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# Controlled-Release Fertilizer Improves Rice Matter Accumulation Characteristics and Yield in Rice–Crayfish Coculture

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**Abstract:** In recent years, rice–fish coculture has gained more popularity at a growing pace in China. Controlled-release fertilizer can provide nutrients in a timely manner and increase nutrient efficiency. A 2-year field experiment, which adopted both conventional japonica and two indica hybrid rice varieties, was performed to evaluate the effects of controlled-release fertilizer and inorganic compound fertilizer on rice matter accumulation and yield in rice–crayfish coculture and conventional rice farming. The results showed that compared to conventional rice farming, rice–crayfish coculture decreased dry matter accumulation at mature stage and yield by 4.02–8.15% and 4.13–9.34%, respectively. This was mainly due to a decrease in the crop growth rate, net assimilation rate, leaf area index, and light accumulation duration before elongation stage. Compared to inorganic compound fertilizer, controlled-release fertilizer increased dry matter accumulation at the mature stage and yield by 5.02–6.95% and 3.29–6.21%, respectively. Compared to conventional rice farming, rice–crayfish coculture decreased N partial factor productivity and N agronomic use efficiency by 4.13–9.34% and 3.96–8.98%, respectively. Compared to inorganic compound fertilizer, controlled-release fertilizer increased those by 3.29–6.15% and 7.36–14.01%. There was a positive linear correlation between the N partial factor productivity, N agronomic use efficiency, and yield.

**Keywords:** rice–crayfish coculture; different rice varieties; controlled-release fertilizer; dry matter accumulation; rice growth characteristics parameters; yield

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## 1. Introduction

Increased and stable rice production is essential to ensure food security around the world since rice feeds more than half of the world's population [1]. However, in order to pursue higher rice production, the excessive application of N fertilizer, one of the main factors in ensuring rice yield, leads to lower N use efficiency, growing environmental pollution, and more diseases, pests and weeds, thus disturbing rice yield [2–4].

As an alternative to the traditional chemical fertilizer, controlled-release fertilizer can make sure nutrient release (release rate and time) correspond to the S-shaped curve of the N requirement at the rice growth stage by coating and adding various biochemical inhibitors [5,6]. This saves fertilizer, increases efficiency, reduces nutrient volatilization, and provides nutrients in a timely manner. Some studies have indicated that controlled-release fertilizer could significantly improve rice yield, the photosynthesis rate, dry matter accumulation, N accumulation, and N use efficiency [7,8], but its effects are impacted by various factors such as rice varieties, fertilizer application, planting methods, and soil types. Some studies, however, have shown that controlled-release fertilizer reduces rice yield. For example, Ye et al. [9] proved that rice yield reduced by 11.5–12.0% with 70% controlled-release N and 30% inorganic N fertilizer compared to an equal amount of inorganic N fertilizer. Mi et al. [10] determined that compared to the step-by-step application of urea, yield increased by 5.2% with the application of controlled-release fertilizer during the manual trans-plantation of rice seedlings and decreased by 3% when rice seedlings were sown directly. Furthermore, controlled-release fertilizer could also reduce N loss in paddy fields [11–13].

Rice–crayfish coculture, a typical eco-circular agricultural mode, has experienced widespread adoption in recent years. China has saw the fastest adoption of rice–fish coculture in the world, with the area surpassing 1.26 million hectares [14]. In this system, rice leaves provide a shady environment for crayfish, which feed on the pathogens and pests that are living at the lower part of stem, reducing the incidence of pests in paddy fields. Therefore, a beneficial symbiotic relationship between rice and crayfish formed. Many studies have concluded that the rice yield of rice–crayfish coculture is not lower than that of conventional rice farming. Using the food-equivalent unit method and arable-land-equivalent unit method, Jin et al. [15] evaluated the overall sustainability of rice systems and showed that the rice yield of RC increased by 4.48% compared to rice monoculture on the basis of 10% arable land being occupied by excavated ring trenches. Hou et al. [16] pointed out the rice yield of rice–crayfish coculture with deep groundwater (50–100 cm below the soil surface) decreased by 30–55% compared to typical rice–rapeseed rotations, while the rice yield of rice–crayfish coculture with shallow groundwater (40–60 cm below the soil surface) was similar to that of conventional rice farming. Moreover, rice–crayfish coculture helps to promote soil nutrient cycling and improve soil quality [17,18].

Currently, there has been some achievements in rice yield, soil fertility, N loss in rice–crayfish coculture, and N use efficiency of controlled-release fertilizer in conventional rice farming [19–21]. In contrast, studies on production management of large-scale rice–crayfish coculture with controlled-release fertilizer have not been reported yet, and in addition whether it can improve rice yield and N use efficiency under deep water irrigation at the middle and later stage of rice–crayfish coculture needs to be further exploration. Therefore, this study aims to examine the effects of controlled-release fertilizer on rice yield formation and dry matter accumulation as well as the correlation of dry matter accumulation, dry matter utilization characteristics, and yield through different types of rice varieties. The results can provide a reference for controlled-release fertilizer application in rice–crayfish coculture.

## 2. Materials and Methods

### 2.1. Experimental Site and Materials

The field experiment was carried out in 2019 and 2020 at the experimental farm of Nanjing Agricultural University (31°47′ N, 118°55′ E), which is located at the middle and lower reaches of the Yangtze River and is characterized by a subtropical monsoon climate, with an annual average air temperature of 16.8 °C, precipitation of 1017.4 mm, and a frost-free period of 237 d. The properties of the 0–20 cm soil in the study area are as follows: pH 6.5, organic matter, 24.4 $g \cdot kg^{-1}$; total N, 1.4 $g \cdot kg^{-1}$; available N, 86.6 $mg \cdot kg^{-1}$; available P, 4.8 $mg \cdot kg^{-1}$; and available K, 72.3 $mg \cdot kg^{-1}$.

The conventional japonica rice varieties that were used in the experiment were Wuyunjing23 (WYJ23) and Nanjingjinggu (NJJG), and the indica hybrid rice varieties were Quanyou0861 (QY0861) and Shenliangyou600 (SLY600). The rice growth period of the two japonica rice varieties totaled 157 d. The number of days from transplanting stage to effective tillering termination stage, from effective tillering termination stage to elongation stage, from elongation stage to heading stage, and from heading stage to mature stage were 28 d, 17 d, 29 d, and 63 d, respectively. The rice growth period of the two indica hybrid rice varieties totaled 137 d, and the number of days from transplanting stage to effective tillering termination stage, from effective tillering termination stage to elongation stage, from elongation stage to heading stage, and from heading stage to mature stage was 26 d, 15 d, 26 d, and 47 d, respectively. Crayfish (Procambarus clarkii) were used as the tested fish in this experiment, and were fed with drones. No chemical pesticides were used in rice–crayfish coculture.

The nutrient ratios of the tested fertilizer were as follows: resin-coated controlled-release fertilizer ($N\text{-}P_2O_5\text{-}K_2O$ = 26%-11%-11%), inorganic compound fertilizer ($N\text{-}P_2O_5$-

$K_2O$ = 17%-17%-17%). The fertilizer used in the auxiliary experiment contained the following: urea (N = 46.2%), calcium superphosphate ($P_2O_5$ = 12.4%), and potassium chloride ($K_2O$ = 60%).

### *2.2. Experimental Design*

The experiment took fertilizer type as the main plot, set conventional rice farming with inorganic compound fertilizer (CR-IF), conventional rice farming with controlled-release fertilizer (CR-CF), rice–crayfish coculture with inorganic compound fertilizer (RC-IF), rice-crayfish coculture with controlled-release fertilizer (RC-CF) as four treatments. Each treatment was conducted with three replicates. Each replicate covered an area of 4 ha and was separated by film-wrapped ridges. The ditches, which were shaped like homocentric squares around the rice-crayfish coculture, were 3 m wide and 1.5 m deep. The rice varieties were sown on 20 May, and seedlings were mechanically transplanted into a hole with a row spacing of 30 cm and a plant spacing of 12 cm on 12 June. Four seedlings of the japonica rice varieties were placed in each hole, while two seedlings of the indica rice varieties were placed in each hole. The indica rice varieties were harvested on 3 October, and the japonica rice varieties were harvested on 26 October.

The experiment was conducted with an equal amount of nutrients, including 240 kg N $ha^{-1}$, 102 kg $P_2O_5$ $ha^{-1}$, and 102 kg $K_2O$ $ha^{-1}$. The specific fertilization methods are shown in Table 1. At transplanting stage, the machine insertion mode and deep fertilization were adopted, where a trench was dug at a depth of 5 cm and at a distance of 4 cm away from one side of the seedlings, and then fertilizer was spread evenly over the trench. Conventional rice farming without N fertilizer and rice–crayfish coculture without N fertilizer were used as auxiliary experiments.

**Table 1.** Fertilizer management in rice–crayfish coculture and conventional rice farming (kg·$ha^{-1}$).

| Treatments | Basic Fertilizer | The First Tiller Fertilizer at 7th Day after Transplanting Stage | The Second Tiller Fertilizer at 15th Day after Transplanting Stage | Spikelet Promoting Fertilizer | Spikelet Developing Fertilizer |
|---|---|---|---|---|---|
| | | Urea | | | Urea |
| Inorganic compound fertilizer | 373.0 | 93 | 94 | 224.0 | 112.0 |
| Controlled-release fertilizer | 577.0 | - | - | 346.0 | - |

During rice growth, the following water management of conventional rice farming were maintained: a 3–5 cm water layer was maintained from transplanting stage until initial tillering occurrence stage, with the wet and dry irrigation modes being alternated until effective tillering termination stage. From effective tillering termination stage to elongation stage, the water was drained. After the repeated application of alternating wet and dry irrigation until the 7th day prior to mature stage, water was cut off. Water management in the rice–crayfish coculture was similar to that in conventional rice farming before effective tillering termination stage, with the exception of a deeper water layer. After elongation stage, a 20–40 cm water layer was irrigated but was drained on the 10th day before mature stage.

### *2.3. Plant Sampling and Analysis*

#### 2.3.1. Tiller Dynamics

The number of tillers was investigated every 7 d after transplanting stage through the selection of twenty contiguous holes in each plot until elongation stage in order to calculate the panicle rate according to the proportion of effective panicles to the number of peak seedlings.

#### 2.3.2. Dry Matter Weight

Plants with the average number of tillers ± 1 were chosen from five holes in each plot at effective tillering termination stage, elongation stage, heading stage, and mature stage according to the average number of tillers surveyed at each stage.

The stem and sheath as well as the leaves and panicles (heading stage and mature stage) were separated and dried at 105 °C for 30 min, oven-dried at 80 °C until a constant weight was reached, and the dry matter weight was then determined.

### 2.3.3. Yield and Its Components

Representative plants from five holes per plot were selected to measure the yield components, including the number of grains per panicle, the seed-setting rate, and the grain weight. In each plot, 1/3 ha of rice was harvested to determine the yield at mature stage. The yields of the japonica and indica rice varieties were conversed according to the standard water contents of 14.5% and 13.5%, respectively.

### 2.3.4. Data Calculation

The rice growth characteristics and dry matter utilization evaluation index used in this experiment were carried out according to equations of Ye et al. [9], Liu et al. [22], Dou et al. [23], and Chen et al. [24]. The relevant evaluation methods were as follows:

$$\text{Leaf area index} = \frac{\text{plant green leaf area}}{\text{per unit land area}} \tag{1}$$

$$\text{Panicle rate } (\%) = \frac{\text{effective panicle number at mature stage}}{\text{peak seedling number at tillering stage}} \times 100 \tag{2}$$

$$\text{Crop growth rate } \left(\mathrm{g{\cdot}m^{-2}{\cdot}d^{-1}}\right) = \frac{(\mathrm{W_2} - \mathrm{W_1})}{(\mathrm{T_2} - \mathrm{T_1})} \tag{3}$$

where $W_1$ and $W_2$ represent the dry matter weight per unit land area at the beginning and end of a time interval, respectively, and $T_1$ and $T_2$ are the corresponding days.

$$\text{Light accumulation duration } \left(\mathrm{m^2{\cdot}d{\cdot}m^{-2}}\right) = \frac{(\mathrm{L_1} + \mathrm{L_2}) \times (\mathrm{T_2} - \mathrm{T_1})}{2} \tag{4}$$

where $L_1$ and $L_2$ represent the leaf area per unit land area at the beginning and end of a time interval, respectively, and $T_1$ and $T_2$ are the corresponding days.

$$\text{Net assimilation rate } \left(\mathrm{g{\cdot}m^{-2}{\cdot}d^{-1}}\right) = \frac{\left[\frac{(\ln \mathrm{L_2} - \ln \mathrm{L_1})}{(\mathrm{L_2} - \mathrm{L_1})}\right] \times (\mathrm{W_2} - \mathrm{W_1})}{(\mathrm{T_2} - \mathrm{T_1})}$$

where $L_1$ and $L_2$ are the leaf area index at the beginning and end of a time interval, respectively; $W_1$ and $W_2$ are the dry matter weight per unit land area at the beginning and end of a time interval; and $T_1$ and $T_2$ are the corresponding days.

$$\text{N partial factor productivity } \left(\mathrm{kg{\cdot}kg^{-1}}\right) = \frac{\text{yield}}{\text{the amount of applied N}} \tag{5}$$

$$\text{N agronomic use efficiency } \left(\mathrm{kg{\cdot}kg^{-1}}\right) = \frac{(\text{rice yield} - \text{ rice yield without N fertilizer})}{\text{the amount of applied N}} \tag{6}$$

$$\text{Harvest index} = \frac{\text{yield}}{\text{dry matter weight at mature stage}} \tag{7}$$

### 2.3.5. Data Analysis

SPSS (IBM SPSS 24, USA) was adopted to statistically analyze experimental data, which were expressed as the mean value ± standard error. One-way ANOVA was used to analyze the significance of variation among treatments and the least significant difference (LSD) tests were used for pairwise comparisons. The correlation between N partial factor productivity, N agronomic use efficiency, harvest index, and rice yield were analyzed by

Pearson's correlation analysis. Excel 2019 and Origin (version 8.1, USA) was employed for figure preparation.

## 3. Results

### *3.1. Rice Yield and Its Components*

As shown in Table 2, the rice variety has a significant effect on rice yield. The yield of the japonica rice varieties was 0.13–1.60 t·ha$^{-1}$ higher than that of the indica rice varieties. Among the four rice varieties, NJJG obtained the highest actual yield, while obtained QY0861 lowest.

The yields of the japonica and indica rice varieties in rice–crayfish coculture were significantly reduced by 6.28–9.34% and 4.13–5.91%, respectively, compared to the yield in conventional rice farming, which was mainly due to a steep decline of 3.61–6.03% and 4.45–6.45% in the 1000-grain weight of the japonica and indica rice varieties, respectively, in rice–crayfish coculture. Nonetheless, the panicle rate of the japonica and indica rice varieties in rice–crayfish coculture grew by 1.42–3.31% and 1.41–6.23% compared to in conventional rice farming, respectively.

The yields of japonica and indica rice varieties in controlled-release fertilizer treatments significantly increased by 3.29–4.70% and 4.73–6.21%, respectively, compared to that of inorganic fertilizer. In addition, effective panicles, peak seedlings, panicle rate, the number of grains per panicle of japonica and indica rice varieties in controlled-release fertilizer treatments increased by 4.51–6.71% and 5.94–8.29%, 1.51–3.46% and 1.02–4.41%, 1.80–5.07% and 2.97–7.15%, and 2.54–3.39% and 2.07–3.86%, respectively. In addition, the yield of CR-CF was 3.29–6.21% higher than that of CR-IF; the yield of RC-CF was 4.22–6.15% higher than that of RC-IF.

### *3.2. Dry Matter Accumulation*

Compared to the indica rice varieties, there was a decrease in the dry matter accumulation of the japonica rice varieties before elongation stage but an increase after elongation stage compared to indica rice varieties (Figure 1). There were significant differences in the dry matter accumulation of difference rice varieties at mature stage among the different treatments, which was expressed by the lowercase letters in Figure 1. The dry matter accumulation of the japonica rice varieties at the mature stage increased by 0.06–3.48 t·ha$^{-1}$ compared to the indica rice varieties. Among the four rice varieties, NJJG had the highest dry matter accumulation at the mature stage, while QY0861 had the lowest.

Compared to conventional rice farming, rice–crayfish coculture significantly decreased the dry matter accumulation of the japonica and indica rice varieties by 5.48–7.83% and 3.00–7.06% from elongation stage to heading stage, by 8.21–10.80% and 2.69–8.80% from heading stage to mature stage, and by 5.94–8.15% and 4.02–5.69% at mature stage, respectively.

The dry matter accumulation of the japonica and indica rice varieties grew significantly by 4.26–6.78% and 5.15–8.76% from elongation stage to heading stage and by 6.84–8.88 and 4.81–10.42% from heading stage to mature stage, respectively. The dry matter accumulation of the japonica and indica rice varieties at mature stage increased by 5.02–6.76% and 5.54–6.95% in rice–crayfish coculture, respectively, compared to in conventional rice farming. In addition, the dry matter accumulation of CR-CF at mature stage was 5.22–6.86% higher than that of CR-IF, while the dry matter accumulation of RC-CF was 5.02–6.95% higher than that of RC-IF.

**Table 2.** Yield and its components in different rice varieties under two types of fertilizer treatments.

| Year | Varieties | Treatments | Effective Panicle (×$10^4$ ha$^{-1}$)) | Peak Seedling (×$10^4$ ha$^{-1}$) | Panicle Rate (%) | No. of Grains Per Panicle | Seed-Settingrate | 1000-Grain Weight | Actual Yield (t·ha$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | (%) | (%) | |
| 2019 | WYJ23 | CR-IF | 336.06 ± 4.93 e | 409.05 ± 10.76 d | 82.16 ± 0.62 e | 138.01 ± 2.45 fg | 91.08 ± 0.57 ab | 26.71 ± 0.16 ab | 10.18 ± 0.20 c |
| | | CR-CF | 358.41 ± 4.54 c | 415.22 ± 9.28 a | 86.32 ± 0.46 c | 141.51 ± 3.08 f | 90.93 ± 0.56 ab | 26.12 ± 0.24 bc | 10.55 ± 0.21 bc |
| | | RC-IF | 330.77 ± 4.76 e | 389.73 ± 6.61 k | 84.87 ± 0.02 d | 133.91 ± 3.77 g | 90.89 ± 0.64 b | 25.48 ± 0.44 cd | 9.25 ± 0.15 f |
| | | RC-CF | 352.96 ± 6.26 c | 403.20 ± 8.51 g | 87.54 ± 0.28 b | 137.38 ± 2.89 fg | 90.73 ± 0.82 c | 24.75 ± 0.13 de | 9.64 ± 0.20 e |
| | NJJG | CR-IF | 349.72 ± 7.05 c | 414.75 ± 10.59 b | 84.32 ± 0.17 d | 134.60 ± 2.27 g | 92.02 ± 0.59 ab | 27.12 ± 0.18 a | 10.72 ± 0.21 bc |
| | | CR-CF | 368.73 ± 6.69 a | 425.1 ± 10.37 a | 86.74 ± 0.21 c | 138.60 ± 2.47 g | 91.88 ± 0.58 ab | 26.33 ± 0.36 b | 11.08 ± 0.16 a |
| | | RC-IF | 343.32 ± 6.92 d | 397.80 ± 8.45 i | 86.30 ± 0.13 c | 131.35 ± 3.86 g | 91.82 ± 0.55 ab | 26.14 ± 0.21 bc | 9.92 ± 0.07 d |
| | | RC-CF | 361.45 ± 4.39 b | 407.25 ± 13.67 e | 88.75 ± 1.28 a | 134.82 ± 3.53 g | 91.74 ± 0.73 ab | 25.35 ± 0.45 cd | 10.38 ± 0.15 c |
| | QY0861 | CR-IF | 238.04 ± 4.12 f | 385.82 ± 6.41 l | 61.70 ± 0.11 k | 193.44 ± 2.17 b | 84.88 ± 0.40 ef | 25.76 ± 0.25 c | 9.13 ± 0.13 f |
| | | CR-CF | 252.85 ± 3.56 f | 395.41 ± 6.92 j | 63.95 ± 0.09 j | 198.58 ± 2.31 a | 84.67 ± 0.39 f | 25.13 ± 0.45 d | 9.69 ± 0.08 de |
| | | RC-IF | 233.95 ± 4.23 f | 369.90 ± 8.87 n | 63.25 ± 0.23 j | 188.18 ± 4.0 6c | 84.79 ± 0.59 ef | 24.56 ± 0.34 e | 8.70 ± 0.04 g |
| | | RC-CF | 247.84 ± 4.60 f | 380.44 ± 12.41 m | 65.15 ± 0.62 i | 194.47 ± 3.08 ab | 84.61 ± 0.70 f | 23.82 ± 0.32 f | 9.18 ± 0.17 f |
| | SLY600 | CR-IF | 262.05 ± 6.10 f | 405.15 ± 10.55 f | 64.68 ± 0.01 i | 182.03 ± 3.88 d | 85.84 ± 0.43 e | 25.45 ± 0.20 cd | 9.47 ± 0.18 ef |
| | | CR-CF | 281.70 ± 5.89 f | 409.28 ± 7.42 c | 68.83 ± 0.33 g | 186.32 ± 2.65 cd | 85.66 ± 0.40 ef | 24.58 ± 0.41 e | 9.92 ± 0.09 d |
| | | RC-IF | 258.34 ± 5.35 f | 381.30 ± 9.37 m | 67.75 ± 0.03 h | 176.87 ± 1.62 e | 85.75 ± 0.70 ef | 23.89 ± 0.10 f | 9.00 ± 0.21 f |
| | | RC-CF | 278.42 ± 5.53 f | 398.11 ± 7.49 k | 69.94 ± 0.26 f | 183.70 ± 3.06 cd | 85.59 ± 1.29 ef | 23.06 ± 0.38 g | 9.51 ± 0.08 e |
| 2020 | WYJ23 | CR-IF | 331.40 ± 7.16 e | 406.05 ± 8.32 c | 81.62 ± 0.25 f | 134.24 ± 3.84 ef | 90.83 ± 1.24 a | 26.58 ± 0.25 ab | 9.86 ± 0.12 cd |
| | | CR-CF | 346.92 ± 7.34 c | 414.44 ± 7.80 a | 83.71 ± 0.36 d | 137.74 ± 2.26 ef | 90.78 ± 0.63 a | 25.56 ± 0.13 bc | 10.24 ± 0.16 bc |
| | | RC-IF | 325.36 ± 7.52 e | 387.91 ± 8.50 i | 83.88 ± 0.31 d | 130.56 ± 3.74 f | 90.64 ± 0.53 b | 25.12 ± 0.34 c | 8.94 ± 0.13 f |
| | | RC-CF | 342.78 ± 7.01 c | 401.12 ± 9.82 f | 85.46 ± 0.05 b | 134.35 ± 2.41 ef | 90.62 ± 0.42 b | 24.16 ± 0.13 d | 9.36 ± 0.17 e |
| | NJJG | CR-IF | 342.30 ± 4.91 c | 412.20 ± 8.71 a | 83.04 ± 0.33 e | 130.86 ± 2.06 f | 91.87 ± 0.89 a | 26.88 ± 0.67 a | 10.33 ± 0.17 b |
| | | CR-CF | 357.82 ± 4.74 a | 423.25 ± 6.14 a | 84.54 ± 0.04 c | 135.29 ± 3.69 ef | 91.79 ± 0.88 a | 26.08 ± 0.16 b | 10.75 ± 0.09 a |
| | | RC-IF | 338.53 ± 4.72 d | 395.25 ± 6.90 f | 85.65 ± 0.09 b | 127.42 ± 2.54 f | 91.72 ± 0.45 a | 25.26 ± 0.46 c | 9.62 ± 0.19 d |
| | | RC-CF | 353.81 ± 5.34 b | 405.45 ± 7.21 d | 87.26 ± 0.25 a | 131.47 ± 2.21 f | 91.61 ± 0.83 a | 24.73 ± 0.34 cd | 10.03 ± 0.14 c |
| | QY0861 | CR-IF | 231.49 ± 5.17 g | 381.75 ± 6.77 j | 60.64 ± 0.36 m | 187.66 ± 1.76 b | 84.68 ± 0.38 cd | 25.62 ± 0.23 bc | 8.82 ± 0.07 fg |
| | | CR-CF | 249.70 ± 5.06 fg | 392.34 ± 11.85 g | 63.64 ± 0.37 k | 192.51 ± 3.21 a | 84.45 ± 0.68 e | 24.92 ± 0.42 cd | 9.25 ± 0.19 e |
| | | RC-IF | 228.34 ± 5.67 g | 364.28 ± 12.25 l | 62.68 ± 0.33 l | 182.30 ± 2.81 c | 84.53 ± 0.38 d | 24.48 ± 0.23 d | 8.31 ± 0.10 h |
| | | RC-CF | 243.20 ± 5.04 fg | 376.80 ± 8.03 j | 64.54 ± 0.13 j | 188.69 ± 3.62 ab | 84.35 ± 0.33 e | 23.65 ± 0.31 e | 8.72 ± 0.14 f |
| | SLY600 | CR-IF | 255.43 ± 5.66 fg | 403.35 ± 13.28 e | 63.33 ± 0.47 k | 179.63 ± 1.43 c | 85.66 ± 0.71 c | 25.28 ± 0.10 c | 9.16 ± 0.20 ef |
| | | CR-CF | 276.61 ± 6.39 f | 407.65 ± 11.30 b | 67.85 ± 0.05 h | 183.34 ± 1.67 bc | 85.43 ± 0.50 cd | 24.43 ± 0.68 d | 9.72 ± 0.10 d |
| | | RC-IF | 251.87 ± 4.53 fg | 374.40 ± 10.70 k | 67.27 ± 0.42 i | 174.27 ± 2.51 d | 85.52 ± 0.39 cd | 23.65 ± 0.28 e | 8.62 ± 0.13 g |
| | | RC-CF | 272.19 ± 4.74 fg | 389.25 ± 7.84 h | 69.93 ± 0.04 g | 179.24 ± 3.78 c | 85.38 ± 0.58 cd | 22.88 ± 0.37 f | 9.15 ± 0.14 ef |
| | V | | ** | ** | ** | ** | ** | ** | ** |
| | R | | ns | ** | ** | ** | ns | ** | ** |
| | F | | ** | ** | ** | ** | ns | ns | ** |
| | V*R | | * | * | ** | ns | ns | ns | ** |
| | V*F | | ** | ** | ** | ns | ns | ns | ns |
| | R*F | | ns | * | ns | ns | ns | ns | ns |
| | V*R*F | | ns | ns | ** | ns | ns | ns | ** |

All the data presented are the means of three replicates ± standard errors. Different lowercase letters indicate the significant differences among all treatments in the four varieties at the 5% level in the same year. CR, conventional rice cultivation; RC, rice–crayfish coculture system; IF, inorganic compound fertilizer; CF, controlled-release fertilizer; V, rice variety; R, rice cropping mode; F, fertilizer type. * and ** indicate significant differences at the $p < 0.05$ and 0.01 levels, respectively. “ns” means not significant.

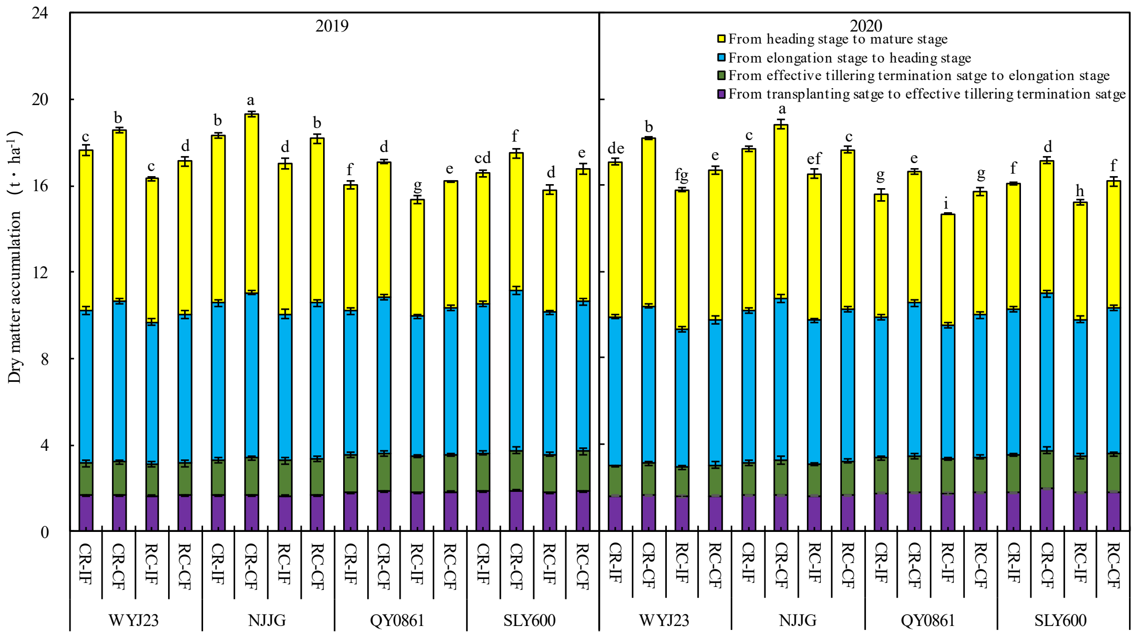

**Figure 1.** Dry matter accumulation of different rice varieties under two types of fertilizer treatments. The error bars were presented as the standard errors of the dry matter accumulation of transplanting stage to effective tillering termination stage, effective tillering termination stage to elongation stage, elongation stage to heading stage, heading stage to mature stage. Different lowercase letters indicate significant differences of dry matter accumulation at mature stage among all treatments of four varieties in the same year at the 5% level according to LSD tests (0.05).

### 3.3. Leaf Area Index

The leaf area index represents the ability of rice leaves to capture and utilize light energy during rice growth. During rice growth, leaf area indexes of the different rice varieties increased gradually from transplanting stage to heading stage, peaked at heading stage, and then decreased (Figure 2). Compared to the indica rice varieties, the leaf area indexes of the japonica rice varieties decreased by 0.21–0.42, 0.92–1.07, and 0.35–0.02 at effective tillering termination stage, elongation stage, and heading stage, respectively, but increased by 0.13–0.37 at mature stage.

There was a significant difference in the leaf area index at heading stage and mature stage in rice–crayfish coculture compared to conventional rice farming, and rice–crayfish coculture significantly decreased the leaf area index of the japonica and indica rice varieties by 5.05–6.20% and 5.12–5.98% at heading stage, respectively. Compared to inorganic compound fertilizer, controlled-release fertilizer increased the leaf area index of the japonica and indica rice varieties by 3.42–4.79% and 3.49–5.12% at the heading stage and by 3.12–4.97% and 4.21–5.39% at the mature stage.

### 3.4. Light Accumulation Duration and Net Assimilation Rate

Light accumulation duration, a measure of leaf area population and photosynthetic sustainability, marks the accumulation of crop leaf area during the whole or a certain growth stage in rice and plays an important role in evaluating dry matter accumulation. The results showed light accumulation duration of japonica rice varieties decreased before elongation stage but increased after elongation stage compared to the indica rice varieties (Table 3). Meanwhile, SLY600 had the highest light accumulation duration and WYJ23 had the lowest before elongation stage, but after elongation stage, NJJG had the highest light accumulation duration and QY0861 had the lowest.

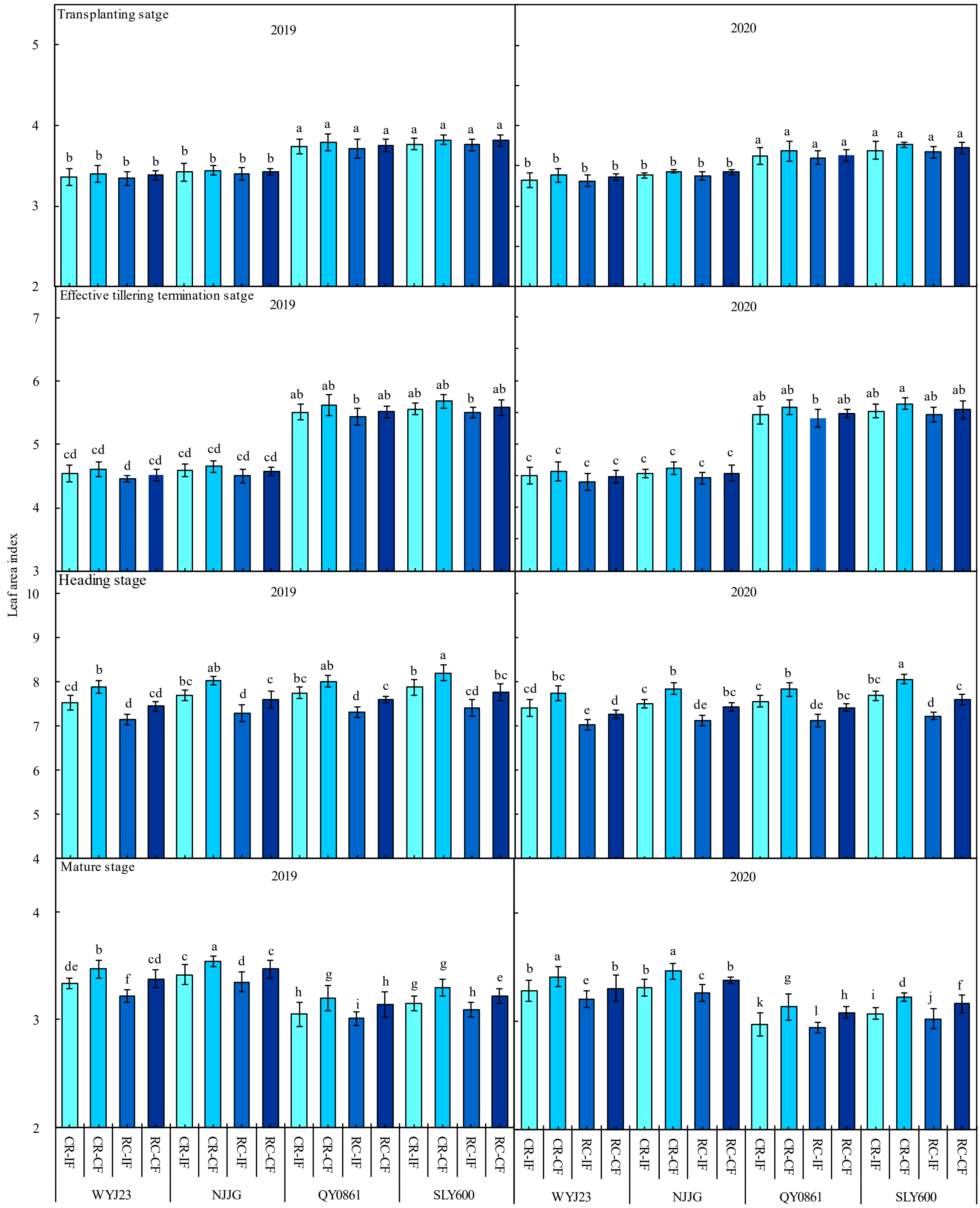

**Figure 2.** Leaf area indexes of different rice varieties under two types of fertilizer treatments. Different lowercase letters indicate significant differences among all treatments of four varieties in the same year at the 5% level according to LSD tests (0.05).

**Table 3.** Light accumulation duration and net assimilation rate of different rice varieties under two types of fertilizer treatments.

| Year | Varieties | Treatments | Light Accumulation Duration($m^2 \cdot d \cdot m^{-2}$) | | | | Net Assimilation Rate ($g \cdot m^{-2} \cdot d^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Transplanting Stage-Effective Tillering Termination Stage | Effective Tillering Termination Stage-Elongation Stage | Elongation Stage-Heading Stage | Heading Stage-Mature Stage | Transplanting Stage-Effective Tillering Termination Stage | Effective Tillering Termination Stage-Elongation Stage | Elongation Stage-Heading Stage | Heading Stage-Mature Stage |
| 2019 | WYJ23 | CR-IF | 48.86 ± 1.19 b | 67.15 ± 1.45 b | 174.87 ± 3.10 bc | 342.09 ± 7.09 d | 5.94 ± 0.19 ab | 2.25 ± 0.05 c | 4.13 ± 0.04 bc | 2.29 ± 0.02 d |
| | | CR-CF | 49.42 ± 1.25 b | 68.09 ± 1.78 b | 181.11 ± 3.17 ab | 357.53 ± 7.15 cd | 6.00 ± 0.13 ab | 2.25 ± 0.07 c | 4.20 ± 0.04 ab | 2.35 ± 0.03 cd |
| | | RC-IF | 48.58 ± 1.12 b | 66.22 ± 1.32 b | 173.85 ± 2.47 bc | 367.78 ± 6.75 bc | 5.93 ± 0.08 ab | 2.22 ± 0.11 c | 3.86 ± 0.07 d | 1.90 ± 0.04 h |
| | | RC-CF | 49.14 ± 0.72 b | 67.15 ± 1.53 b | 179.40 ± 2.63 ab | 384.11 ± 7.98 ab | 5.95 ± 0.14 ab | 2.25 ± 0.08 c | 3.90 ± 0.09 d | 1.95 ± 0.02 h |
| | NJJG | CR-IF | 49.70 ± 0.76 b | 68.09 ± 1.34 b | 177.92 ± 2.46 b | 349.65 ± 6.84 d | 5.90 ± 0.12 ab | 2.45 ± 0.03 b | 4.17 ± 0.08 ab | 2.34 ± 0.04 d |
| | | CR-CF | 49.98 ± 0.70 b | 68.77 ± 1.25 ab | 183.72 ± 2.55 a | 364.14 ± 6.77 c | 5.99 ± 0.15 ab | 2.48 ± 0.04 b | 4.27 ± 0.06 a | 2.4 ± 0.03 cd |
| | | RC-IF | 49.42 ± 0.84 b | 67.15 ± 1.84 b | 176.70 ± 2.84 bc | 377.37 ± 6.61 b | 5.83 ± 0.06 b | 2.44 ± 0.05 b | 3.91 ± 0.03 d | 1.94 ± 0.02 h |
| | | RC-CF | 49.84 ± 0.56 b | 68.00 ± 1.52 b | 182.55 ± 2.97 ab | 392.99 ± 6.78 a | 5.90 ± 0.24 ab | 2.47 ± 0.08 b | 4.05 ± 0.05 c | 2.03 ± 0.03 g |
| | QY0861 | CR-IF | 50.96 ± 0.88 ab | 69.38 ± 1.71 ab | 172.25 ± 3.16 c | 253.57 ± 8.31 h | 5.91 ± 0.25 ab | 2.52 ± 0.11 ab | 3.90 ± 0.05 d | 2.47 ± 0.04 b |
| | | CR-CF | 51.61 ± 1.30 a | 70.58 ± 1.52 ab | 177.19 ± 3.44 b | 263.44 ± 6.67 gh | 5.97 ± 0.02 ab | 2.53 ± 0.08 ab | 4.12 ± 0.06 bc | 2.55 ± 0.05 a |
| | | RC-IF | 50.57 ± 0.81 ab | 68.63 ± 1.35 b | 171.99 ± 2.43 c | 278.37 ± 7.12 fg | 5.90 ± 0.16 ab | 2.51 ± 0.06 b | 3.78 ± 0.09 d | 2.06 ± 0.04 fg |
| | | RC-CF | 51.09 ± 0.72 ab | 69.53 ± 1.42 ab | 177.12 ± 2.86 b | 289.98 ± 6.68 ef | 5.95 ± 0.19 ab | 2.52 ± 0.04 ab | 3.87 ± 0.07 d | 2.15 ± 0.02 e |
| | SLY600 | CR-IF | 51.35 ± 0.85 a | 69.98 ± 1.58 ab | 174.59 ± 4.11 bc | 258.97 ± 6.94 gh | 6.03 ± 0.01 ab | 2.56 ± 0.09 ab | 4.00 ± 0.04 d | 2.49 ± 0.03 b |
| | | CR-CF | 52.00 ± 0.67 a | 71.25 ± 1.41 a | 180.44 ± 2.65 ab | 270.25 ± 6.71 g | 6.11 ± 0.16 a | 2.65 ± 0.08 a | 4.16 ± 0.08 bc | 2.50 ± 0.02 ab |
| | | RC-IF | 51.22 ± 0.30 ab | 69.45 ± 1.29 ab | 174.15 ± 2.57 bc | 283.23 ± 6.91 f | 5.94 ± 0.12 ab | 2.54 ± 0.12 ab | 3.81 ± 0.03 d | 2.12 ± 0.04 f |
| | | RC-CF | 51.87 ± 0.58 a | 70.43 ± 1.90 ab | 180.09 ± 2.65 ab | 296.46 ± 7.62 e | 6.03 ± 0.18 ab | 2.65 ± 0.13 a | 3.88 ± 0.07 d | 2.21 ± 0.05 e |
| 2020 | WYJ23 | CR-IF | 48.30 ± 0.98 c | 66.47 ± 1.83 b | 172.84 ± 2.72 bc | 337.05 ± 6.75 d | 5.84 ± 0.09 ab | 2.10 ± 0.02 d | 4.08 ± 0.05 c | 2.25 ± 0.02 f |
| | | CR-CF | 49.14 ± 0.36 c | 67.58 ± 1.16 b | 178.50 ± 2.47 ab | 351.23 ± 6.84 cd | 5.87 ± 0.11 ab | 2.21 ± 0.04 cd | 4.17 ± 0.06 a | 2.34 ± 0.03 de |
| | | RC-IF | 48.16 ± 0.32 c | 65.54 ± 1.02 b | 171.30 ± 4.33 bc | 362.81 ± 6.35 bc | 5.75 ± 0.11 ab | 2.09 ± 0.05 d | 3.80 ± 0.03 de | 1.87 ± 0.04 m |
| | | RC-CF | 48.86 ± 0.84 c | 66.64 ± 1.42 b | 176.10 ± 3.73 ab | 374.88 ± 6.78 ab | 5.79 ± 0.02 ab | 2.17 ± 0.08 cd | 3.88 ± 0.02 d | 1.95 ± 0.03 k |
| | NJJG | CR-IF | 49.14 ± 0.45 c | 67.24 ± 1.22 b | 174.44 ± 3.44 b | 340.52 ± 6.54 d | 5.80 ± 0.16 ab | 2.27 ± 0.09 c | 4.13 ± 0.05 b | 2.33 ± 0.05 e |
| | | CR-CF | 49.84 ± 0.76 bc | 68.43 ± 1.90 a | 180.82 ± 2.46 a | 356.27 ± 7.11 c | 5.84 ± 0.06 ab | 2.37 ± 0.04 bc | 4.23 ± 0.07 a | 2.39 ± 0.02 c |
| | | RC-IF | 49.00 ± 0.45 c | 66.56 ± 1.57 b | 173.70 ± 2.74 b | 368.49 ± 7.29 b | 5.74 ± 0.08 b | 2.26 ± 0.03 c | 3.90 ± 0.08 d | 1.93 ± 0.04 l |
| | | RC-CF | 49.70 ± 0.30 bc | 67.66 ± 1.75 b | 179.55 ± 3.58 ab | 383.76 ± 6.82 a | 5.81 ± 0.11 ab | 2.35 ± 0.04 bc | 4.00 ± 0.04 c | 2.02 ± 0.03 j |
| | QY0861 | CR-IF | 49.40 ± 0.50 bc | 68.10 ± 2.26 ab | 169.26 ± 3.21 c | 247.46 ± 6.46 g | 5.85 ± 0.08 ab | 2.42 ± 0.10 b | 3.88 ± 0.04 d | 2.46 ± 0.03 b |
| | | CR-CF | 50.18 ± 0.56 b | 69.45 ± 1.73 a | 174.33 ± 2.69 b | 257.56 ± 6.19 g | 5.87 ± 0.13 a | 2.46 ± 0.01 ab | 4.10 ± 0.06 b | 2.53 ± 0.02 a |
| | | RC-IF | 49.14 ± 0.80 c | 67.50 ± 1.06 b | 169.16 ± 2.80 c | 271.89 ± 6.55 f | 5.77 ± 0.12 ab | 2.40 ± 0.09 b | 3.69 ± 0.08 e | 2.03 ± 0.04 ij |
| | | RC-CF | 49.53 ± 0.38 bc | 68.33 ± 1.44 ab | 174.15 ± 3.37 b | 283.5 ± 6.63 ef | 5.86 ± 0.08 ab | 2.46 ± 0.12 ab | 3.81 ± 0.06 de | 2.15 ± 0.03 h |
| | SLY600 | CR-IF | 50.31 ± 0.41 ab | 69.08 ± 1.47 a | 171.73 ± 2.63 bc | 252.86 ± 6.54 g | 5.89 ± 0.18 ab | 2.53 ± 0.11 ab | 3.96 ± 0.08 cd | 2.47 ± 0.05 b |
| | | CR-CF | 51.22 ± 0.34 ab | 70.43 ± 1.07 a | 177.97 ± 2.46 ab | 265.08 ± 7.00 fg | 6.33 ± 0.09 a | 2.56 ± 0.05 a | 4.12 ± 0.07 b | 2.50 ± 0.03 ab |
| | | RC-IF | 50.05 ± 0.77 bc | 68.48 ± 1.90 a | 171.32 ± 3.03 bc | 276.75 ± 6.97 f | 5.85 ± 0.10 ab | 2.50 ± 0.09 ab | 3.73 ± 0.03 e | 2.08 ± 0.04 i |
| | | RC-CF | 50.70 ± 0.83 ab | 69.45 ± 2.31 a | 177.39 ± 3.23 ab | 290.52 ± 6.65 e | 5.89 ± 0.14 ab | 2.55 ± 0.11 a | 3.84 ± 0.05 d | 2.15 ± 0.02 gh |
| | V | | ** | ** | ** | ** | ** | ** | ** | ** |
| | R | | ns | * | ns | ** | ** | ns | ** | ** |
| | F | | ** | ** | ** | ** | ns | ** | ** | ** |
| | V*R | | ns | ns | ns | ns | ns | ns | * | * |
| | V*F | | ns | ns | ns | ns | ns | ns | * | ns |
| | R*F | | ns | ns | ** | ns | * | ** | ** | * |
| | V*R*F | | ns | ns | ** | * | ns | ns | * | * |

All the data presented are the means of three replicates ± standard errors. Different lowercase letters indicate the significant differences among all treatments in the four varieties at the 5% level in the same year. CR, conventional rice cultivation; RC, rice–crayfish coculture system; IF, inorganic compound fertilizer; CF, controlled-release fertilizer; V, rice variety; R, rice cropping mode; F, fertilizer type. * and ** indicate significant differences at the $p < 0.05$ and 0.01 levels, respectively. “ns” means not significant.

Light accumulation duration of the japonica and indica rice varieties in rice–crayfish coculture decreased before elongation stage but showed significant increases of 3.76–8.82% and 9.37–10.08%, respectively, from heading stage to mature stage compared to conventional rice farming. However, light accumulation duration of different rice varieties of controlled-release fertilizer significantly increased after elongation stage compared to that of inorganic compound fertilizer. The light accumulation duration of RC-CF increased by 2.80–3.66% from elongation stage to heading stage and by 2.87–3.63% from heading stage to mature stage compared to that of RC-IF, while the light accumulation duration of the CR-CF increased by 3.33–4.63% from elongation stage to heading stage and by 3.89–4.98% from heading stage to mature stage compared to those of CR-IF.

Net assimilation rate represents the ability of rice to synthesize dry matter per unit leaf area per unit time. According to the results, SLY600 had the highest net assimilation rate, and NJJG had the lowest from transplanting stage to effective tillering termination stage, from effective tillering termination stage to elongation stage, SLY600 had the highest net accumulation rate and WYJ23 had the lowest (Table 3). NJJG had the highest net accumulation rate and QY0861 had the lowest from elongation stage to heading stage, and SLY600 had the highest net accumulation rate and WYJ23 had the lowest from heading stage to mature stage.

Net assimilation rate of the japonica and indica rice varieties of rice–crayfish coculture significantly decreased by 5.17–7.06% and 3.09–7.14% from elongation stage to heading stage and by 15.31–17.22% and by 11.66–17.55% from heading stage to mature stage, respectively, compared to those of conventional rice farming. Controlled-release fertilizer increased net assimilation rate of the different rice varieties after elongation stage. Net assimilation rate of CR-CF increased by 1.70–5.67% from elongation stage to heading stage and by 0.36–3.74% from heading stage to mature stage compared to CR-IF, while the net assimilation rate of RC-CF increased by 1.23–3.59% from elongation stage to heading stage and by 2.58–5.81% from heading stage to mature stage compared to RC-IF.

### *3.5. Crop Growth Rate*

Crop growth rate represents the dry matter accumulation per unit land area per unit time and is an important index describing the rate of population dry matter production and photosynthetic accumulation effect. During the rice growth period, the crop growth rate of different rice varieties increased before heading stage but decreased after heading stage (Table 4). Among the four rice varieties, crop growth rate of SLY600 had the highest crop growth rate, and WYJ23 had the lowest at each growth stage.

Crop growth rate of the japonica and indica rice varieties grown under rice–crayfish coculture decreased significantly by 8.63–10.90% and 6.60–10.50% from elongation stage to heading stage and by 18.55–20.85% and 15.30–20.62% from heading stage to mature stage, respectively, compared to those under conventional rice farming. Controlled-release fertilizer increased the crop growth rate of different rice varieties after elongation stage compared to inorganic compound fertilizer. Crop growth rate of CR-CF, increased by 5.1–8.8% from elongation stage to heading stage and by 4.8–8.1% from heading stage to mature stage compared to CR-IF, respectively, while crop growth rate of RC-CF increased by 4.26–6.78% from elongation stage to heading stage and by 7.23–10.42% from heading stage to mature stage compared to those of RC-IF.

### *3.6. Dry Matter Utilization Characteristics*

N partial factor productivity of the japonica rice varieties was 0.54–6.66 $\mathrm{kg \cdot kg^{-1}}$ higher than that of the indica rice varieties (Table 5). Among the four rice varieties, N partial factor productivity of NJJG was the highest, but that of QY0861 was the lowest. Rice–crayfish coculture significantly reduced N partial factor productivity of the japonica and indica rice varieties by 6.28–9.34% and 4.13–5.91%, respectively, compared to that of conventional rice farming. In rice–crayfish coculture, the decrease in the japonica rice varieties was greater than that in the indica rice varieties. Compared to inorganic compound fertilizer, controlled-release fertilizer significantly improved N partial factor productivity. CR-CF increased N partial factor productivity by 3.29–6.21% compared to CR-IF, while RC-CF increased N partial factor productivity by 4.22–6.15% compared to RC-IF.

**Table 4.** Crop growth rate of different rice varieties under two types of fertilizer treatments (Unit: g·m$^{-2}$·d$^{-1}$).

| Year | Varieties | Treatments | Transplanting Stage-Effective Tillering Termination Stage | Effective Tillering Termination Stage-Elongation Stage | Elongation Stage-Heading Stage | Heading Stage-Mature Stage |
|---|---|---|---|---|---|---|
| 2019 | WYJ23 | CR-IF | 5.90 ± 0.10 de | 8.81 ± 0.41 d | 24.38 ± 0.44 f | 11.78 ± 0.31 c |
| | | CR-CF | 6.01 ± 0.18 de | 8.95 ± 0.19 d | 25.61 ± 0.37 de | 12.63 ± 0.25 b |
| | | RC-IF | 5.86 ± 0.08 e | 8.57 ± 0.14 d | 21.93 ± 0.44 h | 9.35 ± 0.26 g |
| | | RC-CF | 5.93 ± 0.11 de | 8.82 ± 0.28 d | 22.87 ± 0.35 g | 10.03 ± 0.30 f |
| | NJJG | CR-IF | 5.94 ± 0.06 de | 9.73 ± 0.33 c | 25.03 ± 0.33 e | 12.30 ± 0.28 b |
| | | CR-CF | 6.05 ± 0.10 d | 9.97 ± 0.30 c | 26.41 ± 0.32 c | 13.14 ± 0.22 ab |
| | | RC-IF | 5.84 ± 0.10 e | 9.56 ± 0.21 c | 22.60 ± 0.44 g | 9.83 ± 0.33 f |
| | | RC-CF | 5.95 ± 0.17 de | 9.83 ± 0.39 c | 24.13 ± 0.46 f | 10.70 ± 0.26 e |
| | QY0861 | CR-IF | 6.93 ± 0.13 bc | 11.51 ± 0.26 b | 25.62 ± 0.42 de | 12.45 ± 0.29 b |
| | | CR-CF | 7.08 ± 0.10 bc | 11.73 ± 0.22 b | 27.77 ± 0.48 b | 13.36 ± 0.24 a |
| | | RC-IF | 6.88 ± 0.07 c | 11.35 ± 0.14 b | 23.93 ± 0.27 f | 9.96 ± 0.18 f |
| | | RC-CF | 7.00 ± 0.11 bc | 11.55 ± 0.14 b | 25.16 ± 0.29 de | 10.85 ± 0.19 e |
| | SLY600 | CR-IF | 7.11 ± 0.10 ab | 11.81 ± 0.48 b | 26.62 ± 0.32 c | 12.83 ± 0.24 ab |
| | | CR-CF | 7.28 ± 0.06 a | 12.40 ± 0.44 a | 28.54 ± 0.38 a | 13.45 ± 0.31 a |
| | | RC-IF | 7.00 ± 0.07 bc | 11.61 ± 0.21 b | 24.38 ± 0.31 f | 10.48 ± 0.19 e |
| | | RC-CF | 7.17 ± 0.13 ab | 12.27 ± 0.32 ab | 25.67 ± 0.27 d | 11.39 ± 0.28 d |
| 2020 | WYJ23 | CR-IF | 5.75 ± 0.21 c | 8.14 ± 0.84 f | 23.82 ± 0.48 ef | 11.43 ± 0.33 c |
| | | CR-CF | 5.85 ± 0.05 c | 8.71 ± 0.49 ef | 25.10 ± 0.5 cd | 12.35 ± 0.30 b |
| | | RC-IF | 5.64 ± 0.10 c | 8.02 ± 0.33 f | 21.33 ± 0.32 h | 9.07 ± 0.31 g |
| | | RC-CF | 5.75 ± 0.22 c | 8.43 ± 0.17 ef | 22.37 ± 0.48 g | 9.77 ± 0.38 fg |
| | NJJG | CR-IF | 5.78 ± 0.23c | 8.92 ± 0.27 de | 24.31 ± 0.38 e | 11.92 ± 0.33 bc |
| | | CR-CF | 5.89 ± 0.13c | 9.48 ± 0.22 d | 25.79 ± 0.52 bc | 12.83 ± 0.46 ab |
| | | RC-IF | 5.71 ± 0.10c | 8.78 ± 0.25 e | 22.17 ± 0.37 g | 9.55 ± 0.26 g |
| | | RC-CF | 5.85 ± 0.15c | 9.31 ± 0.38 de | 23.47 ± 0.44 f | 10.39 ± 0.32 ef |
| | QY0861 | CR-IF | 6.71 ± 0.1b | 10.86 ± 0.16 bc | 25.04 ± 0.41 cd | 12.09 ± 0.32 b |
| | | CR-CF | 6.81 ± 0.33 ab | 11.24 ± 0.24 b | 27.23 ± 0.46 a | 12.98 ± 0.40 ab |
| | | RC-IF | 6.59 ± 0.10 b | 10.64 ± 0.16 c | 22.94 ± 0.46 fg | 9.59 ± 0.26 fg |
| | | RC-CF | 6.73 ± 0.21 b | 11.06 ± 0.27 bc | 24.37 ± 0.48 d | 10.59 ± 0.33 d |
| | SLY600 | CR-IF | 6.85 ± 0.15 ab | 11.51 ± 0.31 ab | 25.92 ± 0.34 b | 12.43 ± 0.30 b |
| | | CR-CF | 7.04 ± 0.10 a | 11.85 ± 0.20 a | 27.88 ± 0.34 a | 13.17 ± 0.42 a |
| | | RC-IF | 6.77 ± 0.10 ab | 11.26 ± 0.16 ab | 23.49 ± 0.37 f | 10.02 ± 0.34 fg |
| | | RC-CF | 6.88 ± 0.19 ab | 11.65 ± 0.55 ab | 25.04 ± 0.46 d | 10.89 ± 0.29 cd |
| | V | | ** | ** | ** | ** |
| | R | | ** | ** | ** | ** |
| | F | | ** | ** | ** | ** |
| | V*R | | ns | ns | ns | ns |
| | V*F | | ns | ns | ** | ns |
| | R*F | | * | ** | * | ns |
| | V*R*F | | ns | ns | ** | * |

All the data presented are the means of three replicates ± standard errors. Different lowercase letters indicate the significant differences among all treatments in the four varieties at the 5% level in the same year. CR, conventional rice cultivation; RC, rice–crayfish coculture system; IF, inorganic compound fertilizer; CF, controlled-release fertilizer; V, rice variety; R, rice cropping mode; F, fertilizer type. * and ** indicate significant differences at the $p < 0.05$ and 0.01 levels, respectively. "ns" means not significant.

N agronomic use efficiency of the japonica rice varieties was 0.34–3.17 kg·kg$^{-1}$ higher than that of the indica rice varieties. Among the four rice varieties, N agronomic use efficiency of NJJG was the highest and that of QY0861 was the lowest. Rice–crayfish coculture reduced significantly N agronomic use efficiency of the japonica and indica rice varieties by 3.96–8.95% and 4.26–8.09%, respectively, compared to conventional rice farming. Compared to inorganic compound fertilizer, controlled-release fertilizer significantly increased N agronomic use efficiency. CR-CF increased N agronomic use efficiency by 7.36–13.88% compared to CR–IF, while RC-CF increased N agronomic use efficiency by 9.15–14.01% compared to RC-IF.

No obvious differences in the harvest index can be found between rice–crayfish coculture and conventional rice farming or controlled-release fertilizer and inorganic compound fertilizer. There was a slight decrease of 0.30–1.83% and 0.07–0.46%, respectively, in the harvest index of the japonica and indica rice varieties in rice–crayfish coculture compared to that in conventional rice farming. In contrast to inorganic fertilizer, controlled-release fertilizer decreased the harvest index by 0.76–2.32% in two years.

**Table 5.** Evaluation indexes of the dry matter utilization of different rice varieties under two types of fertilizer treatments.

| Year | Varieties | Treatments | N Partial Factor Productivity (kg·kg$^{-1}$) | N Agronomic Use Efficiency (kg·kg$^{-1}$) | Harvest Index |
|---|---|---|---|---|---|
| 2019 | WYJ23 | CR-IF | 42.43 ± 0.77 cd | 18.67 ± 0.25 d | 49.16 ± 0.86 ab |
| | | CR-CF | 43.94 ± 0.82 bc | 20.18 ± 0.23 b | 48.32 ± 0.85 b |
| | | RC-IF | 38.54 ± 0.32 fg | 17.76 ± 0.16 e | 48.26 ± 0.78 b |
| | | RC-CF | 40.17 ± 0.77 e | 19.38 ± 0.55 c | 47.90 ± 0.85 b |
| | NJJG | CR-IF | 44.68 ± 0.44 b | 19.94 ± 0.22 bc | 49.85 ± 0.84 a |
| | | CR-CF | 46.15 ± 0.75 a | 21.40 ± 0.39 a | 48.82 ± 0.81 ab |
| | | RC-IF | 41.33 ± 0.62 d | 18.48 ± 0.26 d | 49.63 ± 0.75 ab |
| | | RC-CF | 43.25 ± 0.79 c | 20.40 ± 0.43 b | 48.64 ± 0.79 b |
| | QY0861 | CR-IF | 38.02 ± 0.08 f | 17.00 ± 0.52 f | 48.41 ± 0.88 b |
| | | CR-CF | 40.38 ± 0.96 de | 19.36 ± 0.60 c | 48.24 ± 0.60 b |
| | | RC-IF | 36.25 ± 0.75 g | 16.28 ± 0.39 g | 48.27 ± 0.57 b |
| | | RC-CF | 38.25 ± 0.37 fg | 18.28 ± 0.21 de | 48.20 ± 0.58 b |
| | SLY600 | CR-IF | 39.47 ± 0.71 ef | 17.66 ± 0.35 e | 48.64 ± 0.56 b |
| | | CR-CF | 41.33 ± 0.79 d | 19.53 ± 0.43 c | 48.27 ± 0.50 b |
| | | RC-IF | 37.48 ± 0.46 fg | 16.31 ± 0.10 g | 48.42 ± 0.48 b |
| | | RC-CF | 39.63 ± 0.87 ef | 18.45 ± 0.51 d | 48.21 ± 0.53 b |
| 2020 | WYJ23 | CR-IF | 41.09 ± 0.62 cd | 18.25 ± 0.26 cd | 49.12 ± 0.84 ab |
| | | CR-CF | 42.65 ± 0.41 bc | 19.81 ± 0.32 b | 47.98 ± 0.81 b |
| | | RC-IF | 37.25 ± 0.25 f | 16.61 ± 0.33 e | 48.23 ± 0.76 b |
| | | RC-CF | 39.00 ± 0.79 e | 18.36 ± 0.43 cd | 47.76 ± 0.78 b |
| | NJJG | CR-IF | 43.05 ± 0.37 b | 19.13 ± 0.18 b | 49.74 ± 0.78 a |
| | | CR-CF | 44.79 ± 0.87 a | 20.87 ± 0.51 a | 48.67 ± 0.78 ab |
| | | RC-IF | 40.08 ± 0.50 d | 18.00 ± 0.14 cd | 49.59 ± 0.64 ab |
| | | RC-CF | 41.79 ± 0.66 cd | 19.71 ± 0.30 b | 48.44 ± 0.66 b |
| | QY0861 | CR-IF | 36.76 ± 0.08 fgh | 15.96 ± 0.41 f | 48.22 ± 0.84 b |
| | | CR-CF | 38.54 ± 0.83 e | 17.74 ± 0.47 d | 47.31 ± 0.85 b |
| | | RC-IF | 34.63 ± 0.46 h | 15.11 ± 0.10 g | 48.13 ± 0.71 b |
| | | RC-CF | 36.33 ± 0.96 fgh | 16.82 ± 0.60 e | 47.22 ± 0.73 b |
| | SLY600 | CR-IF | 38.17 ± 0.41 ef | 17.15 ± 0.33 de | 48.46 ± 0.72 ab |
| | | CR-CF | 40.50 ± 0.91 d | 19.48 ± 0.55 b | 47.87 ± 0.85 b |
| | | RC-IF | 35.92 ± 0.50 g | 15.76 ± 0.14 f | 48.23 ± 0.75 b |
| | | RC-CF | 38.13 ± 0.62 ef | 17.97 ± 0.26 cd | 48.07 ± 0.76 b |
| | V | | ** | ** | ** |
| | R | | ** | ** | ns |
| | F | | ** | ** | ** |
| | V*R | | ** | * | ns |
| | V*F | | ns | * | ns |
| | R*F | | ** | * | ns |
| | V*R*F | | ns | ns | ns |

The yield of conventional rice farming and rice–crayfish coculture without N fertilizer in 2019 and 2020 were as follows: WYJ23:380.13 kg·kg$^{-1}$, 332.52 kg·kg$^{-1}$ and 365.45 kg·kg$^{-1}$, 328.18 kg·kg$^{-1}$; NJJG: 395.90 kg·kg$^{-1}$, 365.65 kg·kg$^{-1}$ and 382.68 kg·kg$^{-1}$, 353.35 kg·kg$^{-1}$; QY0861: 336.37 kg·kg$^{-1}$, 319.57 kg·kg$^{-1}$ and 332.81 kg·kg$^{-1}$, 312.24 kg·kg$^{-1}$; SLY600: 348.88 kg·kg$^{-1}$, 338.78 kg·kg$^{-1}$, and 336.38 kg·kg$^{-1}$, 322.48 kg·kg$^{-1}$, respectively. All the data presented are the means of three replicates ± standard errors. Different lowercase letters indicate the significant differences among all treatments in the four varieties at the 5% level in the same year. CR, conventional rice cultivation; RC, rice–crayfish coculture system; IF, inorganic compound fertilizer; CF, controlled-release fertilizer; V, rice variety; R, rice cropping mode; F, fertilizer type. * and ** indicate significant differences at the $p < 0.05$ and 0.01 levels, respectively. “ns” means not significant.

The determination coefficient $R^2$ can reflect the fitting of the model and data. Results showed that there was a positive correlation between N partial productivity, N agronomic use efficiency and rice yield; the fitting ($R^2$) of N partial productivity and yield was 0.998 **, N agronomic use efficiency and yield was 0.483 **, while harvest index and yield was not significantly correlated (Figure 3).

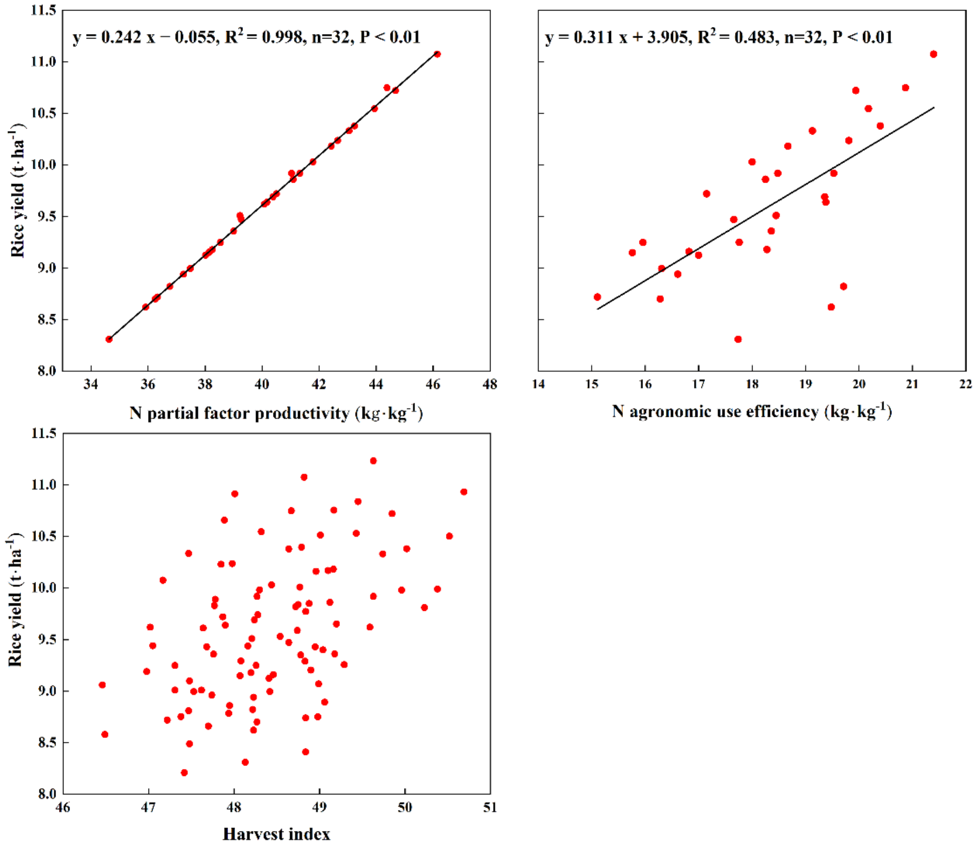

**Figure 3.** Correlation between rice yield and the dry matter utilization characteristics.

## 4. Discussion and Conclusions

### *4.1. Dry Matter Accumulation and Rice Yield*

This study suggests that the yield and the dry matter accumulation of japonica rice varieties at mature stage were higher than those of the indica rice varieties. Compared to the indica rice varieties, the number of grains per panicle of the japonica rice varieties decreased, while the effective panicle number and the 1000-grain weight increased (Table 2 and Figure 1). This was mainly due to the roots of the indica rice varieties featuring premature senescence [25], leading to a reduction in the nutrient uptake and dry matter accumulation from heading to mature stage. Wei et al. [26] showed that compared to indica rice varieties, the dry matter accumulation of japonica rice from elongation stage to heading stage and from heading stage to mature stage increased by 16.33–32.00% and 14.06–23.00%, respectively, and the yield increased by 3.81–6.73%. Xu et al. [27] showed that japonica rice varieties have a higher yield and better quality compared to indica rice varieties. Uyeh et al. [28] concluded that japonica rice varieties feature a higher yield than indica hybrid rice varieties. However, Sun et al. [29] showed that compared to japonica rice, indica hybrid rice has a higher yield, dry matter, and N uptake throughout all growth stages. Generally speaking, the higher yield observed in the japonica and indica rice varieties was a result of genetic characteristics as well as cultivation measures, including the rice growth period, the number of panicle types, the seed setting rate, dry matter accumulation at the mature stage, and climatic influence. Additionally, this was also due to higher plant density of japonica rice varieties, compared to indica rice varieties.

Whether the rice yield of rice–crayfish coculture is higher than that of conventional rice farming, the results are different at present. Sun et al. [30] stated the rice yield resulting from rice–crayfish coculture had declined by 30.8–30.9% compared to rice monocultures. In contrast, Sun et al. [31] pointed out that rice–crayfish coculture reduced rice yield by 28.5% compared to rice monocultures. However, Wu et al. [32] believed that compared to conventional rice production, rice–crayfish coculture with extremely high nutrients status was accompanied by 14% rice yields reduction, while rice–crayfish coculture with appropriately improved soil quality created favorable nutrient status accompanied by 15% rice yield increase. This study showed that rice–crayfish coculture decreased rice yield by 4.14–9.34% compared to conventional rice farming, mainly because the deep-water irrigation from elongation stage to mature stage in rice–crayfish coculture made it difficult for the available nutrients in the soil to fully meet the uptake and utilization requirements of rice. Moreover, the poor root activity of rice led to a decline in its photosynthetic production capacity in deep water conditions [33], as well as in the amount of dry matter accumulation after elongation stage, disrupting rice yield.

Controlled-release fertilizer was able to control the release rate of nutrients and promote their uptake, meeting the needs of N demands for rice, reducing fertilization times, and boosting N use efficiency [34,35]. Mohammad et al. [36] showed that compared to urea, different types of controlled-release fertilizer contributed to a better uptake of N in rice plants, especially in rice grains. In addition, compared to inorganic fertilizer, controlled-release fertilizer decreased the amylose content by 3.05%, improved peak viscosity and breakdown by 9.62% and 8.53%, and decreased setback by 19.39% [37]. In this study, compared to inorganic compound fertilizer, controlled-release fertilizer improved the dry matter accumulation of rice from effective tillering termination stage to mature stage, increased the effective panicles and the rice yield, and reduced the seed setting rate and 1000-grain weight. This might because that controlled-release fertilizer prolonged N release and provided synchronous N supply to rice. At the same time, controlled-release fertilizer also promoted the growth of rice roots and their distribution in deep soil, which was conducive to maintaining root activity [38,39].

### 4.2. Photosynthetic Production Characteristics

As the characteristics of photosynthetic production serves as the main determinant of rice yield, a better photosynthetic capacity after heading stage is a key factor that is responsible for high rice yield. The present results are different regarding the photosynthetic production characteristics of different rice varieties. Li et al. [40] reported rice yield decreased as rice seedlings aged, because younger seedlings promote rice growth after the heading stage, achieving higher photosynthetic production and higher yield. Yamori et al. [41] indicated that photosynthesis was an important biochemical process supporting plant growth and grain yield. Gong et al. [42] indicated that dry matter accumulation, light accumulation duration, the crop growth rate, and the net assimilation rate of conventional japonica rice varieties were lower than those of indica rice varieties from transplanting stage to elongation stage but higher from elongation stage to mature stage. This study showed that compared to the indica rice varieties, the japonica rice varieties decreased the crop growth rate, net assimilation rate, and leaf area index before heading stage and decreased the light accumulation duration before elongation stage but increased crop growth rate, net assimilation rate, and leaf area index after heading stage and increased the light accumulation duration after elongation stage. Therefore, the japonica rice varieties were better than the indica rice varieties in terms of the photosynthetic production characteristics at the later rice growth stages, laying a sound foundation for yield formation.

In addition to the genetic factors of rice varieties, the rice cropping mode also had a significant effect on the photosynthetic production characteristics of rice. Related studies have compared conventional rice production to six coculture modes (rice–crayfish, rice–turtle, rice–loach, rice–catfish, rice–carp, and rice–duck), showing a decrease in leaf area index, light accumulation duration, crop growth rate, and net assimilation rate at main growth stages [22,43]. Yao et al. [44] thought that compared to conventional rice cultivation modes, rice–crayfish coculture demonstrated a slight decline in the leaf area index at the later growth stages, a higher population growth rate, and better leaf photosynthetic characteristics. This study showed that compared to conventional rice farming, rice–crayfish coculture decreased the crop growth rate, net assimilation rate, and leaf area index from transplanting stage to mature stage and the light accumulation duration before elongation stage but increased the light accumulation duration after heading stage.

The proper application of controlled-release fertilizer is an important measure to improve the light environment and to optimize the characteristics of photosynthetic production. Xu et al. [19] reported that the controlled release fertilizer met N demands at each rice growth stage and had higher N accumulation, photosynthetic activity, and above-ground matter accumulation as well as a higher leaf area index at heading stage and mature stage. Yang et al. [6] indicated that controlled-release fertilizer enhanced the activities of glutamine synthetase, glutamine 2-oxoglutarate aminotransferase, and nitrate reductase in leaves, thus improving the photosynthetic production of rice. In this study, controlled-release fertilizer increased the leaf area index, light accumulation duration, crop growth rate, and net assimilation rate, thus obviously promoting the photosynthetic production characteristics, because the slow nutrient release of controlled-release fertilizer in the early growth stages provides a sufficient nutrient supply for rice in the middle and later stages. Therefore, the separate application of controlled-release fertilizer can also improve the light environment that is necessary for crop growth.

### *4.3. Dry Matter Utilization Characteristics and the Relationship with Rice Yield*

The dry matter utilization characteristics of rice involves multiple physiological and biochemical processes such as carbohydrate metabolism, the transmission of nutrient signals, N metabolism, plant protein synthesis, and degradation, which are important for the exploration of rice growth and yield formation. In this study, N partial factor productivity and N agronomic use efficiency of the japonica rice varieties were higher than those of the indica rice varieties. Compared to conventional rice farming, rice–crayfish coculture decreased N partial factor productivity, N agronomic use efficiency, harvest index. N partial factor productivity and N agronomic use efficiency in controlled-release fertilizer were higher than those in inorganic compound fertilizer, but harvest index was opposite. In this study, there was a positive correlation between N partial factor productivity, N agronomic use efficiency, and the rice yield, but there was no significant correlation between the harvest index and the rice yield, which was mainly due to similar fertility characteristics and the same climate conditions in this experiment.

## 5. Conclusions

Rice–crayfish coculture has gained widespread popularity in recent years, features high ecological and economic benefits. Compared to conventional rice farming, a decline could be seen in rice–crayfish coculture in terms of rice dry matter accumulation, N partial factor productivity, N agronomic use efficiency, and yield. This was mainly due to the fact that rice–crayfish coculture was not beneficial to the leaf area index, crop growth rate, net assimilation rate, and light accumulation duration of different rice varieties at different growth stages. However, the application of controlled-release fertilizer in rice–crayfish coculture increased the dry matter accumulation at the mature stages as well as N partial factor productivity and N agronomic use efficiency, and yield, mainly because controlled-release fertilizer improved the leaf area index, crop growth rate, and net assimilation rate of different rice varieties at different growth stages as well as the light accumulation duration before the elongation stage. In addition, whether in indica rice or japonica rice varieties, controlled release fertilizer can increase rice yield in rice–crayfish coculture, but in this study, japonica rice varieties have more yield advantages. The application of controlled-release fertilizer in rice–crayfish coculture can not only enhance rice dry matter accumulation, N partial productivity, and N agronomic use efficiency, but also increase rice yield, so as to boost the benefit of large-scale rice–crayfish coculture.

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