Effects of a One-Time Application of Controlled-Release Nitrogen Fertilizer on Yield and Nitrogen Accumulation and Utilization of Late Japonica Rice in China

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Abstract: A mixture of controlled-release nitrogen (N) fertilizers (CRNFs) and conventional urea (CU) as a single application of basal fertilizer could simplify fertilization in rice cultivation from the traditional and more labor-intensive fertilization strategy of multiple applications of nitrogen. However, the reported benefits of this combined approach in increasing rice yield have varied substantially for various reasons, including that various types of rice are characterized by different N requirements to obtain high yield. In this study, two late japonica rice cultivars, Jia58 (J58) and Jia67 (J67), were used to determine the best combination of one of two short-acting CRNFs (release periods were 40 and 60 days) and one of three long-acting CRNFs (release periods were 80, 100 and 120 days) to apply with the CU as a one-time application of basal fertilizer. Six combinations of CRNFs were established based on their release periods: A1, 40 + 80 days; A2, 40 + 100 days; A3, 40 + 120 days; B1, 60 + 80 days; B2, 60 + 100 days; and B3, 60 + 120 days. CU applied split at basal, tillering and panicle differentiation stages, respectively as control (CK). The effects of the different treatment combinations of CRNFs on late-rice grain yield, N accumulation and N-use efficiency in a two-year field experiment were determined. Results showed that, the A2 treatment achieved the same yield as that of CK, and yield of the B2 treatment exceeded the yield of CK. Yield of J58 applied with B2 was 7.35% higher in 2018 and 7.40% higher in 2019 than that of the corresponding yield of CK; yield of J67 applied with B2 was 6.05% higher in 2018 and 6.87% higher in 2019 than that of CK. Compared with other CRNF treatments, the release of N from A2 and B2 was most synchronized with nitrogen uptake by the two cultivars, which indicates that fertilizer combination completely met the nitrogen demands during each growth stage of rice. Rice of the A2 and B2 treatments had higher N accumulation, higher aboveground biomass accumulation and LAI (leaf area index) at the heading and maturity stages and higher photosynthetic activity than those of other CRNF treatments. In conclusion, for late japonica rice in China, the application of the A2 and B2 treatments as optimal type of CRNF can achieve labor saving and yield increasing simultaneously in rice production.

Keywords: controlled-release nitrogen fertilizer; one-time application; yield; nitrogen accumulation and utilization

1. Introduction

Nitrogen (N) is one of the most important nutrients for rice growth [1]. Application of nitrogen fertilizer has been an effective way of improving rice yields [2]. China is the world’s largest consumer of nitrogen fertilizer, accounting for 30% of the world’s total nitrogen consumption. In China, split application of conventional urea (CU) was still the most widely used method in rice production [3]. In this method, CU is typically divided into three or four broadcast applications. Split CU applications require extra time and labor, which will unlikely meet the high-efficiency demands of modern rice production.
Controlled release nitrogen fertilizer (CRNF) was designed to have a release pattern that matched a crop’s pattern of N demand [4]. The advantage of CRNF is that it reduces the number of fertilizer applications from the traditional multiple applications of nitrogen, which saves time and reduces labor [5]. However, because there are several peaks of N demand throughout the growing season of rice, a single application of a CRNF that generally presents a pattern of N release resembling an “S” or “J” curve with only a single peak of nitrogen release would not be able to meet the N requirements of rice [6]. Another disadvantage of CRNF is that CRNFs have been considered too expensive for use in rice production, especially in developing countries.

Recently, a better fertilizer management strategy has been developed using CRNF, which is the combined applications of CRNF and urea as a basal fertilizer. This strategy has made it possible to use CRNF in rice production [7]. Several researchers found that the combined use of CRNF and CU as basal fertilizer could meet rice N demands [8,9]. At the same time, the amount of CRNFs could be reduced to save the costs of purchased fertilizers [6]. However, reported effects of combined use of CRNF and CU as basal fertilizer in increasing rice yield have varied. Some research has indicated that compared to CU alone, a mixture of CRNF and CU as basal fertilizer could enhance yield due to larger leaf area index [10] and higher photosynthetic potential [11] in rice. Moreover, the mix of CRNF and CU as basal fertilizer has reduced greenhouse gas emissions, including release of methane and nitrous oxide [12]. However, some studies found that basal application of a combination of CRNF and CU had no advantage in rice production compared with split applications of CU [13,14]. Hu et al. [15] showed that lodging and delayed ripening may occur with application of CRNF and CU as a basal fertilizer in rice production. Discrepancies between results of various studies may result from that rice yield was strongly affected by the synchronicity of CRNF release and N requirement characteristics of rice.

Various types of rice are characterized by different N requirements throughout growth to obtain high grain yields. A large amount of nitrogen needs to be absorbed to promote more effective panicles and achieve production of more panicles in the early stage for early rice, [16]. The rice was absorbed N evenly at each stage of N demand to achieve higher numbers of both panicles and spikelets for middle rice [17]. Higher N uptake occurring in the middle and late growth stages can increase the dry matter accumulation after heading for late rice, which reportedly is beneficial to the production of grain yield [18]. It can be seen that yields were greater when the release of CRNF is synchronized with the critical periods of nitrogen requirement of rice [19]. Therefore, to effectively use CRNFs in rice production, it is important to develop a one-time application of a CRNF formula that can synchronize N fertilizer release rate with the pattern of N requirements according to the N uptake characteristics of different types of rice.

The Yangtze River Delta region is the largest rice-producing region and an important commercial grain base in China [20]; the rice planting area and yield also rank at the top compared to other regions in China. Late japonica rice is one of the main types of rice grown in this region due to the greater potential yields. Late japonica rice has a longer growing period, usually more than 155 days. Its duration of N uptake from transplanting to the jointing stage was long, and it needs to absorb greater amounts of N in the middle and late periods of growth. In the Yangtze River Delta, a serious labor shortage has occurred recently with urbanization. Thus, for this area of rice production, finding a suitable formula of a one-time application of CRNF to meet N demands according to the critical periods of N uptake by late Japonica rice is more urgently needed in order to maximize agronomic benefits as well as to minimize time and labor costs. Therefore, in this study, a field experiment testing with various combinations of CRNF was conducted to determine the optimal formula appropriate for the late japonica rice grown in the Yangtze River Delta. The main objectives of this study were: (1) evaluate the effects of different combinations of CRNF and CNF on rice grain yield, N uptake and N-use efficiency; and (2) determine the optimum CRNF formula and provide empirical evidence that can realize the dual benefits
of cost savings and rice yield increases to support the use of this fertilization strategy to grow late japonica rice in the Yangtze River Delta of China.

2. Materials and Methods

2.1. Experimental Location

Field experiments were conducted at Ningbo City (29°47′ N, 121°53′ E), Zhejiang Province, China, during the rice growing seasons of 2018 and 2019. The field soil was blue purple clay with the following properties: organic matter 37.57 g kg\(^{-1}\), total N 1.7 g kg\(^{-1}\), available P 6.51 mg kg\(^{-1}\), and available K 173.22 mg kg\(^{-1}\).

2.2. Plant Materials, Growth Conditions, and Treatments

Late japonica rice cultivars Jia67 and Jia58, the most popular rice cultivar grown in the Yangtze River Delta, were used as materials. Seedlings were sown on 26 May in 2018 and 27 May in 2019 with a seeding rate of 120 g of dry seeds per plastic plate. Seedlings were mechanically transplanted in hills on 15 June in both 2018 and 2019. Hill spacing was 11.7 cm × 30 cm with four seedlings per hill. The average times from transplanting to the jointing and heading stages for the two late japonica rice were 45 and 77 days, respectively.

Various combinations of CRNFs were tested in determining the best combination as a one-time application of fertilizer to replace the traditional fertilization methods that require more labor and time. There were two types of CRNFs with short release periods (40 and 60 days) and three types of CRNFs with long controlled-release periods (80, 100, and 120 days). One short CRNF was combined with one long CRNF to establish the six treatment combinations listed in Table 1. Short and long CRNFs were mixed in a ratio of 1:4, and then they were mixed with a CU as a one-time application of basal fertilizer. Treatments were applied at a rate of 270 kg ha\(^{-1}\) N in a CRNF to CU ratio of 5:5. The control treatment (CK) consisted of a CU that was divided and applied at four different times: 35% as a basal application, 35% at 7 days after transplanting, 15% as a spikelet promotion fertilizer when the rice had four leaves that had not appeared, and 15% as a spikelet development fertilizer when the rice had two leaves that had not appeared. The amount of CU used as basal fertilizer was the same amount used in all CRNF treatments. All N fertilizer types and rates are listed in Table 1. Other fertilizers consisting of 150 kg ha\(^{-1}\) P (superphosphate) and 150 kg ha\(^{-1}\) K (KCl) were also incorporated into soil prior to transplanting. Treatments were applied to 25 m\(^2\) (5 m × 5 m) plots with three replications for each treatment. Each plot was separated by a soil ridge (35 cm wide and 20 cm high) and covered with plastic film. The experimental field was flooded post-transplantation and remained flooded until 7 days before the maturity stage. Insect pests, pathogens, and weeds were controlled using common chemical treatments.

Table 1. Nitrogen fertilizer types and application amounts (kg ha\(^{-1}\)) and timing for different treatments.

| Treatment | Basal N Fertilizer | Types of CRNF | CU | CU | CU | CU |
|-----------|--------------------|---------------|----|----|----|----|
|           | TF | SPF | SDF |     |     |     |     |
| A1        | 27 | 0   | 108 | 0   | 0   | 135 | 0   |
| A2        | 27 | 0   | 0   | 108 | 0   | 135 | 0   |
| A3        | 27 | 0   | 0   | 0   | 108 | 135 | 0   |
| B1        | 0  | 27  | 108 | 0   | 0   | 135 | 0   |
| B2        | 0  | 27  | 0   | 108 | 0   | 135 | 0   |
| B3        | 0  | 27  | 0   | 0   | 108 | 135 | 0   |
| CK        | 0  | 0   | 0   | 0   | 0   | 94.5| 94.5|

CRNF: controlled release N fertilizer; CU: conventional urea; TF: tillering fertilizer; SPF: spikelet-promoting fertilizer; SDF: spikelet development fertilizer.
2.3. Sampling and Measurements

All rice plants in an 8 m$^2$ area in the middle of each plot were hand-harvested at maturity, and the grain yield was weighed. The final grain yield was adjusted to 14% moisture content. Plants covering an area of 1 m$^2$ (excluding the border rows) in each plot were collected to determine the number of panicles per square meter. All plants from 30 hills in each plot were collected to determine the number of spikelets per panicle, filled-grain percentage, and 1000-grain weight.

Leaf area index (LAI) and above-ground biomass accumulation were determined at the jointing, heading and maturity stages. Plants from five hills were sampled from each plot and all samples were separated into green leaf, stem (internode plus sheath) and panicle tissues. Green leaf area was measured with a leaf area meter (LI-3100, LI-COR, USA). Samples of each plant part were then dried separately and weighed to determine total aboveground biomass per unit area per plot. Each component of the rice plants was bagged and oven-dried separately at 105 $^\circ$C for 30 min and then at 80 $^\circ$C to a constant weight. Nitrogen concentrations were determined by semi-micro-Kjeldahl digestion [21].

Accumulation of N in the plant was calculated by multiplying the N concentration (%) by the plant total biomass.

The amount of CU used as a basal fertilizer is the same in all CRNF treatments. The nitrogen cumulative release rate of each treatment was determined by the N release curve of CRNF. The actual N release rate of CRNF in the field plot was measured by using the buried mesh bag method [22]. The fertilizer weighed (10 ± 0.01) g was placed into a nylon mesh bag (12 cm × 8 cm) with a hole diameter of 1.0 mm, strung onto a line and then buried in field. The bags were buried 5–8 cm below the soil surface. Three bags were sampled every ten days. CRNF was removed from each bag and rinsed with distilled water before being placed in a vacuum oven at 60 $^\circ$C for 72 h. After drying, the particles were weighed to determine the weight of the remaining CRNF and then ground to pass through a 0.25 mm sieve to determine the residual N content by using the Kjeldahl digestion method [21].

2.4. Equations and Data Analysis

The percentage of cumulative N release from the CRNF, photosynthetic potential, crop growth rate, N accumulation, and N-use efficiency were calculated using the following formulas:

Cumulative N release percentage (%) = ($\beta_1 \times M_1 - \beta_2 \times M_2$)/($\beta_1 \times M_1$) × 100%,

where $\beta_1$ = weight of CRNF before burial, $M_1$ = N content of CRNF before burial, $\beta_2$ = weight of CRNF after burial, $M_2$ = N content of CRNF after burial.

Decreasing rate of leaf area × $10^4$ m$^2$ d$^{-1}$ = ($L_1 - L_2$)/(t$^2$ − t$^1$) and photosynthetic potential ($\times 104$ m$^2$ d ha$^{-1}$)

=1/2($L_1 + L_2$) × (t$^2$ − t$^1$),

where $L_1$ and $L_2$ are the first and second measurements of LAI, respectively, and t$^1$ and t$^2$ represent the first and second times (day) of measurements, respectively.

Crop growth rate (g m$^{-2}$ d$^{-1}$) = (W$^2$ − W$^1$)/(t$^2$ − t$^1$),

where W$^1$ and W$^2$ are the first and second measurements of above-ground biomass accumulation, respectively, and t$^1$ and t$^2$ represent the first and second times (day) of measurement, respectively.

N accumulation (kg ha$^{-1}$) = above-ground biomass accumulation × N content.

N accumulation in the panicle after heading (kg ha$^{-1}$) = nitrogen accumulation at maturity stage − nitrogen accumulation at heading stage.

Apparent recovery efficiency of N fertilizer (%) = [N accumulation in N-application plots − N accumulation in N-omission plots (kg)]/amount of applied N fertilizer (kg) × 100.
Internal N-use efficiency = grain yield (kg)/N accumulation in a plant (kg).

Agronomic N-use efficiency = [grain yield in N-application plots − grain yield in N-omission plots (kg)]/amount of applied N fertilizer (kg).

Physiological N-use efficiency = [grain yield in N-application plots − grain yield in N-omission plots (kg)]/[N accumulation in N-application plots − N accumulation in N-omission plots (kg)].

Data were analyzed by ANOVA with SPSS 13.0 for Windows. The statistical model included sources of variation due to year, rice cultivar, treatment and the interactions of year × rice cultivar, year × treatment, and year × rice cultivar × treatment. The means were compared by the least significant difference test at the 0.05 probability level.

3. Results
3.1. Cumulative N Release Rate

Nitrogen was continuously and steadily released from CRNFs over time as expected; however, they differed in the pattern of release. For the A1 and B1 treatments, large amounts of nitrogen were released from CRNFs early on; about 50% of the nitrogen was released by day 40 and about 85% was released by day 80. For the A2 and B2 treatments, about 30% and 86% of the nitrogen was released from CRNF by days 40 and 100, respectively. For the A3 and B3 treatments, less than 30% and about 86% of the nitrogen was released from CRNF by, respectively, days 40 and 120 (Figure 1).

Figure 1. Cumulative nitrogen release rates of CRNF in 2018 and 2019.

3.2. Grain Yield and Its Components

The yield of rice grown under the A2 and B2 treatments reached or exceeded that of rice grown under CK. Yield of B2 of J58 was 7.35% higher in 2018 and 7.40% higher in 2019 than that of the CK of J58. Yield of B2 of J67 was 6.05% higher in 2018 and 6.87% higher in 2019 than that of CK of J67. Rice grown under the A2 and B2 treatments had higher numbers of panicles and spikelets per panicle than those of rice grown under other CRNF treatments. The A1 and B1 treatments resulted in higher numbers of panicles and spikelets per panicle, but lower seed setting rates and 1000-grain weights, so yield was lower than that of A2 and B2. The numbers of panicles and spikelets per panicle were lowest in the A3 and B3 treatments; thus, these treatments were not conducive to increasing yield (Table 2).
Table 2. Differences in yield and yield components of late japonica rice.

| Cultivar | Treatment | Panicle Number (×10^4 ha⁻¹) | Spikelet Number per Panicle | Seed-Setting Rate (%) | 1000-Grain Weight (g) | Grain Yield (t ha⁻¹) |
|----------|-----------|-------------------------------|-----------------------------|-----------------------|-----------------------|---------------------|
|          |           |                               |                             |                       |                       |                     |
| 2018     |           |                               |                             |                       |                       |                     |
| J58      | CK        | 368.70 b                      | 123.09 b                    | 92.06 a               | 26.15 b               | 10.21 b             |
|          | A1        | 360.90 d                      | 120.66 c                    | 91.16 b               | 25.16 c               | 9.53 d              |
|          | A2        | 370.05 b                      | 123.25 b                    | 92.01 a               | 26.16 b               | 10.29 b             |
|          | A3        | 342.75 e                      | 114.54 e                    | 92.08 a               | 26.20 b               | 9.16 f              |
|          | B1        | 365.85 c                      | 120.35 c                    | 91.21 b               | 25.11 c               | 9.68 c              |
|          | B2        | 378.00 a                      | 128.71 a                    | 92.27 a               | 26.72 a               | 10.96 a             |
|          | B3        | 345.60 d                      | 118.97 d                    | 92.02 a               | 26.18 b               | 9.31 e              |
| J67      | CK        | 335.70 b                      | 135.20 b                    | 94.08 a               | 25.17 a               | 10.08 b             |
|          | A1        | 325.50 cd                     | 128.87 d                    | 94.43 a               | 25.65 a               | 9.03 f              |
|          | A2        | 337.50 b                      | 135.68 b                    | 94.11 a               | 25.09 a               | 10.19 b             |
|          | A3        | 315.15 e                      | 123.30 e                    | 94.26 b               | 24.86 b               | 9.47 c              |
|          | B1        | 328.80 c                      | 130.22 c                    | 94.06 a               | 25.15 a               | 10.69 a             |
|          | B2        | 345.00 a                      | 140.31 a                    | 94.15 a               | 25.33 a               | 9.19 e              |
|          | B3        | 319.80 d                      | 125.48 e                    | 94.37 a               | 25.32 a               | 10.04 b             |
| 2019     |           |                               |                             |                       |                       |                     |
| J58      | CK        | 371.70 b                      | 128.09 b                    | 92.70 a               | 26.28 a               | 10.14 b             |
|          | A1        | 358.95 d                      | 122.05 d                    | 91.34 b               | 25.13 b               | 9.43 d              |
|          | A2        | 373.50 b                      | 128.20 b                    | 92.18 a               | 26.32 a               | 10.23 b             |
|          | A3        | 345.45 f                      | 114.54 f                    | 92.17 a               | 26.25 a               | 9.13 f              |
|          | B1        | 361.95 c                      | 125.23 c                    | 91.12 b               | 25.11 b               | 9.59 c              |
|          | B2        | 376.80 a                      | 131.71 a                    | 92.27 a               | 26.20 a               | 10.89 a             |
|          | B3        | 347.70 e                      | 119.04 e                    | 92.48 a               | 26.05 a               | 9.25 e              |
| J67      | CK        | 352.95 b                      | 136.00 b                    | 94.37 a               | 25.32 a               | 10.04 b             |
|          | A1        | 343.50 c                      | 130.39 cd                   | 94.85 b               | 24.76 b               | 9.46 d              |
|          | A2        | 353.10 b                      | 135.88 b                    | 94.49 a               | 25.31 a               | 10.13 b             |
|          | A3        | 327.45 e                      | 126.17 e                    | 94.50 a               | 25.51 a               | 9.12 f              |
|          | B1        | 345.15 c                      | 133.95 c                    | 92.83 b               | 25.09 b               | 9.62 c              |
|          | B2        | 363.00 a                      | 141.01 a                    | 94.21 a               | 25.40 a               | 10.73 a             |
|          | B3        | 335.10 d                      | 128.61 d                    | 94.13 a               | 25.14 a               | 9.27 e              |

Analysis of variance

|                      | Year (Y) | Treatment (T) | Cultivar (C) | Y × C | Y × T | T × C | Y × T × C |
|----------------------|----------|---------------|--------------|-------|-------|-------|-----------|
|                      | ns       | *             | ns           | **    | *     | *     | ns        |

Different letters indicate statistical significances at the p = 0.05 level. ns, not significant at the p = 0.05 level; * significant at the p = 0.05 level; ** significant at the p = 0.01 level.

3.3. Amount and Percentages of Above-Ground Biomass Accumulation

The amounts and percentages of above-ground biomass accumulation were nearly the same at each measured growth stage of rice (Table 3). The amounts and percentages from sowing to jointing stages of A1 and A2 were higher than those of CK. The above-ground biomass accumulation of rice grown under the B2 treatments from heading to maturity stages was higher than that of rice grown under the CK. Among the CRNF treatments, above-ground biomass accumulation from seeding to the jointing stage ranked as follows: A1 > A2 > A3 and B1 > B2 > B3. The above-ground biomass accumulation from heading to maturity stages was significantly higher in A2 and B2 than in all other treatments (Table 3).
Table 3. Differences in the amounts and percentages of above-ground biomass accumulation of japonica rice.

| Cultivar | Treatment | Sowing–Jointing | Jointing–Heading | Heading–Maturity |
|----------|-----------|-----------------|------------------|-----------------|
|          | Biomass (t ha\(^{-1}\)) | Percentage (%) | Biomass (t ha\(^{-1}\)) | Percentage (%) | Biomass (t ha\(^{-1}\)) | Percentage (%) |
| 2018     |           |                 |                  |                 |                   |                |
| J58      | CK        | 3.55 d          | 17.73 d          | 8.29 b          | 41.41 d          | 8.18 b         | 40.86 b        |
|          | A1        | 3.80 a          | 19.93 a          | 7.80 e          | 40.90 e          | 7.47 d         | 39.17 d        |
|          | A2        | 3.68 bc         | 18.24 c          | 8.30 b          | 41.15 d          | 8.19 b         | 40.60 b        |
|          | A3        | 3.61 cd         | 19.30 b          | 8.01 c          | 42.83 b          | 7.08 f         | 37.86 e        |
|          | B1        | 3.73 ab         | 19.28 b          | 7.91 d          | 40.88 e          | 7.71 c         | 39.84 c        |
|          | B2        | 3.59 cd         | 17.04 e          | 8.82 a          | 41.86 c          | 8.66 a         | 41.10 a        |
|          | B3        | 3.45 e          | 18.16 c          | 8.27 b          | 43.53 a          | 7.28 e         | 38.32 f        |
| J67      | CK        | 3.50 de         | 17.71 e          | 8.09 c          | 40.94 c          | 8.17 b         | 41.35 b        |
|          | A1        | 3.78 a          | 20.29 a          | 7.36 f          | 39.51 e          | 7.49 d         | 40.20 d        |
|          | A2        | 3.65 bc         | 18.27 d          | 8.14 b          | 40.74 d          | 8.19 b         | 40.99 c        |
|          | A3        | 3.52 d          | 19.11 c          | 7.89 e          | 42.83 a          | 7.01 f         | 38.06 f        |
|          | B1        | 3.70 b          | 19.53 b          | 7.26 g          | 38.31 f          | 7.99 c         | 42.16 a        |
|          | B2        | 3.60 c          | 17.52 e          | 8.46 a          | 41.17 b          | 8.49 a         | 41.31 b        |
|          | B3        | 3.44 e          | 18.34 d          | 8.02 d          | 42.75 a          | 7.30 e         | 38.91 e        |
| 2019     |           |                 |                  |                 |                   |                |
| J58      | CK        | 3.65 bc         | 18.35 cd         | 7.98 c          | 40.12 c          | 8.26 b         | 41.53 a        |
|          | A1        | 3.82 a          | 20.25 a          | 7.46 e          | 39.55 d          | 7.58 d         | 40.19 c        |
|          | A2        | 3.70 b          | 18.45 c          | 8.06 b          | 40.20 c          | 8.29 b         | 41.35 ab       |
|          | A3        | 3.60 c          | 19.32 b          | 7.91 d          | 42.46 a          | 7.12 f         | 38.22          |
|          | B1        | 3.71 b          | 19.35 b          | 7.48 e          | 39.02 e          | 7.98 c         | 41.63 a        |
|          | B2        | 3.60 c          | 17.19 e          | 8.75 a          | 41.79 b          | 8.59 a         | 41.02 b        |
|          | B3        | 3.43 d          | 18.19 d          | 7.98 c          | 42.31 a          | 7.45 e         | 39.50 d        |
| J67      | CK        | 3.51 de         | 17.84 e          | 8.00 c          | 40.65 c          | 8.17 b         | 41.51 a        |
|          | A1        | 3.83 a          | 20.24 a          | 7.61 d          | 40.22 c          | 7.48 d         | 39.53 c        |
|          | A2        | 3.66 c          | 18.44 d          | 8.01 c          | 40.35 c          | 8.18 b         | 41.21 a        |
|          | A3        | 3.55 d          | 19.08 c          | 7.96 c          | 42.77 a          | 7.10 f         | 38.15 e        |
|          | B1        | 3.74 b          | 19.43 b          | 7.66 d          | 39.79 d          | 7.85 c         | 40.78 b        |
|          | B2        | 3.62 c          | 17.54 f          | 8.48 a          | 41.09 b          | 8.54 a         | 41.38 a        |
|          | B3        | 3.46 e          | 18.28 d          | 8.13 b          | 42.95 a          | 7.34 e         | 38.77 d        |

Analysis of variance

| Year (Y) | Treatment (T) | Cultivar (C) | Y × C | Y × T | Y × T × C |
|----------|---------------|--------------|-------|-------|-----------|
| ns       | *             | ns           | *     | ns    |           |
| ns       | ns            | ns           | *     | ns    |           |
| ns       | ns            | ns           | *     | ns    |           |
| ns       | ns            | ns           | *     | ns    | **        |

Different letters indicate statistical significances at the \( p = 0.05 \) level. ns, not significant at the \( p = 0.05 \) level; * significant at the \( p = 0.05 \) level; ** significant at the \( p = 0.01 \) level.

3.4. Leaf Area Index and Decreasing Rate of Leaf Area

The LAI of the different treatments was basically consistent between the two years (Table 4). Except for B3, LAI for all treatments was significantly higher than that for CK at the jointing stage. LAI for the A2 and B2 treatments was significantly higher than that for CK at the mature stage. Among the CRNF treatments, LAI ranked the treatments A1 > A2 > A3 and B1 > B2 > B3 at the jointing stage and A2 > A1 > A3 and B2 > B1 > B3 at the heading stage. DRLA of A1 and B1 was significantly higher than that under the other treatments.
Table 4. Differences in leaf area index of japonica rice.

| Cultivar | Treatment | Jointing | Heading | Maturity | DRLA (LAI d⁻¹) |
|----------|-----------|----------|---------|----------|----------------|
|          |           | 2018     |         |          |                |
| J58      | CK        | 3.45 f   | 7.90 b  | 2.89 b   | 0.0808 cd      |
|          | A1        | 3.78 a   | 7.80 c  | 2.32 f   | 0.0884 a       |
|          | A2        | 3.68 c   | 7.89 b  | 2.88 b   | 0.0808 cd      |
|          | A3        | 3.51 e   | 7.63 e  | 2.62 d   | 0.0808 cd      |
|          | B1        | 3.72 b   | 7.82 c  | 2.49 e   | 0.0860 b       |
|          | B2        | 3.56 d   | 7.99 a  | 2.99 a   | 0.0806 d       |
|          | B3        | 3.39 g   | 7.72 d  | 2.69 c   | 0.0811 c       |
| J67      | CK        | 3.54 e   | 7.84 b  | 2.80 b   | 0.0826 b       |
|          | A1        | 3.76 a   | 7.71 d  | 2.31 f   | 0.0885 a       |
|          | A2        | 3.65 c   | 7.83 b  | 2.79 b   | 0.0826 b       |
|          | A3        | 3.60 d   | 7.60 f  | 2.60 d   | 0.0820 bc      |
|          | B1        | 3.71 b   | 7.76 c  | 2.37 e   | 0.0884 a       |
|          | B2        | 3.58 d   | 7.94 a  | 2.93 a   | 0.0821 bc      |
|          | B3        | 3.46 f   | 7.65 e  | 2.67 c   | 0.0816 c       |
|          |           | 2019     |         |          |                |
| J58      | CK        | 3.51 d   | 7.88 b  | 2.83 b   | 0.0815 b       |
|          | A1        | 3.77 a   | 7.68 d  | 2.36 f   | 0.0858 a       |
|          | A2        | 3.69 b   | 7.87 b  | 2.84 b   | 0.0811 b       |
|          | A3        | 3.65 c   | 7.50 e  | 2.62 d   | 0.0787 c       |
|          | B1        | 3.72 b   | 7.78 c  | 2.44 e   | 0.0861 a       |
|          | B2        | 3.54 d   | 7.98 a  | 2.95 a   | 0.0811 b       |
|          | B3        | 3.35 e   | 7.54 e  | 2.73 c   | 0.0776 d       |
| J67      | CK        | 3.53 e   | 7.85 b  | 2.83 b   | 0.0823 b       |
|          | A1        | 3.84 a   | 7.67 c  | 2.31 f   | 0.0879 a       |
|          | A2        | 3.70 c   | 7.87 b  | 2.82 b   | 0.0828 b       |
|          | A3        | 3.60 d   | 7.54 d  | 2.65 d   | 0.0802 c       |
|          | B1        | 3.75 b   | 7.73 c  | 2.36 e   | 0.0880 a       |
|          | B2        | 3.59 d   | 7.97 a  | 2.94 a   | 0.0825 b       |
|          | B3        | 3.45 f   | 7.60 d  | 2.71 c   | 0.0802 c       |

Analysis of variance

| Year (Y) | Treatment (T) | Cultivar (C) | Y × C | Y × T | T × C | Y × T × C |
|----------|---------------|--------------|-------|-------|-------|-----------|
| ns       | *             | ns           | *     | *     | *     | *         |
| Treatment (T) | *      | ns           | *     | *     | ns    | *         |
| Cultivar (C) | ns            | *            | ns    | *     | *     | ns        |

1 DRLA, decreasing rate of leaf area. Different letters indicate statistical significances at the p = 0.05 level. ns, not significant at the p = 0.05 level; * significant at the p = 0.05 level.

3.5. Crop Growth Rate and Photosynthetic Potential

Except for the B3 treatment, the crop growth rates for all CRNF treatments were significantly higher than that for CK from seeding to the jointing stage. The crop growth rate under the B2 treatment was higher than that under CK from the jointing to heading stages, and the crop growth rate under the B2 treatment was higher than that under CK from the heading to maturity stages. There was no significant difference in the crop growth rates between the A2 treatment and CK from the heading to maturity stages (Table 5).

Except for B3, the photosynthetic potential for all CRNF treatments was significantly higher than that for CK from the jointing to heading stages, and the photosynthetic potential for the A2 and B2 treatments was higher than or equal to that for CK from the heading to maturity stages (Table 5).
### Table 5. Differences in photosynthetic potential and crop growth rate of japonica rice.

| Cultivar | Treatment | Crop Growth Rate (g m⁻² d⁻¹) | Photosynthetic Potential (×10⁴ m² d hm⁻²) |
|----------|-----------|-------------------------------|----------------------------------------|
|          |           | Sowing–Jointing | Jointing–Heading | Heading–Maturity | Sowing–Jointing | Jointing–Heading | Heading–Maturity |
| **2018** |           |                 |                  |                |                 |                  |               |
| J58      | CK        | 5.63 e           | 25.91 b          | 13.20 b        | 108.68 f        | 181.60 b         | 334.49 b       |
|          | A1        | 6.03 a           | 24.37 d          | 12.04 d        | 119.07 a        | 183.28 a         | 313.72 e       |
|          | A2        | 5.84 c           | 25.95 b          | 13.20 b        | 115.92 c        | 185.12 a         | 333.87 b       |
|          | A3        | 5.73 d           | 25.03 c          | 11.41 f        | 110.57 e        | 178.24 c         | 317.75 d       |
|          | B1        | 5.92 b           | 24.71 c          | 12.44 c        | 117.18 b        | 184.64 a         | 319.61 d       |
|          | B2        | 5.70 d           | 27.55 a          | 13.97 a        | 112.14 d        | 184.80 a         | 340.38 a       |
|          | B3        | 5.48 f           | 25.85 b          | 11.74 e        | 106.79 g        | 177.76 c         | 322.71 c       |
| J67      | CK        | 5.47 e           | 24.51 bc         | 13.40 b        | 113.28 c        | 187.77 b         | 324.52 b       |
|          | A1        | 5.90 a           | 22.30 e          | 12.27 d        | 120.32 a        | 189.26 ab        | 305.61 e       |
|          | A2        | 5.70 c           | 24.67 b          | 13.43 b        | 116.80 b        | 189.42 ab        | 323.91 b       |
|          | A3        | 5.50 e           | 23.91 d          | 11.49 f        | 115.20 bc       | 184.80 c         | 311.10 d       |
|          | B1        | 5.78 b           | 21.99 f          | 13.09 c        | 118.72 a        | 189.26 ab        | 308.97 d       |
|          | B2        | 5.63 d           | 25.63 a          | 13.92 a        | 114.56 c        | 190.08 a         | 331.54 a       |
|          | B3        | 5.38 f           | 24.30 e          | 11.96 e        | 110.72 d        | 183.32 c         | 314.76 c       |
| **2019** |           |                 |                  |                |                 |                  |               |
| J58      | CK        | 5.70 c           | 24.93 c          | 13.32 b        | 112.32 d        | 182.24 c         | 332.01 b       |
|          | A1        | 5.97 a           | 23.32 e          | 12.23 d        | 120.64 a        | 183.20 bc        | 311.24 e       |
|          | A2        | 5.78 b           | 25.19 b          | 13.36 b        | 118.08 b        | 184.96 a         | 332.01 b       |
|          | A3        | 5.63 d           | 24.71 d          | 11.49 f        | 116.80 c        | 178.40 d         | 313.72 de      |
|          | B1        | 5.80 b           | 23.38 e          | 12.87 c        | 119.04 b        | 184.00 ab        | 316.82 cd      |
|          | B2        | 5.63 d           | 27.36 a          | 13.86 a        | 113.28 d        | 184.32 ab        | 338.83 a       |
|          | B3        | 5.36 e           | 24.95 c          | 12.02 e        | 107.20 e        | 174.24 e         | 318.37 c       |
| J67      | CK        | 5.40 de          | 24.24 c          | 13.40 b        | 114.73 e        | 187.77 b         | 325.74 b       |
|          | A1        | 5.89 a           | 23.07 f          | 12.26 d        | 124.80 a        | 189.92 a         | 304.39 f       |
|          | A2        | 5.64 c           | 24.28 c          | 13.41 b        | 120.25 c        | 190.91 a         | 326.05 b       |
|          | A3        | 5.46 d           | 24.12 d          | 11.64 f        | 117.00 d        | 183.81 c         | 310.80 d       |
|          | B1        | 5.75 b           | 23.21 e          | 12.87 c        | 121.88 b        | 189.42 ab        | 307.75 e       |
|          | B2        | 5.57 c           | 25.68 a          | 14.00 a        | 116.68 d        | 190.74 a         | 332.76 a       |
|          | B3        | 5.33 e           | 24.64 b          | 12.02 e        | 112.13 f        | 182.33 c         | 314.46 c       |

**Analysis of variance**

- **Year (Y)**: ns ns ns ns ns ns
- **Treatment (T)**: * * * * * *
- **Cultivar (C)**: ns ns * ns ns *
- **Y × C**: ns * ns ns ns *
- **Y × T**: * * ns * *
- **T × C**: ns * ns ns ns
- **Y × T × C**: * * ** ns *

Different letters indicate statistical significances at the $p = 0.05$ level. ns, not significant at the $p = 0.05$ level; * significant at the $p = 0.05$ level; ** significant at the $p = 0.01$ level.

### 3.6. Amount and Percentage of N Accumulation

The highest amount of total N accumulated in the B2 treatment and was more than 5% higher than that in CK in 2018 and 2019. The N accumulation measured from the A2 treatment was similar to that from CK at the mature stage of rice, and the total N accumulation from the other treatments was lower than that from the CK. Nitrogen accumulation of the A1 and A2 treatments was significantly higher than that of CK from sowing to the jointing stage, and N accumulation of the A2 treatment was significantly higher than that of CK, however, there was no significant difference between the A1 treatment and CK at rice maturity (Table 6).
Table 6. Differences in nitrogen accumulation and its percentages in rice.

| Cultivar | Treatment | Total N | Sowing to Jointing | Jointing to Heading | Heading to Maturity |
|----------|-----------|---------|--------------------|---------------------|---------------------|
|          |           | Accumulation (kg/hm²) | Accumulation (t/hm²) | Percentage (%) | Accumulation (t/hm²) | Percentage (%) | Accumulation (t/hm²) | Percentage (%) |
| 2018     | J58 CK    | 189.55 b | 70.54 d | 37.21 e | 83.85 c | 44.24 c | 35.16 b | 18.55 a |
|          | A1        | 175.52 d | 75.71 a | 43.13 a | 75.53 c | 43.03 d | 24.28 f | 13.83 c |
|          | A2        | 190.75 b | 72.99 b | 38.26 d | 82.55 d | 43.28 d | 35.21 b | 18.46 a |
|          | A3        | 163.46 f | 69.40 e | 42.46 b | 65.78 g | 40.24 e | 28.28 d | 17.30 b |
|          | B1        | 181.79 c | 71.67 c | 39.43 c | 85.09 b | 46.81 b | 25.03 e | 13.77 c |
|          | B2        | 200.46 a | 68.52 f | 34.18 f | 95.05 a | 47.42 a | 36.89 a | 18.40 a |
|          | B3        | 170.62 e | 65.14 g | 38.18 d | 74.76 f | 43.82 c | 30.72 d | 18.00 a |
| 2019     | J58 CK    | 187.76 b | 70.82 d | 37.22 f | 83.39 b | 44.41 c | 33.55 c | 17.87 d |
|          | A1        | 172.56 a | 74.86 a | 43.38 b | 74.40 e | 43.12 e | 23.30 g | 13.50 g |
|          | A2        | 188.80 b | 72.07 c | 38.17 e | 82.25 c | 43.56 d | 32.08 f | 18.26 b |
|          | A3        | 161.13 f | 70.47 de | 41.73 d | 70.07 g | 42.22 f | 26.40 e | 15.94 d |
|          | B1        | 180.06 c | 72.91 b | 40.49 c | 95.05 a | 47.42 a | 20.20 c | 13.70 c |
|          | B2        | 198.45 a | 69.88 e | 35.21 g | 92.61 a | 46.67 a | 35.96 a | 18.46 f |
|          | B3        | 165.33 e | 64.42 f | 38.96 d | 69.60 f | 42.10 f | 31.31 d | 18.29 a |
| J67      | CK        | 187.76 b | 70.73 d | 37.22 f | 83.39 b | 44.41 c | 33.55 c | 17.87 d |
|          | A1        | 172.56 a | 74.86 a | 43.38 b | 74.40 e | 43.12 e | 23.30 g | 13.50 g |
|          | A2        | 188.80 b | 72.07 c | 38.17 e | 82.25 c | 43.56 d | 32.08 f | 18.26 b |
|          | A3        | 161.13 f | 70.47 de | 41.73 d | 70.07 g | 42.22 f | 26.40 e | 15.94 d |
|          | B1        | 180.06 c | 72.91 b | 40.49 c | 95.05 a | 47.42 a | 20.20 c | 13.70 c |
|          | B2        | 198.45 a | 69.88 e | 35.21 g | 92.61 a | 46.67 a | 35.96 a | 18.46 f |
|          | B3        | 165.33 e | 64.42 f | 38.96 d | 69.60 f | 42.10 f | 31.31 d | 18.29 a |

Analysis of variance

- Year (Y): ns ns ns * ns ns ns
- Treatment (T): * * * ns * * ns
- Cultivar (C): ns ns * ns * * *
- Y × C: ** * * * ns ns ns
- Y × T: * * * ns * * *
- T × C: ns ns ** * ns * *
- Y × T × C: * * * * ns ns

Different letters indicate statistical significances at the p = 0.05 level. ns, not significant at the p = 0.05 level; * significant at the p = 0.05 level; ** significant at the p = 0.01 level.

Among the CRNF treatments, nitrogen accumulation determined for the A1 treatment was significantly higher than that for the other treatments from seeding to the jointing stage. Nitrogen accumulation of the B2 treatment was significantly higher than that of the other treatments from the jointing to heading stages. Nitrogen accumulation of the B2 treatment was higher than that of the other treatments from heading to maturity (Table 6).

3.7. Nitrogen Accumulation in Organs

Leaf nitrogen accumulation in the A1 and B1 treatments was higher than that in CK at the heading stage. Nitrogen accumulation in the stem and leaf in the A3 and B3 treatments was higher than that under CK at maturity. Nitrogen accumulation in the panicle of CK plants was significantly lower than that of the B2 plants, but not significantly different from that of the A2 rice at maturity. Among the CRNF treatments, nitrogen accumulation in leaves was highest for the A1 and B1 treatments of rice at the heading stage, and nitrogen accumulation in panicles of rice grown under the A2 and B2 treatments was significantly higher than that under other treatments at rice maturity (Table 7).
Table 7. Differences in N accumulation in each rice organ at the heading and maturity stages.2

| Cultivar | Treatment | Nitrogen Accumulation (kg/hm²) | NAPH |
|----------|-----------|-------------------------------|------|
|          |           | Heading | Panicle | Maturity | Stem | Leaf | Panicle | (kg ha⁻¹) |
|          |           | Stem | Leaf | Panicle | Stem | Leaf | Panicle |
| 2018     | J58 CK    | 56.05 b | 82.08 b | 16.26 c | 35.86 a | 48.18 c | 105.50 b | 89.24 b |
|          | A1        | 58.23 a | 78.50 c | 14.51 d | 33.40 c | 40.09 e | 102.03 c | 87.52 c |
|          | A2        | 56.45 b | 82.84 b | 16.25 b | 35.18 b | 49.37 b | 106.20 b | 89.95 b |
|          | A3        | 50.75 d | 72.40 e | 12.03 f | 30.85 d | 37.35 f | 95.26 e | 83.23 e |
|          | B1        | 58.27 a | 79.02 c | 19.47 a | 33.40 c | 40.09 e | 102.03 c | 87.52 c |
|          | B2        | 57.68 a | 89.14 a | 16.75 b | 36.43 a | 51.74 a | 112.29 a | 95.54 a |
|          | B3        | 52.94 c | 74.19 d | 12.77 e | 31.09 d | 39.95 e | 99.58 d | 86.81 c |
|          | J67 CK    | 57.09 c | 84.83 b | 12.29 c | 35.53 b | 44.06 c | 108.17 b | 95.88 b |
|          | A1        | 57.81 b | 78.29 c | 13.16 b | 33.54 c | 36.85 f | 102.17 c | 89.01 c |
|          | A2        | 55.83 d | 86.06 b | 12.43 c | 35.90 ab | 45.05 b | 107.85 b | 95.42 b |
|          | A3        | 51.55 e | 70.90 d | 10.50 e | 30.85 d | 37.35 f | 96.05 e | 85.55 d |
|          | B1        | 60.85 a | 78.87 c | 14.31 a | 33.43 a | 42.80 d | 103.83 c | 89.52 c |
|          | B2        | 57.54 bc | 90.66 a | 14.29 a | 36.26 a | 46.33 a | 115.86 a | 101.57 a |
|          | B3        | 51.83 e | 71.20 d | 10.99 d | 30.29 d | 37.68 e | 96.73 e | 85.74 d |
| 2019     | J58 CK    | 57.19 a | 83.28 c | 18.30 b | 35.68 ab | 46.16 c | 107.11 b | 88.81 b |
|          | A1        | 56.04 b | 79.92 d | 16.77 d | 32.44 d | 40.54 e | 102.46 d | 85.69 e |
|          | A2        | 55.39 bc | 84.93 b | 17.29 c | 35.98 ab | 47.43 b | 106.28 b | 88.99 b |
|          | A3        | 52.60 d | 77.05 e | 9.52 f | 31.93 d | 39.38 f | 94.26 f | 84.74 f |
|          | B1        | 58.02 a | 79.99 d | 18.50 b | 35.36 b | 41.47 d | 104.62 c | 86.12 d |
|          | B2        | 57.95 a | 89.95 a | 19.59 a | 36.39 a | 49.92 a | 115.91 a | 96.32 a |
|          | B3        | 54.97 c | 77.90 d | 10.11 e | 33.98 c | 39.03 f | 97.97 e | 87.68 c |
|          | J67 CK    | 57.14 b | 83.86 c | 13.59 c | 35.42 b | 44.39 b | 107.95 b | 94.36 c |
|          | A1        | 56.59 b | 79.21 d | 11.46 e | 34.09 c | 35.41 e | 102.24 d | 90.78 d |
|          | A2        | 55.08 c | 85.87 d | 12.01 d | 36.80 a | 41.46 c | 108.09 b | 96.08 b |
|          | A3        | 51.10 d | 72.22 f | 9.73 f | 33.94 c | 33.87 f | 93.52 f | 83.79 g |
|          | B1        | 58.28 a | 79.69 d | 16.08 a | 36.94 a | 38.24 d | 105.81 c | 89.73 e |
|          | B2        | 57.05 b | 89.64 a | 15.80 b | 37.12 a | 46.20 a | 115.08 a | 99.28 a |
|          | B3        | 52.01 d | 74.34 e | 9.92 f | 35.82 b | 34.13 f | 96.73 e | 86.81 f |

Analysis of variance

| Year (Y) | Treatment (T) | Cultivar (C) | Y × C | Y × T | Y × T × C |
|----------|---------------|--------------|-------|-------|----------|
| ns       | *             | ns           | **    | *     | ns       |
| ns       | *             | ns           | **    | *     | ns       |
| ns       | *             | ns           | **    | *     | ns       |
| ns       | *             | ns           | **    | *     | ns       |
| ns       | *             | ns           | **    | *     | ns       |
| ns       | *             | ns           | **    | *     | ns       |

2 NAPH, N accumulation in the panicle after heading. Different letters indicate statistical significances at the p = 0.05 level. ns, not significant at the p = 0.05 level; * significant at the p = 0.05 level; ** significant at the p = 0.01 level.

3.8. Nitrogen-Use Efficiency

In both years, compared with CK, the highest apparent recovery efficiency of N fertilizer, physiological N-use efficiency, and agronomic N-use efficiency values were observed in the A2 and B2 treatments. Compared with the other treatments, all measurements of the different types of N-use efficiencies, except internal N-use efficiency, were highest in the B2 treatment (Table 8).
Table 8. Differences in N-utilization efficiency.

| Cultivar | Treatment | RNUE (%)  | INUE (kg Grain kg$^{-1}$) | PNUE (kg kg$^{-1}$) | ANUE |
|----------|-----------|-----------|---------------------------|---------------------|------|
| 2018     |           |           |                           |                     |      |
| J58      | CK        | 40.70 c   | 53.88 cd                  | 39.51 bc            | 16.08 c |
|          | A1        | 35.51 e   | 54.31 bc                  | 38.19 d             | 13.56 e |
|          | A2        | 41.15 b   | 53.93 bcd                 | 39.75 b             | 16.36 b |
|          | A3        | 31.04 g   | 56.05 a                   | 39.27 c             | 12.19 g |
|          | B1        | 37.83 d   | 53.22 d                   | 37.25 f             | 14.09 d |
|          | B2        | 44.74 a   | 54.66 b                   | 42.11 a             | 18.84 a |
|          | B3        | 33.69 f   | 54.57 bc                  | 37.83 c             | 12.74 f |
| J67      | CK        | 39.04 b   | 53.69 b                   | 41.76 c             | 16.30 c |
|          | A1        | 33.41 d   | 53.97 b                   | 40.29 d             | 13.46 e |
|          | A2        | 39.43 b   | 53.98 b                   | 42.40 b             | 16.72 b |
|          | A3        | 29.19 f   | 56.01 a                   | 42.49 b             | 12.40 g |
|          | B1        | 36.19 c   | 52.61 c                   | 38.84 e             | 14.06 d |
|          | B2        | 43.00 a   | 53.86 b                   | 43.16 a             | 18.56 a |
|          | B3        | 30.73 e   | 55.60 a                   | 42.34 b             | 13.01 f |
| 2019     |           |           |                           |                     |      |
| J58      | CK        | 40.22 b   | 53.67 b                   | 39.55 c             | 15.91 c |
|          | A1        | 35.22 d   | 53.77 b                   | 37.74 e             | 13.29 e |
|          | A2        | 40.50 b   | 53.90 b                   | 40.06 b             | 16.22 b |
|          | A3        | 31.56 f   | 55.14 a                   | 38.55 d             | 12.17 g |
|          | B1        | 37.44 c   | 52.84 c                   | 37.02 f             | 13.86 d |
|          | B2        | 45.14 a   | 53.88 b                   | 41.44 a             | 18.70 a |
|          | B3        | 33.50 e   | 54.13 b                   | 37.60 e             | 12.60 f |
| J67      | CK        | 39.30 b   | 53.47 d                   | 41.51 c             | 16.31 c |
|          | A1        | 33.37 e   | 55.10 b                   | 42.49 b             | 14.18 e |
|          | A2        | 38.78 c   | 54.34 c                   | 42.90 b             | 16.64 b |
|          | A3        | 29.51 g   | 56.51 a                   | 43.70 a             | 12.90 g |
|          | B1        | 36.79 d   | 53.17 d                   | 40.15 d             | 14.77 d |
|          | B2        | 43.24 a   | 54.09 c                   | 43.65 a             | 18.88 a |
|          | B3        | 31.49 f   | 55.65 b                   | 42.81 b             | 13.48 f |

Analysis of variance

| Year (Y) | Treatment (T) | Cultivar (C) | Y × C | Y × T | T × C | Y × T × C |
|----------|---------------|--------------|-------|-------|-------|-----------|
|          | Ns            | **           | ns    | *     |       |           |
|          | *             | ns           | *     | **    |       |           |
|          | ns            | *            | ns    | **    |       |           |
|          | *             | ns           |       |       | *     |           |
|          | *             | ns           |       |       | *     | **        |

3 RNUE, apparent recovery efficiency of N fertilizer; INUE, internal N-use efficiency; ANUE, agronomic N-use efficiency; PNUE, physiological N-use efficiency. Different letters indicate statistical significances at the $p = 0.05$ level. ns, not significant at the $p = 0.05$ level; * significant at the $p = 0.05$ level; ** significant at the $p = 0.01$ level.

4. Discussion

4.1. Effects of One-Time N Application on N Uptake and Utilization of Late Japonica Rice

Nitrogen uptake and utilization are important factors affecting grain yield production in rice [23]. In this study, results of the similarities and differences in nitrogen accumulation among the different treatments was mainly due to the different controlled-release periods of the CRNF. After transplanting, the two cultivars of late japonica rice grew for 25–30 days, 45–50 days, 50–55 days, and 77–80 days to reach the respective growth stages of effective tillering, jointing, panicle differentiation, and heading. The peak of N release from the short-acting CRNFs of the A2 and B2 treatments was about 25–30 days after transplantation, which coincided with the effective tillering period and led to moderate levels of N accumulation from sowing to the jointing stage (Table 6). The peak of N release from the long-acting CRNF of the A2 and B2 treatments was about 50 days after transplanting, which met the N demand of late japonica rice during the panicle initiation stage and led to the highest N accumulation after heading (Table 6). Low N accumulation in stems
and leaves and higher N accumulation in panicles have been shown to be the important characteristics of cultivars with high N-use efficiency in the late stage of grain filling [24]. In this study, the proportions of N released from the A2 and B2 fertilizers after 70 days from transplanting (the heading stage) may have promoted the transport of stored N from leaves and stems to panicles [25] and may result in higher nitrogen accumulation in panicles and lower nitrogen accumulation in the leaves and stems of A2 and B2 plants [26]. Therefore, the apparent recovery efficiency of N fertilizer was highest (Table 8).

Compared with the A2 and B2 treatments, the earlier peak release of N from the CRNF of the A1 and B1 treatments (Figure 1) likely facilitated the higher N accumulation in A1 and B1 compared to that of CK from seeding to the jointing stage. The earlier peak release of N may have also contributed to the significantly lower N accumulation observed in A1 and B1 than in CK after jointing. The results indicate that the nitrogen supplied by A1 and B1 treatments could meet the nitrogen demands of late japonica rice before jointing stage. However, A1 and B1 treatments demonstrated an insufficient ability to supply N from the jointing stage to maturity stage, which resulted in relatively low 1000-grain weights and seed-setting rates. Compared with A2 and B2, the peak of N release from the long-acting CRNF of A3 and B3 occurred later (Figure 1). As a result, the amounts of nitrogen accumulated in A3 and B3 rice were significantly lower than that of the CK rice during the whole growth period (Table 6). Another consequence of the later occurrence of the peak of N release was the lowest observed RNUE (Table 8). These results indicate that the duration of N released from the A3 and B3 treatments was too long, and thus the released N from the long-term controlled fertilizer could not meet the nitrogen demands of rice for growth.

4.2. Effects of One-Time N Application on Yield of Late Japonica Rice

The ideal fertilization strategy using CRNFs is a one-time application of N release that matches the timing of peak N demands in rice growth to achieve the same or greater grain yields attained by the traditional strategy of multiple-split applications of a CU while saving costs of time and labor. The results of this study show that the A2 and B2 formulas of a one-time application could achieve the same or higher yields of late japonica rice as that of the CK.

Increasing the total number of spikelets (effective panicle × spikelets per panicle) and maintaining stable seed-setting rates and 1000-grain weights are important ways to promote rice yield [27,28]. Rice yield is also determined by above-ground biomass accumulation, distribution, transportation and transformation of rice [29]. In our experiment, moderate nitrogen accumulation was observed in the A2 and B2 treatments from transplanting to heading of rice. The time period from transplanting to heading is not only the key period for panicle differentiation and determination of grain number per panicle [30], but that period is also important to the formation and growth of the top four leaves of the rice canopy [31]. Moderate nitrogen accumulation in rice applied with the A2 and B2 treatments could result in good roots and leaves at the tillering stage [32], and it also contributed to the formation of larger panicles that had more than 45,000 spikelets per hectare (Table 2) and an LAI (Table 4) of more than 7 at the heading stage. These traits of large panicles and high LAI are strong indicators of better fullness of grain [33]. The accumulation of photosynthates after heading is the key factor affecting yield components and grain yield of rice [34]. After heading, rice grown under the A2 and B2 treatments likely absorbed the part of small and appropriate amount of nitrogen from the CRNF, which could enhance root activity at later growth stage and results in the production of higher leaf area with a delay of leaf senescence [35]. This in turn likely increased the photosynthetic rate (Table 5), above-ground biomass accumulation (Table 3), and eventually increased the seed setting rate and 1000-grain weight in our two rice cultivars (Table 2).

Although adequate N uptake observed in the A1 and B1 treatments of rice in jointing stage led to the highest above-ground biomass accumulation (Table 3), photosynthetic potential and crop growth rate (Table 5) from sowing to the jointing stage, it also resulted
in a large number of ineffective tillers, which ultimately reduced the panicle number of rice to lower than that of the CK rice (Table 2). Moreover, the nitrogen uptake in rice of the A1 and B1 treatments was insufficient at the late growth stage. After heading, the nitrogen deficiency reduced above-ground biomass accumulation (Table 3), photosynthetic potential and crop growth rate (Table 5) in the rice of these two treatments, which led to the decline of seed-setting rate and 1000-grain weight (Table 2). The N accumulation of A3 and B3 treatments was all the least (Table 6) for the whole rice growing period. The least N accumulation limited photosynthetic production capacity and reduced above-ground biomass accumulation, thereby resulting in fewer panicles and spikelets and the lowest yield [36].

5. Conclusions

Compared with the other CRNF treatments, A2 and B2 treatments of a one-time application could achieve the same or higher yields of the multiple-split applications of CU in late japonica rice. The release of nitrogen from A2 and B2 was most synchronized with nitrogen uptake by late japonica rice, resulting in higher yield. Moreover, rice in the A2 and B2 treatments had higher N accumulation, higher aboveground biomass accumulation and LAI at the heading and maturity stages and higher photosynthetic activity. These factors are considered to be responsible for the greater yields achieved by the A2 and B2 treatments.

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References

1. Grant, C.A.; Wu, R.F.; Harker, K.N.; Clayton, G.W.; Bittman, S.; Zebarth, B.J.; Lupwayi, N.Z. Crop yield and nitrogen concentration with controlled release urea and split applications of nitrogen as compared to non-coated urea applied at seeding. *Field Crop. Res.* 2012, 127, 170–180. [CrossRef]
2. Duan, J.; Shao, Y.; He, L.; Li, X.; Hou, G.; Li, S.; Feng, W.; Zhu, Y.; Wang, Y.; Xie, Y. Optimizing nitrogen management to achieve high yield. high nitrogen efficiency and low nitrogen emission in winter wheat. *Sci. Total Environ.* 2019, 697, 134088. [CrossRef]
3. Peng, S.B.; Buresh, R.J.; Huang, J.L.; Yang, J.C.; Zou, Y.B.; Zhong, X.H.; Wang, G.H.; Zhang, F.S. Strategies for overcoming low agronomic nitrogen use efficiency in irrigated rice systems in China. *Field Crop. Res.* 2006, 96, 37–47. [CrossRef]
4. Song, C.; Guan, Y.; Wang, D.; Zewudie, D.; Li, F.M. Palygorskite-coated Fertilizers with a timely release of nutrients increase potato productivity in a rain-fed cropland. *Field Crop. Res.* 2014, 166, 10–17. [CrossRef]
5. Geng, J.B.; Sun, Y.B.; Zhang, M.; Li, C.L.; Yang, Y.C.; Liu, Z.G.; Li, S.L. Long-term effects of controlled release urea application on crop yields and soil fertility under rice-oliseed rape rotation system. *Field Crop. Res.* 2015, 184, 65–73. [CrossRef]
6. Farmaha, B.S.; Sims, A.L. The Influence of Polymer-Coated Urea and Urea Fertilizer Mixtures on Spring Wheat Protein Concentrations and Economic Returns. *Agron. J.* 2013, 105, 1328–1334. [CrossRef]
7. Ye, Y.S.; Liang, X.Q.; Chen, Y.X.; Liu, J.; Gu, G.T.; Guo, R.; Li, L. Alternate wetting and drying irrigation and controlled-release nitrogen fertilizer in late-season rice. Effects on dry matter accumulation yield, water and nitrogen use. *Field Crop. Res.* 2013, 144, 212–224. [CrossRef]
8. Miao, X.K.; Xing, X.M.; Ke, J.; Liu, Z.H.; Tang, S.; Ding, C.Q.; Wang, S.H.; Li, G.H. Yield and nitrogen uptake of bowl-seeding machine-transplanted rice with slow-Release nitrogen fertilizer. *Agron. J.* 2016, 108, 313–320. [CrossRef]

9. Wei, H.Y.; Li, H.L.; Cheng, J.Q.; Zhang, H.C.; Xu, K.; Guo, B.W.; Hu, Y.J.; Cui, P.Y. Effects of slow/controlled release fertilizer types and their application regime on yield in rice with different types of panicle. *Acta Agron. Sin.* 2017, 43, 730–740. [CrossRef]

10. Wei, H.Y.; Chen, Z.F.; Xing, Z.P.; Zhou, L.; Liu, Q.Y.; Zhang, Z.Z.; Jiang, Y.; Hu, Y.J.; Zhu, J.Y.; Cui, P.Y.; et al. Effects of slow or controlled release fertilizer types and fertilization modes on yield and quality of rice. *J. Integr. Agr.* 2018, 17, 2222–2234. [CrossRef]

11. Xing, X.M.; Li, X.C.; Ding, Y.F.; Wang, S.H.; Liu, Z.H.; Tang, S.; Ding, C.Q.; Li, G.H.; Wei, G.B. Effects of types of controlled released nitrogen fertilizer types and fertilization modes on yield and dry mass production. *Sci. Agric. Sin.* 2015, 48, 4892–4902.

12. Ni, B.; Liu, M.; Lv, S.; Xie, L.; Wang, Y. Environmentally friendly slow-release nitrogen fertilizer. *J. Agric. Food Chem.* 2011, 59, 10169–10175. [CrossRef]

13. Li, Y.; Li, Y.H.; Zhao, J.H.; Sun, Y.J.; Xu, H.; Yan, F.J.; Xie, H.Y.; Ma, J. Effects of slow-and controlled-release nitrogen fertilizer on nitrogen utilization characteristics and yield of machine-transplanted rice. *J. Zhejiang Univ. Agric. Life Sci.* 2015, 41, 673–684.

14. Lv, X.H.; Fu, L.D.; Wang, Y.; Sui, X.; Ren, H.; Li, X.; Li, B.J. Effect of proportioning application of slow-release fertilizer and available nitrogen fertilizer on machine-transplanted rice yield and nitrogen utilization efficiency. *Jiangsu Agric. Sci.* 2016, 44, 115–118.

15. Hu, C.H.; Luo, G.B.; Zeng, J.H.; Pan, X.Z. Influence of different types of slow-release nitrogen fertilizer on rice yield and nitrogen fertilizer use efficiency. *Chin. Agric. Sci. Bull.* 2011, 27, 174–177.

16. Zeng, Y.J.; Shi, Q.H.; Pan, X.H.; Han, T. Effects of Nitrogen Application Amount on Characteristics of Nitrogen Utilization and Yield Formation in High Yielding Early Hybrid Rice. *Acta Agron. Sin.* 2008, 34, 1409–1416. [CrossRef]

17. Li, M.Y.; Shi, Q.H.; Huang, C.L.; Zeng, L.; Pan, X.H.; Tang, X.M. Effects of Nitrogen Application of Panicle Fertilizer on Source-Sink Characteristics and Nitrogen Fertilizer Use Efficiency of Super Hybrid Rice Ganxin 688. *Hybrid Rice.* 2010, 25, 63–72.

18. Wei, H.H.; Meng, T.Y.; Li, C.; Xu, K.; Huo, Z.Y.; Wei, H.Y.; Guo, B.W.; Zhang, H.C.; Dai, Q.G. Comparisons of grain yield and nutrient accumulation and translocation in high-yielding japonica/indica hybrids; indica hybrids; and japonica conventional varieties. *Field Crop. Res.* 2017, 204, 101–109. [CrossRef]

19. Ding, Y.F.; Li, G.H.; Li, W.W.; Gao, S.; Wang, Y.H.; Liu, Z.H.; Chen, L.; Ding, C.Q.; Tang, S.; Jiang, Y. Introduction to the one-time Fertilization Technology for Mechanized Transplanting Rice: Side Deep Application of Controlled-release Blend Fertilizer. *China Rice.* 2020, 26, 11–15.

20. Li, J.J.; Xu, M.G.; Xin, J.S.; Duan, J.J.; Ren, Y.; Li, D.C.; Huang, J.; Shen, H.P.; Zhang, H.M. Spatial and Temporal Characteristics of Basic Soil Productivity in China. *Sci. Agric. Sin.* 2016, 49, 510–1519.

21. Douglas, L.A.; Riazi, A.; Smith, C.J. A semi-micro method for determining total nitrogen in soils and plant material containing nitrate and nitrite. *Soil Sci. Soc. Am. J.* 1980, 44, 431–433. [CrossRef]

22. Yang, Y.C.; Zhang, M.; Zheng, L.; Cheng, D.D.; Liu, M.; Geng, Y.Q. Controlled Release Urea Improved Nitrogen Use Efficiency; Yield; and Quality of Wheat. *Agron. J.* 2011, 103, 479. [CrossRef]

23. Xiong, Q.Q.; Tang, G.P.; Zhong, L.; He, H.H.; Chen, X.R. Response to nitrogen deficiency and compensation on physiological characteristics, yield formation, and nitrogen utilization of rice. *Front. Plant Sci.* 2018, 9, 1075. [CrossRef] [PubMed]

24. Hu, Y.J.; Wu, P.; Zhu, M.; Xing, Z.P.; Dai, Q.G.; Huo, Z.Y.; Xu, K.; Wei, H.Y.; Guo, B.W.; Zhang, H.C. Characteristics of Nitrogen Uptake and Utilization of Mechanically-transplanted Pot-tubed rice Seedlings. *Chin. J. Rice Sci.* 2018, 32, 257–264.

25. Lin, L.; Yang, J.; Jiao, J.M.; Li, M.C.; Gui, C.C. Phloem transport capacity of transgenic rice ttc19 (cry1c*) under several potassium fertilizer levels. *PLoS ONE* 2018, 13, e0195058.

26. Ntanos, D.A.; Koutoubas, S.D. Dry matter and N accumulation and translocation for indica and japonica rice under Mediterranean conditions. *Field Crop. Res.* 2002, 74, 93–101. [CrossRef]

27. Ling, Q.H.; Zhang, H.C.; Dai, Q.G.; Ding, Y.F.; Ling, L.; Su, Z.F.; Xu, M.; Que, J.H.; Wang, S.H. Study on precise and quantitative N application in rice. *Sci. Agric. Sin.* 2005, 38, 2457–2467.

28. Zhang, H.C.; Wu, G.C.; Wu, W.G.; Dai, Q.G.; Huo, Z.Y.; Xu, K.; Gao, H.; Wei, H.Y.; Huang, X.F.; Gong, J.L. The SOI model of quantitative cultivation of super-high yielding rice. *Sci. Agric. Sin.* 2010, 43, 2645–2660.

29. Wei, H.Y.; Zhang, H.C.; Dai, Q.G.; Huo, Z.Y.; Xu, K.; Hang, J.; Ma, Q.; Zhang, S.F.; Zhang, Q.; Liu, Y.Y. Characteristics of matter production and accumulation in rice genotypes with different N use efficiency. *Acta Agron. Sin.* 2007, 33, 1802–1809.

30. Sui, B.; Feng, X.M.; Tian, G.L.; Hu, X.Y.; Shen, Q.R.; Guo, S.W. Optimizing nitrogen supply increases rice yield and nitrogen use efficiency by regulating yield formation factors. *Field Crop. Res.* 2013, 150, 99–107. [CrossRef]

31. Zhang, Y.F. Application and research of rice precise and quantitative cultivation technology. *J. Jiangsu Agric. Sci.* 2012, 40, 77–78.

32. Meng, T.Y.; Wei, H.H.; Li, X.; Dai, Q.D.; Huo, Z.Y. A better root morpho-physiology after heading contributing to yield superiority of japonica/indica hybrid rice. *Field Crop. Res.* 2018, 228, 135–146. [CrossRef]

33. Li, H.; Liu, L.; Wang, Z.; Yang, J.; Zhang, J. Agronomic and physiological performance of high-yielding wheat and rice in the lower reaches of Yangtze River of China. *Field Crop. Res.* 2012, 133, 119–129. [CrossRef]

34. Yang, J.C.; Zhang, J.H. Grain filling of cereals under soil drying. *New Phytol.* 2006, 169, 223–236. [CrossRef]
35. Li, C.; Wei, H.H.; Xu, J.W.; Wang, Z.J.; Xu, K.; Zhang, H.C.; Dai, Q.G.; Huo, Z.Y.; Wei, H.Y.; Guo, B.W. Characteristics of nitrogen uptake, utilization and translocation in the indica-japonica hybrid rice of Yongyou series. *Plant Nutr. Fertil. Sci.* 2016, 22, 177–186.

36. Wei, H.Y.; Zhang, H.C.; Blumwald, E.; Li, H.L.; Cheng, J.C.; Dai, Q.G.; Huo, Z.Y.; Xu, K.; Guo, B.W. Different characteristics of high yield formation between inbred japonica super rice and inter-sub-specific hybrid super rice. *Field Crop. Res.* 2016, 198, 179–187. [CrossRef]