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Comparison of Short-Duration and Long-Duration Rice Cultivars Cultivated in Various Planting Densities

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Abstract: The selection of high-yielding, short-duration rice cultivars is essential for the double-rice cropping system. High hill density could be achieved with less labor under machine transplanted conditions. Therefore, dense planting is more practical for machine-transplanted rice. While few studies have been conducted to certify the feasibility of short-duration cultivar combined with dense planting in machine transplanted conditions. The current study was executed to determine the effects of dense planting on yield attributes and grain yield of short-duration cultivars under mechanically transplanted conditions. A field experiment comprises two treatments—i.e., the short-duration cultivar Lingliangyou104 cultivated at a high planting density (SDH) and the long-duration Taiyou390 cultivar cultivated at a low planting density (LDL)—were conducted in the 2018 and 2019 late seasons. The results showed that the SDH exhibited 17% and 19% higher panicle number in a unit, 26% and 24% higher spikelet filling, 8% and 8% higher grain weight, 21% and 11% higher harvest index, and consequently 12% and 4% higher grain yield and 13 and 15 days shortened growth duration compared to the LDL in the 2018 and 2019, respectively. The data revealed that the difference in grain yield between the SDH and LDL was mainly due to the higher harvest index and reasonable dry matter distribution of the SDH, which was conducive to improving yield components and increasing rice grain yield. As a result, short-duration rice cultivars combined with dense planting is a feasible strategy for improving the grain yield of mechanically transplanted late rice.

Keywords: dense planting; late rice; machine-transplanted; short growth duration; yield

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1. Introduction

The rural working-age labor force has reduced on a large scale with the rapid economic development in recent years. The production of double-cropping rice urgently needs to introduce modern agricultural production technology and professional facilities Mechanization has become the main way to develop double-cropping rice production [1,2]. The transfer from manually transplanted rice to mechanically transplanted rice has resulted in large rice seeding rates, which has been used to avoid the loss of grain yield from missing plants due to low seed germination rate. The seedling age was shortened under such high seeding rates [3]. Meanwhile, a new class of farmers who rented large-scale farming emerged in recent years in China [4]. Under such large-scale farming systems, the increased operation time of farming made the growth duration of rice to be further shortened. The shortened time of the rice growth duration is approximately equal to that of the increase in operation time of farming. Farmers would prefer to choose short-growth-duration rice cultivars to allow for added farming operation time. Therefore, the growth duration of rice becomes a determinant key factor of crop productivity in double-season rice systems, and reducing the growth duration of rice is essential for implementing the double-rice cropping system. The selection and identification of short-duration rice cultivars and the techniques associated with high-yielding of short-duration rice are essential for the double-season rice system.

Rice yield is mostly associated with growth duration. In a certain growth period, rice yield increases with the extension of the growth duration, and the number of days of the whole growth duration is one of the important yield limit factors [5–7]. However, some rice cultivars with short growth duration also had high yields [7–9], indicating that short growth duration rice cultivars also have high yield potential. Because of the short growth duration, the biomass accumulation of the short growth duration cultivars is generally lower than that of the long growth duration cultivars. Therefore, it is believed that the high biomass production of the short-growth duration cultivars is a prerequisite for high yield and high crop growth rate [6,10–12]. The formation of crop yield is not only a process of biomass accumulation but also a process of biomass distribution [13–16]. Crop yield mainly depends on the accumulation of dry matter and the proportion of dry matter distributed to grains [17]. Therefore, the harvest index is also an important factor affecting rice grain yield [18–20]. The yield of rice is the result of the comprehensive effect of genetic characteristics of cultivars and cultivation environment conditions. Among various cultivation measures, density is one of the key factors affecting the development of rice growth and yield formation [5,21–24]. Dense planting is more practical for machine-transplanted rice. However, few studies have been conducted to certify the feasibleness of dense planting combined with a short-duration cultivar in machine transplanted conditions.

A rice cultivar with a long growth duration and a rice cultivar with a short growth duration were evaluated with two planting densities under the mechanically transplanted condition in this study. The yield, yield contributions, dry matter accumulation, net assimilation rate, and carbon accumulation were investigated. The purpose of the study was to identify whether dense planting with a short-duration rice cultivar is a feasible way of mechanically transplanting late rice.

2. Materials and Methods

2.1. Plant Material and Field Experiments

Experiments were carried out in the late season, from late June to mid-October in 2018 and 2019 in Yongan, Hunan Province, China (28°09′ N, 113°37′ E, 43 m asl). Two treatments were implemented in this study: i.e., (1) the first treatment involves the short-duration cultivar Lingliangyou104 cultivated at a high planting density of 25 × 11 cm, was designated (SDH); and (2) the second treatment involves the long-duration Taiyou390 cultivar cultivated at a low planting density of 25 × 17 cm, was designated (LDL). The soil of the experimental field has the following properties: pH = 6.12, organic matter = 34.3 g kg^{-1}, the available N = 164 mg kg^{-1}, the available P = 20.1 mg kg^{-1}, and the available K = 113 mg kg^{-1}. Soil samples were collected from the upper 20 cm layer of the experimental site soil in 2018 before the beginning of the experiments.

2.2. Experimental Design and Measurements

Three replications were conducted in the experiment and designed in a randomized block. The plot size was 60 m^2. Seeds were printed on particular paper [25]. The printed seeds were sown on 25 June. A high-speed rice transplanter was used to transplant the 23-day-old seedlings. The nitrogen (150 kg N ha^{-1}) was split-applied with 50% one day before transplanting, 30% at the mid-tillering stage, and 20% at the panicle initiation stage. Phosphorus (75 kg P_2O_5 ha^{-1}) was applied as a basal fertilizer. Potassium (150 kg K_2O ha^{-1}) was 50% applied basally and 50% at panicle initiation. The experimental field was kept with hallow irrigation (2–3 cm), midseason drainage (10–15 d), and shallow irrigation until 7 days before maturity. Chemicals were used to control pests, weeds, and diseases.

2.3. Phenotypic Evaluation

At the panicle initiation stage (PI), booting stage (BT), heading stage (HD), 10 days after heading (HD10), and 20 days after heading (HD20), 10 hills were sampled from all plots diagonally. The straw, leaves, and panicles were separated by hand. Leaf area was measured by a LI -3000C portable leaf areometer. All parts were dried to a constant weight in an oven at 70 °C.

At the maturity stage (MA), 10 hills were sampled from the middle of the plot diagonally. The panicles of each hill were counted to calculate the panicles per unit of land. The straw (including rachis) and spikelets were manually separated. The submergence in water was implemented to separate filled from unfilled spikelets. Three subsamples of 30 g of the filled grain and all unfilled spikelets were counted by hand. After oven-drying at 70 °C to a constant weight, straw, filled, and unfilled spikelets were weighed. Grain yield was estimated from an area of 5 m^2 in each plot and adjusted to a standard moisture content of 14%. The daily grain yield was estimated by dividing grain yield by the number of days of the total growth period from sowing to the maturity stage.

2.4. Statistical Analysis

The Statistix 8.0 software (Analytical Software, Tallahassee, FL, USA) was employed for the analysis of the variance of all measured phenotypic traits. Significantly different means were compared by the least significant difference (LSD) test at the 0.05 probability level.

3. Results

3.1. Climatic Conditions

The average maximum (max) and minimum (min) temperatures of the SDH/LDL during the growing season were 31.8/30.2 and 22.8/21.5 °C, and 32.8/31.6 and 22.7/21.4 °C in 2018 and 2019, respectively. The average max and min temperatures of the SDH/LDL during the transplanting to heading stage were 34.8/34.3 °C and 25.6/25.0 °C, and 35.7/34.9 °C and 25.6/25.0 °C in 2018 and 2019, respectively. The average max and min temperatures of the SDH/LDL during the heading to maturity stage were 27.5/23.9 °C and 18.6/16.1 °C, and 28.5/26.2 °C and 18.5/15.7 °C in 2018 and 2019, respectively (Figure 1a,b). Seasonal daily solar radiation of SDH/LDL was 16.7/15.2 MJ m^{-2} d^{-1} and 17.2/16.3 MJ m^{-2} d^{-1} in 2018 and 2019, respectively (Figure 1c,d).

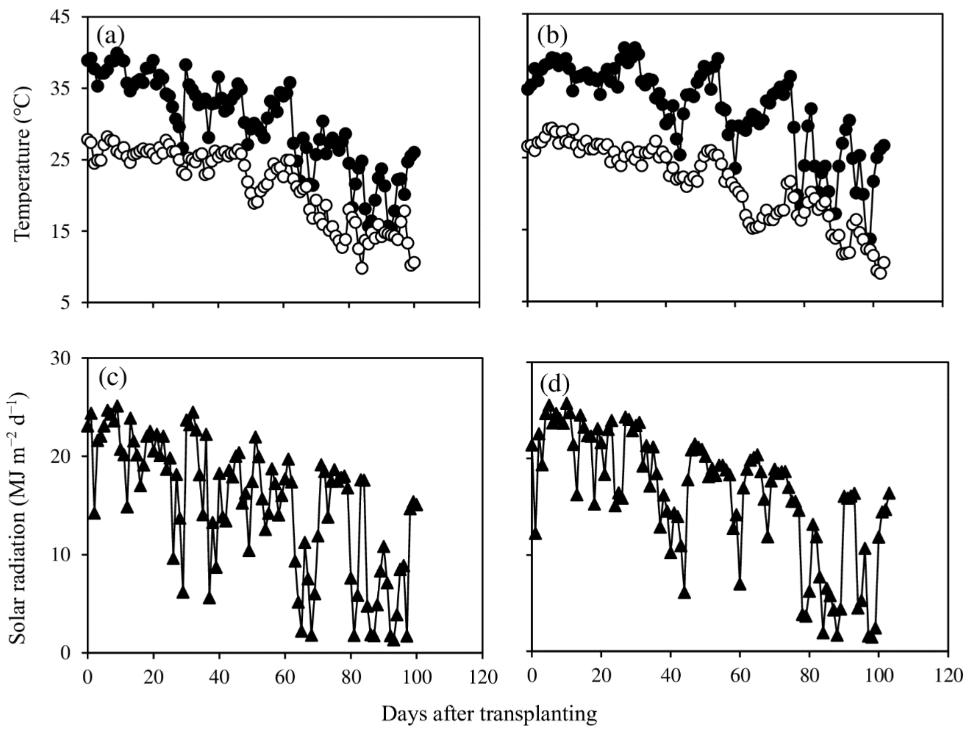

Figure 1. Daily maximum temperature (•), minimum temperature (○), and solar radiation (▲) in 2018 (**a**,**c**) and 2019 (**b**,**d**).

3.2. Crop Growth Duration

Compared to the LDL, SDH exhibited a shorter growth duration period (Table 1). The average differences in growth duration between the SDH and LDL were 15 and 13 days in 2018 and 2019, respectively, which mainly occurred during the transplanting to heading stage. On average, the growth duration period of the SDH was 10 and 4 days shorter than that of the LDL in transplanting to heading and heading to maturity stage in 2018 and 2019, respectively (Table 1).

Table 1. Grain yield, daily grain yield, and growth duration of two growth duration rice cultivars under two planting densities in 2018 and 2019.

Year	Cultivar	Density	Grain Yield ($t\ hm^{-2}$)	Daily Grain Yield ($kg\ hm^{-2}\ d^{-1}$)	Growth Duration (d)	Days of TP to HD (d) *	Days of HD to MA (d) *
2018	Lingliangyou 104	25 × 11 cm	7.55 a	69.9 a	108	50	35
	Taiyou 390	25 × 17 cm	6.75 a	54.9 b	123	60	40
2019	Lingliangyou 104	25 × 11 cm	6.63 a	58.7 a	113	53	37
	Taiyou 390	25 × 17 cm	6.38 a	50.6 a	126	63	40

Means followed by the same letters are not significantly different according to LSD (0.05). * TP: transplanting; HD: heading stage; MA: maturity stage.

3.3. Grain Yield and Yield Components

The grain yield of SDH was 12% and 4% higher than LDL, and the daily grain yield of SDH was 27% and 16% higher than that of LDL, in 2018 and 2019, respectively (Table 1). SDH revealed 17% and 19% higher in panicles per m^2, 26% and 24% higher in spikelet filling percentage, and 8% and 8% higher in grain weight compared to LDL in 2018 and 2019, respectively. Meanwhile, the spikelets per panicle in SDH were significantly lower than that of LDL in 2018 and 2019 (Table 2).

Table 2. Yield components of two growth-duration rice cultivars under two planting densities in 2018 and 2019.

Year	Cultivar	Density	Panicles per m^2	Spikelets per Panicle	Spikelet Filling (%)	Grain Weight (mg)
2018	Lingliangyou 104	25 × 11 cm	406 a	90 b	73.8 a	29.3 a
	Taiyou 390	25 × 17 cm	347 b	134 a	58.4 b	27.2 b
2019	Lingliangyou 104	25 × 11 cm	340 a	98 b	74.4 a	29.8 a
	Taiyou 390	25 × 17 cm	285 a	150 a	59.8 a	27.5 b

Means followed by the same letters are not significantly different according to LSD (0.05).

3.4. Biomass Accumulation and Harvest Index

The total aboveground biomass of LDL was significantly higher than the SDH treatment (Table 3). LDL produced higher biomass of PI and BT than SDH in the two years, while SDH produced more biomass during the HD and MA. The main difference in biomass accumulation between the two treatments mainly occurred during the period from transplanting to the panicle initiation stage and from the HD to MA (Table 4). The proportion of biomass accumulation from transplanting to panicle initiation stage to the total biomass accumulation was significantly higher in LDL compared to SDH, whereas it was significantly higher in SDH post-heading. SDH exhibited a harvest index of 0.52 in the two years which was 21% and 11% higher than that of the LDL (0.43 and 0.47) in 2018 and 2019, respectively.

The dry weight ratio of leaf, stem, and panicle to the total biomass of the two treatments showed the maximum values at the PI, BT, and MA, respectively (Table 5). The dry weight ratio of leaf to the total biomass of SDH was significantly lower than that of LDL at PI, while it was higher than LDL from BT to HD. The LAI of SDH was lower than LDL at PI and BT (Figure 2), while SDH exhibited a higher LAI than LDL from HD to MA, and it declined more slowly.

Table 3. Aboveground biomass accumulation and harvest index of two growth duration rice cultivars under two planting densities in 2018 and 2019.

Year	Cultivar	Density	Dry Matter of Growth Stage (g m^{-2}) *						Harvest Index
			PI	BT	HD	HD10	HD20	MA	
2018	Lingliangyou 104	25 × 11 cm	283 b	473 b	741 b	973 a	1166 a	1296 b	0.52 a
	Taiyou 390	25 × 17 cm	377 a	593 a	867 a	927 a	1116 a	1472 a	0.43 b
2019	Lingliangyou 104	25 × 11 cm	242 b	448 b	817 a	1001 a	1119 a	1231 a	0.52 a
	Taiyou 390	25 × 17 cm	300 a	660 a	881 a	970 a	1075 a	1310 a	0.47 a

Means followed by the same letters are not significantly different according to LSD (0.05). * PI: panicle initiation; BT: booting stage; HD: heading stage; HD10: 10 days after heading; HD20: 20 days after heading; MA: maturity stage.

Table 4. Biomass accumulated at different growth stages of two growth-duration rice cultivars under two planting densities in 2018 and 2019.

Year	Cultivar	Density	TP to PI *	PI to BT	BT to HD	HD to HD10	HD10 to HD20	HD20 to MA
			g m^{-2} (%)	g m^{-2} (%)	g m^{-2} (%)	g m^{-2} (%)	g m^{-2} (%)	g m^{-2} (%)
2018	Lingliangyou 104	25 × 11 cm	283 b (22 a)	190 a (15 a)	268 a (21 a)	231 a (18 a)	193 a (15 a)	130 b (10 a)
	Taiyou 390	25 × 17 cm	377 a (26 a)	216 a (15 a)	275 a (19 a)	59 b (4 b)	189 a (13 a)	356 a (24 a)
2019	Lingliangyou 104	25 × 11 cm	242 b (20 a)	206 b (17 b)	370 a (30 a)	184 a (15 a)	118 a (10 a)	112 a (9 a)
	Taiyou 390	25 × 17 cm	300 a (23 a)	360 a (27 a)	221 b (17 b)	89 b (7 b)	105 a (8 a)	235 a (18 a)

Means followed by the same letters are not significantly different according to LSD (0.05). * TP: transplanting; PI: panicle initiation stage; BT: booting stage; HD: heading stage; HD10: 10 days after heading; HD20: 20 days after heading; MA: maturity stage.

Table 5. Dry weight ratio of leaves, stem, and panicle to total biomass at different growth stages of two growth-duration rice cultivars under two planting densities in 2018 and 2019.

Year	Cultivar	Density	Ratio of Leave (%) *						Ratio of Stem (%) *						Ratio of Panicle (%) *			
			PI	BT	HD	HD10	HD20	MA	PI	BT	HD	HD10	HD20	MA	HD	HD10	HD20	MA
2018	Lingliangyou 104	25 × 11 cm	38 b	36 a	25 a	20 a	15 b	10 b	62 a	64 a	57 a	46 a	31 b	28 b	18 a	34 a	55 a	61 a
	Taiyou 390	25 × 17 cm	42 a	34 a	23 b	20 a	16 a	14 a	58 b	66 a	58 a	44 a	34 a	31 a	19 a	36 a	50 b	55 b
2019	Lingliangyou 104	25 × 11 cm	40 b	36 a	22 a	18 a	15 a	12 b	60 a	64 b	61 a	50 b	37 a	28 a	17 a	31 a	49 a	60 a
	Taiyou 390	25 × 17 cm	44 a	30 b	24 a	18 b	16 b	13 a	56 b	70 a	59 a	54 a	34 a	28 a	17 a	29 b	50 a	59 b

Means followed by the same letters are not significantly different according to LSD (0.05). * PI: panicle initiation stage; BT: booting stage; HD: heading stage; HD10: 10 days after heading; HD20: 20 days after heading; MA: maturity stage.

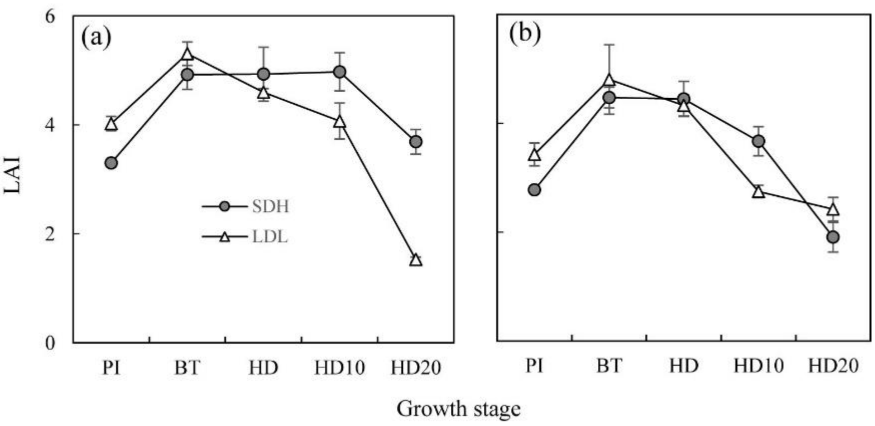

Figure 2. Leaf area index (LAI) of two growth-duration rice cultivars under two planting densities in 2018 (**a**) and 2019 (**b**). PI: panicle initiation stage; BT: booting stage; HD: heading stage; HD10: 10 days after heading; HD20: 20 days after heading.

3.5. Carbon Accumulation and Net Assimilation Rate

Compared to LDL, SDH showed significantly lower carbon accumulation from transplanting to panicle initiation stage in the 2018 and 2019 growing seasons, whereas carbon accumulation of SDH was significantly higher from HD to HD20 (Table 6). The net assimilation rate of the two treatments showed inconsistent patterns during the two growing seasons (Table 7). However, SDH exhibited a higher net assimilation rate from BT to HD10.

Table 6. Carbon accumulated at different growth stages of two growth-duration rice cultivars under two planting densities in 2018 and 2019.

Year	Cultivar	Density	Carbon Accumulation (g m^{-2}) *				
			TP to PI	PI to BT	BT to HD	HD to HD10	HD10 to HD20
2018	Lingliangyou 104	25 × 11 cm	110 b	76 b	107 a	90 a	79 a
	Taiyou 390	25 × 17 cm	145 a	89 a	105 a	16 b	82 a
2019	Lingliangyou 104	25 × 11 cm	96 b	75 b	142 a	103 a	54 a
	Taiyou 390	25 × 17 cm	114 a	132 a	118 b	52 b	40 a

Means followed by the same letters are not significantly different according to LSD (0.05). * TP: transplanting day; PI: panicle initiation stage; BT: booting stage; HD: heading stage; HD10: 10 days after heading; HD20: 20 days after heading.

Table 7. Net assimilation rate of two growth-duration rice cultivars under two planting densities in 2018 and 2019.

Year	Cultivar	Density	Net Assimilation Rate (g m^{-2} d^{-1}) *			
			PI to BT	BT to HD	HD to HD10	HD10 to HD20
2018	Lingliangyou 104	25 × 11 cm	4.68 a	5.46 a	4.68 a	4.51 a
	Taiyou 390	25 × 17 cm	4.65 a	5.56 a	1.38 b	7.29 a
2019	Lingliangyou 104	25 × 11 cm	5.81 b	8.28 a	4.54 a	4.37 a
	Taiyou 390	25 × 17 cm	8.83 a	4.87 b	2.57 b	4.05 a

Means followed by the same letters are not significantly different according to LSD (0.05). * PI: panicle initiation stage; BT: booting stage; HD: heading stage; HD10: 10 days after heading; HD20: 20 days after heading; MA: maturity stage.

4. Discussion

For rice cultivars with different growth duration, the length of each growth stage and the meteorological conditions at the same growth stage will be different, which may lead to the difference in biomass accumulation and yield formation. It has been widely reported that the yield potential of rice is associated with the extension of growth duration under the normal condition [6,7]. However, in this study, the short duration cultivar cultivated at high planting density (SDH) showed 12% and 4% higher grain yield compared to the long duration cultivar cultivated at low planting density (LDL), suggesting that cultivating short duration rice at a high transplanting density can achieve high grain yield under mechanized-transplanted conditions.

Sink size consists of panicles per m^2 and spikelets per panicle. In the present study, SDH revealed a smaller sink size but higher spikelet filling rate and grain weight, which compensated for its small sink size. The heading date of SDH was about 10 days earlier than LDL which led to the SDH having experienced higher temperatures during the post-heading period compared to the LDL (Figure 1). The higher grain filling rate and grain weight of the SDH were mainly due to the exposure to these higher temperatures.

Rice grain yield is the result of dry matter accumulation, distribution, transportation, and transformation [13–16,26]. The rice cultivars with different growth duration require differential growth environmental conditions and have different utilization of nutrients, temperatures, and light resources, which to some extent affect their growth. In this study, significant differences in yield-related traits between the SDH and LDL were observed. The total dry matter accumulation of the SDH was lower than that of the LDL, and these differences were mainly due to the period from transplanting to the panicle initiation stage. However, at maturity, the ratio of panicle biomass to the total biomass of the SDH was higher than that of the LDL, and consequently, its harvest index was higher.

Compared to the long-duration rice cultivars, the short-duration rice cultivars are characterized by exhibiting a higher harvest index. The harvest index was important to the grain yield of the short-duration rice cultivars [1,18,27]. The harvest index of the SDH in the two years was stable and reached as high as 0.52. Therefore, the difference in the grain yield in the two years seems to be likely due to the accumulation of dry matter. These findings suggest that obtaining a high grain yield from short-duration cultivars was crucial to promoting biomass accumulation as much as possible on the basis of maintaining a high harvest index. SDH has a larger proportion of dry matter of panicle at maturity than LDL, which was the guarantee of a high harvest index. Indicating that, compared to the LDL, the distribution of dry matter between organs in the SDH was reasonable. The high yield in 2018 was mainly due to the high dry matter accumulation and spikelet filling rate, which were mainly related to the high temperature after heading.

Wu et al. [13] showed that biomass accumulation from jointing to the heading stage was significantly positively correlated with the grain yield. A large amount of dry matter accumulated after heading was conducive to the later grain filling and promotes yield improvement [28,29]. In this study, the dry matter accumulation of the SDH was higher than that of the LDL from the booting stage to 20 days after heading, which may be one reason for the high yield obtained from the SDH. The higher biomass accumulation during the heading stage of the SDH compared to the LDL is mainly due to the higher net assimilation rate. The higher net assimilation rate was mainly associated with the higher carbon accumulation. Meanwhile, the SDH showed a higher leaf area index than the LDL in the middle and late growth stages, which was the reason for the high carbon assimilation and net assimilation rate.

5. Conclusions

A short-duration rice cultivar combined with dense transplanting can obtain a high yield, which is mainly due to the high harvest index and reasonable dry matter distribution.

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