Effects of Nitrogen Reduction Combined with Controlled-Release Urea on Rice Yield and Nitrogen Use Efficiency: Postprint

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Abstract

Using controlled-release urea with a release period of 60–90 days as the experimental material, field experiments were conducted in Taishan City and Wengyuan County, Guangdong Province, in 2015 to investigate the effects of conventional split fertilization (CF), one-time application of 25% controlled-release urea nitrogen (25%CRU), and one-time application of 50% controlled-release urea nitrogen (50%CRU) on rice growth, yield, and nitrogen use efficiency under full nitrogen application [195 kg(N) · hm ^{2}], 20% nitrogen reduction [156 kg(N) · hm ^{2}], and 40% nitrogen reduction [117 kg(N) · hm ^{2}], providing a reference for the promotion and application of controlled-release urea in rice production. The results showed that during the rice vegetative growth stage, the number of tillers per hill was basically consistent across different nitrogen application treatments, and leaf SPAD values increased slightly with increasing nitrogen application rate. With increasing nitrogen application rate, rice yield first increased and then decreased, with the highest rice yield achieved at a nitrogen application rate of 156 kg(N) · hm ^{2}. Under equal nitrogen conditions, rice grain yields were basically consistent among the 25%CRU, 50%CRU, and CF treatments; there were no significant differences in nitrogen uptake and accumulation in grain and straw among different nitrogen application treatments. Rice nitrogen uptake and accumulation increased with increasing nitrogen application rate, while nitrogen partial factor productivity and nitrogen harvest index gradually decreased. Under equal nitrogen conditions, the nitrogen agronomic efficiency and nitrogen physiological use efficiency of the 25%CRU and 50%CRU treatments were significantly higher than those of the conventional fertilization treatment ($P<0.05$), with average increases at the two sites of 14.99% and 17.23% for nitrogen agronomic efficiency, and 98.22% and 57.44% for nitrogen physiological use efficiency, respectively. When the nitrogen application rate was 195 kg(N) · hm ^{2}, the nitrogen harvest index of the 25%CRU and 50%CRU treatments increased by 6.99% and 6.69% compared with the conventional fertilization treatment (CF), with the increase reaching a significant level at the Taishan experimental site ($P<0.05$). The soil alkali-hydrolyzable nitrogen content was significantly reduced under the 117 kg(N) · hm ^{2} treatment ($P<0.05$). The fertilization treatment with one-time application of 25% controlled-release nitrogen fertilizer blended at a nitrogen rate of 156 kg(N) · hm ^{2} achieved relatively high yield and nitrogen use efficiency at both the Taishan and Wengyuan experimental sites, and represents an optimal nitrogen management pattern that can achieve stable rice yield increases, significantly improve nitrogen use efficiency, and maintain soil fertility in the double-cropping rice region of Guangdong Province.

Full Text

Abstract

Field experiments were conducted in Taishan City and Wengyuan County, Guangdong Province during the 2015 rice growing season to investigate the effects of different blending ratios of controlled-release urea (CRU) and conventional urea (CU) under reduced nitrogen (N) application rates on rice growth, yield, N uptake, and N use efficiency. The CRU used had a nutrient release period of 60–90 days. Three N application rates were tested: conventional rate [195 kg(N) · hm ^{2}], 20% reduction [156 kg(N) · hm ^{2}], and 40% reduction [117 kg(N) · hm ^{2}]. At each N rate, three fertilization methods were compared: conventional split application (CF), single basal application of 25% CRU plus 75% CU (25%CRU), and single basal application of 50% CRU plus 50% CU (50%CRU). The results showed that tiller numbers at vegetative growth stages were similar across N treatments, while leaf SPAD values increased slightly with N rate. Grain yield initially increased then decreased with increasing N application, reaching maximum at 156 kg(N) · hm ^{2}. Under equivalent N rates, grain yields were comparable among CF, 25%CRU, and 50%CRU treatments, with no significant differences in N accumulation in grain and straw. Total N uptake increased with N application rate, while N partial factor productivity and N harvest index decreased gradually. At equivalent N rates, both 25%CRU and 50%CRU treatments significantly increased agronomic N use efficiency and physiological N use efficiency compared to CF ($P < 0.05$), with average increases of 14.99% and 17.23%, and 98.22% and 57.44%, respectively, across both sites. At the conventional N rate [195 kg(N) · hm ^{2}], N harvest indices under 25%CRU and 50%CRU were 6.99% and 6.69% higher than CF, respectively, with significant differences observed at the Taishan site ($P < 0.05$). Soil alkali-hydrolyzable N content decreased significantly under the 117 kg(N) · hm ^{2} treatment ($P < 0.05$). The 25%CRU treatment at 156 kg(N) · hm ^{2} achieved high yield and N use efficiency at both experimental sites, demonstrating potential for increasing rice yield, improving N use efficiency, and maintaining soil fertility in double-cropping rice regions of Guangdong Province. This represents an optimal N management strategy.

Keywords: Rice; Controlled-release fertilizer; Basal-blending application; Low nitrogen application; Nitrogen use efficiency; Nutrient uptake; Yield

Introduction

Most soils in southern China’s double-cropping rice region are nitrogen-deficient, and the hot, rainy climate accelerates mineralization of soil organic nitrogen and increases N loss risk [1-2]. During long-term cultivation, rice farmers in Guangdong’ s double-cropping rice region have developed a “one basal plus three topdressings” fertilization pattern. However, this approach suffers from excessive application rates, numerous applications, and low nutrient use efficiency [3]. Scientific and rational N application is one of the most effective measures for achieving high and stable rice (Oryza sativa) yields [4-5]. Due to the important role of nitrogen fertilizer in crop production, N application rates in China have continuously increased [6]. With increasing fertilizer use and gradual improvement of soil fertility, the yield response to N fertilizer and N use efficiency have declined year by year [4,6-7], resulting not only in energy waste but also serious ecological environmental problems [2,7-8]. Therefore, reducing N loss from paddy fields and improving N use efficiency are critically important.

Controlled-release nitrogen fertilizers control nutrient release through various coating technologies, synchronizing nutrient supply with crop demand and representing an effective approach to improve fertilizer use efficiency. This has become a research hotspot worldwide [1,9-11]. Numerous studies have demonstrated that single application of controlled-release fertilizers in Guangdong’ s double-cropping rice region significantly increases yield, substantially improves N use efficiency, and maintains stable or increased rice production under reduced N application [1,10,12-15]. However, the high cost of controlled-release fertilizers for field crops such as rice severely limits their widespread adoption [1,11]. Research has shown that blending controlled-release fertilizers with quick-release fertilizers can also ensure crop yield and represents an effective pathway for promoting controlled-release fertilizers in rice and other field crops [11,16-17]. Nevertheless, research on optimal blending ratios of controlled-release urea with conventional urea and optimized N application rates for double-cropping rice remains limited, restricting the application and extension of this technology in rice production.

Therefore, this study used Agromaster controlled-release urea (ICL Specialty Fertilizers) with a nutrient release period of 60–90 days as test material to conduct rice fertilizer experiments in typical double-cropping paddy fields in Guangdong Province. The objective was to investigate the effects of different blending ratios of controlled-release and quick-release fertilizers under varying N application conditions on rice growth, N accumulation and distribution, N use efficiency, and yield, thereby exploring efficient N application pathways for rice production in Guangdong and providing technical support for improving N efficiency and reducing N use in China.

1.1 Experimental Materials

Field experiments were conducted from March to July 2015 at two locations: Doushan Town, Taishan City (112.58°E, 22.05°N) in southern Guangdong, and Sanhua Town, Wengyuan County (114.03°E, 24.18°N) in northern Guangdong. Wengyuan has a mid-subtropical monsoon climate with an average annual temperature of 20.4°C, annual rainfall of 1,778 mm, and a frost-free period of 312 days. Taishan has a subtropical maritime monsoon climate with an average annual temperature of 21.8°C, annual rainfall of 1,936 mm, and a frost-free period exceeding 360 days. The basic physicochemical properties of the experimental soils at both sites are presented in Table 1 . The controlled-release urea (CRU) used was Agromaster controlled-release urea (ICL Specialty Fertilizers) containing 43% N with a nutrient release period of 60–90 days.

1.2 Experimental Design

A completely randomized split-plot design was employed with no N application as control. The main plots consisted of three fertilization methods: conventional split application (CF), single basal application of 25% CRU plus 75% CU (25%CRU), and single basal application of 50% CRU plus 50% CU (50%CRU). The subplots comprised three N application rates: conventional rate [195 kg(N)·hm ^{2}], 20% reduction [156 kg(N)·hm ^{2}], and 40% reduction [117 kg(N)·hm ^{2}]. Detailed N application schemes and fertilizer management are shown in Table 2 . All treatments received 45 kg(P O)·hm ^{2} of phosphorus as superphosphate and 114 kg(K O)·hm ^{2} of potassium as potassium chloride, applied as basal fertilizer one day before transplanting. Plot soil was leveled with hoes and rakes, maintaining a water layer depth of approximately 3–5 cm. Fertilizers were mixed into the surface soil.

All treatments were replicated four times in a randomized complete block design with plot area of 20 m². Ridges covered with plastic film were constructed between plots to prevent water and nutrient seepage. The rice variety at Wengyuan was 'Shenyou 9786' , transplanted on March 30 at a density of 20 cm × 20 cm, and harvested on July 14. The rice variety at Taishan was 'Wushan Simiao' , transplanted on March 6 at a density of 18 cm × 20 cm, and harvested on July 5. Fields were irrigated after transplanting to promote seedling recovery. Other field management practices followed local conventional methods.

1.3 Sampling and Measurement Methods

Before the experiment, 0–20 cm topsoil samples were collected to determine pH, organic matter, alkali-hydrolyzable N, available P, and available K. During the vegetative growth period (within 40 days after transplanting), tiller numbers and leaf SPAD values were measured weekly. At maturity, five hills of panicle samples were collected from each plot for yield component evaluation, and two representative hills were sampled for biomass and N content determination in grain and straw. Topsoil samples were collected from each plot after harvest for total N and alkali-hydrolyzable N analysis. Each plot was harvested and threshed separately for yield measurement.

Biomass determination: Samples were washed and dried immediately after collection. Grain and straw were separated, killed at 105°C for 30 minutes, then dried to constant weight at 75°C.

Plant N content determination: Stem, leaf, and panicle samples were killed at 85°C for 30 minutes, then dried to constant weight at 75°C, ground, and passed through a 0.5 mm sieve. Samples were digested using H SO -H O method and analyzed using an AA3 auto-analyzer.

Soil analysis: Air-dried and sieved soil samples were analyzed using conventional soil agrochemical analysis methods [18]. Soil pH (2.5:1 water:soil) was measured by potentiometry, organic matter by potassium dichromate volumetric method, alkali-hydrolyzable N by alkali diffusion method, available P by Olsen method, and available K by ammonium acetate extraction-flame photometry.

1.4 Calculation Methods

Parameters related to N uptake and N use efficiency [12,17] were calculated as follows (with the no-N treatment (CK) as control):

Nitrogen agronomic efficiency [NAE, kg(grains) · kg ^{1}(N)] = (Grain yield of N treatment - Grain yield of control) / N application rate (1)

Nitrogen partial factor productivity [PFP, kg(grains) · kg ^{1}(N)] = Grain yield of N treatment / N application rate (2)

Nitrogen recovery efficiency (NRE, %) = (Aboveground N uptake of N treatment - Aboveground N uptake of control) / N application rate × 100 (3)

Nitrogen physiological efficiency [NPE, kg(grains) · kg ^{1}(N)] = (Grain yield of N treatment - Grain yield of control) / (Aboveground N uptake of N treatment - Aboveground N uptake of control) (4)

N harvest index (NHI, %) = Grain N uptake / Aboveground N uptake × 100 (5)

1.5 Statistical Analysis

Data were statistically analyzed and plotted using Microsoft Excel 2007 and R software.

Results

2.1 Effects of Different Fertilization Treatments on Rice Tillering

Tiller numbers increased gradually one week after transplanting, rose rapidly during weeks 2–4, and stabilized by week 5 (Figure 1 [Figure 1: see original paper]). In early tillering stages, tiller numbers were similar across treatments. During mid-to-late tillering stages (weeks 2–5 after transplanting), N application significantly increased tiller numbers compared to the no-N treatment ($P < 0.05$), with no significant differences among N application methods at equivalent N rates. At the Taishan site, tiller numbers were generally consistent across different N treatments, while at Wengyuan, tiller numbers increased with N rate. The difference between sites may be attributed to temperature effects on tillering response to N application. Taishan, located in southwestern Guangdong, has favorable light and temperature conditions, resulting in early tillering with minimal response to N rate. In contrast, Wengyuan, in northern Guangdong, has lower early rice season temperatures, leading to slower tillering that is more sensitive to N application.

2.2 Effects of Different Fertilization Treatments on Rice SPAD Values

As shown in Figure 2 [Figure 2: see original paper], leaf SPAD values at Taishan remained relatively stable during rice growth, while those at Wengyuan showed a "decrease-increase" trend. The low SPAD values at Wengyuan during weeks 2–3 after transplanting may be due to low soil temperature, slow N mineralization, and weak root absorption capacity. As plants grew, leaf N content became diluted, causing SPAD values to decline initially. With subsequent temperature increases, N mineralization rate and root absorption capacity improved, increasing plant N content and SPAD values. Both sites showed SPAD value lows during weeks 2–3 after transplanting. Nitrogen application significantly increased leaf SPAD values at both sites ($P < 0.05$). No differences were observed among N treatments one week after transplanting. As rice grew, leaf SPAD values increased with N rate, with conventional N rate [195 kg(N) · hm ^{2}] showing significantly higher values than the 40% reduction treatment [117 kg(N) · hm ^{2}] by week 5 ($P < 0.05$). Conventional split application showed slightly higher SPAD values than CRU treatments in early stages, but CRU treatments gradually caught up, reaching similar levels by weeks 3–4. SPAD values were comparable between 25%CRU and 50%CRU treatments.

2.3 Effects of Different Fertilization Treatments on Rice Grain Yield and Yield Components

Nitrogen application significantly increased grain yield ($P < 0.05$), with average increases of 10.92% at Taishan and 12.94% at Wengyuan compared to the no-N treatment (11.93% average). Grain yields differed significantly among N treatments, with 25%CRU-2 producing the highest yield, followed by 50%CRU-2. At Taishan, CF3 and 50%CRU-3 yields were significantly lower than 25%CRU-2 and 50%CRU-2 ($P < 0.05$), while at Wengyuan, CF1 yield was significantly lower than 25%CRU-2 ($P < 0.05$). Grain yield increased initially then decreased with N rate, reaching maximum at 156 kg(N) · hm ^{2}. Under equivalent N rates, no significant differences in grain yield were observed among fertilization methods.

Nitrogen application significantly increased effective panicles and grains per panicle at Taishan, and filled grains per panicle at Wengyuan ($P < 0.05$), but had no significant effect on seed-setting rate or 1000-grain weight. Under equivalent N rates, no differences were found in effective panicles, filled grains, seed-setting rate, or 1000-grain weight among fertilization methods. At Taishan, effective panicles increased with N rate but differences were not significant. At Wengyuan, N rate had no significant effect on effective panicles, while filled grains per panicle showed an initial increase then decrease with N rate, though differences were not significant. Seed-setting rate decreased gradually with increasing N rate at both sites, with no significant differences among treatments.

2.4 Effects of Different Fertilization Treatments on Rice N Uptake and Use Efficiency

Nitrogen application significantly increased N uptake compared to the no-N treatment ($P < 0.05$), with straw N uptake increasing by 72.01% (Taishan) and 94.19% (Wengyuan), and grain N uptake increasing by 27.26% (Taishan) and 36.95% (Wengyuan). Nitrogen treatments significantly affected total N uptake, with CF1 showing the highest uptake, followed by 25%CRU-1. Total N uptake increased with N application rate, but the 40% reduction treatment at Taishan showed significantly lower N accumulation than conventional N rate, with CF3 showing the largest reduction. Straw N uptake showed the most pronounced decrease, while CRU treatments showed relatively smaller reductions. Under equivalent N rates, no significant differences in straw and grain N accumulation were observed among fertilization methods.

Agronomic N efficiency increased initially then decreased with N rate, reaching maximum at 20% N reduction [156 kg(N) · hm^{2}]. Under equivalent N rates, 25%CRU and 50%CRU increased agronomic N efficiency by 16.72% (Taishan) and 21.20% (Wengyuan), and 13.26% (Taishan) and 13.27% (Wengyuan), respectively, compared to CF, with average increases of 14.99% and 17.23% across both sites. Partial factor productivity decreased significantly with increasing N rate ($P < 0.05$) and was not significantly affected by fertilization method at equivalent N rates. Nitrogen physiological efficiency was significantly affected by N treatments, with CF1 showing significantly lower values than other treatments. Physiological efficiency increased initially then decreased with N rate. Under equivalent N rates, 25%CRU and 50%CRU showed higher physiological efficiency than CF at Taishan, with increases of 105.98% ($P < 0.05$) and 45.01% at 195 kg(N) · hm^{2}. At Wengyuan, both CRU treatments showed significantly higher physiological efficiency than CF at 195 kg(N) · hm^{2}, with increases of 90.48% ($P < 0.05$) and 69.87% ($P < 0.05$). Average increases across both sites were 98.22% and 57.44%, respectively. Nitrogen application significantly reduced N harvest index ($P < 0.05$), which decreased gradually with N rate. At 195 kg(N) · hm^{2}, N harvest indices under 25%CRU and 50%CRU were 9.37% (Taishan) and 4.61% (Wengyuan), and 9.40% (Taishan) and 3.98% (Wengyuan) higher than CF, with average increases of 6.99% and 6.69%, respectively. The increases were significant at Taishan ($P < 0.05$). No significant differences in N recovery efficiency were observed among treatments.

2.5 Effects of Different N Treatments on Soil Alkali-Hydrolyzable N Content

Nitrogen application significantly increased soil alkali-hydrolyzable N content (Table 5). Soil alkali-hydrolyzable N decreased gradually with reduced N rate, with more pronounced decreases at Taishan. Under equivalent N rates, fertilization method had no effect on soil alkali-hydrolyzable N content.

Discussion and Conclusion

Vigorous and stable tillering during early rice growth is crucial for high-yield cultivation, with N supply being particularly important [19-20]. This study showed that N application significantly increased tiller numbers, which tended to increase with N rate. Controlled-release urea releases nutrients slowly and may not meet N demand during the vigorous tillering stage, potentially resulting in weaker tillering [11,21-23]. Some researchers have adjusted N release curves by blending controlled-release fertilizers with different release characteristics to meet early-season N demand and increase tiller numbers [24-25]. Our results indicated that under equivalent N rates, 25%CRU and 50%CRU produced tillering vigor comparable to conventional split application during the vigorous tillering stage, with similar leaf SPAD values at weeks 3-4 after transplanting. This demonstrates that single basal application of blended controlled-release and conventional urea can meet N nutritional requirements during the early vigorous tillering stage, providing an important guarantee for high rice yields.

Energy materials for grain filling originate partly from remobilization of stored stem and leaf reserves and partly from post-heading photosynthates, making late-season N supply crucial for yield formation [25]. Studies have shown that appropriate panicle fertilizer application can improve panicle formation, seed-setting rate, and grain yield [26-27]. Controlled-release urea provides stable, long-lasting nutrient supply through controlled release [9]. Research by Xie et al. [13] and Tang et al. [22] indicated that single application of controlled-release fertilizer provides sufficient N supply during mid-to-late rice growth, maintaining higher chlorophyll content and panicle formation rates. Other studies demonstrated that single application of controlled-release fertilizer significantly promotes root development, building a large and active root system that expands nutrient absorption area and supports late-season nutrient supply [10,15]. Using controlled-release fertilizer as a carrier can extend the nutrient supply period, meeting N demand throughout the rice growth period and increasing yield [1]. Our results also showed that 50%CRU and 25%CRU produced effective panicles, seed-setting rates, and 1000-grain weights comparable to conventional split application. Grain yields under 50%CRU and 25%CRU were not different from CF under equivalent N rates, indicating that single basal application of blended controlled-release and conventional urea can meet mid-to-late season

N demand, ensuring high panicle formation, seed-setting rate, and 1000-grain weight for stable high yields.

The tillering, jointing-to-heading, and heading-to-maturity stages are critical periods for rice N nutrition. Conventional urea requires multiple applications to match the multi-peak N absorption pattern throughout the rice growth period [28]. Controlled-release urea provides continuous nutrient release, optimizing spatiotemporal nutrient supply and synchronizing fertilizer release with rice uptake [1,29-30]. Our results showed that under equivalent N rates, N accumulation in 50%CRU and 25%CRU treatments was not significantly different from conventional split application. Under reduced N conditions, grain N accumulation in CRU treatments was slightly higher than in conventional split application, with 50%CRU showing higher accumulation than 25%CRU. This occurs because conventional split application concentrates most fertilizer during vegetative growth, meeting early straw nutrient accumulation but causing insufficient late-season supply, which substantially reduces grain N accumulation. Therefore, single basal application of blended controlled-release and conventional urea can meet the multi-peak N absorption demand throughout the rice growth period.

Agronomic N efficiency, partial factor productivity, and physiological efficiency reflect crop N absorption and utilization [7,31]. Constrained by cultivation techniques, fertilization technology, and application machinery, rice agronomic N efficiency and N recovery efficiency in China are relatively low, at only 30–35% and 10 kg · kg ^{1}, respectively [5,7,31]. Numerous studies have shown that controlled-release N fertilizers significantly increase agronomic efficiency, recovery efficiency, and physiological efficiency in rice, wheat (Triticum aestivum), maize (Zea mays), and other crops [1,11,16-17,23]. Our results also demonstrated that under equivalent N rates, CRU treatments showed significantly higher agronomic and physiological efficiency than conventional split application, with greater increases under 50%CRU. Nitrogen recovery efficiency was similar between CRU and conventional split application. Partial factor productivity is significantly correlated with N application rate [7], and our results confirmed a significant negative correlation with N rate but minimal influence from fertilization method.

High-yield cultivation modes that sacrifice soil fertility are unsustainable; coordinating crop production with soil fertility maintenance is essential for sustainable agriculture. Some studies have shown that controlled-release urea application can effectively increase topsoil N content [24]. Our results indicated that soil alkali-hydrolyzable N content after harvest was similar between CRU and conventional split application under equivalent N rates. This may be due to the 60–90 day release period of the controlled-release urea used in this experiment, which allowed complete nutrient release during the rice growth period without significantly affecting soil N content at harvest. Soil alkali-hydrolyzable N content was significantly affected by N application rate, with a 40% reduction [117 kg(N) · hm ^{2}] significantly decreasing soil N content and affecting soil fertility.

In conclusion, single basal application of blended controlled-release and conventional urea (CRU) can ensure adequate N supply during vegetative growth, maintain strong tillering vigor, and establish robust plant populations, providing strong support for high and stable rice yields. At 40% N reduction [117 kg(N) · hm ^{2}], N recovery efficiency was relatively high, but soil N content decreased significantly after harvest. At conventional N rate [195 kg(N) · hm ^{2}], rice N accumulation increased substantially, but N use efficiency and yield were lowest. At 20% N reduction [156 kg(N) · hm ^{2}], rice yield was highest and 25%CRU showed the highest N use efficiency. Therefore, considering crop growth, yield response, N uptake, N use efficiency, and soil fertility, the 25% controlled-release N fertilizer blended single basal application at 156 kg(N) · hm ^{2} represents an optimal N management strategy.

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