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# Combining Controlled-Release Urea and Normal Urea to Improve the Yield, Nitrogen Use Efficiency, and Grain Quality of Single Season Late *japonica* Rice

**Can Zhao, Zijun Gao, Guangming Liu, Yue Chen, Wei Ni, Jiaming Lu, Yi Shi, Zihui Qian, Weiling Wang and Zhongyang Huo ***

Jiangsu Key Laboratory of Crop Genetics and Physiology/Jiangsu Key Laboratory of Crop Cultivation and Physiology/Jiangsu Co-Innovation Center for Modern Production Technology of Grain Crops/Agricultural College, Yangzhou University, 88 Daxue South Road, Yangzhou 225009, China

* Correspondence: huozy69@163.com

**Abstract:** Controlled-release urea (CRU) is widely adopted to improve yields and nitrogen use efficiencies (NUEs) in rice. However, there are few studies on the effects of the mixed application of CRU and normal urea (at different N ratios) on rice yield, nitrogen efficiency, and grain quality. A series of simplified fertilization modes (SFMs) were set up in 2018–2019. CRU with release periods of 80 days and 120 days were mixed with urea at N ratios of 7:3, 6:4, 5:5, 4:6, and 3:7 and applied during the rice-growing season. We determined the rice yield, dry matter accumulation, NUEs, and grain quality. The yields of SFM_80_6/4 (CRU with release periods of 80 days were mixed with urea at N ratios of 6:4) and SFM_120_5/5 (CRU with release periods of 120 days were mixed with urea at N ratios of 5:5) were 3.69% and 4.39% higher than that of fractionated urea (FU), respectively, across 2018 and 2019. Combining the application of controlled-release urea and normal urea improved the dry matter accumulation, nitrogen accumulation, and nitrogen uptake rate when compared with FU. SFMs improved the processing quality and appearance quality of rice grains and did not reduce the cooking and eating quality. SFM_80_6/4 and SFM_120_5/5 are a one-time fertilization mode with high yield, high efficiency, and good grain quality, which is worthy of further promotion and application.

**Keywords:** rice; controlled-release urea; yield; nitrogen use efficiency; grain quality



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## 1. Introduction

Rice is one of the main food crops in China. Its planting area accounts for nearly 30% of the total cultivated area in China and plays a very important role in China's food production and consumption [1,2]. Nitrogen (N) is a determining factor for crop growth and plays a vital role in maintaining rice production [3]. The world applies more than 120 million tons of nitrogen fertilizer every year, while China consumes 30% of the world's total nitrogen fertilizer. The average fertilizer utilization efficiency in China is only about 35%, which is seriously lower than that in developed countries [4]. In recent years, with the transfer of the rural labor force to urban areas, repeated topdressing, which is pursued by high-yield cultivation technology, has been difficult to implement in rice planting. The inappropriate amount of fertilization is not conducive to high yield, quality, and efficiency of rice [5,6]. The number of times of application of traditional fertilization is generally 4, which is time-consuming and has seriously restricted the sustainable development of modern agriculture [7,8].

Controlled-release N fertilizer contains N in a form which delays availability for plant uptake post-application, thus eliminating the need for multiple applications, and mainly consists of resin coating and urea [9]. As a new type of fertilizer, controlled-release urea (CRU) was designed to release nutrients into the soil solution at rates which closely match the N demands of crops, which has the advantages of slow nutrient release, long fertilizer effect period, saving topdressing times, etc. [10–12]. Compared with normal urea, CRU can significantly reduce nutrient loss (e.g., nitrogen leaching, ammonia volatilization), reduce environmental pollution caused by fertilization, improve nitrogen fertilizer utilization, improve crop growth and development, and significantly increase yield [12–14]. However, since the nutrient release rate of CRU is lower than that of normal urea, one-time basal application will lead to insufficient nutrients in the early stage of rice growth, thus affecting yield [15]. It is reported that the production process of slow-release fertilizer is complex, and the cost is high, which leads to its high price, and thus it often fails to achieve ideal economic benefits [16]. In order to deal with the shortcomings of slow-release fertilizer, people often mix CRU with normal urea as basal fertilizer [17].

In recent years, with the continuous improvement of people's living conditions, the requirements for rice quality are also getting higher and higher, and the demand for high-yield and high-quality rice is increasing. Therefore, it is essential to achieve the coordination and unity of rice yield and grain quality. Grain quality mainly includes processing quality, appearance quality, nutritional quality, and cooking and eating quality [18,19]. Proper application of nitrogen fertilizer can improve rice quality [20]. The application of slow-release fertilizer alone or the split application of urea could increase rice yield and nitrogen efficiency and improve rice quality. However, there are few studies on the effects of the mixed application of CRU and normal urea (at different N ratios) on rice yield, nitrogen efficiency, and grain quality [11,15]. There must be an optimal N ratio to make rice yield, nitrogen efficiency, and rice quality better. In our study, CRU with release periods of 80 days and 120 days were mixed with urea at different N ratios and applied during the rice-growing season to study the effect of simplified one-time basal fertilization on rice yield, nitrogen efficiency, and rice quality and to identify one-time fertilization modes with high yield, high quality, and high nitrogen efficiency. Our results will provide a theoretical basis for the design of the simplified fertilization of japonica rice with good taste in Jiangsu province.

## 2. Materials and Methods

### *2.1. Experiment Location and Weather Conditions*

Our study was conducted at Shatou innovation experimental base (32°31′ N, 119°55′ E) in Guangling district, Yangzhou City in 2018 and 2019. The soil type is pond paddy soil with a sticky texture. The 0~20 cm soil layer has a pH of 7.09, containing 25.6 g $kg^{-1}$ organic matter, 1.40 g $kg^{-1}$ soil total nitrogen, 106.72 mg $kg^{-1}$ alkali hydrolyzed nitrogen, 281.4 mg $kg^{-1}$ available potassium, and 23.4 mg $kg^{-1}$ available phosphorus. The minimum ($T_{min}$), maximum ($T_{max}$), and mean ($T_{mean}$) temperatures; rainfall; mean relative humidity; and sunshine duration (SD) during the rice-growing seasons of 2018 and 2019 are shown in Table 1.

**Table 1.** The minimum ($T_{min}$), maximum ($T_{max}$), mean ($T_{mean}$) temperature, rainfall, mean relative humidity, and sunshine duration (SD) in the rice growing season.

| | $T_{min}$ (°C) | | $T_{max}$ (°C) | | $T_{mean}$ (°C) | | Rainfall (mm) | | $RH_{mean}$ (%) | | SD (h) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2018 | 2019 | 2018 | 2019 | 2018 | 2019 | 2018 | 2019 | 2018 | 2019 | 2018 | 2019 |
| May | 13 | 9.2 | 36.3 | 36.4 | 21.8 | 22.1 | 251.9 | 34.2 | 79 | 56 | 147.3 | 198 |
| June | 18.4 | 18.5 | 37.6 | 36.4 | 26.3 | 25.5 | 55.7 | 71.5 | 70.4 | 68.5 | 222.3 | 173.9 |
| July | 23.4 | 20.8 | 36.6 | 37.6 | 29.5 | 28.4 | 146.6 | 54.3 | 83.4 | 76.4 | 239.6 | 156.2 |
| August | 23.3 | 21.2 | 36.2 | 36.3 | 29.4 | 28.2 | 217.8 | 143 | 85 | 75.2 | 232.6 | 210.9 |
| September | 17.4 | 16.9 | 32.9 | 31.6 | 24.7 | 23.8 | 39.9 | 105.6 | 78.9 | 76.4 | 170.1 | 161 |
| October | 7.7 | 7.5 | 26.6 | 30.6 | 17.6 | 18.5 | 9.4 | 2.7 | 64.7 | 71.7 | 223.9 | 149.6 |
| November | 5.5 | 1.6 | 23.2 | 25.5 | 12.1 | 13.1 | 83.5 | 31.4 | 87.1 | 65.4 | 123.3 | 157.2 |

### 2.2. Experimental Design and Field Management

In this experiment, Nanjing 9108 (NJ9108) were used in this study, and growth stages of NJ9108 are presented in Table S1 (please see Supplementary Information). Seeds were sown on plastic plates on 28 May in 2018 and 2019, with 100 g of dry seeds per plate. The seedlings were manually transplanted onto hills on 21 June. The area of each experimental plot was 20 $m^2$, with 50 cm spaces between adjacent plots, and the hill spacing was 12 cm × 30 cm, with four seedlings per hill. All the plots were separated by soil ridges (35 cm wide and 20 cm high) and covered with plastic film. Twelve fertilization treatments were applied: no N fertilization (0 N), typical fractionated urea (FU) (total N was 285 kg $ha^{-1}$), and ten simplified fertilization modes (SFMs) (Table 2). SFM_80_7/3-SFM_80_3/7 refer to a mixture of CRU with a release period of 80 days and normal urea at N (total N was 285 kg $ha^{-1}$) ratios of 7:3, 6:4, 5:5, 4:6, and 3:7, respectively. SFM_120_7/3-SFM_120_3/7 refer to a mixture of CRU with a release period of 120 days and normal urea at N (total N was 285 kg $ha^{-1}$) ratios of 7:3, 6:4, 5:5, 4:6, and 3:7, respectively. The FU consists of the application of nitrogen fertilizer four times during the growth period of rice. Calcium superphosphate ($P_2O_5$ content: 12%) and potassium chloride ($K_2O$ content: 60%) were applied as basal fertilizers at rates of 150 kg $P_2O_5$ $ha^{-1}$ and 240 kg $K_2O$ $ha^{-1}$, respectively. Insect pests, pathogens, and weeds were controlled using common chemical treatments [7].

**Table 2.** Details of nitrogen application treatment.

| Treatment | The N Ratio of Controlled-Release Urea [a] and Normal Urea | N Rate (kg N $ha^{-1}$) | | | | Total N (kg $ha^{-1}$) | Nitrogen Application Time |
|---|---|---|---|---|---|---|---|
| | | Before Transplanting | Mid-Tillering | 13th Leaf Order | 15th Leaf Order | | |
| 0 N | / | 0 | 0 | 0 | 0 | 0 | 0 |
| FU | / | 99.75 | 99.75 | 42.75 | 42.75 | 285 | 4 |
| SFM_80_7/3 | 7:3 | 285 | 0 | 0 | 0 | 285 | 1 |
| SFM_80_6/4 | 6:4 | 285 | 0 | 0 | 0 | 285 | 1 |
| SFM_80_5/5 | 5:5 | 285 | 0 | 0 | 0 | 285 | 1 |
| SFM_80_4/6 | 4:6 | 285 | 0 | 0 | 0 | 285 | 1 |
| SFM_80_3/7 | 3:7 | 285 | 0 | 0 | 0 | 285 | 1 |
| SFM_120_7/3 | 7:3 | 285 | 0 | 0 | 0 | 285 | 1 |
| SFM_120_4/6 | 6:4 | 285 | 0 | 0 | 0 | 285 | 1 |
| SFM_120_5/5 | 5:5 | 285 | 0 | 0 | 0 | 285 | 1 |
| SFM_120_4/6 | 4:6 | 285 | 0 | 0 | 0 | 285 | 1 |
| SFM_120_3/7 | 3:7 | 285 | 0 | 0 | 0 | 285 | 1 |

0 N, FU, SFM represent no nitrogen application, fractionated urea, and simplified fertilization mode, respectively. [a] The release longevity of controlled-release urea was 80 days (from SFM_80_7/3 to SFM_80_3/7) and 120 days (from SFM_120_7/3 to SFM_120_3/7), respectively.

### 2.3. Plant Sampling and Data Collection

At the maturity stage, rice yield was determined from all plants in an area of 6.0 $m^2$ (except border plants) in each plot and was calculated based on a standardized moisture content of 14%. The number of panicles per $m^2$, number of spikelets per panicle, filled grains, and grain weight were determined from 50 plants (excluding border ones) sampled randomly from each plot. To record the total above-ground biomass, the sampled plants were dried at 105 °C for 30 min to halt biological activity and then dried at 80 °C to constant weight (DHG-9625A, Shanghai Yiheng Scientific Instruments Co., Ltd., Shanghai, China). Six hills of plants were sampled from each plot according to average tiller number at the tilling stage (TS), jointing stage (JS), heading stage (HS), and maturity stage (MS).

Total N analysis was conducted on plant samples collected at JS, HT, and MS. The method of determining the N content was described by Zhao et al. [21]. The plant samples (0.50 g) were digested for 2 h in $H_2SO_4$-$H_2O_2$ solution at 420 °C and analyzed by the micro-Kjeldahl method (KjeltecTM 8400, FOSS, Denmark). N uptake was calculated using the formula TDM × NC, where TDM represents the total dry matter of panicles, leaves, and stems with leaf sheaths, and NC represents the N concentration in panicles, leaves, and stems with leaf sheaths. Aspects of N use efficiency, such as N recovery efficiency (NRE), N agronomic use efficiency (NAE), N particle productivity (NPP), and N physiological efficiency (NPE) were calculated according to the following formulas [22]:

$$NRE = (N_{up} - N0_{up})/FN \quad (1)$$

$$NAE = (GY - GY0)/FN \quad (2)$$

$$NPP = GY/FN \quad (3)$$

$$NPE = (GY - GY0)/(N_{up} - N0_{up}) \quad (4)$$

where GY and GY0 represent grain yields in N-fertilized plots and N0 plots, respectively; $N_{up}$ and $N0_{up}$ denote total N uptake above-ground in N-fertilized plots and N0 plots, respectively; FN denotes the total N application rate in N-fertilized plots.

The methods for determination of milling quality and appearance quality were modified from those described by Huang et al. [23]. Eating quality score was measured in a Cooked Rice Taste Analyzer STA1A (Satake Co., Ltd., Hiroshima, Japan) according to the Mikami's methods [24]. The gel consistency of the rice grains was determined according to the method illustrated by Zhao et al. [25]. The amylose content was determined as described by Wang et al. [26]. The protein content was measured from the nitrogen content using the Kjeldahl method with a conversion coefficient of 5.95 [27].

### *2.4. Data Analysis*

Multivariate analyses of variance (MANOVA) were conducted to determine the effects of year, variety, and treatment as well as their interaction effects on the yield and yield's components at a significance level of 5%. Data were tested for normality (Shapiro-Wilk test, $p > 0.05$) and homogeneity of variance (Levene's test, $p > 0.05$) before MANOVAs. When comparing the twelve treatments, the LSD test ($p < 0.05$) was used. All statistical analyses were conducted using the SPSS software package (18.0; SPSS Inc., Chicago, IL, USA). The values in the figures are presented as the mean ± standard error (SE). The values in the tables are presented as the mean.

## 3. Results

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

The analysis of variance between years and among treatments showed that there were significant differences in yield between years and among treatments. Among SFM_80_7/3 to SFM_80_3/7, SFM_80_6/4 (CRU with the release longevity of 80 days and normal urea with N ratios of 6:4) had the highest yield, which was 1.45–13.99% higher than other treatments across 2018 and 2019 (Table 3). In the two years, the yield of SFM_80_6/4 and SFM_80_5/5 had no significant difference and was higher than that of FU. The average yield of SFM_80_6/4 was 3.69% higher than that of FU (Table 3). Among SFM_120_7/3-SFM_120_3/7, the average yield of SFM_120_5/5 (CRU with the release longevity of 120 days and normal urea with N ratios of 5:5) was the highest across 2018 and 2019. The yield of SFM_120_5/5 was 3.19–6.86% higher than that of other treatments across 2018 and 2019 (Table 3). In 2018, the yield of SFM_120_5/5 was 4.39% higher than that of FU, while in 2019 there was no significant difference between the two. The number of panicles per m2 of SFMs was higher than that of FU. Among SFM_120_7/3 to SFM_120_3/7, the number of panicles per $m^2$ of SFM_120_4/6 was the highest, and there was no significant difference with FU. In 2018 and 2019, SFM_80_3/7 had the highest spikelets per panicle, which was 18.20% and 10.49% higher than that of FU, respectively, in 2018 and 2019. Whether in 2018 or 2019, the number of spikelets per panicle of FU was significantly higher than that under SFMs, by 5.12–20.39%. The filled grains of SFM_80_6/4 and SFM_120_5/5 were 4.08–6.81% higher than those of FU (Table 3). The economic benefit of SFM_80_6/4 and SFM_120_5/5 was 10.14% and 3.14% higher than that of FU, respectively, across 2018 and 2019 (Table S2).

**Table 3.** Grain yield and its components in different fertilizer treatments of 2018 and 2019.

| Year | Treatment | Panicles per m$^2$ | Spikelets per Panicle | Filled Grains (%) | 1000-Grain Weight (g) | Grain Yield (t ha$^{-1}$) |
|---|---|---|---|---|---|---|
| 2018 | 0 N | 246.98f | 85.41f | 95.89ab | 28.69a | 5.22g |
| | FU | 362.14e | 109.21a | 92.08cd | 28.28ab | 9.79d |
| | SFM_80_7/3 | 391.85bcd | 92.91cd | 95.58ab | 27.65abc | 9.00f |
| | SFM_80_6/4 | 409.88ab | 92.28cd | 95.84ab | 28.54a | 10.29ab |
| | SFM_80_5/5 | 422.62a | 90.99de | 95.24abc | 27.93abc | 10.06c |
| | SFM_80_4/6 | 427.62a | 90.71de | 93.11bcd | 27.86abc | 9.73d |
| | SFM_80_3/7 | 428.34a | 88.06ef | 91.15d | 27.15bc | 9.04f |
| | SFM_120_7/3 | 381.57de | 95.00bc | 96.42ab | 27.64abc | 9.41e |
| | SFM_120_4/6 | 383.51cde | 96.48b | 97.57a | 27.94abc | 9.87d |
| | SFM_120_5/5 | 392.09bcd | 96.50b | 97.33a | 27.83abc | 10.22bc |
| | SFM_120_4/6 | 406.23abc | 96.69b | 96.25ab | 27.53abc | 10.39a |
| | SFM_120_3/7 | 404.88abcd | 92.64cd | 95.72ab | 26.91c | 9.44e |
| 2019 | 0 N | 246.05f | 93.50g | 98.06a | 28.28a | 5.43f |
| | FU | 380.79cd | 137.23a | 88.83c | 26.91ab | 12.45ab |
| | SFM_80_7/3 | 389.49bcd | 128.73bc | 92.93b | 27.19ab | 11.23e |
| | SFM_80_6/4 | 402.99abc | 125.40cde | 94.88b | 27.34ab | 12.77a |
| | SFM_80_5/5 | 408.05ab | 121.16e | 94.25b | 27.11ab | 12.67a |
| | SFM_80_4/6 | 415.79a | 115.18f | 89.19c | 26.79ab | 11.41de |
| | SFM_80_3/7 | 420.73a | 112.70f | 87.98c | 26.31b | 11.29de |
| | SFM_120_7/3 | 350.32e | 127.09bcd | 93.45b | 27.34ab | 11.48de |
| | SFM_120_4/6 | 363.76de | 126.61bcd | 93.99b | 28.39a | 11.73cd |
| | SFM_120_5/5 | 374.48de | 130.54b | 94.47b | 28.17a | 12.07bc |
| | SFM_120_4/6 | 383.48bcd | 126.27bcd | 93.76b | 27.70ab | 12.01c |
| | SFM_120_3/7 | 376.63d | 123.27de | 93.83b | 27.63ab | 11.42de |
| Analysis of variance | Year | ** | ** | ** | * | ** |
| | Treatment | ** | ** | ** | NS | ** |
| | Y × T | NS | ** | NS | NS | ** |

0 N, FU, SFM represent no nitrogen application, fractionated urea, simplified fertilization mode, respectively. SFM_80_7/3- SFM_80_3/7 represents the proportion of controlled-release urea (the release longevity was 80 days) and normal urea at 7:3, 6:4, 5:5, 4:6, 3:7, respectively. SFM_120_7/3-SFM_120_3/7 represents the proportion of controlled-release urea (the release longevity was 120 days) and normal urea at 7:3, 6:4, 5:5, 4:6, 3:7, respectively. NS, not significant at the $p$ = 0.05 level; *, significant at the $p$ = 0.05 level; **, significant at the $p$ = 0.01 level. Different letters indicate statistical significance at $p$ = 0.05 within the same column, year, and variety.

### *3.2. Leaf Area Index (LAI) and Dry Matter Accumulation*

The analysis of variance showed that there were significant differences in LAI between years and among treatments, and the results were averaged over the years (2018 and 2019) for leaf area index, as there was no interaction in Y × T ($p$ > 0.05). The leaf area index at the tillering stage, jointing stage, heading stage, and mature stage reached a very significant level among the treatments (Table 4). The LAI of SFM_80_3/7 at the tillering stage was 23.68% higher than that of FU. The LAIs of SFM_80_3/7 and SFM_120_3/7 were 51.91% and 12.57% higher than those of FU, respectively, at the jointing stage (Table 4). The LAI of FU was significantly higher than that of other treatments at the heading stage. At maturity, the LAI of SFM_120_7/3 was 18.67% higher than that of FU (Table 4).

The analysis of variance among treatments showed that the differences in dry matter accumulation from the sowing stage (S) to the tillering stage (T), from T to the jointing stage (J), from J to the heading stage (H), and from H to the maturity stage (M) were all significant, and the results were averaged over the years for dry matter accumulation from the sowing stage (S) to the tillering stage (T), from T to the jointing stage (J), and from J to the heading stage (H), as there was no interaction in Y × T ($p$ > 0.05) (Table 5). From S to T, dry matter accumulation of SFM_80_3/7 was the highest and was 17.24% higher than that of FU (Table 5). From T to J, dry matter accumulation of SFM_80_6/4 and SFM_120_3/7 were 54.86% and 21.79% higher than that of FU, respectively. From SFM_80_7/3 to SFM_80_3/7, dry matter accumulation of those treatments from J to H were significantly higher than that of FU, and SFM_120_5/5 had the highest dry matter accumulation from J to H. With the decrease in the proportion of CRU, the dry matter accumulation of rice from heading to maturity first increased and then decreased both in 2018 and 2019 (Table 5).

**Table 4.** Effects of different fertilization modes on the leaf area index (LAI) of rice.

| Treatment | Tillering Stage | Jointing Stage | Heading Stage | Maturity Stage |
|---|---|---|---|---|
| 0 N | 1.11e | 1.71g | 2.55g | 1.54f |
| FU | 2.28c | 3.66e | 7.04a | 3.00d |
| SFM_80_7/3 | 2.07d | 3.83cde | 6.67bc | 3.07cd |
| SFM_80_6/4 | 2.41b | 4.02cd | 6.73b | 3.02cd |
| SFM_80_5/5 | 2.72a | 4.57b | 6.59bc | 2.96d |
| SFM_80_4/6 | 2.71a | 5.26a | 6.42d | 2.96d |
| SFM_80_3/7 | 2.82a | 5.56a | 6.54cd | 2.65e |
| SFM_120_7/3 | 2.07d | 2.78f | 6.55cd | 3.56a |
| SFM_120_4/6 | 2.08d | 3.09f | 6.68bc | 3.36ab |
| SFM_120_5/5 | 2.22c | 3.54e | 6.73b | 3.3abc |
| SFM_120_4/6 | 2.30bc | 3.80de | 5.82e | 3.09bcd |
| SFM_120_3/7 | 2.30c | 4.12c | 5.65f | 3.10bcd |

0 N, FU, SFM, represent no nitrogen application, fractionated urea, simplified fertilization mode, respectively. SFM_80_7/3- SFM_80_3/7 represents the proportion of controlled-release urea (the release longevity was 80 days) and normal urea at 7:3, 6:4, 5:5, 4:6, 3:7, respectively. SFM_120_7/3-SFM_120_3/7 represents the proportion of controlled-release urea (the release longevity was 120 days) and normal urea at 7:3, 6:4, 5:5, 4:6, 3:7, respectively. Different letters indicate statistical significance at $p = 0.05$ within the same column.

**Table 5.** Effects of different fertilization modes on the dry matter accumulation (t ha$^{-1}$) of rice.

| Treatment | S-T | T-J | J-H | H-M-2018 | H-M-2019 |
|---|---|---|---|---|---|
| 0 N | 1.13f | 1.33h | 6.03h | 3.00f | 3.20i |
| FU | 2.03c | 2.57de | 10b | 4.77bc | 4.73e |
| SFM_80_7/3 | 1.76e | 3.42b | 9.44c | 3.88e | 3.53h |
| SFM_80_6/4 | 1.99c | 3.98a | 9.11d | 4.08e | 4.54ef |
| SFM_80_5/5 | 2.28b | 3.42b | 6.75g | 5.84a | 6.33a |
| SFM_80_4/6 | 2.29ab | 3.87a | 6.79g | 4.20de | 4.48f |
| SFM_80_3/7 | 2.38a | 3.79a | 7.01f | 4.53cd | 4.18g |
| SFM_120_7/3 | 1.89d | 1.66g | 10.02b | 5.59a | 5.58c |
| SFM_120_4/6 | 1.87d | 1.98f | 9.88b | 5.97a | 5.95b |
| SFM_120_5/5 | 1.84de | 2.53e | 10.5a | 5.86a | 5.83b |
| SFM_120_4/6 | 2.08c | 2.75d | 9.64c | 5.11b | 5.08d |
| SFM_120_3/7 | 2.05c | 3.13c | 8.75e | 4.55cd | 4.53ef |

S, sowing stage; T, tillering stage; J, jointing stage; H, heading stage; M, maturity stage. 0 N, FU, SFM represent no nitrogen application, fractionated urea, simplified fertilization mode, respectively. SFM_80_7/3- SFM_80_3/7 represents the proportion of controlled-release urea (the release longevity was 80 days) and normal urea at 7:3, 6:4, 5:5, 4:6, 3:7, respectively. SFM_120_7/3-SFM_120_3/7 represents the proportion of controlled-release urea (the release longevity was 120 days) and normal urea at 7:3, 6:4, 5:5, 4:6, 3:7, respectively. Different letters indicate statistical significance at $p = 0.05$ within the same column, year, and variety.

### *3.3. N Accumulation and N Use Efficiency (NUE)*

Analysis of variance showed that there was a significant difference in nitrogen accumulation among treatments, and there was no interaction between them; the data were averaged over the years for N accumulation (Table 6). As the proportion of CUR decreased, the nitrogen accumulation of each treatment showed an upward trend. Nitrogen accumulation of SFMs from sowing to tillering is higher than that of FU (Table 6). The nitrogen accumulation of SFM_80_3/7 and SFM_120_3/7 from S to T was 26.2% and 19.98% higher than that of FU, respectively. In contrast, the nitrogen accumulation from T to J and from J to H decreased with the decrease in CUR proportion. The nitrogen accumulation of SFM_80_7/3 was the highest among SFM_80_7/3 to SFM_80_3/7 from T to J, which was 31.75% higher than that of FU (Table 6). Among SFM_120_7/3 to SFM_120_3/7, the average nitrogen accumulation from tillering to jointing in SFM_120_5/5 was the highest, which was 90.72% higher than that in FU. From H to M, SFM_80_7/3 and SFM_120_5/5 were 30.8% and 90.72% higher than that of FU, respectively (Table 6).

**Table 6.** Effects of different fertilization modes on the nitrogen accumulation (kg ha$^{-1}$) of rice.

| Treatment | S-T | T-J | J-H | H-M |
|---|---|---|---|---|
| 0 N | 16.99g | 26.69i | 28.08fg | 20.29h |
| FU | 50.35f | 61.26e | 48.41a | 31.04e |
| SFM_80_7/3 | 53.25e | 80.71a | 45.63b | 40.6d |
| SFM_80_6/4 | 54.88d | 75.14b | 48.41a | 32.68e |
| SFM_80_5/5 | 59.17c | 68.49c | 36.84cd | 32.09e |
| SFM_80_4/6 | 61.01b | 62.76d | 36.21d | 27.5f |
| SFM_80_3/7 | 63.54a | 57.16f | 28.99f | 24.51g |
| SFM_120_7/3 | 50.24f | 63.19d | 37.88c | 56.18b |
| SFM_120_4/6 | 54.93d | 57.93f | 33.17e | 59.12a |
| SFM_120_5/5 | 59.21c | 53.31g | 33.81e | 59.2a |
| SFM_120_4/6 | 60.82b | 46.53h | 27.41g | 56.33b |
| SFM_120_3/7 | 60.41bc | 45.83h | 25.89h | 53.18c |

S, sowing stage; T, tillering stage; J, jointing stage; H, heading stage; M, maturity stage. 0 N, FU, SFM represent no nitrogen application, fractionated urea, simplified fertilization mode, respectively. SFM_80_7/3- SFM_80_3/7 represents the proportion of controlled-release urea (the release longevity was 80 days) and normal urea at 7:3, 6:4, 5:5, 4:6, 3:7, respectively. SFM_120_7/3-SFM_120_3/7 represents the proportion of controlled-release urea (the release longevity was 120 days) and normal urea at 7:3, 6:4, 5:5, 4:6, 3:7, respectively. Different letters indicate statistical significance at $p$ = 0.05 within the same column, year, and variety.

With the decrease in the CRU ratio, N agronomic use efficiency (NAE) increased first and then decreased. Among SFM_80_7/3-SFM_80_3/7, the NAE of SFM_80_6/4 was 10.79% and 4.55% higher than that of FU, respectively in 2018 and 2019 (Figure 1). With the decrease in the CRU ratio, N recovery efficiency (NRE) decreased gradually. The NRE of SFM_80_7/3, SFM_80_6/4, and SFM_80_5/5 was 4.78–32.19% higher than that of FU across 2018 and 2019. The NRE of SFM_120_7/3-SFM_120_5/5 was 13.03–17.10% higher than that of FU (Figure 1). The N particle factor productivity increased first and then decreased with decreasing CRU ratio. The N particle productivity of SFM_80_6/4 was 3.67% higher than that of FU in 2018 and 2019 on average (Figure 1). The N physiological efficiency (NPE) increased gradually with the decrease in the proportion of CRU in 2018 and 2019 (Figure 1).

### *3.4. Grain Quality*

Analysis of variance showed that there was a significant difference in brown rice rate, milled rice rate, head rice rate, chalky rate, and chalkiness treatments, and there was no interaction between year and treatment; the data were averaged over the years for rice milling quality and appearance quality. Rice milling quality decreased gradually with the decrease in the proportion of CRU (Table 7). The brown rice rates of SFM_80_7/3 and SFM_120_7/3 were all significantly higher than that of FU (Table 7). The milled rice rate of each simplified fertilization mode was significantly higher than that of FU, and the milled rice rates of SFM_80_7/3 and SFM_120_7/3 were higher. The head rice rate of each simplified fertilization mode was significantly higher than that of FU except for SFM_80_3/7 and SFM_120_3/7. Appearance quality of rice in each treatment gradually deteriorated with the decrease in the CRU ratio (Table 7). Among SFMs with different proportions of slow-release fertilizer (the release longevity was 80 days) and urea, the chalky rate and chalkiness of SFM_80_7/3 were the lowest. Among SFMs with different proportions of slow-release fertilizer (the release longevity was 120 days) and urea, the chalky rate and chalkiness of SFM_120_7/3 were the lowest. The chalky rate of SFM_80_7/3 and SFM_120_7/3 was 4.36% and 16.05% lower than that of FU, respectively. The chalkiness of SFM_80_7/3 and SFM_120_7/3 was 15.32% and 14.1% lower than that of FU, respectively.

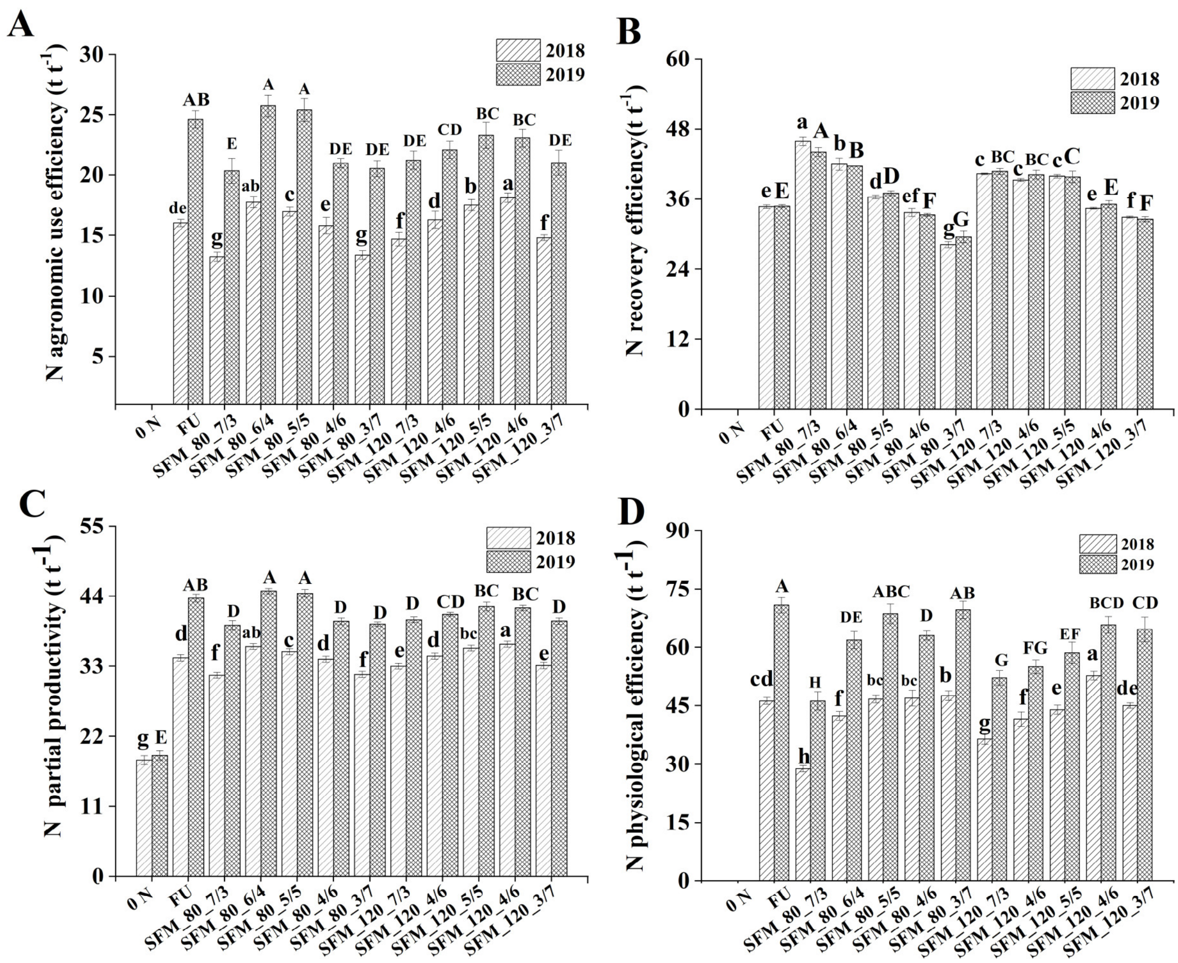

**Figure 1.** Effects of different fertilization modes on N agronomic use efficiency (NAE) (**A**), N recovery efficiency (NRE) (**B**), N particle productivity (NPP) (**C**), N physiological efficiency (NPE) (**D**) in 2018 and 2019. 0 N, FU, SFM represent no nitrogen application, fractionated urea, simplified fertilization mode, respectively. SFM_80_7/3- SFM_80_3/7 represents the proportion of controlled-release urea (the release longevity was 80 days) and normal urea at 7:3, 6:4, 5:5, 4:6, 3:7, respectively. SFM_120_7/3-SFM_120_3/7 represents the proportion of controlled-release urea (the release longevity was 120 days) and normal urea at 7:3, 6:4, 5:5, 4:6, 3:7, respectively. Different lowercase letters indicate statistically significant differences among fertilization modes in 2018 according to an LSD test ($p < 0.05$). Different capital letters indicate statistically significant differences among fertilization modes in 2019 according to an LSD test ($p < 0.05$). The data are presented as mean ± SE ($n = 3$).

The hardness of cooked rice decreases with the decrease in the proportion of CRU (Table 8). The visibility and balance of cooked rice in SFM_80_4/6 were significantly higher than those in FU (Table 8). Except for SFM_120_7/3, the taste value of other treatments (the controlled-release period of CRF was 120 days) was significantly higher than that of FU. The taste values of SFM_80_4/6, SFM_120_5/5, SFM_120_4/6, and SFM_120_3/7 were all significantly higher than that of FU. The amylose and protein content of rice decreased with the decrease in the proportion of CRU, while the gel consistency increased with the decrease in the proportion of CRU. The amylose content of SFM_80_6/4 was 9.03% higher than that of FU, while amylose content of SFM_120_5/5 was 5.31% higher than that of FU. The gel consistency of SFMs is significantly lower than that of FU. Except SFM_80_3/7, SFM_120_7/3, and SFM_120_3/7, there is no significant difference between other treatments and FU in protein content (Table 8).

**Table 7.** Effects of different fertilization modes on rice milling and appearance quality.

| Treatment | Brown Rice Rate (%) | Milled Rice Rate (%) | Head Rice Rate (%) | Chalky Rate (%) | Chalkiness (%) |
|---|---|---|---|---|---|
| 0 N | 83.97g | 74g | 58.08i | 62.52a | 21.17a |
| FU | 85.05cd | 75.1f | 68.71gh | 54.38def | 18.02b |
| SFM_80_7/3 | 85.71a | 77.81a | 73.15ab | 52.01fg | 15.24d |
| SFM_80_6/4 | 85.26abc | 77.18bc | 72.38bc | 53.49ef | 16.07cd |
| SFM_80_5/5 | 85.07cd | 76.94c | 71.85cd | 56.65bcd | 17.5bc |
| SFM_80_4/6 | 84.66def | 76.72cd | 69.98ef | 56.49bcd | 18.52b |
| SFM_80_3/7 | 84.36fg | 75.99e | 68.02h | 58.08bc | 19.22b |
| SFM_120_7/3 | 85.58ab | 77.54ab | 73.47a | 45.65h | 15.47d |
| SFM_120_4/6 | 85.15bcd | 77.14bc | 71.83cd | 49.64g | 14.68d |
| SFM_120_5/5 | 84.92cde | 76.81c | 71de | 54.33def | 15.79cd |
| SFM_120_4/6 | 84.36fg | 76.22de | 70.62e | 55.26cde | 16.13cd |
| SFM_120_3/7 | 84.43efg | 76.18e | 69.23fg | 58.9b | 18.52b |

0 N, FU, SFM represent no nitrogen application, fractionated urea, simplified fertilization mode, respectively. SFM_80_7/3- SFM_80_3/7 represents the proportion of controlled-release urea (the release longevity was 80 days) and normal urea at 7:3, 6:4, 5:5, 4:6, 3:7, respectively. SFM_120_7/3-SFM_120_3/7 represents the proportion of controlled-release urea (the release longevity was 120 days) and normal urea at 7:3, 6:4, 5:5, 4:6, 3:7, respectively. Different letters indicate statistical significance at $p = 0.05$ within the same column, year, and variety.

**Table 8.** Effects of different fertilization modes on rice eating quality, amylose content, and gel consistency.

| Treatment | Hardness | Viscosity | Balance | Taste Value | Amylose Content (%) | Gel Consistency (mm)—2018 | Gel Consistency (mm)—2019 | Protein Content (%) |
|---|---|---|---|---|---|---|---|---|
| 0 N | 5.65cd | 8.95a | 8.75a | 86.25a | 9.26e | 97.00cde | 95.00fg | 6.82f |
| FU | 6.20a | 8.07def | 7.75d | 78.05def | 9.41de | 108.67a | 106.00a | 7.85bcd |
| SFM_80_7/3 | 6.18a | 7.90f | 7.70d | 76.75f | 10.09a | 90.00g | 92.67gh | 8.22ab |
| SFM_80_6/4 | 6.16a | 8.00ef | 7.73d | 77.42def | 10.26a | 94.00ef | 98.67bcde | 7.75bcde |
| SFM_80_5/5 | 5.78bc | 8.33cde | 8.20c | 79.33cdef | 9.95ab | 92.00fg | 96.67def | 8.03abc |
| SFM_80_4/6 | 5.82bc | 8.53bc | 8.40bc | 81.58bc | 10.11a | 95.00def | 100.00bcd | 7.68cde |
| SFM_80_3/7 | 5.85bc | 8.45bcd | 8.27c | 79.58cde | 9.68bcd | 99.67bc | 101.33b | 7.28ef |
| SFM_120_7/3 | 6.16a | 8.07def | 7.72d | 77.00ef | 10.26a | 98.00bcd | 90.67h | 8.41a |
| SFM_120_4/6 | 5.93b | 8.46bc | 8.24c | 80.00cd | 10.03ab | 97.67bcd | 96.33ef | 8.07abc |
| SFM_120_5/5 | 5.91b | 8.59abc | 8.23c | 81.17bc | 9.91abc | 99.00bc | 96.00efg | 7.6cde |
| SFM_120_4/6 | 5.73bcd | 8.56bc | 8.41bc | 81.33bc | 9.54cde | 99.00bc | 97.33cdef | 7.35de |
| SFM_120_3/7 | 5.55d | 8.77ab | 8.68ab | 83.75ab | 9.47de | 100.67b | 100.33bc | 7.3ef |

0 N, FU, SFM represent no nitrogen application, fractionated urea, simplified fertilization mode, respectively. SFM_80_7/3- SFM_80_3/7 represents the proportion of controlled-release urea (the release longevity was 80 days) and normal urea at 7:3, 6:4, 5:5, 4:6, 3:7, respectively. SFM_120_7/3-SFM_120_3/7 represents the proportion of controlled-release urea (the release longevity was 120 days) and normal urea at 7:3, 6:4, 5:5, 4:6, 3:7, respectively. Different letters indicate statistical significance at $p = 0.05$ within the same column, year, and variety.

## 4. Discussion

### *4.1. Effects of Different Fertilization Modes on Yield, LAI, and Dry Matter Accumulation*

The yield of rice mainly depends on panicles $m^{-2}$, spikelets per panicle, seed-setting rate, and 1000-grain weight [28]. Our study indicates that a one-off application of controlled-release fertilizer mixed with urea could achieve a grain yield of 9 t/ha–12.77 t/ha across 2018–2019. Compared with the application of common urea alone, the mixed application of CRU and normal urea can significantly increase the rice yield and the number of panicles per $m^2$ [29]. Our research results are consistent with that, and we found that the rice yield of SFM_80_6/4 (CRU with the release longevity of 80 days and normal urea with N ratios of 6:4) and SFM_120_5/5 (CRU with the release longevity of 120 days and normal urea with N ratios of 5:5) were 3.69–4.39% higher than that of FU across 2018 and 2019 (Table 3). After applying CRU, sufficient nutrient supply can form a high-yield population, maintain leaf color, delay plant senescence, promote grain filling, increase grains per panicle, and then improve rice yield [27,30,31]. Rational application of urea provides N supply at early stage of rice, increases the number of tillers and panicles per $m^2$, and further forms a better population. It is worth noting that the combination of CRU and normal urea increased the seed-setting rate (Table 3), possibly because the nitrogen released by the fertilizer during rice development matched the nutrients required for spikelet differentiation and meiosis, thus improving the seed-setting rate. However, high costs have limited the use of CRUs in rice production in Jiangsu province. In the present study, the net profit of SFM_80_6/4 (CRU with the release longevity of 80 days and normal urea with N ratios of 6:4) and SFM_120_5/5 (CRU with the release longevity of 120 days and normal urea with N ratios of 5:5) were 10.14% and 3.14% higher than that of FU across 2018 and 2019 (Table S2), which showed that SFM_80_6/4 and SFM_120_5/5 were both cost-saving fertilization methods. Compared with SFM_120_5/5, SFM_80_6/4 was more-cost saving.

LAI is helpful for measuring the canopy light interception and photosynthetic capacity, and it is also an indirect measure of the ability of leaves to use photosynthesis to produce dry matter [32]. In our study, the SPAD value and dry matter accumulation of SFMs were higher than those of FU (Tables 4 and 5). Yield is the result of dry matter accumulation, transportation, distribution, and transformation of rice plants. Dry matter accumulation and leaf SPAD value are the basis for a high yield of rice [33]. The difference in dry matter accumulation is the most direct manifestation of rice population formation [34]. The combined application of CRU and urea increased the dry matter accumulation of plants, which may be because the CRU enhanced the LAI and SPAD value of plants, ensuring that there was still strong photosynthesis in the late growth stage of rice, thus promoting dry matter accumulation [7].

Zheng et al. [35] found that under the one-time fertilization mode, the yield of the combined application of CRU and urea was significantly higher than that of the single application of CRU. However, a single basal application of CRU did not significantly affect the grain yield of late rice compared to a split application of urea in central China [36]. These differences in results may be caused by different environmental conditions, soil types, and rice varieties in these studies. Environmental factors (temperature, water, pH) can affect the nutrient release of slow-release fertilizer, which may be the reason why the spikelets per panicle of SFMs is lower than that of FU. Generally, moisture and temperature are the key factors that restrict the release of N by CRU [3,37]. It is reported that the nitrogen demand of rice plants from the tillering stage to the milky stage is higher, but the nitrogen demand at the seedling stage and the maturity stage is lower, showing an S-shaped curve [38]. Our research shows that SFM_80_6/4 and SFM_120_5/5 can meet the fertilizer demand of rice. Under this fertilization mode, the yield and dry matter accumulation are higher than those of FU, which is in line with the law of fertilizer demand of rice. The nutrient release rate of slow-release fertilizer can basically keep pace with the demand of rice growth and development to increase yield [39]. However, the soil N content and N release rate after the mixed application of CRU and urea will be the focus of upcoming research.

### 4.2. Effects of Different Fertilization Modes on Nitrogen Accumulation and NUEs

In our study, we found that nitrogen accumulation of SFMs was higher than that of FU (Table 6), which was consist with the results of Sun et al. [14]. The trend in N use efficiency followed a similar pattern as rice grain yield when compared with FU both in 2018 and 2019 (Table 6, Figure 1). Normal urea releases N faster than crops can effectively absorb and assimilate it for growth, and this discrepancy is a main reason for the low NUE [40]; the N supply under the urea treatments surpassed the N uptake of the rice plants before the heading stage [41]. In the present study, at the same application rates for N, mixed urea treatments provided a consistent improvement in nitrogen accumulation and NUEs of rice compared with urea treatments. Yang et al. [41] reported that the controlled release of urea can improve nitrogen use efficiency of rice. We found that the application of CRU significantly increased nitrogen use efficiency during the rice growing season (Figure 1). The improvement in N use efficiency by mixed application of CRU and urea may be explained by the fact that the N release characteristic of CRU closely matched the demand for N during the whole growth period of rice, which enhanced the activities of enzymes related to nitrogen transformation in leaves, such as glutamine synthetase, glutamine 2-oxoglutarate transaminase, and nitrate reductase [41].

Studies have shown that the application of controlled-release fertilizer can increase N recovery efficiency [35]. It has been reported that the application of CRU can effectively reduce nitrogen loss through denitrification, $NH_3$ volatilization, leaching, and surface runoff, thus further improving nitrogen recovery efficiency [42]. The nutrient release rate of slow-release fertilizer can basically synchronize with the demand of rice growth and development, which promotes the absorption of nitrogen in rice and improves the nitrogen use efficiency [39,43]. Understanding the relationship between N uptake requirements and grain yield is essential for devising fertilizer management practices to optimize N fertilizer application and increase grain yield [44]. Importantly, the mixed application of CRU and urea can be applied once without the need for topdressing, which saves labor and is adoptable to address the shortage of rural labor in China. Hence, synchronizing fertilizer input with the crop's requirement is very important for crop production. In our study, we speculate that the urea in SFM_80_6/4 and SFM_120_5/5 provides the nitrogen required for the early growth of rice, and the slow-release fertilizer provides the nitrogen required in the middle and late stages. However, the contents of total nitrogen, ammonium nitrogen, and nitrate nitrogen in soil need to be further studied.

### *4.3. Effects of Different Fertilization Modes on Grain Quality*

Both the amount and time of nitrogen application can affect the rice grain quality [25,45]. Wei et al. [27] reported that the types of controlled-release fertilizer and fertilization modes are important for improving rice yield and quality. We found that combining application of controlled-release urea and normal urea improved rice milling quality and appearance quality (Table 7). Previous research reveals that the appropriate amount of N fertilizer can decrease the chalky kernel rate and overall chalkiness [46], while overuse of N can increase the chalky kernel rate and undesirable grain appearance. As we all know, the grain filling period is the most critical period for the formation of rice quality. The possible reason was that SFMs improved the grain filling characteristics. The eating and cooking quality of rice can be determined by several factors, including the content of amylose and protein, gel consistency, and starch viscosity [47]. Our results showed that there were no significant differences between SFMs and FU in cooking and eating quality (Table 8), indicating that SFM was a fertilization mode that could maintain good grain quality. Under the one-time fertilization mode, the relationship between grain filling characteristics and rice quality and its physiological mechanism will be the focus of further research.

## 5. Conclusions

The yield, economic benefits, and nitrogen use efficiency of SFM_80_6/4 and SFM_120_5/5 were higher, which could meet the nitrogen demand of crops and finally achieve the coordination of high yield and high efficiency. The one-off application of a mixture of CRU and urea with an appropriate ratio could maintain grain quality. These findings contribute to our understanding of mixing CRU and urea in a one-off application to optimize N management in an economical way. This approach resulted in improved the crop yields and NUEs with reduced costs of fertilizer and labor as compared to the split application of normal urea.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13010276/s1, Table S1: The main growth stages of Nangeng 9108 in 2018 and 2019; Table S2: Economic benefits under different nitrogen treatments.

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**Data Availability Statement:** Data are contained within the article.

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## References

1. Che, S.G.; Zhao, B.Q.; Li, Y.T.; Liang, Y.; Wei, L.; Lin, Z.; Bing, S. Review grain yield and nitrogen use efficiency in rice production regions in China. *J. Integr. Agric.* **2015**, *14*, 2456–2466. [CrossRef]
2. China Agricultural Yearbook. *China Agricultural Yearbook*; China Agricultural Publishing House: Beijing, China, 2013; pp. 206–222.
3. Grant, C.A.; Wu, R.; Selles, 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]
4. Peng, S.B.; Buresh, R.J.; Huang, J.L.; Zhong, X.H.; Zou, Y.B.; Yang, J.C.; Wang, G.H.; Liu, Y.Y.; Hu, R.F.; Tang, Q.; et al. Improving nitrogen fertilization in rice by site-specific N management. A review. *Agron. Sustain. Dev.* **2010**, *30*, 649–656. [CrossRef]
5. Ke, J.; He, R.; Hou, P.; Ding, C.; Ding, Y.; Wang, S.; Li, G. Combined controlled-released nitrogen fertilizers and deep placement effects of N leaching, rice yield and N recovery in machine-transplanted rice. *Agric. Ecosyst. Environ.* **2018**, *265*, 402–412. [CrossRef]
6. National Bureau of Statistics. *China Agriculture Yearbook*; China Agriculture Press: Beijing, China, 2013.
7. Can, Z.; Huang, H.; Qian, Z.H.; Jiang, H.X.; Liu, G.M.; Ke, X.U.; Hu, Y.J.; Dai, Q.G.; Huo, Z.Y. Effect of side deep placement of nitrogen on yield and nitrogen use efficiency of single season late japonica rice. *J. Integr. Agric.* **2021**, *20*, 2–17.
8. Zhang, W.; Cao, G.; Li, X.; Zhang, H.; Wang, C.; Liu, Q.; Dou, Z. Closing yield gaps in China by empowering smallholder farmers. *Nature* **2016**, *537*, 671–674. [CrossRef]
9. Trenkel, M.E. *Controlled-Release and Stabilized Fertilizers in Agriculture*; International Fertilizer Industry Association: Paris, France, 1997; pp. 11–12.
10. Ye, Y.; Liang, X.; Chen, Y.; Liu, J.; Gu, J.; 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]
11. Zhang, W.; Liang, Z.; He, X.; Wang, X.; Shi, X.; Zou, C.; Chen, X. The effects of controlled release urea on maize productivity and reactive nitrogen losses: A meta-analysis. *Environ. Pollut.* **2019**, *246*, 559–565. [CrossRef]
12. Kenawy, E.R.; Hosny, A.; Saad-Allah, K. Reducing nitrogen leaching while enhancing growth, yield performance and physiological traits of rice by the application of controlled-release urea fertilizer. *Paddy Water Environ.* **2021**, *19*, 173–188. [CrossRef]
13. Tian, X.F.; Li, C.L.; Zhang, M.; Li, T.; Lu, Y.Y.; Liu, L.F. Controlled release urea improved crop yields and mitigated nitrate leaching under cotton- garlic intercropping system in a 4-year field trial. *Soil Tillage Res.* **2018**, *175*, 158–167. [CrossRef]
14. Sun, H.; Zhou, S.; Zhang, J.; Zhang, X.; Wang, C. Effects of controlled-release fertilizer on rice grain yield, nitrogen use efficiency, and greenhouse gas emissions in a paddy field with straw incorporation. *Field Crop Res.* **2020**, *253*, 107814. [CrossRef]
15. Farmaha, B.S.; Sims, A.L. The influence of PCU and urea fertilizer mixtures on spring wheat protein concentrations and economic returns. *Agron. J.* **2013**, *105*, 1328–1334. [CrossRef]
16. Noellsch, A.J.; Motavalli, P.P.; Nelson, K.A.; Kitchen, N.R. Corn response to conventional and slow-release nitrogen fertilizers across a claypan landscape. *Agron. J.* **2009**, *101*, 607–614. [CrossRef]
17. Payne, K.M.; Hancock, D.W.; Cabrera, M.L.; Lacy, R.C.; Kissel, D.E. Blending Polymer-Coated nitrogen fertilizer improved Bermuda grass forage production. *Crop Sci.* **2015**, *55*, 2918–2928. [CrossRef]
18. Butardo, V.M.; Sreenivasulu, N.; Juliano, B.O. Improving rice grain quality: State-of-the-art and future prospects. *Rice Grain Qual.* **2019**, *19*, 55.

19. Balindong, J.L.; Ward, R.M.; Liu, L.; Rose, T.J.; Pallas, L.A.; Ovenden, B.W.; Snell, P.J.; Waters, D.L.E. Rice grain protein composition influences instrumental measures of rice cooking and eating quality. *J. Cereal Sci.* **2018**, *79*, 35–42. [CrossRef]
20. Gu, J.F.; Chen, J.; Chen, L.; Wang, Z.; Zhang, H.; Yang, J.C. Grain quality changes and responses to nitrogen fertilizer of japonica rice cultivars released in the Yangtze River Basin from the 1950s to 2000s. *Crop J.* **2015**, *3*, 285–297. [CrossRef]
21. Zhao, C.; Gao, Z.J.; Liu, G.M.; Qian, Z.H.; Jiang, Y.; Li, G.; Huo, Z.Y. Optimization of combining controlled-release urea of different release period and normal urea improved rice yield and nitrogen use efficiency. *Arch. Agron. Soil Sci.* **2022**, 1–14. [CrossRef]
22. Han, M.; Okamoto, M.; Beatty, P.H.; Rothstein, S.J.; Good, A.G. The genetics of nitrogen use efficiency in crop plants. *Annu. Rev. Genet.* **2015**, *49*, 269–289. [CrossRef]
23. Huang, J.W.; Pan, Y.P.; Chen, H.F.; Zhang, Z.X.; Fang, C.X.; Shao, C.H.; Amjad, H.R.; Lin, W.W.; Lin, W.X. Physiochemical mechanisms involved in the improvement of grain-filling, rice quality mediated by related enzyme activities in the ratoon cultivation system—ScienceDirect. *Field Crop Res.* **2020**, *258*, 107962. [CrossRef]
24. Mikami, T. Development of evaluation systems for rice taste quality. *Jpn. J. Food Eng.* **2009**, *10*, 191–197. [CrossRef]
25. Zhao, C.; Liu, G.M.; Chen, Y.; Jiang, Y.; Shi, Y.; Zhao, L.T.; Huo, Z.Y. Excessive nitrogen application leads to lower rice yield and grain quality by inhibiting the grain filling of inferior grains. *Agriculture* **2022**, *12*, 962. [CrossRef]
26. Wang, W.; Ge, J.; Xu, K.; Gao, H.; Liu, G.; Wei, H.; Zhang, H. Differences in starch structure, thermal properties, and texture characteristics of rice from main stem and tiller panicles. *Food Hydrocoll.* **2020**, *99*, 105341–105348. [CrossRef]
27. Wei, H.Y.; Chen, Z.F.; Xing, Z.P.; Lei, Z.; Liu, Q.Y.; Zhang, Z.Z.; Zhang, H.C. Effects of slow or controlled release fertilizer types and fertilization modes on yield and quality of rice. *J. Integr. Agric.* **2018**, *17*, 2222–2234. [CrossRef]
28. Fageria, N.K. Yield physiology of rice. *J. Plant Nutr.* **2007**, *30*, 843–879. [CrossRef]
29. Xue, X.X.; Wu, X.P.; Wang, W.B.; Zhang, Y.F.; Luo, X.H.; Wang, D.P. Effects of combined application of common urea and controlled-loss urea on grain yield and nitrogen use efficiency in paddy rice. *Chin. J. Trop. Crop.* **2018**, *39*, 2132–2139.
30. 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.* **2015**, *41*, 673–684.
31. Wei, H.Y.; Li, H.L.; Cheng, J.Q.; Zhang, H.C.; Dai, Q.G.; Huo, Z.Y.; 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 panicles. *Act Agron. Sin.* **2017**, *43*, 730–740. [CrossRef]
32. Vaesen, K.; Gilliams, S.; Nackaerts, K.; Coppin, P. Ground-measured spectral signatures as indicators of ground cover and leaf area index: The case of paddy rice. *Field Crop Res.* **2001**, *69*, 13–25. [CrossRef]
33. Hu, Y.J.; Wei, D.W.; Xing, Z.P.; Gong, J.L.; Zhang, H.C.; Dai, Q.G.; Huo, Z.Y.; Xu, K.; Wei, H.Y.; Guo, B.W. Modifying nitrogen fertilization ratio to increase the yield and nitrogen up take of super japonica rice. *J. Plant Nutr. Fert.* **2015**, *21*, 12–22.
34. Girsang, S.S.; Quilty, J.R.; Correa, T.Q.; Sanchez, P.B.; Buresh, R.J. Rice yield and relationships to soil properties for production using overhead sprinkler irrigation without soil submergence. *Geoderma* **2019**, *352*, 277–288. [CrossRef]
35. Zheng, W.; Liu, Z.; Zhang, M.; Shi, Y.; Zhu, Q.; Sun, Y.; Geng, J. Improving crop yields, nitrogen use efficiencies, and profits by using mixtures of coated controlled-released and uncoated urea in a wheat-maize system. *Field Crop Res.* **2017**, *205*, 106–115. [CrossRef]
36. Li, P.; Lu, J.; Hou, W.; Pan, Y.; Wang, Y.; Khan, M.R.; Li, X. Reducing nitrogen losses through ammonia volatilization and surface runoff to improve apparent nitrogen recovery of double cropping of late rice using controlled release urea. *Environ. Sci. Pollut. Res.* **2017**, *24*, 11722–11733. [CrossRef] [PubMed]
37. Zhang, S.; Shen, T.; Yang, Y.; Li, Y.C.; Wan, Y.; Zhang, M.; Allen, S.C. Controlled-release urea reduced nitrogen leaching and improved nitrogen use efficiency and yield of direct-seeded rice. *J. Environ. Manage* **2018**, *220*, 191–197. [CrossRef] [PubMed]
38. Shi, W.J.; Xiao, G.; Struik, P.C.; Jagadish, K.S.; Yin, X.Y. Quantifying source-sink relationships of rice under high night-time temperature com-bined with two nitrogen levels. *Field Crop Res.* **2017**, *202*, 36–46. [CrossRef]
39. Yang, X.; Geng, J.; Liu, Q.; Zhang, H.; Hao, X.; Sun, Y.; Lu, X. Controlled-release urea improved rice yields by providing nitrogen in synchrony with the nitrogen requirements of plants. *J. Sci. Food Agric.* **2021**, *101*, 4183–4192. [CrossRef] [PubMed]
40. Ladha, J.K.; Pathak, H.; Krupnik, T.J.; Six, J.; Kessel, C.V. Efficiency of fertil-izer nitrogen in cereal production: Retrospects and prospects. *Adv. Agron.* **2005**, *87*, 85–156.
41. Yang, Y.; Zhang, M.; Li, Y.C.; Fan, X.; Geng, Y. Controlled release urea improved nitrogen use efficiency, activities of leaf enzymes, and rice yield. *Soil Sci. Soc. Am. J.* **2012**, *76*, 2307–2317. [CrossRef]
42. Mi, W.H.; Zheng, S.Y.; Yang, X.; Wu, L.H.; Liu, Y.L.; Chen, J.Q. Comparison of yield and nitrogen use efficiency of different types of nitrogen fertilizers for different rice cropping systems under subtropical monsoon climate in China. *Eur. J. Agron.* **2017**, *90*, 78–86. [CrossRef]
43. Geng, J.; Sun, Y.; Zhang, M.; Li, C.; Yang, Y.; Liu, Z.; Li, S. Long-term effects of controlled release urea application on crop yields and soil fertility under rice-oilseed rape rotation system. *Field Crops Res.* **2015**, *184*, 65–73. [CrossRef]
44. Setiyono, T.D.; Walters, D.T.; Cassman, K.G.; Witt, C.; Dobermann, A. Estimating maize nutrient uptake requirements. *Field Crop. Res.* **2010**, *118*, 158–168. [CrossRef]
45. Jiang, Y.; Chen, Y.; Zhao, C.; Liu, G.; Shi, Y.; Zhao, L.; Huo, Z.Y. The starch physicochemical properties between superior and inferior grains of japonica rice under panicle nitrogen fertilizer determine the difference in eating quality. *Foods* **2022**, *11*, 2489. [CrossRef] [PubMed]

46. Zhou, L.J.; Liang, S.S.; Ponce, K.; Marundon, S.; Ye, G.Y.; Zhao, X.Q. Factors affecting head rice yield and chalkiness in indica rice. *Field Crop Res.* **2015**, *172*, 1–10. [CrossRef]
47. Aluko, G.; Martinez, C.; Tohme, J.; Castano, C.; Bergman, C.; Oard, J.H. QTL mapping of grain quality traits from the interspecific cross *Oryza sativa* × *O. glaberrima*. *Theor. Appl. Genet.* **2004**, *109*, 630–639. [CrossRef] [PubMed]