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Yield and Resource Utilization Efficiency Gap in Early Maturing Japonica Rice Cultivars under Different Management Strategies—A Different Location Investigation

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Abstract: High input costs and poor management options have resulted in a large rice yield gap. Thus, there is a need to reduce production costs and improve resource-use efficiency by using new cultivation techniques at different locations. The objective of this study was to determine yield and utilization efficiency gaps in early maturing japonica rice under four treatments; no nitrogen application (N0), local farmer practice (FP), high-yield, high-efficiency practice (HYP), and super-high-yield practice (SHY). The average yields under N0, FP, HYP, and SHY were 5012, 7356, 8448, and 9629 kg ha^{-1}, respectively. Differences among treatments were as: N0 to FP (gap 1); FP to HYP (gap 2); and HYP to SHY (gap 3). Yield gaps 1, 2, and 3 were 2337, 1092, and 1181 kg ha^{-1}, respectively. Yield gap was positively associated with panicles per square meter. Yield under HYP and SHY was 14.8% and 30.9% higher than that under FP, respectively. This increase in yield was mainly associated with a higher number of panicles. For resources, gaps 1, 2, and 3 were as follows: water-use efficiency, 0.1706, 0.1513, and 0.1089 kg m^{-3}; radiation-use efficiency, 0.3285%, 0.1780%, and 0.0941%; and heat-use efficiency, 1.8685, 1.0339, and 0.8798 kg °C^{-1} d^{-1} ha^{-1}, respectively. The yield was positively correlated with water, radiation, and heat-use efficiencies. The differences in yield and resource-use efficiency were significant between sites. A reduction in yield and efficiency gaps can ensure sufficient panicle per square meter, stabilize grain number per panicle, and increase harvest index and biomass. Overall, HYP is a promising option to increase the yield of early maturing japonica rice yield in cold regions.

Keywords: rice; yield gap; water-use efficiency; radiation-use efficiency; heat-use efficiency

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1. Introduction

Global food production requires efficient management techniques to meet the demands of the growing population [1]. By 2050, the world population is expected to reach 9 billion [2], which will increase food demand by 70–100% [3,4]. To meet this demand in China, grain growth should be increased by at least 2% per year [5]. Rice (*Oryza sativa* L.) is the main food crop, consumed by more than 50% of the world's population [6], and is thus globally important for food production. Rice is the primary food crop in China, which is the world's largest rice producer and consumer. Poor crop management and high input cost reduce rice productivity. The increase in total grain production depends mainly on the expansion of the production area and the increase in grain yield per unit area. However, unregulated development has caused the gradual depletion of water and land resources. With an increase in the cultivated land area, ecologically fragile lands with poor fertility need to be developed and utilized, which disturbs the ecology of such lands [7]. However, China has limited cultivated land. Therefore, an increase in grain production depends primarily on the increase in grain yield per unit area [8,9], requiring improved management and production methods. There are large yield gaps between potential and actual yields, between regions, and even between fields in the same area [10,11]. To reduce these gaps and to address increasing food demand, grain production must be increased [12,13].

Climatic resource-use efficiency refers to the absolute or relative amount of biomass or economic yield based on light, heat, and precipitation during the growing period [14]. Resource-use efficiency in China is low, with potential for improvement [15]. This low efficiency increases production costs, affects farmers' income, and causes ecological problems [16,17]. Resource-use efficiency is an important factor restricting sustainable agricultural development in China [18].

Yield and efficiency gaps have been estimated via modeling [19]. Factors determining yield and efficiency gaps [20], the physiological mechanisms for closing these gaps [21,22], and effective management strategies to achieve this [23] have been studied. These studies have provided a scientific basis for increasing rice yield and reducing yield gaps. However, rice yield gaps and resource-use efficiency in cold regions have not yet been comprehensively analyzed. Therefore, in the present study, we aimed to evaluate the effects of no nitrogen application (N0); local farmer practice (FP); high-yield, high-efficiency practice (HYP) (local farmer practices by applying new cultivation techniques to improve yield and resource-use efficiency); and super-high-yield practice (SHY) on rice yield and resource utilization efficiency gap. We integrate the individual cultivation techniques and measures of the high-yield and high-efficiency cultivation methods in local production, such as the potted raising method, alternate wetting and drying irrigation, and increased application of organic fertilizer, to create a super-high-yield practice. We also examined the associations between production factors and resource-use efficiency of different rice cultivars under different management strategies.

2. Materials and Methods

2.1. Experimental Sites

Field experiments were conducted at two sites in Heilongjiang Province in 2018 and 2019: Wangjiaweizi in Daqing City (46°40′ N, 125°07′ E) and an experimental rice farm in Shangji, Suiling County (47°09′ N, 127°18′ E). Heilongjiang Province, an important commodity grain base, is the northernmost cold rice-producing area in China, with a total rice planting area of 3.813 million hectares. The soil in the Daqing City site is sodic saline-alkali, with pH 8.23, 0.31% soluble salt, 38.9 g kg^{-1} organic matter, 168.03 mg kg^{-1} alkaline nitrogen (N), 47.54 mg kg^{-1} available phosphate (P), and 158.05 mg kg^{-1} available potassium (K). The soil in the Suiling site is black, with pH 6.08, 50.8 g kg^{-1} organic matter, 202.06 mg kg^{-1} alkaline N, 50.10 mg kg^{-1} available P, and 166.00 mg kg^{-1} available K. The daily average temperature and precipitation in the Suling site are 17.8 °C and 5.3 mm from April to October, respectively. The daily average temperature and precipitation in the Daqing site are 19.8 °C and 6.1 mm from April to October, respectively. The specific daily average temperature and precipitation changes are shown in Figure 1.

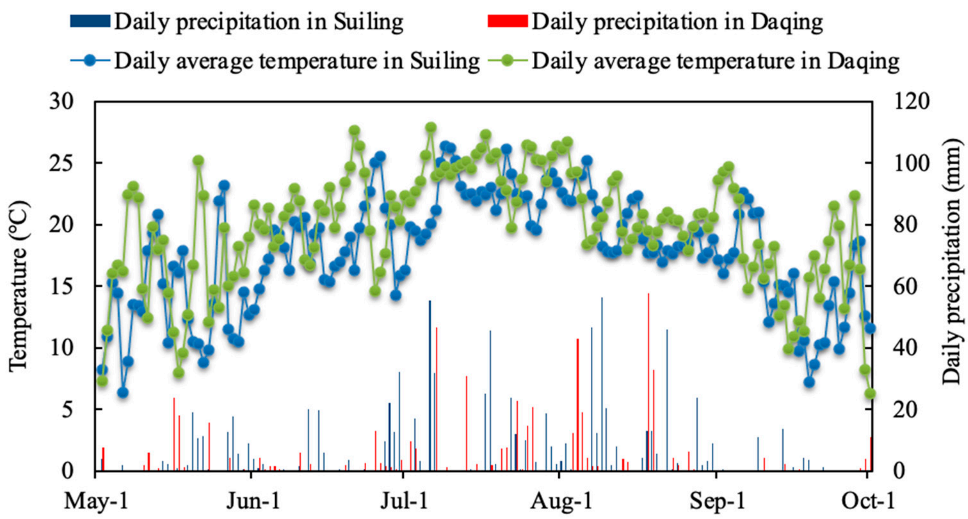

Figure 1. Daily average temperature and precipitation during the rice-growth season in Daqing (46°40′ N, 125°07′ E) and Suiling (46°40′ N, 125°07′ E).

2.2. Experiments and Crop Management

A randomized block arrangement with three replicates was used. The different treatments were N0, FP, HYP, which augments local farmer practice by applying new cultivation techniques to improve yield and resource-use efficiency, and SHY, designed to achieve a high yield regardless of labor or fertilizer input. Experimental details are provided in Table 1. Each plot was 30 × 6 m. In N0 and FP treatments, rice seedlings were transplanted at a hill spacing of 30 × 10 cm in a parallel row layout. In HYP treatment, rice seedlings were transplanted at a hill spacing of 30 × 13.3 cm in a parallel row layout. In SHY treatment, rice seedlings were planted in alternating wide (40 cm) and narrow (20 cm) rows in each plot. Two seedling-raising methods (dry bed and potted raising), two fertilizer-application methods (chemical and biological organic fertilizer), and two irrigation methods (shallow water flood and alternate wetting and drying) were used at each site.

Table 1. Fertilization application regime and cultivation measures under different cultivation modes.

Treatment	SRP	PP	IM	AI (m^3/ha^{-1})	TNFA (ha^{-1})	CF (ha^{-1})	
						Nano-Silicon	Guifuji
N0	DBM	PW	SWF	9750–11,250	0	-	-
FP	DBM	PW	SWF	9750–11,250	150	-	-
HYP	DBM	PW	AWD	7500–8250	160	450	-
SHY	PRM	AWNW	AWD	7500–8250	180	450	15

SRP: seedling-raising patterns; PP: planting patters; IM: irrigation methods; AI: amount of irrigation; TNFA: total N fertilizer application; CF: compound fertilizer; N0: no nitrogen application; FP: local farmer practice; HYP: high-yield, high-efficiency practice; SHY: super-high-yield practice; DBM: dry bed method; PRM: potted raising method; PW: parallel row; AWNW: alternating wide and narrow rows; SWF: shallow water flood irrigation; AWD: alternate wetting and drying irrigation.

In the N0 treatment, 70 kg ha^{-1} P_2O_5 (superphosphate, P_2O_5 = 12%) was applied as a basal fertilizer; 70 kg ha^{-1} K_2O (as potassium sulfate, 50% K_2O) was applied during the pre-transplanting and panicle initiation stages at a ratio of 6:4.

In the FP treatment, 150 kg ha^{-1} N (as urea, 46% N) was applied at a ratio of 4:3:1:2 during the pre-transplanting, re-greening and primary tillering, panicle initiation, and spikelet differentiation stages, respectively. P and K application rates were similar to those in the N0 treatment in terms of quantity and method.

In the HYP and FP treatments, we used the same N application rates and application stages. In the N0, FP, and HYP treatments, the P and K application rates and seedling-raising methods were the same. In contrast, the N, P, and K concentrations were increased to 160, 80, and 130 kg ha^{-1}, respectively. Furthermore, 300 kg ha^{-1} organic fertilizer (Guifuji, a nano-silica compound fertilizer, Guifuji Biotechnology Company, Jiamusi, China) was applied in the pre-transplanting stage.

In the SHY treatment, the N, P, and K concentrations were increased to 180, 90, and 180 kg ha^{-1}, respectively. Organic fertilizer (Guifuji) was applied in the pre-transplanting stage at 450 kg ha^{-1}. SHY-treated seedlings were cultured in pots and planted in alternating wide (40 cm) or narrow (20 cm) rows in each plot.

Salt-tolerant rice cultivars—Kenjing 6 (KJ6) and Kenjing 8 (KJ8), developed and released by Heilongjiang Bayi Agricultural University—were grown at the Daqing site. The time from sowing to maturity was approximately 136 and 142 days, respectively. The pre-germinated seeds were sown on April 19, seedlings in the four-leaf stage were transplanted to the field on May 16, and the plants were harvested on September 23. High-yielding commercial rice cultivars—Longjing 31 (LJ31) and Longjing 46 (LJ46), developed and released by Jiamusi Rice Institute of Heilongjiang Academy of Agricultural Sciences—were grown in the Suiling site. The total growth period was approximately 130 and 127 days, respectively. The pre-germinated seeds were sown on April 5, seedlings in the four-leaf stage were transplanted to the field on May 13, and the plants were harvested on September 21. During the experiment, the plants under each treatment were irrigated and drained separately to prevent mutual treatment effects. Weeds, pests, and diseases were controlled regularly.

2.3. Yield and Yield Components

Rice's theoretical yield depends on the following yield components: the number of panicles per square meter (panicle number), spikelets per panicle (spikelet number), the seed-setting rate, and the 1000-grain weight. To measure actual yield, a 2.5 × 2.0 m subsampling area in each plot was used. Panicles were counted in 20 consecutive hills. Eight hills were transported to the laboratory to determine the yield contributors, namely, the number of filled grains, unfilled grains, empty grains per panicle, and the weight of filled grains. Grain's theoretical yield was calculated by multiplying these values with the number of panicles per square meter. The number of spikelets per panicle, seed-setting rate, and 1000-grain weight was calculated.

2.4. Resource-Use Efficiency

Data on precipitation, solar radiation, and temperature during the growth period were recorded at the Harbin Meteorological Bureau, Heilongjiang Province, China. The total solar radiation at the Daqing site and the Suiling site was 2540.38 and 2251.41 MJ m^{-2} from transplanting to maturity, respectively. These data were used to calculate resource-use efficiency as follows, according to Cui [24].

$$\text{Water-use efficiency} = Y/WC \tag{1}$$

where the unit of water-use efficiency is kg m^{-3}, Y is rice grain yield (kg ha^{-1}), and WC is water consumption (mm m^{-2}), including that of irrigation water and precipitation, from transplanting to maturity.

$$\text{Radiation-use efficiency} = Y \times H/\Sigma Q \times 1 \tag{2}$$

where the unit of radiation-use efficiency is %, Y is rice yield per unit area (kg ha^{-1}), H is the reburning heat of dry matter per unit area (J kg^{-1}), which is taken as 1.799×10^7 J kg^{-1}, and ΣQ is the total solar radiation from transplanting to maturity (MJ m^{-2}).

$$\text{Heat-use efficiency} = Y/\Sigma T \tag{3}$$

where the unit of heat-use efficiency is kg °C^{-1} d^{-1} ha^{-1}, Y is rice yield per unit area (kg ha^{-1}, and ΣT is ≥10 °C accumulated temperature from transplanting to maturity (°C d).

2.5. Statistical Analysis

The data from the 2 years were pooled, and group means were assessed using DPS v. 7.05 [25]. Means were separated using the least significant difference test at the 5% probability level. Differences among treatments were significant at $p < 0.05$. Figures were generated using GraphPad Prism 7 (San Diego, CA, USA).

3. Results

3.1. Yield and Yield Components

Rice yield and yield components were affected by the site and treatment ($p < 0.05$) (Table 2). The site × treatment interaction significantly affected the number of panicles per square meter and spikelets per panicle. Grain yield was 4.5% higher in Suiling than in Daqing. Compared with the FP treatment, the HYP and SHY treatments increased the number of panicles per square meter by 7.7% and 23.0%, spikelets per panicle by 10.1% and 15.9%, and yield by 14.8% and 30.9%, respectively. In terms of yield, the cultivars were ranked LJ31 > KJ6 > LJ46 > KJ8 at both sites. The yield of L31 was 5.9%, 15.7%, and 19.1% higher than that of KJ6, LJ46, and KJ8, respectively, mainly due to the higher number of panicles per square meter.

Table 2. Rice yield and yield component response to different sites, varieties, and cultivation methods.

Treatment		Panicles (m^{-2})	SNP	SSR (%)	1000 GW (g)	TY (Mg ha^{-1})
Sites	Daqing	394.7 b	97.7 a	91.5 a	21.0 b	7.45 b
	Suiling	472.4 a	75.8 b	89.8 b	24.2 a	7.78 a
Cultivation methods	N0	314.8 d	73.7 d	94.5 a	23.4 a	5.02 d
	FP	429.1 c	83.8 c	91.2 b	22.7 b	7.36 c
	HYP	462.0 b	92.3 b	88.5 c	22.6 b	8.45 b
	SHY	528.2 a	97.1 a	88.3 c	21.8 c	9.63 a
				Analysis of variance		
Sites		**	**	**	**	*
Cultivation methods		**	**	**	**	**
Sites × Cultivation methods		*	**	ns	ns	ns
Varieties	KJ6	437.5 b	94.8 b	89.8 b	21.2 c	7.88 b
	KJ8	352.0 c	100.6 a	93.2 a	20.9 c	7.01 c
	LJ31	503.6 a	75.9 c	91.6 a	23.8 b	8.35 a
	LJ46	441.2 b	75.6 c	87.9 c	24.7 a	7.21 c

SNP: spikelet number per panicle; SSR: seed-setting rate; 1000 GW: 1000-grain weight; TY: theoretical yield; N0: no nitrogen application; FP: local farmer practice; HYP: high-yield, high-efficiency practice; SHY: super-high-yield practice; KJ6: Kenjing6; KJ8: Kengjing8; LJ31: Longjing31; LJ46: Longjing46; Within the same column, sites, cultivation methods, and varieties, means not sharing a letter were significantly different at the 0.05 probability level according to Fisher's LSD test. **, *: Significant at 1% and 5% probability levels, respectively. ns: Not significant.

3.2. Yield Gap

The average yield gap between N0 and FP (gap 1, GY1), FP and HYP (gap 2, GY2), and HYP and SHY (gap 3, GY3) was 2336.5, 1091.9, and 1181.4 kg ha^{-1}, respectively. The yield differed by cultivar (Figure 2); GY2 was ranked KJ6 > KJ8 > LJ31 > LJ46, indicating that these cultivars differed in yield under FP treatment compared with other cultivars, KJ6 had the highest yield and lowest potential for yield improvement, whereas LJ46 had the lowest yield and highest potential for improvement. In terms of yield, GY3 was ranked KJ6 > KJ8 > LJ46 > LJ31, revealing that under HYP, these cultivars differed in yield potential. Compared with the other cultivars, KJ6 had the highest yield and least potential for yield improvement, KJ8 had the second-highest yield, and LJ31 had the lowest yield with the highest potential for improvement.

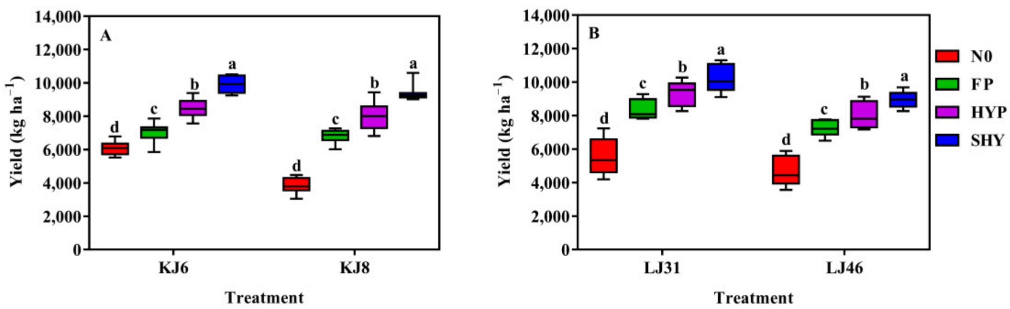

Figure 2. Yield of different cultivars in different sites ((**A**) in Daqing; (**B**) in Suiling) and under different cultivation patterns (N0, FP, HYP, and SHY). KJ: Kenjing 6; KJ8: Kenjing 8; LJ31: Longjing 31; LJ46: Longjing 46; N0: no nitrogen application; FP: local farmer practice; HYP: high-yield, high-efficiency practice; SHY: super-high-yield practice. Bars are mean ± SE (n = 3), different letters indicate statistical significance at the $p < 0.05$ level under different treatments.

3.3. Harvest Index and Biomass

Site, cultivar, and treatment significantly affected the harvest index and biomass yield (Table 3). The site × treatment interaction was not significant. The biomass was significantly higher, and the harvest index was significantly lower in Daqing than in Suiling. Compared with N0, FP resulted in a low harvest index and biomass, but the difference was not significant. HYP and SHY resulted in a higher harvest index and biomass than N0 and FP. Among the cultivars, LJ46 presented the highest harvest index. Under all four treatments, yield increased with an increase in the harvest index and biomass.

Table 3. Harvest index and biomass of different sites, varieties, and treatments.

Treatment		Harvest Index	Biomass (Mg ha^{-1})
Sites	Daqing	0.524 b	14.10 a
	Suiling	0.575 a	13.46 b
Cultivation methods	N0	0.513 b	9.76 d
	FP	0.530 b	13.97 c
	HYP	0.578 a	14.67 b
	SHY	0.577 a	16.70 a
		analysis of variance	
Sites		**	*
Cultivation methods		**	**
Sites × Cultivation methods		ns	ns
Varieties	KJ6	21.2 c	14084.5 a
	KJ8	20.9 c	14107.9 a
	LJ31	23.8 b	13761.1 a
	LJ46	24.7 a	13153.6 b

N0: no nitrogen application; FP: local farmer practice; HYP: high-yield, high-efficiency practice; SHY: super-high-yield practice; KJ6: Kenjing6; KJ8: Kengjing8; LJ31: Longjing31; LJ46: Longjing46; Within the same column, sites, cultivation methods, and varieties not sharing a letter were significantly different at the 0.05 probability level according to Fisher's LSD test. **, *: Significant at 1% and 5% probability levels, respectively. ns: Not significant.

3.4. Resource Utilization Efficiency

3.4.1. Water-Use Efficiency

Cultivation patterns, cultivars, and sites significantly influenced water-use efficiency (WUE) (Figure 3). WUE was 0.092 kg m^{-3} higher in Daqing than in Suiling; the treatment effects differed significantly and were ranked SHY > HYP > FP > N0, consistent with the trend for yield. For WUE, the gaps were ranked GY1 > GY2 > GY3; the treatments were ranked SHY > HYP > FP > N0. LJ46 significantly differed from the other cultivars in terms of WUE.

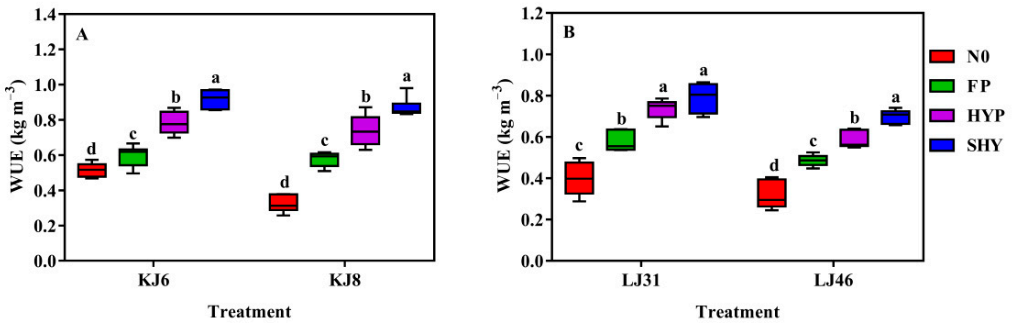

Figure 3. Water-use efficiency (WUE) of different varieties, in different sites ((**A**) in Daqing; (**B**) in Suiling) and under different cultivation patterns (N0, FP, HYP, and SHY). KJ: Kenjing 6; KJ8: Kenjing 8; LJ31: Longjing 31; LJ46: Longjing 46; N0: no nitrogen application; FP: local farmer practice; HYP: high-yield, high-efficiency practice; SHY: super-high-yield practice. Bars are mean ± SE (n = 3). Different letters indicate statistical significance at the $p < 0.05$ level under different treatments.

3.4.2. Radiation-Use Efficiency

The radiation-use efficiency (RUE) was 0.032% higher in Daqing than in Suiling (Figure 4). For RUE, the treatments were ranked SHY > HYP > FP > N0, consistent with the yield trend; the gaps were ranked GY1 > GY3 > GY2. RUE differed significantly between KJ8 and LJ31.

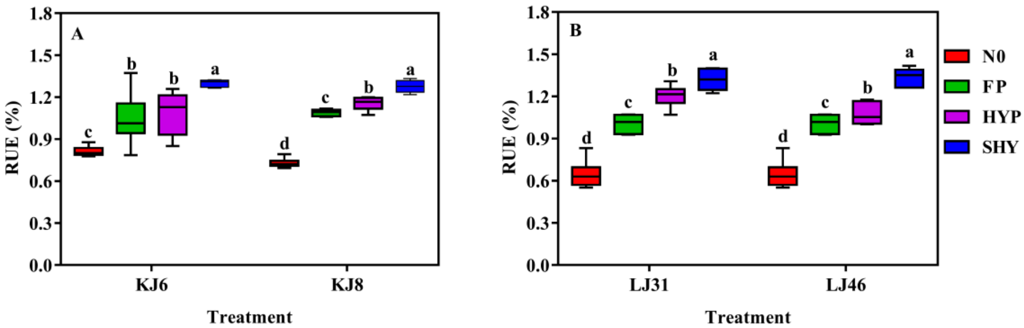

Figure 4. Radiation-use efficiency (RUE) of different varieties at different sites ((**A**) in Daqing; (**B**) in Suiling) and under different cultivation patterns (N0, FP, HYP, and SHY). KJ: Kenjing 6; KJ8: Kenjing 8; LJ31: Longjing 31; LJ46: Longjing 46; N0: no nitrogen application; FP: local farmer practice; HYP: high-yield, high-efficiency practice; SHY: super-high-yield practice. Bars are mean ± SE (n = 3). Different letters indicate statistical significance at the $p < 0.05$ level under different treatments.

3.4.3. Heat-Use Efficiency

The heat-use efficiency (HUE) was 1.374 kg $°C^{-1}$ d^{-1} ha^{-1} higher in Daqing than in Suiling (Figure 5). In terms of fold change in HUE, the treatments were ranked SHY > HYP > FP > N0, consistent with the trends for WUE and RUE. HUE increased with the increase in yield. For HUE, the gaps were ranked GY1 > GY3 > GY2. For HUE, the treatments were ranked SHY > HYP > FP > N0. For KJ6 and KJ8, HUE significantly differed among the treatments.

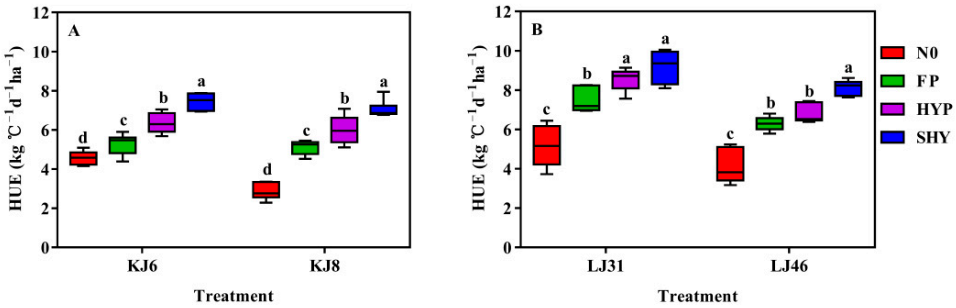

Figure 5. Heat-use efficiency (HUE) of different varieties at different sites ((**A**) in Daqing; (**B**) in Suiling) and under different cultivation patterns (N0, FP, HYP, and SHY). KJ: Kenjing 6; KJ8: Kenjing 8; LJ31: Longjing 31; LJ46: Longjing 46; N0: no nitrogen application; FP: local farmer practice; HYP: high-yield, high-efficiency practice; SHY: super-high-yield practice. Bars are mean ± SE (n = 3). Different letters indicate statistical significance at the p < 0.05 level under different treatments.

3.5. Correlation Analysis

3.5.1. Regression Analysis of Yield and Resource-Use Efficiency

The regression analysis showed that the yield, WUE, RUE, and HUE were positively associated (Figure 6). Improved resource-use efficiency led to higher yields.

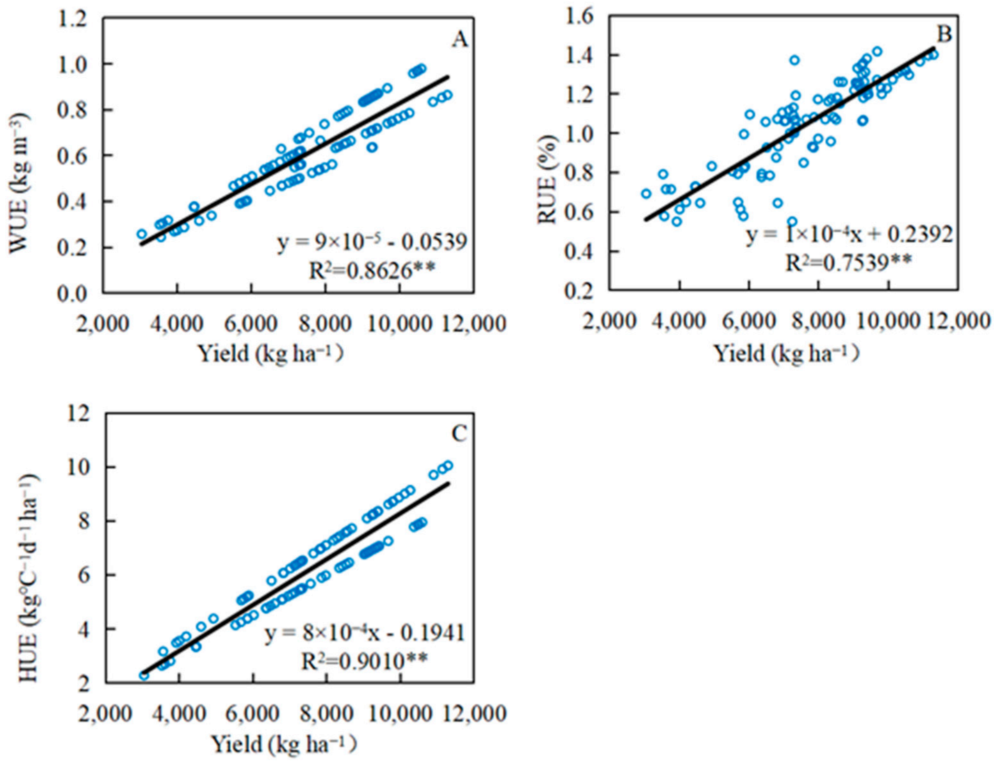

Figure 6. Correlations between yield and water-use efficiency (WUE) (**A**), radiation-use efficiency (RUE) (**B**), and heat-use efficiency (HUE) (**C**) throughout the growth period. **: Significant at 1% probability levels.

3.5.2. Correlations between Yield Components and Resource-Use Efficiency

The number of panicles and grains per panicle was positively associated with WUE, RUE, and HUE (Figure 7). Therefore, a higher resource-use efficiency improved the number of panicles per square meter and grains per panicle, thereby improving yield.

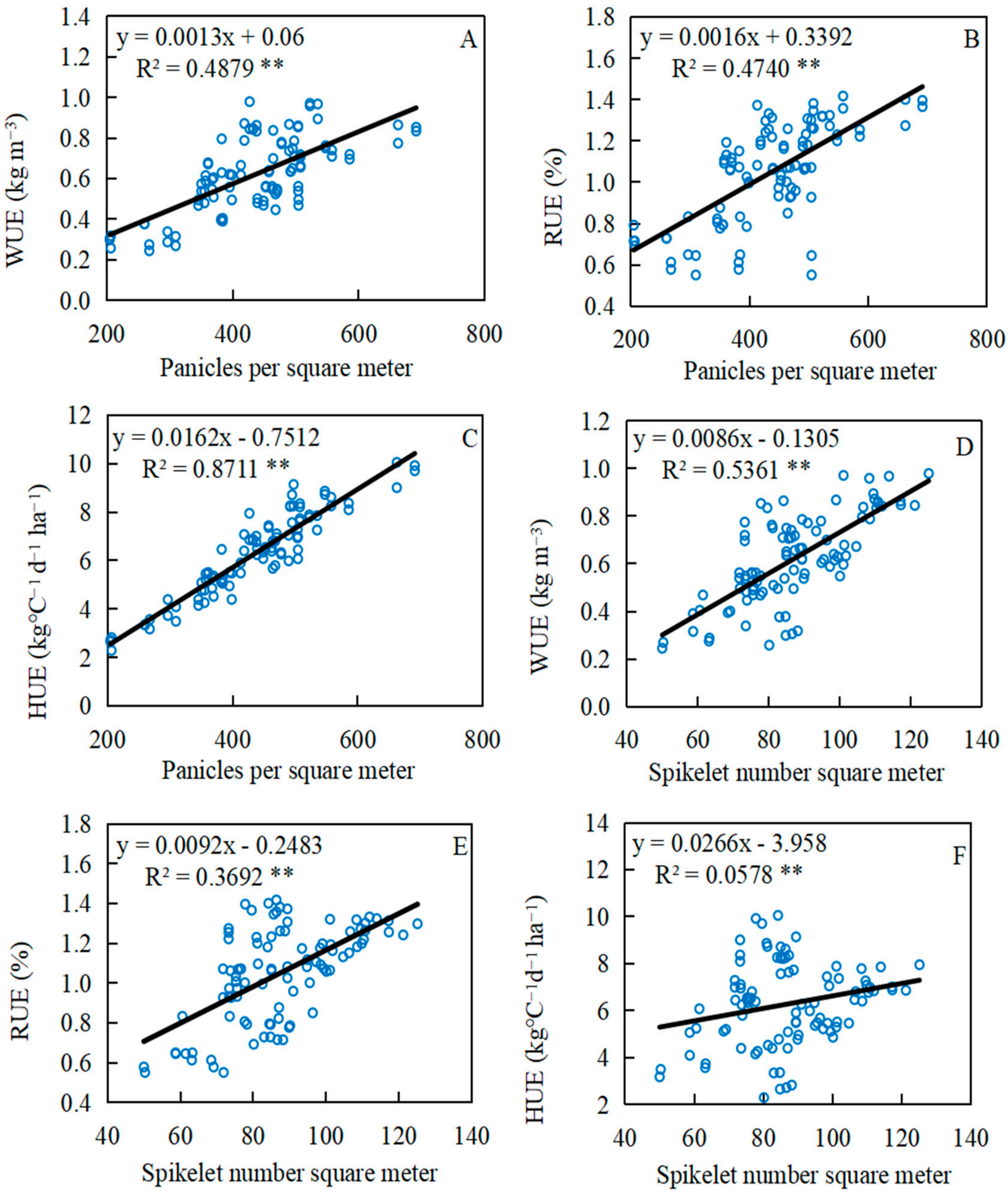

Figure 7. Correlations between panicles per square meter and water-use efficiency (WUE) (**A**), radiation-use efficiency (RUE) (**B**), and heat-use efficiency (HUE) (**C**); and spikelets per panicle and WUE (**D**), RUE (**E**), and HUE (**F**) throughout the growth period. **: Significant at 1% probability level, respectively.

3.5.3. Correlations among the Harvest Index, Biomass, and Resource-Use Efficiency

The harvest index and biomass were positively associated with WUE, RUE, and HUE (Figure 8). Therefore, a greater resource-use efficiency improved the harvest index and biomass.

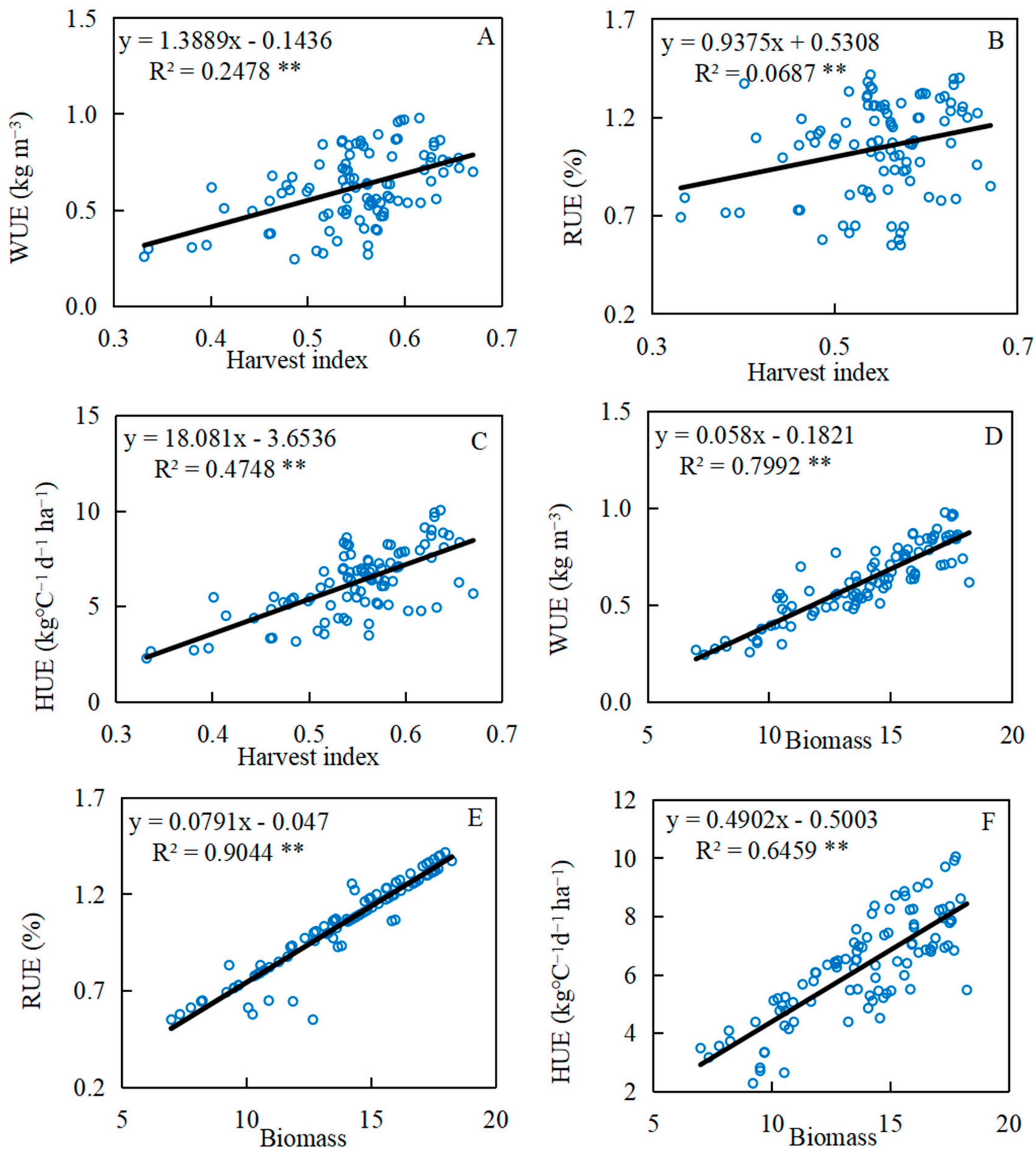

Figure 8. Correlations between the harvest index and water-use efficiency (WUE) (**A**), radiation-use efficiency (RUE) (**B**), and heat-use efficiency (HUE) (**C**); and biomass and WUE (**D**), RUE (**E**), and HUE (**F**) throughout the growth period. **: Significant at 1% probability levels.

3.5.4. Correlations between Rice Yield and Yield Components, Harvest Index, and Biomass

As shown in Table 4, the seed-setting rate and theoretical yield were significantly negatively associated. The number of panicles per square meter, harvest index, biomass, and theoretical yield was significantly positively associated under SHY, HYP, and N0. Under FP, the number of panicles per square meter, 1000-grain weight, harvest index, biomass, and theoretical yield were significantly positively associated with the theoretical yield. FP effectively increased yield by improving the harvest index and biomass, ensuring sufficient panicles per square meter.

Table 4. Correlation coefficient between theoretical yield, yield components, harvest index, and biomass.

Treatments	Panicles (m^{-2})	SNP	SSR	1000 GW	HI	Biomass
N0	0.8902 **	0.1229 ns	0.0185 ns	−0.1013 ns	0.7383 **	0.7636 **
FP	0.6707 **	−0.2533 ns	0.2322 ns	0.6219 **	0.5427 **	0.4344 *
HYP	0.6130 **	0.0085 ns	0.3654 ns	0.2947 ns	0.5698 **	0.6049 **
SHY	0.5820 **	−0.0228 ns	0.1731 ns	−0.0094 ns	0.6465 **	0.5298 **
All	0.8861 **	0.4893 **	−0.4032 **	−0.1794	0.6246 **	0.9054 **

SNP: spikelet number per panicle; SSR: seed-setting rate; 1000 GW: 1000-grain weight; HI: harvest index; N0: no nitrogen application; FP: local farmer practice; HYP: high-yield, high-efficiency practice; SHY: super-high-yield practice; **, *: Significant at 1% and 5% probability levels, respectively. ns: Not significant.

4. Discussion

Yield gap is an important indicator in formulating targeted measures to improve crop yield [26]. In this study, new management practices were used to improve rice yield and physiology in multiple locations in a cold region. Here, the yield gap between N0 and FP (GY1), FP and HYP (GY2), and HYP and SHY (GY3), was 2336.5, 1091.9, and 1181.4 kg ha^{-1}, respectively (Figure 2). These findings revealed a high potential to improve rice yield under current local farmer practices. To reduce the yield gap between conventional practices and higher yield and efficiency practices, it is essential to improve grain production in Heilongjiang Province. Under HYP and SHY, the yield was 14.8% and 30.9% higher than that under FP, respectively (Table 2). This was associated with improved resource-use efficiency, which led to a higher number of panicles per square meter.

The yield component values differed between the sites and among the cultivars. The numbers of panicles per square meter and grains per panicle are positively associated with yield [27,28]. Studies have suggested that optimizing the total N input and adjusting the topdressing time can increase the number of panicles per square meter, indicating the importance of the number of panicles per square meter in improving yield [29,30]. However, in Northeast China, because of the low temperature, the number of spikelets per square meter is an indicator conventionally targeted by optimizing N application and increasing the transplanting density [31,32].

Both HYP and SHY treatments resulted in more panicles per square meter and grains per panicle than local farmers' practices, thereby increasing yield [33]. The negative association between biomass and the harvest index causes an increase in yield [34]). In the present study, the yield components differed substantially with yield, owing to the variations in the number of panicles and grains per panicle. The effects of the seed-setting rate and 1000-grain weight on yield were low and in some cases, negative. High- and super-high-yields were achieved by increasing the number of panicles per square meter, resulting in a more consistent number of grains per panicle and an increase in the harvest index and biomass. This is related to the fact that Heilongjiang is a cold-climate rice-producing region. Furthermore, most of the cultivars used were panicle-type varieties.

In China, agricultural irrigation WUE is only 1.0 kg m^{-3}, which is lower than that in developed countries at 2.0 kg m^{-3}. China's water productivity is predicted to increase between 1.5 and 1.8 kg m^{-3} by 2030 [35]. Maximum yields can be achieved when the temperature and amount of intercepted radiation are optimal during the growth period [36]. RUE is a key factor determining crop production. Thus, agronomists have comprehensively analyzed accumulated temperature and daily maximum and minimum temperatures [37]. The optimal use of heat and light during the growing season can increase the yield [38].

In the present study, the treatments resulted in different use efficiencies for water, radiation, and energy; in terms of resource-use efficiency, the treatments were ranked SHY > HYP > FP > N0 (Figures 3–5). In addition, the radiation-use efficiency in the region was not synchronized with the heat-use efficiency. The radiation-use efficiency in Daqing was greater than that in Suiling, while the heat-use efficiency was the opposite. This may be because Daqing is in a semi-arid area, with good lighting conditions and high temperatures during the growth period. The excessive temperature has caused a waste of heat resources, resulting in its radiation-use efficiency being higher than that in Suiling, while the heat-use efficiency is lower. The number of panicles per square meter and grains per panicle and the harvest index, biomass, and theoretical yield were positively associated with WUE, RUE, and HUE. This result indicated that an increase in resource-use efficiency increased these yield component values, thereby increasing rice yield. These findings are valuable for improving resource-use efficiency, ensuring environmental protection, reducing the rice yield gap, and promoting sustainable agricultural development in China.

Under FP treatment, the yield was lower than that under the HYP and SHY treatments. This was primarily due to the lack of theoretical guidance and regulation in this type of rice cultivation, leading to poor management and lower yields [39]. Although cultivation methods and technological improvements have contributed substantially to an increase in rice yield, there is a large yield gap [40]. Our findings demonstrated that there is great potential to improve early maturing japonica rice yields in this cold-climate region. Closing this yield gap should be the main focus of research to increase yield in this important grain-producing area.

Our results suggest that high yield can be achieved by increasing the number of panicles per square meter, grains per panicle, harvest index, and biomass. Rice growth and yield are affected by climatic and ecological variations, and cultivars and cultivation methods must be selected to achieve high yields under specific conditions [41,42]. Although optimizing cultivation methods can improve rice yields [43,44] (Zhang et al., 2019; Lv et al., 2020), optimizing single aspects of cultivation does not effectively achieve this [45]. To increase yield, an integrated super-high-yield method that considers multiple factors is required [46]. The HYP and SHY methods significantly improved the number of panicles per square meter and grains per panicle in this study. This resulted in an 8.44–27.45% higher yield than that under the local farmer practices [33]. The application of fertilizer at the appropriate rate and time can improve aboveground biomass and can increase rice yield [47]. The SHY method maximized rice yield due to the optimal management of fertilizer, water, and other agronomic factors [48]. The HYP and SHY methods increased panicles per square meter by 7.7% and 23.1% (high and super-high, respectively); grains per panicle by 10.1% and 15.9%; harvest index by 9.06% and 9.01%; biomass by 5.0% and 19.5%; and yield by 14.8% and 30.9%, respectively (Tables 2 and 3). These increases were strongly associated with the efficient utilization of available resources. Further, we estimated the production cost under the integrated cultivation measures. Compared with FP, the production cost of HYP increased by CNY 1000 ha^{-1}, income increased by CNY 2800 ha^{-1}, and economic benefit increased by CNY 1800 ha^{-1}. The production cost of SHY increased by CNY 2800 ha^{-1}, income increased by CNY 5900 ha^{-1}, and economic benefit increased by CNY 3100 ha^{-1}. However, this is only the output and income under the ideal state under the conditions of this experiment. In real large-scale production, SHY may have the risk of lodging, blueness, or disease aggravation due to the large amount of fertilizer application and population growth. Therefore, from the perspective of economic benefits and safety production, farmers are recommended to adopt the HYP cultivation method.

5. Conclusions

In this study, different management techniques strongly influenced yield and physiology in early maturing japonica rice cultivars in a cold-climate region. Compared with the local farmer's practices, rice yield increased by 14.8% and 14.0% under HYP and SHY management practices, respectively. The increase in yield was strongly associated with efficient resource utilization, which further improved yield components. There was a small yield gap between local farmer's and the high-yield practices. This gap can be overcome as a short-term target to increase production. In contrast, a larger yield gap between the HYP and SHY practices was noticed; it was difficult to eliminate larger yield gaps under the existing conditions. Improving resource-use efficiency, the number of panicles per square meter and spikelets per panicle, harvest index, and biomass led to increasing yields. In this study, HYP was identified as an efficient management technique for improving yield and reducing yield gaps in early maturing japonica rice in cold regions.

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