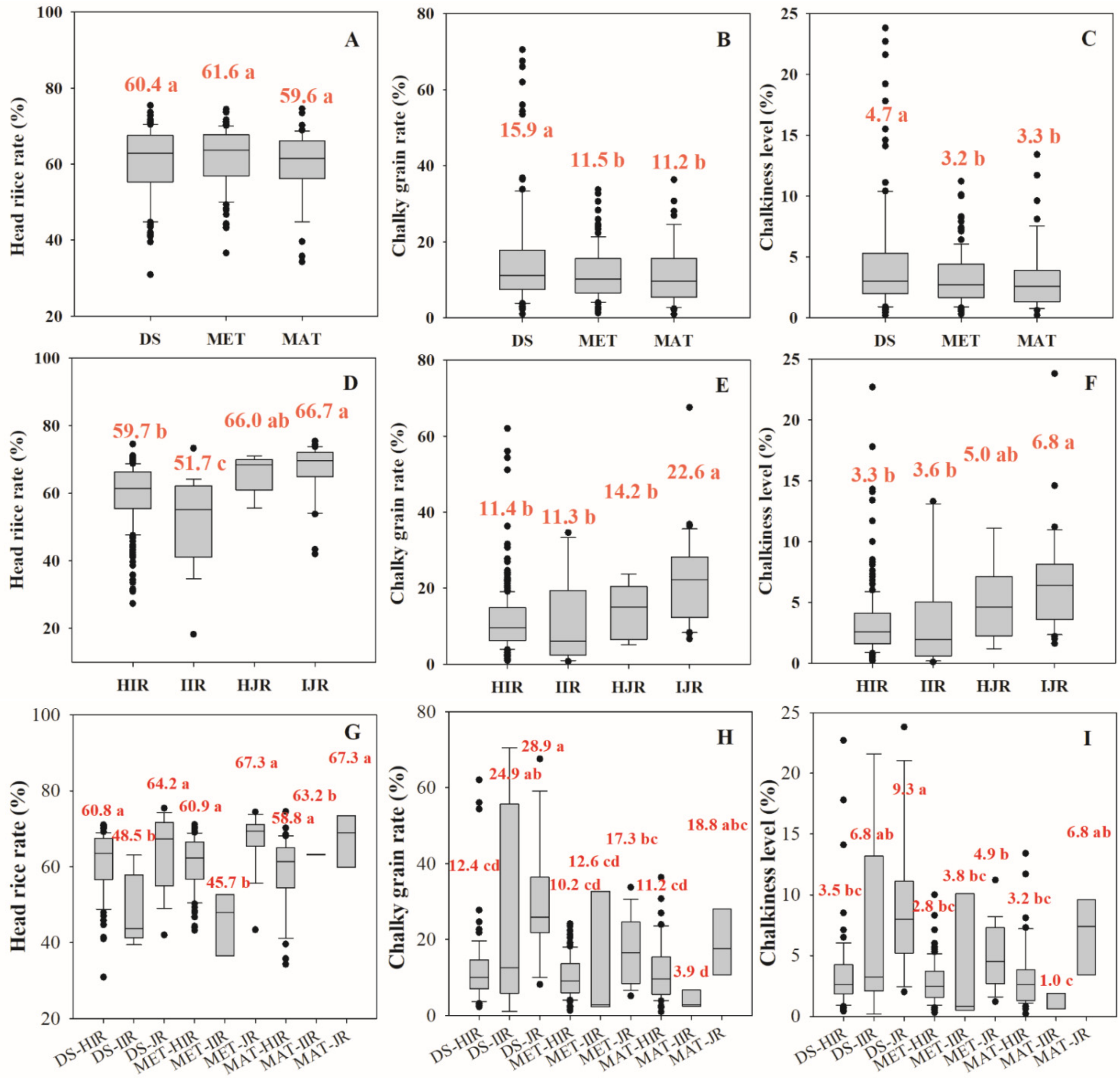

Figure 4. Differences in rice grain quality across different establishment methods ((**A**) head rice rate; (**B**) chalky grain rate; (**C**) chalkiness level), different types of rice ((**D**) head rice rate; (**E**) chalky grain rate; (**F**) chalkiness level) and their interactions ((**G**) head rice rate; (**H**) chalky grain rate; (**I**) chalkiness level). DS, MET, and MAT represent directed seeded, mechanical, and manual transplanted method. HIR, IIR, HJR, and IJR represent hybrid *indica* rice, inbred *indica* rice, hybrid *japonica* rice, and inbred *japonica* rice, respectively. JR represents *japonica* rice (including hybrid and inbred *japonica* rice). The red data is the average value of each series. The same letters are not significantly different at $p = 0.05$. Data were pooled from examinations conducted in 2020.

Moreover, the chalky grain rate and chalkiness level of IJR was significantly higher than those of HJR (Figure 4D–F). The interaction between cultivars and establishment methods also particularly impact on grain quality. For example, the grain quality of IIR was the best in MAT, while for HIR and JR, the grain quality was the best in MET. Among different establishment methods, each cultivar of rice performed the poorest appearance quality under DS (Figure 4G–I).

For HIR, there were also some differences in grain quality among different panicle size cultivars (Table 5). In DS, the large panicle cultivars performed the highest head rice rate and showed the lowest variation. The tendencies of head rice rate of different panicle size cultivars were similar in three establishment methods. It is observed that in small panicle cultivars (grains number per panicle ≤ 155), chalkiness, the chalky grain rate and the chalkiness level were lower than those of large and medium panicle cultivars in DS and MAT. On the other hand, both the medium and small panicle cultivars obtained low chalkiness in MET.

Table 5. Variation of grain quality for hybrid indica rice (HIR) with different panicle sizes in different establishment methods. DS, MET, and MAT represent directed-seeded rice, mechanical transplanted method, and manual transplanted method.

Rice Establishment Methods	Panicle Size (Grains Panicle^{-1})	Head Rice Rate (%)				Chalky Grain Rate (%)				Chalkiness Level (%)			
		Max	Min	Mean	Cv (%)	Max	Min	Mean	Cv (%)	Max	Min	Mean	Cv (%)
DS	≥190	70.7	50.0	63.4	8.7	27.7	4.1	12.0	46.3	8.5	0.9	3.4	55.2
	155–190	71.0	30.9	58.2	16.8	62.0	2.2	14.2	104.8	22.7	0.4	4.1	120.9
	≤155	70.7	45.8	61.5	13.6	24.6	3.0	9.5	64.2	8.5	0.6	2.7	73.0
MET	≥190	70.2	47.9	62.5	9.6	23.5	3.6	10.9	44.7	10.0	0.7	3.2	55.9
	155–190	68.4	44.0	60.3	12.0	24.1	2.1	9.2	65.8	8.3	0.6	2.5	80.9
	≤155	71.1	43.2	58.0	12.8	22.3	1.3	9.4	64.9	5.5	0.3	2.4	67.2
MAT	≥190	70.2	35.8	60.1	14.1	36.3	2.1	13.9	72.3	13.4	0.6	4.2	88.6
	155–190	68.5	34.3	59.1	15.4	22.0	4.4	10.0	56.5	7.3	1.1	2.8	77.9
	≤155	74.5	35.7	56.6	20.9	15.8	0.9	8.5	62.4	5.0	0.2	2.3	64.4

Data were pooled from examinations conducted in 2020.

4. Discussion

4.1. Effect of Establishment Methods on Rice Grain

Rice grain yield responses to establishment methods have been widely studied in the past few decades, especially in single rice systems. Previous studies stated that MET and DS performance better with high yield [9–12]. Previously experiments were conducted with enough labor to ensure a sufficient number of seedlings to attain the suitable and enough panicle per m^2. However, it is not easy to reach suitable and enough panicles per m^2 with the decreased labor input in farmers' fields. The better performance of MET might be because of synchronization of planting time [23], reduced transplanting shock by use of young seedlings [24], early seedling vigor and uniform plant stand [25]. It is consistent with the result that the rice grain yield was the maximum under MET, followed by DS and the lowest in MAT in the present study. Besides, our results showed that grain yield variation was the lowest under MET, followed by DS and the largest in MAT. These indicated that MET would perform better than MAT and DS at farmers' fields. However, some studies also showed that the rice grain yield between MET and MAT does not differ in a single season [24,26,27]. This result is because the previous studies were conducted with enough labor to ensure a sufficient number of seedlings to obtain suitable and enough panicles per m^2. However, in fact, it is challenging to reach the desired number of panicles per m^2 with the decreased input of labor in farmers' fields (Figure 5), resulting from a labor shortage (especially young farmers) and an increase in wages [6,24]. Instead of MAT, MET was conducive to forming a high-yielding population (suitable and enough panicle per m^2) [9]. The results demonstrated that MET had significantly higher panicle per m^2 than MAT and obtained high biomass and high yield in the present study. Similarly, previous studies proved that panicle per m^2 and biomass production are the essential attributes for high yield [5,28,29]. These findings indicated that MET had high yield potential at farmers' fields, because of the high-yielding population (suitable and enough panicle per m^2) and high biomass production.

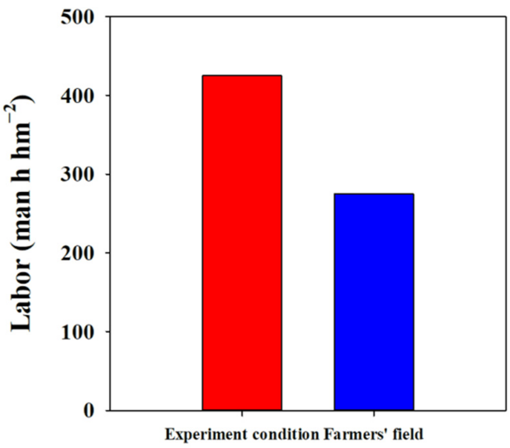

Figure 5. The labor input for MAT in experiment conditions and at farmers' fields. The data of these were the mean value in our previous five years' field experiment and the average value in the surveyed study. Data were pooled from examinations conducted in 2020.

Numerous studies stated that HIR had a significantly higher yield than IIR, which might be attributed to better sink regulation [23,30], larger panicle size and/or higher tillering capacity [2,23], and higher average grain weight [23]. Similarly, HIR performed a better yield than IIR in the present study. According to the panicle size data of cultivars from China Rice Data Center (China Rice Center, 2021), the HIR cultivars were divided into large panicle size HIR (grains number per panicle $\geq$ 190), medium panicle size HIR (155 < grains number per panicle < 190) and small panicle size HIR (grains number per panicle $\leq$ 155). Numerous studies proved that the panicle size correlates significantly to the rice grain yield [18,28,31]. Likewise, in the present study, the larger panicle size HIR displayed better yield performance than the small panicle size HIR under MET. For two major subspecies, the rice grain yield of JR was higher than *indica* rice (IR, including hybrid *indica* rice and inbred *indica* rice). It was consistent with the finding that JR had a higher yield potential than indica rice [18]. Furthermore, the results also presented that JR under MET (MET-JR) reached the highest grain yield in the present study. This might be attributed to the fact that JR had better root morpho-physiology, stronger photosynthetic capacity, and improved group structure than IR after heading [32–34]. Thus, using MET with JR and/or large-size HIR will be conducive to reaching a high rice yield in farmers' fields.

4.2. Differences in Rice Quality in Response to Establishment Methods

The head rice rate and chalkiness play roles in determining the commercial value of rice [35,36]. For milling quality, the result showed that the head rice rate under MET was higher than that in DS and MAT, but there were no significant differences. The main reason was that the growth period of machine transplanting and artificial transplanting rice was the same, meaning they had almost the same temperature and light resource conditions. It was consistent with the previous studies that a similar milling recovery of grain was obtained in all establishment methods [37,38]. However, the chalky grain rate and the chalkiness level under DS were significantly higher than in MET and MAT. This result indicated that the rice would have low commercial value under DS. The following facts primarily depicted the reasons for this result: (1) most of the DS in this region were random broadcasting seeds with high seed rates, without seed priming, and most of the soil in this region was puddled soil; and (2) DS shortened the rice growth duration resulting in early flowering. These facts suggested that it was easy to cause poor uniformity of seedling emergence and high weed [39], which would induce poor crop establishment and eventually may increase rice chalkiness [40].

Moreover, early heading would occur in DS [35], which may lead the grain filling period to be in high temperature in middle rice system, resulting in an increasing chalkiness [41]. Thus, special rice cultivars and appropriate management strategies should be developed for DS in the future [39,42]. However, MET showed considerable grain quality as MAT, which might be attributed to early seedling vigor and uniform plant stand [12].

Many evident studies proved that there were some differences in grain quality among different cultivars [3,18], such as the HIR showing a better milling quality than IIR [43], and had a better appearance quality than JR [14]. Similar results were validated in this study. It is well-known that the head rice rate and chalkiness play roles in determining the commercial value of rice [35]. This suggested that HIR is a better selection to improve grain quality and commercial value. However, there were also some differences in rice quality among different panicle size cultivars. The results showed that the small panicle size HIR had low chalkiness and even a high head rice rate in each establishment method in the present study. Instead, the larger panicle size HIR had poor rice quality, which mainly induced poor grain-filling of later-flowering inferior spikelets [44,45]. Previous studies showed that nitrogen and water management affected the sink strength of inferior spikelets [46]. Hence, enhancing the sink strength of inferior spikelets during grain filling through better nitrogen and water management is needed to adopt large panicle-size HIR successfully. Furthermore, compared with IR, JR showed a higher head rice rate and similar trends were displayed in each establishment method. Similar results were reported by Zeng et al. [14,18]. However, *japonica* rice obtained a higher chalkiness result from being sensitive to high temperatures during the grain filling stage [14]. Thus, cultivars tolerant of high temperatures during the grain-filling phase are needed for the successful large-scale adoption of JR.

Our results showed that MET had higher yield potential and considerable rice quality than MAT and DS. However, there were also some challenges to the successful large-scale adoption of MET. For example, MET required high seed costs and a high initial cost of the machine [2,12]. Challenges hindering MET adoption at a broader scale include limited machines, the unavailability of skilled operators, the lack of maintenance and troubleshooting facilities, the lack of nursery raising skills, and the unsuitability of technology for lowland rainfed ecology [13]. Besides the high requirement of soil preparation, skilled operators in MET also demand more inputs. Therefore, to make MET adoption at scale, we must consider and resolve these challenges in future practice.

5. Conclusions

It is vital to shift establishment methods and apply suitable cultivars to ensure food security during a labor shortage. The present study confirmed that the application of MET obtained high rice yield and grain quality. It was accomplished by receiving adequate panicles per m^2 and high biomass production in farmers' fields in MET. Furthermore, in balancing rice yield and the quality of japonica rice and large panicle (grains number per panicle $\geq$ 190), HIR should also be considered. These results served as an important reference for selecting suitable establishment methods and cultivars to improve rice yield and quality in China and other developing countries with rice–based cropping systems.

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