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Effects of Controlled Release Urea Formula and Conventional Urea Ratio on Grain Yield and Nitrogen Use Efficiency of Direct-Seeded Rice

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Abstract: A one-off application of bulk blend urea (BBU), which includes a controlled release urea formula and conventional urea, has been recommended to simplify fertilisation management for direct-seeded rice. However, the effects of different basal application ratios of controlled-release urea formula and conventional urea on yield and nitrogen (N) use efficiency remain unknown in direct-seeded rice. This study set up three BBU treatments in which the controlled-release urea formula provided 50% (BBU1), 60% (BBU2), and 70% (BBU3) of the total N. This study measured their effects on grain yield and N use efficiency of direct-seeded rice. Split fertilisation with conventional urea was used as the control (CK). The study concluded four key points: (i) the grain yield of direct-seeded rice decreased as the proportion of controlled-release urea formula increased, (ii) BBU1 increased grain yields by 8.1–8.6% and 10.2–10.6% compared to BBU2 and BBU3, respectively, as well as a greater number of panicles and spikelets per m^2, and post-anthesis dry matter accumulation, (iii) the N recovery efficiency and N agronomic efficiency of BBU1 were significantly higher than those of BBU2 and BBU3 treatments, and the nitrogen accumulation was also found to be more, and (iv) compared with the CK, BBU1 achieved considerable grain yield and nitrogen use efficiency while reducing the amount of fertilisation. In conclusion, the appropriate reduction of the basal application ratio of the controlled-release urea formula for direct-seeded rice increased grain yield and nitrogen use efficiency.

Keywords: controlled-released urea formula; direct-seeded rice; grain yield; nitrogen use efficiency

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1. Introduction

Rice (*Oryza sativa* L.) is a major world food crop [1], and diversified cultivation modes have been developed in China, based on transplanting and direct seeding [2]. With advances in the development of seeding machinery [3], significant improvements in the effectiveness of chemical weed control [4], and implementation of large-scale land management [5], direct-seeded rice has been widely planted in many regions of China [6], especially in the middle and lower reaches of the Yangtze River, where more than three million ha of direct-seeded rice has been planted. However, precise cultivation methods such as high-quality soil preparation and precision sowing are difficult to implement for direct-seeded rice under conditions of short crop rotation times and total straw return, owing to low straw fragmentation and low rotary tillage depth. Meanwhile, simplified cultivation measures such as semi-extensification or extensification for land preparation and sowing tend to be adopted for large-scale production [6]. Coupled with inappropriate field management and other factors, simplified cultivation has produced poor yields and inefficient nitrogen (N) utilization. Means of achieving synergistic improvements in direct-seeded rice yield and N use efficiency with simplified cultivation practices are therefore a topic of increasing concern.

Significant efforts [7–9] have been directed toward achieving high and stable yields of direct-seeded rice. However, fertiliser still needs to be applied two or three times, especially N fertiliser. Rainfall during the typical fertilisation period may increase the risk of N leaching and runoff [10], but applying fertiliser earlier or later to avoid unfavorable weather runs the risk of reducing grain yield [11]. In addition, although the use of modern fertilisation machinery has greatly reduced the labor demand for split fertilisation in the context of the declining and aging high-quality workforce in rice production, some labor is still necessary [12,13]. A simpler and more efficient N management technology is therefore required.

Controlled release urea is a new type of fertiliser that uses multiple regulatory mechanisms to achieve nutrient-controlled release in a specific cycle [14]. As the cost of controlled release urea has decreased in recent years, one-off basal nitrogen application with controlled release urea as the main raw material has gradually been adopted for rice production [15]. Numerous studies have tested application rates [16], types [17], and ratios of controlled release urea [18] to conventional urea. However, most studies of the N fertilisation approach are based on transplanted rice, and there are fewer studies on direct-seeded rice. In particular, little research has investigated one-off basal N fertiliser application with the aim of synergistically improving yield and nitrogen utilization efficiency of direct-seeded rice under the conditions of semi-extensification or extensification with simplified cultivation measures for land preparation and seeding. The nitrogen demand for rice follows an S curve during the growth period [19], with lower nitrogen demand at the seedling and maturity stages, and higher nitrogen demand at the tillering to milk ripening stage [20,21]. The shorter growth period of direct-seeded rice compared with transplanted rice is due mainly to the shorter vegetative growth period [22], which leads to significant differences in nitrogen absorption characteristics between direct-seeded rice and transplanted rice. For this reason, the appropriate one-off basal N application technique for direct-seeded rice may be different.

In previous work [23,24], several studies showed that it was difficult to match nutrient release with the nutrient demand of rice. For this reason, some studies suggested combining two types of controlled-release urea with different release longevities to produce a controlled-release urea formula, which is then blended with conventional urea for one-off basal application. The goal of this strategy is to better match fertiliser nutrient release with rice nitrogen uptake. Previous work [25] showed that this strategy could better meet the N requirements of direct-seeded rice and improve yields of direct-seeded rice relative to those achieved with traditional split N applications. However, it is unclear how different ratios of controlled-release urea formula to total N affect yield and N use efficiency of direct-seeded rice, and the appropriate percentage of controlled-release urea formula in a one-off basal N application remains to be clarified. Therefore, this study set up three bulk blend urea (BBU) treatments with different proportions of controlled-release urea formula, and investigated the effects of controlled-release urea formula ratio on direct-seeded rice after a one-off application of N fertiliser, using the controlled-release urea formula developed in previous work [25]. The main aims of this study were: (1) to explore the effects of different basal application ratios of controlled release urea formula on the yield and nitrogen use efficiency of direct-seeded rice, and (2) to find a suitable basal application ratio of controlled-release urea formula that is conducive to promoting simple and efficient production of direct-seeded rice under simplified cultivation methods.

2. Materials and Methods

2.1. Experiment Site and Materials

Field experiments were carried out in 2019 and 2020 at the Heheng experimental site in Jiangyan district, Taizhou city, Jiangsu province (34°54′ N, 120°21′ E). This experiment site was within the rice-wheat crop rotation area in the middle and lower reaches of the

Yangtze River with a subtropical climate. The average annual rainfall and temperature in this area is 1185.7 mm and 16.7 °C, respectively. The daily average temperature and rainfall during the growing season of rice measured at a weather station close to the experimental site are shown in Figure 1. The field soil was a clay loam and its nutrients were determined with reference to the "Soil Agrochemical Analysis" [26]. The topsoil (0–20 cm) contained 31.72 g kg^{-1} organic matter, 1.82 g kg^{-1} total N, 139.0 mg kg^{-1} alkaline hydrolysable N, 37.81 mg kg^{-1} Olsen-P, and 146.48 mg kg^{-1} exchangeable K.

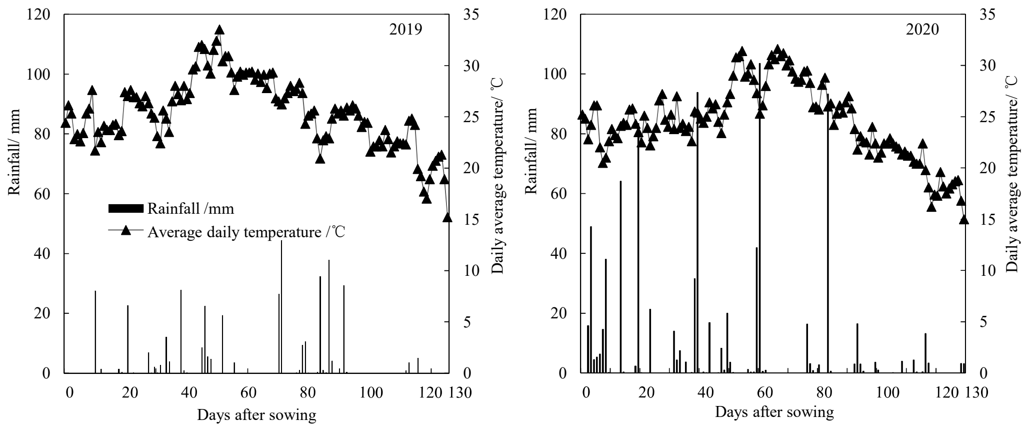

Figure 1. Rainfall (line) and daily average temperature (bars) at the experimental site during the 2019 and 2020 rice growth seasons.

Japonica rice variety Nanjing 9108, which is grown on a large scale in the middle and lower reaches of the Yangtze River with high yield and good quality, was used as material. Mechanical dry strip sowing was performed on 8 June 2019 and 10 June 2020, respectively, and harvested on 25 October 2019 and 29 October 2020, respectively. Two polymer-coated controlled release ureas (CRU) being used were CRU1 (N 43.6%) and CRU2 (N 42.5%), supplied by Mosaic Eco-Fertiliser Co. controlled-release urea formula consisted of CRU1 and CRU2 in a ratio of 2:8 (N), and it was included in all the one-off application of N fertiliser treatments in this study. Conventional urea (46% N), calcium superphosphate (12.5% P_2O_5), and potassium chloride (60% K_2O) were purchased from local fertiliser outlets.

2.2. Experiment Design

The field experiments were carried out in a randomised group design and included three one-off basal N treatments in which the controlled release urea formula accounted for 50% N (BBU1), 60% N (BBU2), and 70% N (BBU3) of total N, and the conventional urea split application (CK), four treatments in total, each treatment was repeated for three plots. In addition, no N treatment (N0) was added to calculate N use efficiency. All treatments were applied at 270 kg N ha^{-1}, except for the N0 treatment, of which three one-off basal applications of N fertiliser were applied as controlled-release urea formula and conventional urea one day before sowing. The nitrogen fertiliser of CK treatment was applied in four splits: 30% N at basal, 30% N at 20 days after seeding (DAS), 20% N as spikelet promotion fertiliser when the rice has four leaves that have not appeared, and 20% N as spikelet development fertiliser when the rice has two leaves that have not appeared, respectively. All treatments were fertilised with a single application of 130 kg ha^{-1} P_2O_5 and 150 kg ha^{-1} K_2O before seeding. The seeding rate of each treatment was 105 kg ha^{-1}, row spacing of 25 cm, and the target basic seedling was 240 $\times$ 10^4 ha^{-1}. The field plot for each treatment was 50 m^2, each plot was separated by a soil ridge (30 cm wide and 20 cm high) and covered with a plastic film. The management of water, pests, pathogens, and weeds in the field was controlled by local chemical methods and was consistent in all treatments.

2.3. Determinations of CRU Release Characteristics

The N release from two types of CRU in the neighbouring rice paddy was evaluated by the burial method [27] in 2020. Briefly, CRU samples (10.0 g) placed in a net bag (10 × 5 cm, diameter 1 mm) were buried to a depth of 5 cm in the soil before rice seeding. Sample was taken every 10 days (d) after being buried, and 3 bags of each CRU were randomly collected until the cumulative N release reached more than 80%. The net bags were cleaned with de-ionized water to remove soil particles, and the residual nitrogen in the net bag was determined by Kjeldahl method [28]. The N release rate of controlled-release urea formula was calculated based on the proportion of CRU1 and CRU2 dispensed. Theoretical N release rate from each treatment at different times was also calculated based on the proportion of controlled-release urea formula applied in BBU1, BBU2 and BBFU treatments.

2.4. Determinations of Tiller Number and NH_4^+-N Content

Twenty plants in each plot were tagged for recording tiller numbers. Counts were made every 10 days from the beginning of tillering (about 20 DAS) to 20 days before maturity (110 DAS). In parallel, soil samples were collected every 10 d at a depth of 20 cm in each plot, and the five replicate soil samples from each plot were mixed and the NH_4^+-N content was measured using a continuous flow analyser [29] (Model AA3, Bran-Luebbe, Hamburg, Germany). Soil moisture was measured by the weight loss method, where the soil was dried at 105 °C in an oven to a constant weight and the weight loss was the weight of the moisture.

2.5. Determinations of Dry Weight, N Uptake and Their Translocation

Twenty consecutive plants were taken from each plot at anthesis (handing) and maturity. Rice plants were divided into stem-sheaths, leaves and panicles at anthesis, stem-sheaths, leaves, grains and chaff at maturity. The dry weight of above-ground plants was measured after drying at 70 °C to constant weight. The plants were ground and the N content of each rice part was measured by Kjeldahl method [28], and the N uptake of each rice part was calculated by multiplying the dry matter weight by the nitrogen content. The dry matter accumulation and N uptake of the whole plant at anthesis and maturity periods can be calculated as the sum of the dry matter weight and nitrogen uptake of each part, respectively. It is assumed that all N losses from the stem-sheath and leaves during rice growth were transferred to the grains and that the translocation of dry matter and N during grain filling can be calculated as proposed by Papakosta and Gagianas [30].

$$DMT = DM_a - (DM_{leaf,\ m} + Dm_{stem\text{-}sheath,\ m} + DM_{panicle,\ m}) \quad (1)$$

$$NT = NT_a - (NT_{leaf,\ m} + NT_{stem\text{-}sheath,\ m} + NT_{panicle,\ m}) \quad (2)$$

in which DMT and NT were dry matter and N translocation, respectively; DM_a and NT_a were the aboveground dry matter and nitrogen accumulation of rice at anthesis, respectively; $DM_{leaf,\ m}$, $DM_{stem\text{-}sheath,\ m}$ and $DM_{panicle,\ m}$ were the dry matter of rice leaves, stem-sheaths and panicle at maturity, respectively; $NT_{leaf,\ m}$, $NT_{stem\text{-}sheath,\ m}$ and $NT_{panicle,\ m}$ were the N accumulation of rice leaves, stem-sheaths and panicle at maturity, respectively.

Dry matter transport efficiency (DMTE) and N transport efficiency (NTE) were calculated according to the following equations.

$$DMTE = DMT/DM_a \quad (3)$$

$$NTE = NT/NT_a \times 100\% \quad (4)$$

The contribution of pre-anthesis dry matter remobilization to grains (CDMRG) and the contribution of nitrogen assimilation to grains (CNRG) were calculated as follows.

$$CDMRG = DMT/DM_{grain} \quad (5)$$

$$\text{CNRG} = \text{NT}/\text{N}_{\text{grain}} \tag{6}$$

DM_{grain} and N_{grain} were the grain dry weight and grain N uptake, respectively.

2.6. Calculation of N Use Efficiency

N recovery efficiency (NRE), agronomic efficiency (NAE), physiological efficiency (NPE), dry matter production efficiency (DME), grain yield production efficiency (GYE) and harvest index (NHI) were calculated as follows:

$$\text{NRE}\ (\%) = \frac{\text{N cumulative uptake of plant from (N treatment} - \text{N0 N treatment)}}{\text{The amount of N applied in the treatment}} \tag{7}$$

$$\begin{array}{r}
\text{NAE}\ (\text{kg N kg}^{-1}) = \frac{\text{The grain yield of (N treatment}-\text{N0 N treatment)}}{\text{The amount of N applied in the treatment}} \\
\text{NPE}\ (\text{kg N kg}^{-1}) = \frac{\text{The grain yield of (Ntreatment}-\text{N0 N treatment)}}{\text{N cumulative uptake of plant from (N treatment}-\text{N0 N treatment)}} \\
\text{DME}\ (\text{kg N kg}^{-1}) = \frac{\text{The dry matter of N treatment}}{\text{N cumulative uptake of plant from N treatment}} \\
\text{GYE}\ (\text{kg N kg}^{-1}) = \frac{\text{The grain yield of N treatment}}{\text{N cumulative uptake of plant from N treatment}} \\
\text{NHI}\ (\%) = \frac{\text{N cumulative uptake of grain}}{\text{N cumulative uptake of plant}}
\end{array} \tag{8}$$

2.7. Measurements of Grain Yield and Its Components

At maturity, three survey points were selected in each plot to investigate the number of effective panicles, with five consecutive rows of 2 m each; and 20 consecutive representative plants were taken in each plot to investigate the spikelet number per panicle and seed-setting rate. The 1000 full grains (dry grains) were weighed and replicated 3 times (error $\leq$ 0.05 g) to calculate the 1000-grain weight, and 10 m^2 were harvested from each plot, dried and converted to the actual yield (14.5% moisture content).

2.8. Data Statistical Analysis

Data were handled using Microsoft Excel 2010 and analysis of variance (ANOVA) was performed using the statistical program SPSS 18.0 (SPSS Statistics, SPSS Inc., Chicago, IL, USA). All data were analysed using a two-way ANOVA including year (Y) and fertiliser treatment (T). Multiple comparisons were made using Fisher's Protected Least Significant Difference (LSD) with a probability of 5%.

3. Results

3.1. Cumulative Release Characteristics of CRU1 and CRU2 in the Paddy Field

The cumulative release of N from CRU1 and CRU2 in the field gradually increased with time, and the release rates of both showed a pattern of increasing and then gradually decreasing (Figure 2). Nonetheless, the N release patterns of CRU1 and CRU2 were significantly different. CRU1 showed a very rapid release in the first 20 d, and the N release rate reached 28.7% at 10–20 d. The release rate gradually decreased thereafter, and over 80% of the N was released by 40 d. CRU2 showed a gradual increase in release rate during the first 50 d, with a maximum N release rate of 19.1% at 40–50 d. After 50 d, the N release rate gradually decreased, and over 80% of the N was released within 90 d. The maximum rate of controlled-release urea formula release occurred at 40–50 d, and the cumulative rate of release reached 80% at 80–90 d. These results suggest that the N release period of the controlled-release urea formula is approximately 80–90 d.

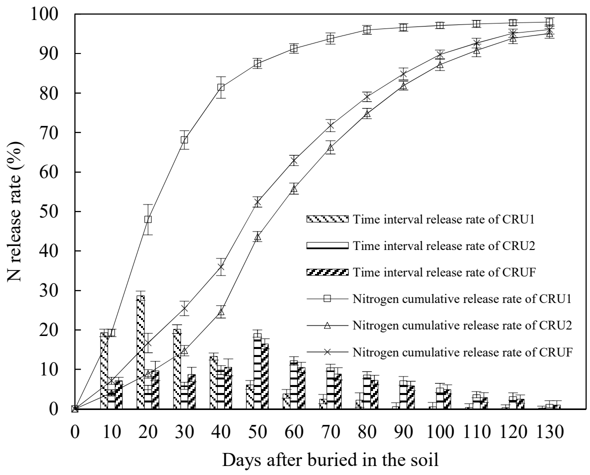

Figure 2. Cumulative nitrogen release rates of CRU1 and CRU2 in paddy field. CRU1 and CRU2 are two kinds of controlled-release nitrogen fertiliser with different release periods, respectively. Controlled-release urea formula (CRUF) is a controlled-release nitrogen fertiliser formula mixed with CRU1 and CRU2 at 2:8 (N). Vertical bars indicate mean standard errors of three replicates.

3.2. Dynamics of Soil NH_4^+-N

As shown in Table 1, the highest soil NH_4^+-N content occurred in the 20 DAS, and the NH_4^+-N content decreased significantly with time to a lower level at 20–90 DAS and remained at that level until rice maturity. Significant effects of fertilisation treatment, experimental year, and their interaction on soil NH_4^+-N content were observed during the early growth stages of rice (20–60 DAS). Compared with that of the BBU2 and BBU3 treatments, the NH_4^+-N content of the BBU1 treatment was significantly higher by 2.5–5.2 mg kg^{-1} and 4.4–8.6 mg kg^{-1}, respectively, at 20–60 DAS. There was no significant difference in NH_4^+-N content between the BBU1, BBU2, and BBU3 treatments at 70–110 DAS. The NH_4^+-N content of the CK treatment was lower than that of the BBU1 treatment during the 20–60 DAS, but differences in soil NH4+-N content between CK and BBU1 were not significant after 60 DAS.

Table 1. N content (mg kg^{-1}) in 0–20 cm soil layer under different treatments.

Year	Treatment	20 DAS	30 DAS	40 DAS	50 DAS	60 DAS	70 DAS	80 DAS	90 DAS	100 DAS	110 DAS
2019	BBU1	58.8 a	48.6 a	39.5 a	29.3 a	26.0 a	18.3 a	14.2 a	13.1 a	12.8 a	12.5 a
	BBU2	54.3 b	46.0 a	36.5 a	25.8 b	25.0 a	18.2 a	13.9 a	12.0 a	11.7 a	11.4 a
	BBU3	50.4 c	41.5 b	32.9 b	23.0 c	23.3 b	16.1 a	13.1 a	11.4 a	11.2 a	10.9 a
	CK	49.5 c	43.3 b	36.8 a	27.0 b	21.6 b	21.0 a	15.8 a	12.8 a	12.6 a	12.4 a
2020	BBU1	52.3 a	46.7 a	39.2 a	30.2 a	22 a	14.5 a	10.2 a	10.4 a	10.0 a	9.7 a
	BBU2	47.0 b	43.5 b	35.3 b	26.8 b	21.3 a	13.9 a	10.4 a	9.1 a	8.8 a	8.5 a
	BBU3	43.7 c	40.5 c	33.1 b	24.5 c	17.8 b	13.1 a	9.4 a	8.2 a	7.8 a	7.5 a
	CK	43.0 c	42.2 b	35.2 b	27.5 b	15.6 b	15.9 a	12.1 a	10.4 a	10.2 a	10.0 a
ANOVA	Year	**	*	NS	*	**	**	**	**	**	**
	Treatment	**	**	**	**	**	NS	NS	NS	NS	NS
	Year × Treatment	**	*	NS	NS	NS	NS	NS	NS	NS	NS

Note: BBU1, BBU2 and BBU3 represent one-off basal fertilisation treatments in which controlled-release nitrogen fertiliser formula accounts for 50%, 60% and 70% of the total N, respectively. CK, split application of conventional urea. Same definitions apply in Tables 2–5. NS, no significant at the $p = 0.05$ level; *, significant at the $p = 0.05$ level; **, significant at the $p = 0.01$ level. Different lowercase letters indicate statistical significance at $p = 0.05$ within the same column and year. Same definitions apply in Tables 2–5.

Table 2. The dynamics of dry matter of direct-seeded rice under different treatments.

Year	Treatment	DW_{grain} (t ha^{-1})	DM (t ha^{-1})			DMT (t ha^{-1})	DMTE (%)	CDMRG (%)
			Anthesis	Maturity	Post-Anthesis			
2019	BBU1	8.6 a	12.4 a	20.1 a	7.7 a	2.7 ab	22.3 b	32.2 b
	BBU2	8.0 b	11.2 b	18.4 b	7.2 bc	2.6 b	23.4 ab	33.0 ab
	BBU3	7.8 b	10.9 b	17.8 b	6.9 c	2.6 b	23.9 a	33.3 a
	CK	8.5 a	12.1 a	19.5 a	7.3 ab	2.8 a	22.8 ab	32.5 ab
2020	BBU1	8.1 a	11.8 a	19.0 a	7.3 a	2.5 a	21.5 ab	31.1 ab
	BBU2	7.5 b	10.8 c	17.3 b	6.6 b	2.4 ab	22.2 ab	31.8 a
	BBU3	7.4 b	10.3 d	16.5 b	6.2 b	2.3 b	22.8 a	31.9 a
	CK	8.0 a	11.3 b	18.3 a	6.9 a	2.4 ab	21.3 b	30.2 b
ANOVA	Year	**	**	**	**	NS	NS	NS
	Treatment	**	**	**	**	**	*	**
	Year × Treatment	NS	NS	NS	NS	NS	NS	NS

Note: DWgrain, dry weight of grain at maturity; DM, dry matter accumulation; DMT, dry matter translocation; DMTE, dry matter translocation efficiency; CDMRG, the contribution of pre-anthesis DM remobilization to grain. NS, no significant at the $p = 0.05$ level; *, significant at the $p = 0.05$ level; **, significant at the $p = 0.01$ level. Different lowercase letters indicate statistical significance at $p = 0.05$ within the same column and year.

Table 3. The dynamics of N in direct-seeded rice under different treatments.

Year	Treatment	N_{grain} (kg ha^{-1})	N Uptake (kg ha^{-1})			NT (kg ha^{-1})	NTE (%)	CNRG (%)
			Anthesis	Maturity	Post-Anthesis			
2019	BBU1	113.7 a	179.5 a	222.4 a	42.9 a	62.0 a	34.5 b	54.5 bc
	BBU2	101.5 b	162.4 b	203.3 b	41.0 b	58.1 bc	35.7 ab	57.1 a
	BBU3	97.8 b	152.8 c	192.6 c	39.8 b	55.1 c	36.1 a	56.3 ab
	CK	114.8 a	175.1 a	217.1 a	42.0 a	60.7 ab	34.7 b	52.8 c
2020	BBU1	118.4 a	166.8 a	211.7 a	45.0 a	65.9 a	39.5 b	55.7 ab
	BBU2	103.2 b	148.6 b	191.5 b	42.9 bc	59.1 b	39.8 b	57.3 a
	BBU3	100.3 b	140.1 b	182.4 b	42.3 c	57.8 b	41.3 a	57.7 a
	CK	116.5 a	160.8 a	205.5 a	44.8 ab	63.4 a	39.4 b	54.5 b
ANOVA	Year	*	NS	**	**	**	**	NS
	Treatment	**	*	**	**	**	*	**
	Year × Treatment	NS	NS	NS	NS	NS	NS	NS

Note: NS, no significant at the $p = 0.05$ level; *, significant at the $p = 0.05$ level; **, significant at the $p = 0.01$ level. Different lowercase letters indicate statistical significance at $p = 0.05$ within the same column and year.

Table 4. Differences in yield and its components of direct-seeded rice under different treatments.

Year	Treatment	Grain Yield (t ha^{-1})	Panicles (m^{-2})	Spikelets per Panicle	Spikelets (m^{-2})	Seed-Setting Rate (%)	1000-Grain Weight (g)
2019	N0	5.8 c	316.1 d	67.5 c	21336.7 c	88.2 a	27.9 a
	BBU1	10.0 a	453.5 a	90.3 b	40951.1 a	87.5 a	27.9 a
	BBU2	9.3 b	405.1 b	92.2 ab	37350.2 b	87.1 a	27.8 a
	BBU3	9.1 b	376.4 c	93.2 ab	35080.5 b	87.9 a	27.7 a
	CK	9.9 a	401.8 b	104.9 a	42148.8 a	87.5 a	27.7 a
2020	N0	5.4 c	300.9 d	72.8 b	21905.1 d	90.4 a	27.6 a
	BBU1	9.5 a	395.2 a	98.4 a	38887.7 a	89.3 a	27.7 a
	BBU2	8.8 b	365.6 b	98.5 a	36011.6 b	89.3 a	27.8 a
	BBU3	8.6 b	344.4 c	98.2 a	33820.1 c	89.5 a	28.2 a
	CK	9.3 a	370.7 b	109.2 a	40480.4 a	89.1 a	27.5 a
ANOVA	Year	**	**	*	NS	NS	NS
	Treatment	**	**	**	**	NS	NS
	Year×Treatment	NS	NS	NS	NS	NS	NS

Note: N0, no nitrogen application. NS, no significant at the $p = 0.05$ level; *, significant at the $p = 0.05$ level; **, significant at the $p = 0.01$ level. Different lowercase letters indicate statistical significance at $p = 0.05$ within the same column and year.

Table 5. Differences in N use efficiency of direct-seeded rice under different treatments.

Year	Treatment	NRE (%)	NAE (kg N kg^{-1})	NPE (kg N kg^{-1})	DME (kg N kg^{-1})	GYE (kg N kg^{-1})	NHI (%)
2019	BBU1	45.2 a	15.2 a	33.6 a	89.7 a	44.9 b	53.7 a
	BBU2	37.7 b	12.4 c	32.8 a	90.3 a	45.7 b	53.0 a
	BBU3	34.3 b	11.8 d	34.4 a	90.7 a	47.1 a	53.6 a
	CK	42.9 a	14.4 b	33.7 a	89.0 a	45.3 b	55.9 a
2020	BBU1	41.4 a	15.7 a	37.8 b	90.3 b	45.1 b	53.2 a
	BBU2	34.3 bc	12.9 c	37.5 b	90.3 b	45.6 b	50.7 a
	BBU3	30.3 c	12.3 c	40.2 a	92.2 a	47.2 a	52.1 a
	CK	39.5 a	15.3 b	38.7 ab	89.6 b	45.7 b	53.7 a
ANOVA	Year	NS	**	NS	NS	NS	NS
	Treatment	**	**	*	*	*	NS
	Year × Treatment	NS	NS	NS	NS	NS	NS

Note: NRE, N recovery efficiency; NAE, N agronomic efficiency; NPE, N physiological efficiency; DME, dry matter production efficiency; GYE, grain yield production efficiency; NHI, N harvest index. NS, no significant at the $p = 0.05$ level; *, significant at the $p = 0.05$ level; **, significant at the $p = 0.01$ level. Different lowercase letters indicate statistical significance at $p = 0.05$ within the same column and year.

3.3. Tiller Dynamics

Tiller dynamics of direct-seeded rice under the different N treatments are shown in Figure 3. The number of rice tillers first increased and then decreased, and the highest number of tillers was recorded at 50 DAS. N treatments had a significant effect on the number of rice tillers. Among the one-off basal N treatments, the number of rice tillers was significantly higher in the BBU1 treatment than in the BBU2 and BBU3 treatments. Compared with tiller numbers in the BBU2 and BBU3 treatments, the number of tillers in the BBU1 treatment was 4.5–7.4% and 11.6–20.7% higher, respectively, at 50 DAS. The number of tillers in the CK treatment was not significantly different from that in the BBU2 treatment, but it did differ significantly from that in the BBU1 and BBU3 treatments. Compared with the BBU1 treatment, the CK treatment had 7.2–9.8% lower tiller numbers at 50 DAS.

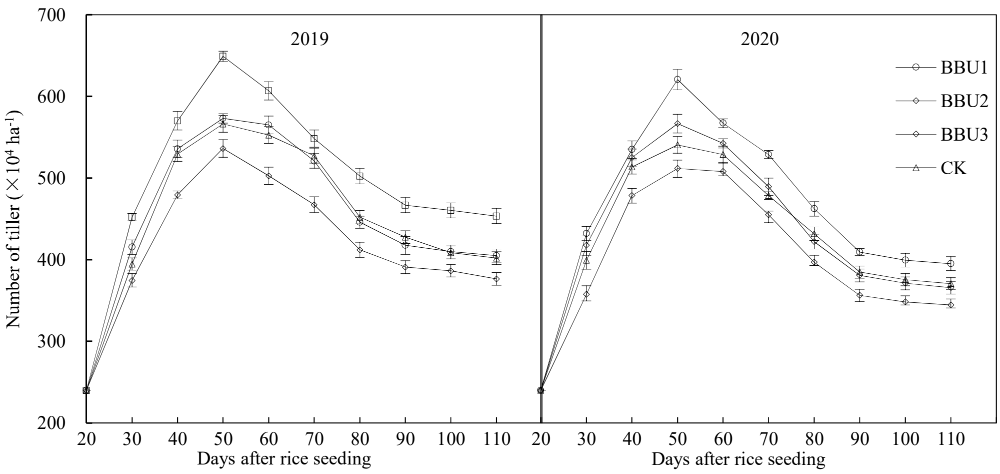

Figure 3. The dynamics of tillers of direct-seeded rice under different treatments. BBU1, BBU2 and BBU3 represent one-off basal fertilisation treatments in which controlled-release nitrogen fertiliser formula accounts for 50%, 60% and 70% of the total N, respectively; CK, split application of conventional urea. Vertical bars indicate mean standard errors of three replicates. Same definitions apply in Figure 4.

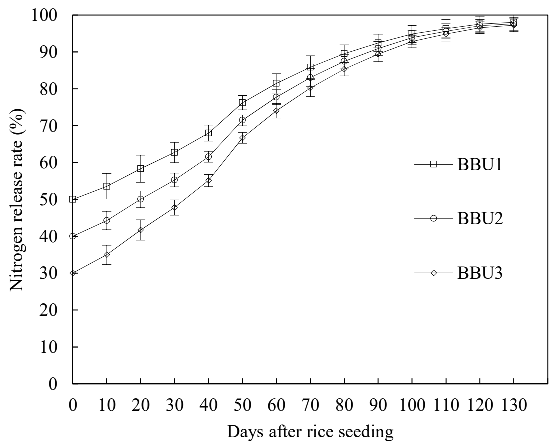

Figure 4. The dynamics of nitrogen release under BBU1, BBU2 and BBU3 treatment.

3.4. Accumulation and Translocation of Dry Matter and N

As shown in Table 2, N treatments had significant effects on the accumulation and translocation of dry matter in direct-seeded rice. Dry matter accumulation was highest in the BBU1 treatment at both anthesis and maturity, followed in order by the CK, BBU2, and BBU3 treatments. The BBU1 and CK treatments had significantly higher post-anthesis dry matter accumulation than the BBU2 and BBU3 treatments. Compared with the BBU3 treatment, the BBU1 and CK treatments had 12.0–16.7% and 6.8–12.3% higher post-anthesis dry matter accumulation, respectively. Post-anthesis dry matter accumulation was higher in the BBU2 treatment than in the BBU3 treatment, but this difference was not significant. The BBU1 treatment had the highest pre-anthesis dry matter translocation (2.5–2.7 t ha^{-1}). However, for pre-anthesis dry matter translocation rate and contribution to grains, the BBU1 and CK treatments were lower than the BBU2 and BBU3 treatments.

The BBU1 and CK treatments produced greater N accumulation at anthesis and maturity and significantly increased post-anthesis N uptake (Table 3). Compared with the BBU3 treatment, the BBU1 and CK treatments had significantly greater post-anthesis N uptake by 6.4–7.8% and 5.4–5.9%, respectively. In addition, pre-anthesis N translocation was higher in the BBU1 and CK treatments than in the BBU2 and BBU3 treatments. As a result, N uptake in the grains was highest in the BBU1 and CK treatments (113.7–118.4 kg ha^{-1} and 114.8–116.5 kg ha^{-1}, respectively) and was significantly higher than that in the BBU2 and BBU3 treatments. However, the N translocation rate and contribution to grain N were higher in the BBU2 and BBU3 treatments than in the BBU1 and CK treatments. This result indicates that post-anthesis N accumulation was significantly lower in the BBU2 and BBU3 treatments than in the BBU1 and CK treatments. The BBU2 and BBU3 treatments did not differ significantly in N accumulation and translocation.

N treatment had a significant effect on direct-seeded rice yield (Table 4). Among the one-off N fertiliser treatments, rice yield gradually decreased as the percentage of controlled-release urea formula in the blend increased. The highest rice yield was obtained with the BBU1 treatment. In comparison with the yields of the BBU2 and BBU3 treatments, that of the BBU1 treatment was 8.1–8.6% and 10.2–10.6% higher, respectively, and there was no significant difference in yield between the BBU1 and CK treatments.

Among the yield components, the effective panicle number was affected by N treatment and year. Among the BBU treatments, BBU1 produced the highest number of effective panicles, and BBU3 produced the lowest. The BBU1 treatment had a significantly higher number of effective panicles by 14.8–20.5% compared with the BBU3 treatment, and there were no significant differences in effective panicle number between BBU2 and BBU3. Effective panicle number was significantly lower in the CK treatment by 6.6–12.9% compared with the BBU1 treatment. The number of spikelets per panicle did not differ significantly among the N fertilisation treatments, and the CK treatment had the most spikelets per panicle. The BBU1 and CK treatments had significantly more spikelets per m^2 than the

BBU2 and BBU3 treatments. This result indicated that the higher number of spikelets per m^2 in the BBU1 treatment was mainly attributable to effective panicle number rather than larger panicle size. There were no significant effects of N treatment, year, or their interaction on seed-setting rate or 1000-grain weight.

3.5. N Use Efficiency

N treatment significantly affected the NRE and NAE of direct-seeded rice (Table 5). BBU1 treatment produced the highest NRE and NAE values (45.2–41.4% and 15.2–15.7%, respectively), significantly higher than those of the BBU2 and BBU3 treatments. The NRE and NAE of the CK treatment were lower than those of the BBU1 treatment and significantly higher than those of the BBU2 and BBU3 treatments. NPE, DME, and GYE were highest in the BBU3 treatment, significantly higher than in the other three treatments, and there were no significant differences among the BBU1, BBU2, and CK treatments. NHI was slightly higher in the BBU1 and CK treatments than in the BBU2 and BBU3 treatments, but there were no significant differences among treatments.

4. Discussion

4.1. Yield

Several studies [31] have shown that a high proportion of controlled-release urea base applications will not only increase the cost but also reduce rice grain yield. This study further supports this view. Results showed that the yield of direct-seeded rice decreased gradually with the increase of the basal application ratio of the controlled release urea formula (Table 4). A possible reason for this result is that a proper reduction of the controlled-release urea formulation basal application ratio is more favorable for the formation of a high yield of direct-seeded rice. Direct-seeded rice has a poor leaf system configuration and lower photosynthetic capacity per plant because of its shorter plant height and severe mutual shading of leaves compared with transplanted rice. These factors make it difficult to achieve high photosynthate accumulation post-anthesis with a lower number of panicles [2]. Therefore, producing more spikelets per m^2 with a sufficient number of panicles, higher leaf area index, and greater light interception capacity after anthesis is an effective way to achieve a high yield of direct-seeded rice [6,32]. As the proportion of controlled-release urea basal application gradually decreased in this study, we noted the markedly higher N release from the BBU1 treatment than the BBU2, BBU3, and CK treatments during the effective panicle formation stage (0–50 DAS). As shown in Figure 4, the BBU1, BBU2, and BBU3 had released 76.2%, 71.5%, and 66.7% of their cumulative N into the soil by 50 DAS, and CK had put 60% N into the soil. Thus, the BBU1 treatment released 4.8%, 9.5%, and 16.2% more N at the effective panicle formation stage than the BBU2, BBU3, and CK treatment. Adequate N supply promoted a significant increase in the NH_4^+-N content of the root zone in the BBU1 treatment (Table 1), contributed to a significant increase in tillering (Figure 3), and ultimately resulted in a higher number of effective panicles (Table 4). The higher dry matter accumulation after anthesis was a major factor for the high yield of rice. In this study, with the gradual increase of controlled-release urea basal application rate, the post-flowering dry matter accumulation of rice in BBU1 treatment was significantly higher than that in BBU2 and BBU3 treatments. This may be because the higher N input at the early stage of rice growth in the BBU1 treatment maintained an appropriate C/N ratio for microbial decomposition of straw in the soil, accelerated the decomposition of wheat straw [7,33], enhanced soil N supply of the BBU1 treatment during grain filling, promoted N uptake by the root system, and increased leaf SPAD values.

4.2. N Use Efficiency

Excessive application of conventional urea during the vegetative growth stage of rice has been proved to be the main reason for large N losses and poor N use efficiency [34]. In this experiment, as the basal application ratio of the controlled-release urea formula was reduced, it did not cause a significant loss of nitrogen from the direct-seeded rice, as higher NRE and NAE were achieved by the BBU1 treatment. This may reflect the fact that the BBU1 treatment promoted straw decay during the early stages of rice growth through higher nitrogen release, reducing the toxic effects of redox substances and organic acids produced by straw decay on rice roots [35], increasing root oxidation activity [36,37], and enhancing root N uptake [38]. In addition, rainfall that occurs around the expected time of fertilisation is also considered to be a cause of nitrogen loss [12]. The rainfall during the rice growth period in 2020 was much higher than that in the same period in 2019 (Figure 1). Frequent heavy rainfall shortly after fertilisation can lead to a large increase in soil NH_4^+-N, resulting in runoff and leaching loss of N [39]. This may have explained the higher soil NH_4^+-N content at 20 DAS in 2020 and the lower pre-anthesis plant N uptake at maturity compared with 2019. Similarly, the one-time basal application of nitrogen fertiliser with controlled-release urea formula less than 50% N was not set in this experiment, so as to avoid nitrogen loss and environmental eutrophication caused by a large amount of conventional urea basal application.

This study found that although BBU1 showed higher pre-anthesis N translocation than the BBU2 and BBU3 treatments, its contribution rate to grain N was lower (Table 3). This suggests that grain N accumulation in the BBU1 treatment was derived mainly from N uptake during the grain filling period rather than from translocation of stored N accumulated pre-anthesis. Several previous reports have shown that the increase in N accumulation during the grain filling period is significantly correlated with an increase in the vigor of the underground root system, the activity of key N assimilation enzymes such as GS, GOGAT, and NR, and leaf photosynthetic rates [40]. Such a synergistic effect of below-ground and aboveground processes may be the fundamental reason for the increased N accumulation during grain filling of the BBU1 treatment.

5. Conclusions

The grain yield of the direct-seeded rice decreased with an increasing ratio of one-time basal application of controlled-release urea formula, and BBU1 showed similar grain yield and nitrogen use efficiency with fewer fertilisation times compared to CK. The increased grain yield and nitrogen use efficiency of BBU1 treatment were mainly due to the increase in the number of panicles and spikelets per m2 and the increased nitrogen accumulation after anthesis. Therefore, the one-off basal application of N fertiliser which appropriately reduces the basal application ratio (e.g., 50% N) of controlled-release N fertiliser formula is beneficial to promoting simple and efficient production of direct-seeded rice under simplified cultivation methods.

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