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Evaluation of Late-Season Short- and Long-Duration Rice Cultivars for Potential Yield under Mechanical Transplanting Conditions

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Received: 17 July 2020; Accepted: 31 August 2020; Published: 2 September 2020

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Abstract: The development of large-scale farming has encouraged the adoption of mechanical transplanting techniques for rice production. However, the increased farming operation times that often occur under large-scale farming conditions necessitate shortening the duration of rice growth, especially that of late-season rice; therefore, rice cultivars with short growth durations are popular under such conditions. A field experiment using two short-duration rice cultivars (SRCs), i.e., Jiuliangyou 3 and Shengyou 9520, and two long-duration rice cultivars (LRCs), i.e., Shengyou 957 and Tianyouhuazhan, was conducted in the late season in Yongan and Santang, Hunan Province, China in 2017 and 2018. The grain yield and yield attributes were compared between the SRCs and LRCs, showing that the SRCs, which exhibited an 11–12-day shorter growth period, revealed similar grain yield to the LRCs. The SRCs also exhibited a 10–31% higher spikelet filling rate and a 13% higher harvest index than the LRCs. Moreover, the biomass accumulation, crop growth rate, and apparent radiation use efficiency of the SRCs were significantly higher than those of the LRCs during the postheading phase. Our results indicate that the higher spikelet filling rate, the harvest index, and the apparent radiation use efficiency of the postheading period were the underlying factors for the SRCs' grain yield.

Keywords: rice; yield; harvest index; short-duration rice; double-cropping rice

1. Introduction

The double-rice cropping system is considered an important and promising technique for sustainable rice production to ensure worldwide food security. However, due to urban expansion and a shortage of the labor required for rice production, the double cropping of rice has substantially declined in China [1,2]. Moreover, high labor input and low economic profits have reduced farmers' enthusiasm for growing double-season rice. Mechanized large-scale farming is an executable way to utilize labor effectively. However, the shift from traditional manual transplanting to mechanical transplanting creates new problems, such as impeding seasonal double-cropping rice (i.e., two rice crops grown consecutively during the wet and dry seasons) [3].

More importantly, the amount of farmland being rented has increased, due to the government subsidizing farming in China in recent years; thus, the leasing of farmland by farmers for large-scale farming systems has emerged as a new type of farming as a result [4]. The development of large-scale farming systems has encouraged the progress of mechanical rice transplanting techniques. Rice growth duration, especially that of late-season rice, must be further shortened under large-scale farming circumstances due to the increased operation time of farming (from early-season rice harvesting, through field preparation, to late-season rice transplantation). The length of time that the growth duration needs to be reduced by, as demanded by large-scale farming systems, is nearly equal to that of the increase in farming operation time and mainly depends on the area of farmland. Therefore, farmers are more likely to choose cultivars with a short growth duration to allow for increased operation time. Longer growth duration in late-season rice would lead to either a delay in sowing or a prolongation of the seedling age to meet the increased operation time of farming in large-scale farming systems. However, a delay in sowing would expose the plants to cold damage, while a prolongation of the seedling age may lead to premature heading, thus resulting in a substantial reduction in grain yield [5,6].

Rice growth duration is a primary decisive factor of crop production in double-season rice systems [7] and shortening the growth duration is beneficial for the implementation of the seasonal double cropping of rice. Before the green revolution, most traditional rice cultivars in Asia were matured in 160–170 days because of their photosensitivity [8]. Given the long growth period required, only a single crop could be grown per year. The availability of modern varieties with a shorter growth duration, which mature in 120–130 days, has led to an increase in the intensity of cropping and in rice production [8]. At present, a further reduction in growth duration would increase the flexibility of crop rotation and would intensify cropping systems under large-scale farming systems.

In this study, two rice cultivars with long growth durations and two rice cultivars with short growth durations were grown under a mechanical transplanting crop establishment system in the late seasons of 2017 and 2018. The yield, yield components, biomass accumulation, crop growth rate, and apparent radiation use efficiency were investigated. The objectives of the study were (1) to compare the yield performance of short- and long-duration rice, and (2) to identify the essential plant traits of short- and long-duration rice grown under mechanical transplanting conditions.

2. Materials and Methods

2.1. Field Experiments and Plant Materials

Field experiments were conducted in the late season (i.e., late June to mid-October) in two successive growing seasons in 2017 and 2018 in Yongan (28°09′ N, 113°37′ E, 43 m asl) and Santang (26°53′ N, 112°28′ E, 71 m asl), Hunan Province, China. The two experimental sites have a moist subtropical monsoon climate. Double-season rice (i.e., early- and late-season rice) cropping is a major rice-based system at both sites. The physical and chemical properties of the soil at the two experimental sites in Yongan and Santang are shown in Table 1. The soils of Yongan and Santang were tidal clay and Ultisol (USDA taxonomy), respectively. Soil samples were collected from the upper 20 cm layer of the soil from the experimental sites in 2017 before the beginning of the experiments.

Table 1. Physical and chemical properties of the soil from the Yongan and Santang experimental sites.

Experimental Site	pH	Organic Matter (mg kg^{-1})	Available N (mg kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})
Yongan	6.21	33.9	178.6	32.5	91.3
Santang	5.86	31.0	145.2	14.1	186.6

Two long-duration rice cultivars (LRCs), i.e., Shengyou 957 and Tianyouhuazhan, and two short-duration rice cultivars (SRCs), i.e., Jiuliangyou 3 and Shengyou 9520, were used in this study. The seeds were sown on 25 June in the two growing seasons, as essentially described in [9]. After 27 and 25 days, the seedlings were transplanted into the field in 2017 and 2018, respectively. A high-speed rice transplanter (PZ80-25; Dongfeng Iseki Agricultural Machinery Co., Ltd., Xiangyang, China) was employed for transplanting at a hill spacing of 25 × 11 cm with 1–2 seedlings per hill.

The nitrogen, phosphorus, and potassium rates were 150 kg N ha^{-1}, 75 kg P_2O_5 ha^{-1}, and 150 kg K_2O ha^{-1}, respectively. N fertilization was applied at three doses, i.e., 50% as basal, 30% at midtillering, and 20% at panicle initiation. Phosphorus was applied as basal fertilizer. Potassium was split equally into two doses, i.e., one as basal fertilizer and the other at panicle initiation. The regimen for water management was in the sequence of flooding, midseason drainage, reflooding, and moist intermittent irrigation. Pests, diseases, and weeds were controlled using chemicals to avoid yield loss. Experiments were arranged in three replicates of randomized complete block design (RCBD) with a plot size of 30 m^2.

2.2. Estimation of the Growth, Yield, and Yield-Contributing Traits

At the full heading stage (when approximately 80% of the panicles had emerged from the flag leaf sheath), 10 hills were diagonally sampled from each plot. Samples were hand-separated into straw and panicles, and each part was dried in an oven at 70 °C until a constant weight was obtained.

At physiological maturity, 10 hills were diagonally sampled in the middle of each plot. The number of panicles on each hill was counted to calculate the number of panicles per m^2. Plant samples were hand-separated into straw (including rachis) and spikelets. Filled spikelets were separated from unfilled ones by submerging them in tap water. Three subsamples of 30 g of filled grain and all unfilled spikelets were manually counted. Straw and filled and unfilled spikelets were weighted after oven-drying at 70 °C to a constant weight. The number of spikelets per panicle, spikelets per m^2, spikelet filling percentage (filled spikelet number × 100/total spikelet number), and harvest index (filled spikelet weight/aboveground total dry weight) were then calculated. The rain yield was determined from a 5 m^2 area in each plot and adjusted to a standard moisture content of 14%. The daily grain yield was calculated as the ratio of grain yield to total growth duration from sowing to maturity. Total biomass accumulation was the total dry matter of straw and filled and unfilled spikelets. The growth durations of preheading and postheading were the growth durations from transplanting to full heading and full heading to maturity, respectively. The postheading biomass accumulation was the difference between total biomass accumulation and preheading biomass accumulation. The translocation of biomass accumulated before heading to the grains (TG) was calculated according to Yang et al. [10]. The source–sink ratio (postheading biomass accumulation per m^2/spikelet number per m^2) was calculated, as was the crop growth rate of preheading (preheading biomass production/growth duration from transplanting to heading) and postheading (postheading biomass production/growth duration from heading to maturity).

Apparent radiation use efficiency was calculated as the ratio of biomass to incident solar radiation during the period from transplanting to heading, heading to maturity, and transplanting to maturity. Solar radiation and minimum and maximum temperatures were recorded daily using an on-site automatic weather station (Vantage Pro2; Davis Instruments Corp., Hayward, CA, USA), which was installed approximately 2 m above the level of the field.

2.3. Statistical Analysis

The PROC MIXED model in the SAS package version 9.2 [11] was implemented to perform an analysis of variance (ANOVA) of all studied traits, and $p < 0.05$ was used to indicate statistical significance. The linear–linear model in the SigmaPlot 14 Software (Systat Software, San Jose, CA, USA) was employed to perform the general linear regression. Significant differences between means were determined by the least significant difference (LSD) test at the 0.05 probability level.

3. Results

3.1. Climatic Conditions

In Yongan, the average mean, maximum, and minimum temperatures of the LRCs/SRCs during the total growth period were 25.4/26.4, 29.9/30.6 °C, and 22.0/23.2 and 25.0/26.0, 31.2/31.2, and 21.3/22.3

°C in 2017 and 2018, respectively. The average mean, maximum, and minimum temperatures of the LRCs/SRCs during the preheading growth phase were 28.6/28.9, 33.1/33.5, and 25.1/25.5 °C and 28.9/29.3, 34.3/34.8, and 25.0/25.5 °C in 2017 and 2018, respectively. The average mean, maximum, and minimum temperatures of the LRCs/SRCs during the postheading phase were 21.1/22.8, 25.4/26.6, and 17.8/19.9 °C and 19.7/21.7, 24.3/26.4, and 16.1/18.1 °C in 2017 and 2018, respectively (Figure 1a,b and Table S1). In Santang, the average mean, maximum, and minimum temperatures of the LRCs and SRCs had the same tendency, also showing higher values for the SRCs than the LRCs (Figure 1c,d and Table S1). The seasonal daily solar radiation of Yongan was 12.9 MJ m^{-2} d^{-1} and 15.6 MJ m^{-2} d^{-1} in the 2017 and 2018 growing seasons, respectively (Figure 1e,f and Table S1). Meanwhile, the seasonal daily solar radiation of Santang was 13.8 MJ m^{-2} d^{-1} and 14.2 MJ m^{-2} d^{-1} in the 2017 and 2018 growing seasons, respectively (Figure 1g,h and Table S1). The 10-year climate conditions of the two experimental sites are given in Table S2.

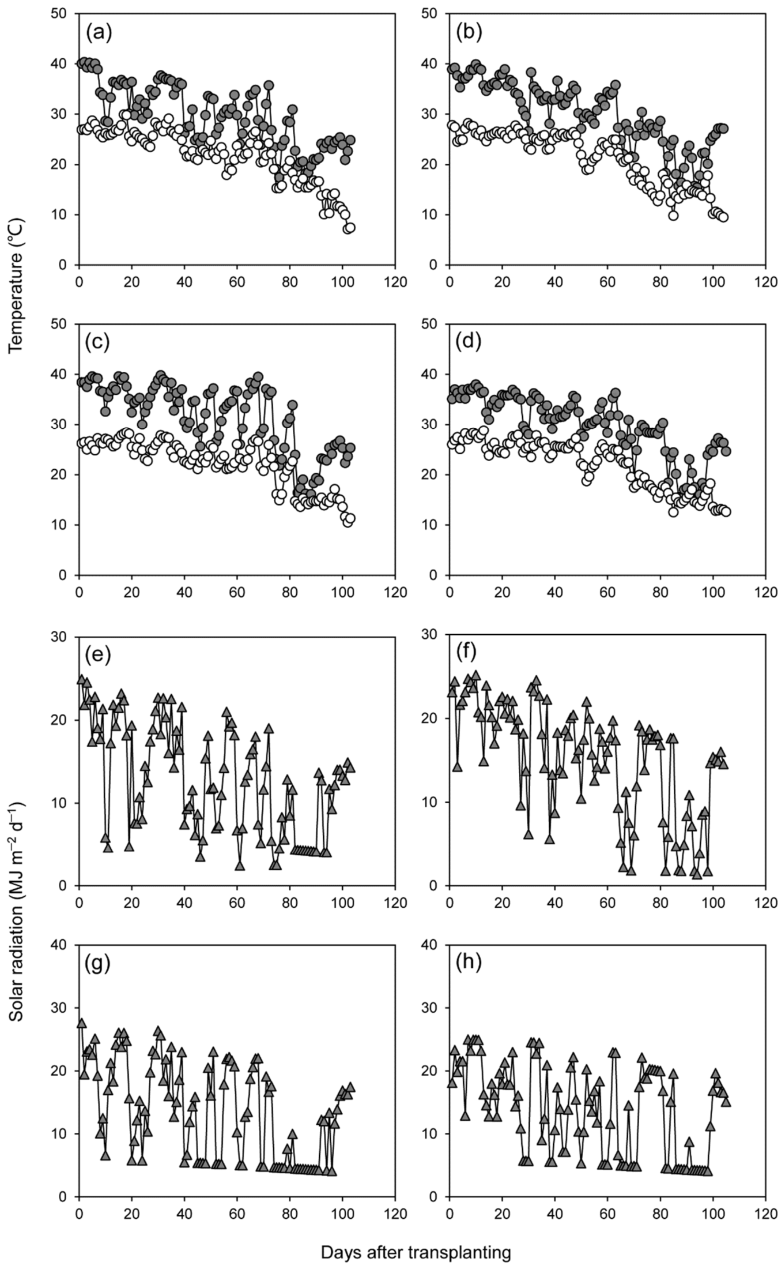

Figure 1. Daily maximum temperature (•), minimum temperature (○), and solar radiation (▲) of Yongan in 2017 (**a**,**e**) and 2018 (**b**,**f**) and of Santang in 2017 (**c**,**g**) and 2018 (**d**,**h**).

3.2. Crop Growth Duration

The SRCs exhibited a shorter growth duration than the LRCs (Table 2). On average, the differences in growth duration of the two experimental sites between the SRCs and LRCs was 11 days in 2017 and 12 days in 2018, which mainly occurred during the preheading and postheading phases. On average, the growth duration of the SRCs was six and five days shorter than that of the LRCs during the preheading and postheading phases, respectively. The duration for the two sites was the same. Overall, the growth duration of the LRCs was longer than that of the SRCs, which was mainly attributed to the preheading phase (Table 3).

Table 2. The *p*-values of the evaluated traits for the four rice cultivars under two different locations over the two growing seasons of 2017 and 2018.

	GD										BA						CGR		CISR		ARUE	
Source of Variance	**TGD**	**Pre-H**	**Post-H**	**GY**	**DGY**	**PN**	**SN**	**SM**	**SF**	**GW**	**Pre-H**	**Post-H**	**TB**	**HI**	**TG**	**SSR**	**Pre-H**	**Post-H**	**Pre-H**	**Post-H**	**Pre-H**	**Post-H**
Season (S)	1.00	0.08	0.00	0.01	0.01	0.00	0.00	0.07	0.60	0.42	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Location (L)	0.35	0.03	0.00	0.00	0.00	0.85	0.00	0.05	0.40	0.00	0.11	0.00	0.00	0.06	0.00	0.65	0.00	0.04	0.00	0.84	0.00	0.22
S × L	0.63	0.44	0.07	0.49	0.71	0.01	0.01	0.00	0.00	0.21	0.00	0.17	0.01	0.04	0.69	0.00	0.75	0.00	0.00	0.08	0.00	0.00
Cultivar types (C)	0.00	0.00	0.00	0.25	0.00	0.75	0.00	0.00	0.00	0.11	0.00	0.00	0.80	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S × C	0.64	0.08	0.07	0.46	0.49	0.29	0.54	0.86	0.68	0.80	0.55	0.54	0.84	0.00	0.64	0.88	0.04	0.29	0.16	0.00	0.05	0.14
L × C	0.64	0.44	0.07	0.14	0.08	0.01	0.38	0.29	0.31	0.44	0.05	0.09	0.01	0.24	0.07	0.31	0.04	0.02	0.30	0.02	0.04	0.04
S × L × C	1.00	0.44	0.00	0.01	0.02	0.82	0.31	0.34	0.04	0.84	0.24	0.16	0.78	0.05	0.58	0.09	0.18	0.38	0.02	0.00	0.44	0.45

$p > 0.05$, no significant difference; $p \leq 0.05$, significant difference; $p \leq 0.01$, highly significant difference. TGD, total growth duration; GD, growth duration; Pre-H, pre-heading; Post-H, post-heading; GY, grain yield; DGY, daily grain yield; PN, number of panicles per m^2; SN, number of spikelets per panicle; SM, number of spikelets per m^2; SF, spikelet filling (%); GW, grain weight; TB, total biomass; HI, harvest index; TG, translation of biomass accumulated before heading to the grain; SSR, source–sink ratio of postheading biomass to spikelets; BA, biomass accumulation; CGR, crop growth rate; CISR, cumulative incident solar radiation; ARUE, apparent radiation use efficiency.

Table 3. Growth duration of the short- and long-duration rice cultivars grown under mechanical transplanting conditions in the 2017 and 2018 growing seasons.

Site	Cultivar Type	Cultivar	Total Growth Duration (d)	Growth Duration of Preheading (d)	Growth Duration of Postheading (d)
2017 growing season					
Yongan	LRC	Shengyou 957	124	54	43
		Tianyouhuazhan	129	59	43
		Mean	127	56.5	43
	SRC	Jiuliangyou 3	116	52	37
		Shengyou 9520	115	50	38
		Mean	116	51	37.5
Santang	LRC	Shengyou 957	124	57	40
		Tianyouhuazhan	129	59	43
		Mean	127	58	41.5
	SRC	Jiuliangyou 3	117	54	36
		Shengyou 9520	115	51	37
		Mean	116	52.5	36.5
2018 growing season					
Yongan	LRC	Shengyou 957	125	58	42
		Tianyouhuazhan	128	60	43
		Mean	127	59	42.5
	SRC	Jiuliangyou 3	116	52	39
		Shengyou 9520	114	50	39
		Mean	115	51	39
Santang	LRC	Shengyou 957	125	57	40
		Tianyouhuazhan	129	59	43
		Mean	127	58	41.5
	SRC	Jiuliangyou 3	116	54	36
		Shengyou 9520	114	51	37
		Mean	115	52.5	36.5

LRC, long-duration rice cultivar; SRC, short-duration rice cultivar.

3.3. Grain Yield and Yield Components

The difference in grain yield between the LRCs and SRCs was not significant, except at Santang in 2017, where the grain yield of the SRCs was significantly higher than that of the LRCs (Table 2). Rice grown in Santang exhibited higher grain yield than that grown in Yongan during both growing seasons. On average, over both experimental sites, the grain yield of the LRCs and SRCs was 7.82 and 8.02 t ha^{-1} in 2017 and 7.62 and 7.66 t ha^{-1} in 2018, respectively. The SRCs achieved a 6% and 17% higher daily grain yield than the LRCs in Yongan and Santang in 2017 and 12% and 9% in 2018, respectively. Overall, the SRCs showed almost the same grain yield as the LRCs, but a higher daily grain yield was observed for the SRCs compared to the LRCs (Table 4).

Table 4. Grain yield and daily grain yield of the short-duration rice cultivars (SRCs) and long-duration rice cultivars (LRCs) grown under mechanical transplanting conditions in the 2017 and 2018 growing seasons.

Site	Cultivar Type	Cultivar	Grain Yield (t ha^{-1})	Daily Grain Yield (kg ha^{-1} d^{-1})
2017 growing season				
Yongan	LRC	Shengyou 957	7.25	58.5
		Tianyouhuazhan	7.70	59.7
		Mean	7.47 a	59.1 a
	SRC	Jiuliangyou 3	6.97	60.1
		Shengyou 9520	7.52	65.4
		Mean	7.25 a	62.7 a
Santang	LRC	Shengyou 957	8.15	65.8
		Tianyouhuazhan	8.18	63.4
		Mean	8.17 b	64.6 b
	SRC	Jiuliangyou 3	8.52	72.8
		Shengyou 9520	9.06	78.8
		Mean	8.79 a	75.8 a
2018 growing season				
Yongan	LRC	Shengyou 957	7.03	56.2
		Tianyouhuazhan	6.84	53.4
		Mean	6.93 a	54.8 b
	SRC	Jiuliangyou 3	7.03	60.6
		Shengyou 9520	7.14	62.7
		Mean	7.09 a	61.6 a
Santang	LRC	Shengyou 957	8.17	65.3
		Tianyouhuazhan	8.45	65.5
		Mean	8.31 a	65.4 b
	SRC	Jiuliangyou 3	8.27	70.7
		Shengyou 9520	8.20	71.3
		Mean	8.23 a	71.0 a

Within the same column for each year, means followed by a different letter are significantly different at the 0.05 significance level according to a least significant difference (LSD) test. LRC, long-duration rice cultivar; SRC, short-duration rice cultivar.

The number of spikelets per m^2 was significantly higher in the LRCs than the SRCs by 4% in 2017 and 16% in 2018 in Yongan. Meanwhile, in Santang, the number of spikelets per m^2 of the LRCs was lower than that of the SRCs (Table 2). The LRCs exhibited a higher number of spikelets per panicle than the SRCs at both experimental sites in the 2017 and 2018 growing seasons.

On average, the number of spikelets per panicle of the LRCs was 8% higher than that of the SRCs, while the spikelet filling percentage of the SRCs was significantly higher (77% in 2017 and 76% in 2018) than that of the LRCs (65% in both 2017 and 2018) across both experimental sites. There were no significant differences in grain weight and spikelets per m^2 between the LRCs and SRCs across the two experimental sites and growing seasons (Table 5).

Table 5. Yield components of the SRCs and LRCs grown under mechanical transplanting conditions in the 2017 and 2018 growing seasons.

Site	Cultivar Type	Cultivar	Panicles m^{-2}	Spikelets $Panicle^{-1}$	Spikelet Filling (%)	Spikelets m^{-2} ($\times 10^3$)	Grain Weight (mg)
	2017 growing season						
Yongan	LRC	Shengyou 957	360	133	67	47.9	28.5
		Tianyouhuazhan	445	131	73	58.5	27.0
		Mean	402 a	132 a	70 b	53.2 a	27.8 a
	SRC	Jiuliangyou 3	394	110	77	43.3	26.9
		Shengyou 9520	381	141	78	53.7	27.8
		Mean	387 a	125 a	77 a	48.5 a	27.4 a
Santang	LRC	Shengyou 957	318	166	66	52.6	28.2
		Tianyouhuazhan	360	179	52	64.3	26.5
		Mean	339 b	172 a	59 b	58.5 a	27.4 a
	SRC	Jiuliangyou 3	410	148	77	60.2	26.2
		Shengyou 9520	368	158	76	57.9	27.0
		Mean	389 a	153 b	77 a	59.1 a	26.6 a
	2018 growing season						
Yongan	LRC	Shengyou 957	313	119	65	37.1	29.8
		Tianyouhuazhan	366	138	53	50.3	26.8
		Mean	339 a	128 a	59 b	43.7 a	28.3 a
	SRC	Jiuliangyou 3	313	118	73	37.0	26.8
		Shengyou 9520	271	120	71	32.5	29.6
		Mean	292 b	119 a	72 a	34.7 b	28.2 a
Santang	LRC	Shengyou 957	299	140	75	41.8	28.2
		Tianyouhuazhan	375	147	65	54.8	26.2
		Mean	337 a	143 a	70 b	48.3 a	27.2 a
	SRC	Jiuliangyou 3	368	128	83	47.0	25.7
		Shengyou 9520	364	142	74	51.4	27.3
		Mean	366 a	135 a	79 a	49.2 a	26.5 a

Within the same column for each year, means followed by a different letter are significantly different at the 0.05 significance level according to an LSD test. LRC, long-duration rice cultivar; SRC, short-duration rice cultivar.

3.4. Biomass Accumulation, Harvest Index, and Crop Growth Rate

The total aboveground biomass, including the biomass production of the preheading and postheading phases, is shown in Table 6. The LRCs produced a higher amount biomass during the preheading phase than the SRCs in both experimental sites in the 2017 and 2018 growing seasons, while the SRCs produced more biomass during the postheading phase.

No significant differences were observed in total biomass accumulation between the LRCs and SRCs in either experimental site or growing season (Table 2). The percentage of postheading biomass accumulation to the total biomass accumulation was significantly higher in the SRCs than in the LRCs. The harvest index of the SRCs ranged from 0.49 to 0.57 with an average of 0.54 (Table 6), while that of the LRCs ranged from 0.44 to 0.52 with an average of 0.48. The SRCs exhibited a harvest index 10%, 21%, 7%, and 4% higher than the harvest index of the LRCs in Yongan and Santang in the 2017 and 2018 growing seasons, respectively. The TG of the SRCs was significantly lower than that of the LRCs in both experimental sites and growing seasons, while the source–sink ratio of the postheading biomass to spikelets (SSR) showed the opposite results.

Compared to the LRCs, the SRCs showed a lower crop growth rate during the preheading growth phase, while the growth rate was higher during the postheading growth phase (Table 7). The crop growth rate of the LRCs ranged from 17.0 to 22.2 g m^{-2} d^{-1} with an average of 19.0 g m^{-2} d^{-1} in the preheading phase, which was, on average, 6% higher than that of the SRCs. Meanwhile, the crop growth rate of the SRCs ranged from 9.6 to 24.1 g m^{-2} d^{-1} with an average of 19.6 g m^{-2} d^{-1} in the postheading phase, which was, on average, 56% higher than that of the LRCs. The crop growth rate had a strong positive linear correlation with apparent radiation use efficiency (Figure 2).

Table 6. Aboveground biomass accumulation and harvest index of the SRCs and LRCs grown under mechanical transplanting conditions in the 2017 and 2018 growing seasons.

Site	Cultivar Type	Cultivar	Biomass Accumulation (g m^{-2})			Harvest Index	TG (g m^{-2})	SSR (mg Spikelet^{-1})
			Preheading [A]	Postheading	Total Biomass			
2017 growing season								
Yongan	LRC	Shengyou 957	1010 (63)	601 (37)	1611	0.49	152	12.4
		Tianyouhuazhan	1196 (60)	792 (40)	1989	0.50	117	13.4
		Mean	1103 (62) a	696 (38) a	1800 a	0.50 b	134 a	12.9 b
	SRC	Jiuliangyou 3	859 (59)	594 (41)	1453	0.53	96	13.6
		Shengyou 9520	870 (49)	914 (51)	1785	0.56	8	17.0
		Mean	865 (54) b	754 (46) a	1619 a	0.55 a	52 b	15.3 a
Santang	LRC	Shengyou 957	1176 (72)	460 (28)	1635	0.51	315	8.7
		Tianyouhuazhan	1309 (75)	445 (25)	1754	0.44	293	6.9
		Mean	1242 (73) a	452 (27) b	1695 a	0.47 b	304 a	7.8 b
	SRC	Jiuliangyou 3	1072 (59)	748 (41)	1820	0.57	183	12.4
		Shengyou 9520	971 (53)	863 (47)	1834	0.56	93	14.9
		Mean	1022 (56) b	805 (44) a	1827 a	0.57 a	138 a	13.6 a
2018 growing season								
Yongan	LRC	Shengyou 957	988 (78)	275 (22)	1263	0.49	278	7.5
		Tianyouhuazhan	1124 (80)	291 (20)	1415	0.44	270	5.7
		Mean	1056 (79) a	283 (21) b	1339 a	0.46 b	274 a	6.6 b
	SRC	Jiuliangyou 3	814 (66)	414 (34)	1228	0.51	133	11.2
		Shengyou 9520	817 (69)	374 (31)	1192	0.49	185	11.5
		Mean	816 (68) b	394 (32) a	1210 a	0.50 a	159 b	11.3 a
Santang	LRC	Shengyou 957	1045 (72)	424 (28)	1469	0.51	271	10.0
		Tianyouhuazhan	1121 (68)	556 (32)	1677	0.48	193	7.8
		Mean	1083 (70) a	490 (30) a	1573 a	0.50 a	232 a	9.9 b
	SRC	Jiuliangyou 3	1125 (68)	532 (32)	1657	0.52	198	11.3
		Shengyou 9520	908 (52)	829 (48)	1737	0.52	28	16.2
		Mean	1016 (60) a	681 (40) a	1697 a	0.52 a	113 b	13.7 a

[A] The data in parentheses represent the percentage of preheading and postheading dry matter production to the total biomass accumulation. Within the same column for each year, means followed by different letters are significantly different at the 0.05 significance level according to an LSD test. LRC, long-duration rice cultivar; SRC, short-duration rice cultivar; TG, translation of biomass accumulated before heading to the grain; SSR, source–sink ratio of postheading biomass to spikelets.

Table 7. Crop growth rate of the SRCs and LRCs grown under mechanical transplanting conditions in 2017 and 2018 growing seasons.

Site	Cultivar Type	Cultivar	Crop Growth Rate (g m^{-2} d^{-1})	
			Preheading	Postheading
2017 growing season				
Yongan	LRC	Shengyou 957	18.7	14.0
		Tianyouhuazhan	20.3	18.4
		Mean	19.5 a	16.2 a
	SRC	Jiuliangyou 3	16.5	16.1
		Shengyou 9520	17.4	24.1
		Mean	17.0 b	20.1 a
Santang	LRC	Shengyou 957	20.6	11.5
		Tianyouhuazhan	22.2	10.4
		Mean	21.4 a	10.9 b
	SRC	Jiuliangyou 3	19.9	20.8
		Shengyou 9520	19.0	23.3
		Mean	19.4 b	22.0 a

Table 7. *Cont.*

Site	Cultivar Type	Cultivar	Crop Growth Rate (g m^{-2} d^{-1})	
			Preheading	Postheading
2018 growing season				
Yongan	LRC	Shengyou 957	17.0	6.6
		Tianyouhuazhan	18.7	6.8
		Mean	17.9 a	6.7 b
	SRC	Jiuliangyou 3	15.7	10.6
		Shengyou 9520	16.3	9.6
		Mean	16.0 b	10.1 a
Santang	LRC	Shengyou 957	18.3	9.9
		Tianyouhuazhan	18.4	12.9
		Mean	18.4 a	11.4 b
	SRC	Jiuliangyou 3	20.8	14.4
		Shengyou 9520	17.8	21.8
		Mean	19.3 a	18.1 a

Within the same column for each year, means followed by a different letter are significantly different at the 0.05 significance level according to an LSD test. LRC, long-duration rice cultivar; SRC, short-duration rice cultivar.

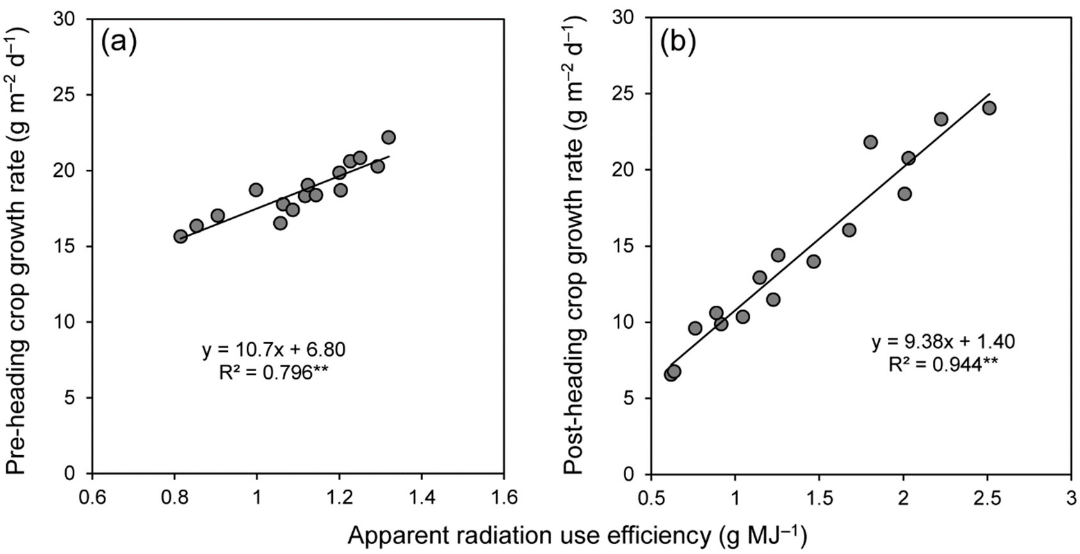

Figure 2. Relationships between the preheading (**a**) and postheading (**b**) crop growth rates and apparent radiation use efficiency. Each data point is the average of three replications. ** Significance at the 0.01 probability level.

3.5. Apparent Radiation Use Efficiency

The apparent radiation use efficiency significantly differed among cultivars and growing seasons and was lower in the preheading than the postheading phase (Table 2). Except for Santang in 2018, the LRCs showed significantly higher values of apparent radiation use efficiency than the SRCs in the preheading phase in 2017 and 2018. Meanwhile, during the postheading phase, the SRCs showed a significantly higher apparent radiation use efficiency than the LRCs only in Santang in the 2018 growing season (Table 8). On average, across both experimental sites and growing seasons, the SRCs exhibited 8% lower and 43% higher apparent radiation use efficiency than the LRCs in the preheading and postheading phases, respectively.

Table 8. Cumulative incident solar radiation and apparent radiation use efficiency of the SRCs and LRCs grown under mechanical transplanting conditions in the 2017 and 2018 growing seasons.

Site	Cultivar Type	Cultivar	Cumulative Incident Solar Radiation (MJ m^{-2})		Apparent Radiation Use Efficiency (g MJ^{-1})	
			Preheading	Postheading	Preheading	Postheading
	2017 growing season					
Yongan	LRC	Shengyou 957	840	410	1.20	1.47
		Tianyouhuazhan	925	394	1.29	2.01
		Mean	883	402	1.25 a	1.74 a
	SRC	Jiuliangyou 3	815	354	1.06	1.68
		Shengyou 9520	801	364	1.09	2.51
		Mean	808	359	1.07 b	2.10 a
Santang	LRC	Shengyou 957	959	374	1.23	1.23
		Tianyouhuazhan	990	426	1.32	1.05
		Mean	975	400	1.27 a	1.14 b
	SRC	Jiuliangyou 3	894	368	1.20	2.03
		Shengyou 9520	866	388	1.12	2.23
		Mean	880	378	1.16 b	2.13 a
	2018 growing season					
Yongan	LRC	Shengyou 957	1092	445	0.90	0.62
		Tianyouhuazhan	1126	457	1.00	0.64
		Mean	1109	451	0.95 a	0.63 a
	SRC	Jiuliangyou 3	1000	467	0.81	0.89
		Shengyou 9520	958	491	0.85	0.76
		Mean	979	479	0.83 b	0.83 a
Santang	LRC	Shengyou 957	934	464	1.12	0.92
		Tianyouhuazhan	979	486	1.14	1.15
		Mean	957	475	1.13 a	1.03 a
	SRC	Jiuliangyou 3	899	424	1.25	1.26
		Shengyou 9520	854	459	1.06	1.81
		Mean	876	441	1.16 a	1.53 a

Within the same column for each year, means followed by a different letter are significantly different at the 0.05 significance level according to an LSD test. LRC, long-duration rice cultivar; SRC, short-duration rice cultivar.

4. Discussion

The sustainable cultivation and production of rice is of great importance for ensuring food security for a large proportion of the world population and for combating poverty. Therefore, great efforts are required to improve rice productivity and to select and identify rice cultivars that can cope with the negative consequences of climate changes. The development of mechanized large-scale double-season rice (i.e., early- and late-season rice) production in China, which is one of the pivotal strategies for achieving sustainable rice production, necessitates the development and identification of high-yielding SRCs.

In the current study, four rice cultivars, i.e., Shengyou 957 and Tianyouhuazhan (the LRCs) and Jiuliangyou 3 and Shengyou 9520 (the SRCs), were evaluated for their growth, yield, and yield-contributing traits to identify high-yielding SRCs that are suitable for late-season machine transplantation.

The results showed that the SRCs exhibited an 11−12-day shorter growth duration than the LRCs. Generally, the yield of rice is most directly related to the growth duration, and the total growth duration is an important factor that can limit the grain yield [12,13]. However, in the present study, the overall average grain yield of the SRCs was similar to that of the LRCs and was significantly higher than that of the LRCs in Santang in the 2017 growing season. A higher daily grain yield, an important criterion for judging the productivity of the rice cultivars with short growth durations [14,15], directly contributed to the yield of the SRCs. Therefore, a higher daily grain yield could be a target for breeding high-yielding cultivars with short growth durations.

In the present study, the SRCs showed a 10–31% higher spikelet filling rate than the LRCs, which compensated for their lower number of spikelets per panicle. The grain filling rate in rice is a critical determinant of grain yield and is influenced by ambient environmental conditions [16]. No cold stress appeared during the 15 days prior to heading through to 7 days after heading. The higher grain filling rate of the SRCs compared to the LRCs could be due to the higher SSR, which was predominantly caused by the higher biomass accumulation in the postheading phase (Table 6). Meanwhile, the higher postheading biomass accumulation of the SRCs was mainly because of their heading date, i.e., approximately one week earlier than that of the LRCs, which led the SRCs experiencing higher temperatures (approximately 2 °C higher) during the postheading phase compared to the LRCs (Figure 1 and Table S1). However, the variations in grain filling between the LRCs and SRCs need further study.

The data revealed significant differences in the yield-contributing traits between the two sets of rice cultivars. Several alternative hypotheses for the lower yield of the LRCs compared to the SRCs, despite the increased resource availability, include the lower harvest index [17], the increased lodging susceptibility and the inability to utilize stored nitrogen resources to enhance yield potentials [18], the lower photosynthetic efficiency [19], and the lower photosynthetic capacity of older leaves [20]. The harvest index of modern high-yielding rice is approximately 0.5 [21]. However, our data showed that, compared to the lower harvest index of the LRCs, the SRCs exhibited a harvest index as high as 0.57 (Table 4), which was positively correlated with grain yield. The importance of the harvest index in enhancing the grain yield of rice cultivars with short growth durations and the association between long growth durations and reduced yield as a result of a reduced harvest index have been widely reported [17,22,23]. Plant physiologists believe that the upper limit of the harvest index for rice is 0.62 [24]. Therefore, it is suggested that developing cultivars with a high harvest index through breeding programs is a possible approach for increasing the grain yield of SRCs.

The harvest index is determined by transient photosynthesis during the postheading phase and/or by the remobilization of stored reserves during the preheading phase [25]. The SRCs exhibited a significantly higher biomass accumulation and biomass percentage during the postheading phase, as well as a lower biomass accumulation and biomass percentage during the preheading phase. Meanwhile, the TG of the SRCs was significantly lower than that of the LRCs (Table 6), indicating that the higher harvest index of the SRCs compared to that of the LRCs was driven by transient photosynthesis during grain formation rather than by remobilization of stored reserves into the growing grain. This result also indicates that dry matter accumulation during the postheading phase is an important factor for grain yield, which is consistent with results from previous studies [26,27]. The higher dry matter accumulation of the SRCs compared to that of the LRCs during the postheading phase was mainly caused by the higher temperature they experienced in the postheading phase (Table S1).

The higher postheading biomass accumulation of the SRCs compared to the LRCs was mainly due to the higher crop growth rate in the postheading phase, and the higher crop growth rate mainly contributed to the higher apparent radiation use efficiency (Figure 2). The representativeness of apparent radiation use efficiency has been confirmed in a previous study [28], which can be used to reflect the efficiency of using radiation, which is closely related to dry matter production [10,29,30].

There were significant differences in grain yield between the two experimental sites. The average grain yield over the two growing seasons in Santang was 17% higher than that in Yongan. The higher yield in Santang could be attributed to the higher number of spikelets per panicle and the higher biomass accumulation compared to Yongan. The higher biomass accumulation in Santang is likely due to higher crop growth rate and apparent radiation use efficiency compared to Yongan. The higher crop growth rate in Santang may due to the higher temperatures, especially the temperature in postheading phase. Meanwhile, in 2017 the grain yield was 3% and 5% higher than in 2018 in Santang and Yongan, respectively. The higher grain yield in the 2017 growing season is mainly due to the higher biomass accumulation compared to that in the 2018 growing season, which, in turn, is mainly due to the apparent radiation use efficiency during the postheading phase.

In conclusion, early-season rice cultivars selected for mechanical transplantation in the late-season growing system should meet two criteria: (1) they should produce a high grain weight and (2) they should exhibit high apparent radiation use efficiency. The SRCs better adapted to mechanical transplantation in the late season, showing a shorter growth period, a higher spikelet filling rate, and a higher harvest index. The significantly higher biomass accumulation, crop growth rate, and apparent radiation use efficiency in the SRCs compared to the LRCs during the postheading phase suggest that these traits are decisive factors in SRC productivity.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/10/9/1307/s1, Table S1: Daily average, maximum, and minimum temperatures and solar radiation during the 2017 and 2018 growing seasons across the Yongan and Santang experimental sites, Table S2: A 10-year climate conditions of the two experimental sites Yongan and Santang.

Author Contributions: Conceptualization, M.H. and Y.Z.; formal analysis, J.C. and M.H.; funding acquisition, M.H.; investigation, J.C., F.C., X.Y. and R.Z.; visualization, J.C. and S.F.A.-E.; writing—original draft, J.C. and S.F.A.-E.; writing—review and editing, S.F.A.-E. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key R&D Program of China (Grant No. 2017YFD0301503).

Acknowledgments: This work was supported by the National Key R&D Program of China (Grant No. 2017YFD0301503).

Conflicts of Interest: The authors declare that there are no conflict of interest.

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