Effects of Biochemical Inhibitor Combinations and Fertilization Patterns on Rice Nutrient Accumulation and Utilization Efficiency in Yellow Mud Paddy Fields: Postprint

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Abstract

Adding biochemical inhibitors is one of the effective approaches to improve rice fertilizer use efficiency. This study investigated the nutrient utilization characteristics for fertilizer saving and efficiency enhancement by combining different fertilization modes, aiming to identify suitable application methods for high-yield and high-efficiency rice production in yellow mud soil regions. A two-factor randomized block design was employed to examine the interactive effects of biochemical inhibitor combinations [urease inhibitors N-(n-butyl) thiophosphoric triamide (NBPT) and N-(n-propyl) thiophosphoric triamide (NPPT), and nitrification inhibitor 2-chloro-6-(trichloromethyl)pyridine (CP)] and fertilization modes (single basal application and split fertilization) on nutrient absorption, utilization, and distribution in rice grown in yellow mud soil, and to explore the relationships among nutrients and between nutrients and yield. The results showed that biochemical inhibitor combinations and fertilization modes exhibited interactive effects on N, P, and K accumulation, translocation, and distribution during main rice growth stages, with synergistic effects among nutrient absorption at various growth stages under interactive conditions. Split urea application increased N, P, and K uptake at rice maturity by 11.0%, 0.9%, and 4.2%, respectively, compared with single basal application; nitrogen fertilizer recovery efficiency and nitrogen agronomic efficiency were significantly increased by 27.5% and 70.8%, respectively. Under different fertilization modes, combined application of inhibitor combinations (NBPT, NPPT/+CP) significantly increased rice N, P, and K uptake, promoted dry matter production and N accumulation after heading, and enhanced nutrient distribution in grains and N use efficiency. The new urease inhibitor NPPT, applied alone or in combination with CP, showed similar effects on rice nutrient uptake and utilization as NBPT. Correlation analysis indicated that under different fertilization modes, N, P, and

K uptake at rice maturity were all extremely significantly positively correlated with grain yield. In conclusion, through the integration and optimization of fertilization techniques and combined inhibitor application, the absorption and translocation of N, P, and K after heading are facilitated, nutrient accumulation is promoted, and the yield and nutrient use efficiency of rice in yellow mud soil are substantially and simultaneously improved.

Full Text

Effects of Combined Biochemical Inhibitors and Fertilization Models on Nutrient Uptake and Use Efficiency of Rice in Yellow Clayey Fields

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Abstract: Application of biochemical inhibitors represents an effective approach for improving fertilizer use efficiency in rice. This study investigated the nutrient utilization characteristics of different fertilization models combined with inhibitors to identify optimal application methods for achieving high yield and efficiency in yellow clayey paddy fields. Using a two-factor randomized block design, we examined the interactive effects of biochemical inhibitors [urease inhibitors N-(n-butyl) thiophosphoric triamide (NBPT) and N-(n-propyl) thiophosphoric triamide (NPPT), and nitrification inhibitor 2-chloro-6-(trichloromethyl) pyridine (CP)] and fertilization models (one-off and split applications) on nutrient absorption, utilization, and distribution in rice, as well as the relationships among nutrients and their correlation with grain yield. Results showed significant interactive effects between inhibitor combinations and fertilization models on N, P, and K accumulation, translocation, and distribution during key growth stages, with synergistic effects among nutrients under interactive conditions. Split urea application increased N, P, and K uptake at maturity by 11.0%, 0.9%, and 4.2%, respectively, compared with one-off application, while significantly improving nitrogen recovery efficiency and agronomic efficiency by 27.5% and 70.8%. Across different fertilization models, inhibitor combinations (NBPT, NPPT/+CP) significantly enhanced rice N, P, and K uptake, promoted dry matter production and N accumulation after heading, and improved nutrient allocation to grains and N use efficiency. The novel urease inhibitor NPPT, applied alone or combined with CP, showed similar effects on nutrient uptake and utilization as NBPT. Correlation analysis revealed highly significant positive relationships between

N, P, and K uptake at maturity and grain yield under different fertilization models. In conclusion, integrated optimization of fertilization techniques combined with inhibitors enhanced N, P, and K uptake and translocation after heading, promoted nutrient accumulation, and simultaneously improved both rice yield and nutrient use efficiency in yellow clayey fields.

Keywords: Urease inhibitor; Nitrification inhibitor; Fertilization model; Yellow clayey field; Nutrient uptake; Nutrient use efficiency

Introduction

China consumes more nitrogen fertilizer than any other country, accounting for approximately 30% of global nitrogen consumption, with paddy fields representing about 24% of total national nitrogen use, primarily as urea. However, nitrogen use efficiency during the cropping season is only 30–35%, and sometimes even lower. While urea is the most widely used nitrogen fertilizer in Chinese agriculture due to its high nitrogen content, low cost, and ease of application, it suffers from low utilization efficiency and short duration of effectiveness. Therefore, improving nitrogen fertilizer use efficiency while ensuring high crop yields and reducing environmental risks represents an urgent challenge for agricultural production and environmental protection.

Co-application of urease inhibitors with urea can delay the conversion of amide nitrogen to ammonium nitrogen (NH -N) for 7-14 days, reduce nitrogen losses, and improve nitrogen use efficiency. Research has demonstrated that N-(n-butyl) thiophosphoric triamide (NBPT) can effectively increase crop yield and nitrogen use efficiency in tropical flooded rice paddies. Regulating nitrogen transformation through nitrification inhibitors represents another effective measure for achieving efficient nitrogen utilization and mitigating nitrogen pollution. Numerous studies have shown that developing slow/controlled-release fertilizers by combining urea with inhibitors can control the hydrolysis and transformation rate of nitrogen, extend the effective fertilization period, reduce nitrogen losses, and improve nitrogen use efficiency in rice (Oryza sativa L.). However, inhibitor effectiveness is influenced by soil texture, organic matter content, temperature, moisture, pH, nitrogen type, and cropping systems.

Yellow clayey paddy fields, widely distributed across southern Chinese provinces, are typical permeable rice soils characterized by insufficient water supply and phosphorus (P) and potassium (K) deficiencies, belonging to the category of low-to-medium yielding paddy fields. In these soils, phosphorus fertilizer is readily fixed by iron and aluminum, while nitrogen and potassium fertilizers are prone to leaching, resulting in low nutrient availability. Application of the nitrification inhibitor chloromethylpyridine (CP) combined with urea has been shown to promote early and late rice growth, increase yield and income, and improve nitrogen use efficiency. Research indicates that CP application increases nitrogen content in rice straw and grains while reducing nitrogen losses through nitrification-denitrification and runoff, thereby enhancing crop nitrogen absorption and use efficiency.

Nitrogen recovery efficiency is known to vary significantly with nitrogen application rate, fertilization method, soil properties, climate conditions, and cultivar type. Determining appropriate nitrogen application rates and ratios can meet rice nitrogen demand at different growth stages, effectively reduce nitrogen losses, and improve use efficiency. Studies have shown that increasing the proportion of panicle fertilizer can enhance nitrogen recovery efficiency and production efficiency. However, research on the interactive effects of inhibitor combinations and fertilization models on rice nutrient absorption, utilization, translocation, and distribution characteristics remains limited. After establishing appropriate nitrogen application rates, how to integrate different inhibitor combinations with suitable nitrogen management strategies to regulate N, P, and K absorption and utilization during key growth stages and their relationships with yield remains unclear. Zhejiang Aofutuo Chemical Company has identified a promising new urease inhibitor, N-(n-propyl) thiophosphoric triamide (NPPT), through multiple screening processes. Building on previous experiments, this study further investigated the characteristics of rice N, P, and K absorption and utilization under interactive conditions of inhibitors and fertilization models, explored relationships among nutrient absorption, distribution, and yield, and sought to identify suitable application methods for high yield and efficiency in this region, providing theoretical basis and technical approaches for direct application of biochemical inhibitors in yellow clayey paddy fields.

1. Materials and Methods

1.1 Experimental Site Overview The field experiment was conducted from May to October 2015 in Jinzhu Village, Langya Town, Wucheng District, Jinhua City, Zhejiang Province (29°01 19 N, 119°27 96 E). The region is located on the eastern edge of the Jinqu Basin with a mid-subtropical monsoon climate, an elevation of 86 m, average annual rainfall of 1,424 mm, and mean annual temperature of 17.5°C. The experimental soil was yellow clayey paddy field following winter fallow. Basic physicochemical properties of the topsoil were: pH(H O) 5.31 (soil:water = 1:1), organic matter 25.60 $\text{g} \cdot \text{kg}^{1}$, total nitrogen 1.87 $\text{g} \cdot \text{kg}^{1}$, alkaline hydrolyzable nitrogen 118.40 $\text{mg} \cdot \text{kg}^{1}$, available phosphorus 7.21 $\text{mg} \cdot \text{kg}^{1}$, and available potassium 93.00 $\text{mg} \cdot \text{kg}^{1}$.

1.2 Experimental Materials The rice cultivar was hybrid indica rice 'Liangyoupeijiu' . Nitrogen fertilizer was urea (46% N), phosphorus fertilizer was calcium superphosphate (12% P O), and potassium fertilizer was potassium chloride (60% K O). The urease inhibitors N-(n-butyl) thiophosphoric triamide (NBPT) and N-(n-propyl) thiophosphoric triamide (NPPT), and the nitrification inhibitor 2-chloro-6-(trichloromethyl) pyridine (CP) as a 24% emulsifiable concentrate were all analytical grade products manufactured by Zhejiang Aofutuo Chemical Limited Company.

1.3 Experimental Design The experiment employed a two-factor randomized block design with two nitrogen application models (one-off and split applications) and six biochemical inhibitor combinations plus a no-nitrogen control (CK), totaling 13 treatments . Nitrogen fertilizer and inhibitors were thoroughly mixed before application. Phosphorus (P O) and potassium (K O) were applied at rates of 90 kg·hm ^{2} and 120 kg·hm ^{2}, respectively, both as basal fertilizers before transplanting. Planting density was 19.8 cm × 19.8 cm (250,000 hills·hm ^{2}) with two seedlings per hill. The single-season rice was sown on May 28, transplanted on June 21, and harvested on October 14, 2015. Each plot measured 30 m^{2} (5 m × 6 m) with three replications. Ridges wrapped with plastic film separated plots, and irrigation/drainage ditches were installed between blocks for individual water management. Other field management followed conventional practices.

Meteorological temperature data during the rice growing season (June–October) were obtained from Jinhua Meteorological Station, Zhejiang Province [Figure 1: see original paper], with maximum, minimum, and mean temperatures of 29.9°C, 22.6°C, and 26.2°C, respectively.

1.4 Measurement Items and Methods At the mid-tillering, panicle initiation, heading, and maturity stages, five representative hills were sampled from each plot according to average tiller numbers. After removing roots, plants were separated into stems/sheaths, leaves, and panicles, then oven-dried, weighed, and ground for nutrient content analysis. Samples were digested with H SO -H O , and N content was determined by the Kjeldahl method, P by vanadium-molybdenum yellow colorimetry, and K by flame photometry. At maturity, all plants in each plot were harvested individually.

Nitrogen use efficiency was calculated as follows:

Total N, P, K accumulation (TNA, TPA, TKA): The sum of N, P, and K accumulation in plants (stems, leaves, and panicles) per unit area at maturity.

Harvest index (HI) = Grain dry weight at maturity / Total plant dry weight at maturity (1)

N, P, K harvest index (NHI, PHI, KHI) = N, P, K accumulation in grains per unit area at maturity / Total accumulation of the respective element in the plant (2)

N recovery efficiency (NRE) (%) = (Aboveground N uptake in N-treated plot - Aboveground N uptake in control plot) / N application rate × 100 (3)

N agronomic efficiency (NAE) (kg·kg ^{1}) = (Grain yield in N-treated plot - Grain yield in control plot) / N application rate (4)

N physiological efficiency (NPE) (kg·kg ^{1}) = (Grain yield in N-treated plot - Grain yield in control plot) / (Aboveground N uptake in N-treated plot - Aboveground N uptake in control plot) (5)

N partial factor productivity (NPFP) (kg • kg ^{1}) = Grain yield in N-treated plot / N application rate (6)

1.5 Data Processing Data were analyzed using Microsoft Excel 2003 and SPSS 17.0 statistical software.

2. Results

2.1 Effects of Biochemical Inhibitor Combinations and Fertilization Models on Rice Dry Matter Accumulation Fertilization model showed significant or highly significant effects on dry matter accumulation at mid-tillering and maturity stages and harvest index (HI) ($P < 0.05$-0.001), while biochemical inhibitor combinations had highly significant effects on dry matter accumulation at mid-tillering and maturity stages ($P < 0.01$-0.001). The interaction between factors significantly affected dry matter accumulation at mid-tillering ($P < 0.05$). Dry matter accumulation increased throughout the growing season, with the CK treatment showing the lowest values at all stages, indicating that nitrogen application promoted dry matter accumulation. At mid-tillering, dry matter accumulation was highest in U and U3 treatments, with no significant differences among other treatments. Differences among N treatments were minimal at panicle initiation and heading stages.

The U3 treatment increased dry matter accumulation at maturity by 3.0% compared with the U treatment. Under one-off application, N treatments increased dry matter accumulation by 33.8–48.5% compared with CK. Compared with U treatment, U+NBPT, U+NPPT, U+CP, U+NBPT+CP, and U+NPPT+CP treatments increased dry matter accumulation at maturity by 1.3%, 5.3%, 11.0%, 7.7%, and 9.3%, respectively. Under split application, N treatments increased dry matter accumulation by 37.8–55.3% compared with CK. Compared with U3 treatment, U3+NBPT, U3+NPPT, U3+CP, U3+NBPT+CP, and U3+NPPT+CP treatments increased dry matter accumulation at maturity by 4.6%, 3.3%, 10.9%, 10.1%, and 12.7%, respectively. These results demonstrate that urea combined with inhibitors prolonged soil N supply and significantly increased dry matter accumulation at maturity, laying the foundation for high yield. The U3 treatment increased HI by 9.2% compared with the U treatment. Under one-off application, inhibitor treatments increased HI by 5.1-10.3% compared with U treatment, while under split application, inhibitor treatments increased HI by 1.0–6.2% compared with U3 treatment.

2.2 Effects of Biochemical Inhibitor Combinations and Fertilization Models on N Absorption, Distribution, and Utilization

2.2.1 N Absorption Fertilization model showed highly significant effects on N accumulation (TNA) at panicle initiation, heading, and maturity stages and on post-heading N accumulation proportion ($P < 0.001$). Biochemical inhibitor combinations had significant or highly significant effects on N absorption indicators (except TNA at heading stage) ($P < 0.05$ or 0.001), and the interaction significantly affected TNA at mid-tillering and panicle initiation stages and post-heading N accumulation ($P < 0.05$). Total N accumulation increased throughout the growing season, with CK showing the lowest values at all stages, confirming that nitrogen application promoted TNA. At mid-tillering, TNA was highest in U and U3 treatments, with minimal differences among other treatments. Differences among N treatments were negligible at panicle initiation stage, but split urea applications were significantly higher than one-off applications at heading stage.

The U3 treatment significantly increased TNA at maturity by 11.0% compared with the U treatment, demonstrating that split fertilization better met rice N demand and significantly increased TNA accumulation at maturity. Under one-off application, N treatments increased TNA by 67.0–98.8% compared with CK. Compared with U treatment, U+NBPT, U+NPPT, U+CP, U+NBPT+CP, and U+NPPT+CP treatments increased TNA at maturity by 9.2%, 11.1%, 19.0%, 18.6%, and 18.6%, respectively. Under split application, N treatments increased TNA by 85.4-120.8% compared with CK. Compared with U3 treatment, U3+NBPT, U3+NPPT, U3+CP, U3+NBPT+CP, and U3+NPPT+CP treatments increased TNA at maturity by 3.8%, 4.8%, 13.6%, 15.8%, and 19.1%, respectively. These results indicate that urea with inhibitors prolonged soil N supply and significantly increased TNA at maturity.

The U3 treatment increased post-heading N accumulation by 8.2% compared with the U treatment, showing that split fertilization enhanced post-heading N accumulation. Under one-off application, N treatments increased post-heading N accumulation by 54.5-129.8% compared with CK. Compared with U treatment, U+NBPT, U+NPPT, U+CP, U+NBPT+CP, and U+NPPT+CP treatments increased post-heading N accumulation by 27.0%, 30.5%, 48.0%, 44.5%, and 48.8%, respectively. Under split application, N treatments increased post-heading N accumulation by 67.2-145.0% compared with CK. Compared with U3 treatment, U3+NBPT, U3+NPPT, U3+CP, U3+NBPT+CP, and U3+NPPT+CP treatments increased post-heading N accumulation by 9.3%, 11.9%, 25.8%, 34.3%, and 46.5%, respectively. These findings demonstrate that urea with inhibitors enhanced post-heading N accumulation, maintaining N assimilation and absorption capacity after heading. The U3 treatment increased N harvest index (NHI) by 1.7% compared with the U treatment. Under one-off application, inhibitor treatments increased NHI by 1.9-10.0% compared with U treatment, while under split application, inhibitor treatments increased NHI by 4.2-11.0% compared with U3 treatment.

2.2.2 N Use Efficiency Fertilization model showed highly significant effects on NRE, NAE, and NPFP ($P < 0.01$-0.001), while biochemical inhibitor combinations had highly significant effects on all nitrogen use efficiency indicators ($P < 0.001$). The interaction between factors was highly significant for NAE and

NPE ($P < 0.01$-0.001).

The U3 treatment significantly increased NRE, NAE, and NPFP by 27.5%, 70.8%, and 14.2%, respectively, compared with the U treatment, confirming that split fertilization better met rice N demand and significantly improved nitrogen use efficiency. Compared with U treatment, U+NBPT, U+NPPT, U+CP, U+NBPT+CP, and U+NPPT+CP treatments increased NRE by 22.8%, 27.6%, 47.4%, 46.4%, and 46.4%, respectively; NAE by 113.7%, 111.1%, 100.2%, 120.3%, and 128.7%, respectively; and NPFP by 22.8%, 22.2%, 20.1%, 24.1%, and 25.8%, respectively. Compared with U3 treatment, U3+NBPT, U3+NPPT, U3+CP, U3+NBPT+CP, and U3+NPPT+CP treatments increased NRE by 8.3%, 10.4%, 29.4%, 34.3%, and 41.4%, respectively; NAE by 36.0%, 45.0%, 42.7%, 40.1%, and 52.6%, respectively; and NPFP by 10.8%, 13.5%, 12.8%, 12.0%, and 15.8%, respectively. These results demonstrate that urea with inhibitors prolonged soil N supply and improved NRE, NAE, and NPFP, establishing the foundation for high yield.

2.2.3 N Distribution At maturity, N accumulation in rice plants followed the pattern: panicle > stem > leaf [Figure 2: see original paper]. Split application resulted in higher N accumulation in panicles and leaves but lower accumulation in stems compared with one-off application, indicating that split fertilization better met rice N demand, promoted N translocation from stems, and increased N accumulation in panicles.

2.3 Effects of Biochemical Inhibitor Combinations and Fertilization Models on P Absorption and Distribution

2.3.1 P Absorption Fertilization model showed significant or highly significant effects on P accumulation (TPA) at mid-tillering and panicle initiation stages and on P harvest index (PHI) ($P < 0.05$ or 0.001). Biochemical inhibitor combinations had significant or highly significant effects on P absorption indicators (except PHI) ($P < 0.05$ or 0.001), and the interaction significantly affected TPA at mid-tillering stage ($P < 0.05$). Total P accumulation increased throughout the growing season, with CK showing the lowest values at all stages, confirming that nitrogen application promoted TPA accumulation. At mid-tillering, TPA was highest in U and U3 treatments, with minimal differences among other treatments. Differences among N treatments were negligible at panicle initiation and heading stages.

The U3 treatment increased TPA at maturity by 0.9% compared with the U treatment, indicating that split fertilization better met rice P demand and increased TPA accumulation at maturity. Under one-off application, N treatments increased TPA by 54.8-68.7% compared with CK. Compared with U treatment, U+NBPT, U+NPPT, U+CP, U+NBPT+CP, and U+NPPT+CP treatments increased TPA at maturity by 6.7%, 6.1%, 9.0%, 8.9%, and 8.5%, respectively. Under split application, N treatments increased TPA by 56.2–77.0%

compared with CK. Compared with U3 treatment, U3+NBPT, U3+NPPT, U3+CP, U3+NBPT+CP, and U3+NPPT+CP treatments increased TPA at maturity by 6.7%, 6.1%, 13.3%, 8.7%, and 10.6%, respectively. These results demonstrate that urea with inhibitors prolonged soil N supply and increased TPA at maturity, establishing the foundation for high yield.

2.3.2 P Distribution At maturity, P accumulation in rice plants followed the pattern: panicle > stem > leaf [Figure 3: see original paper]. Split application resulted in higher P accumulation in panicles but lower accumulation in stems compared with one-off application; P accumulation in leaves was lower with inhibitor treatments than with one-off application. These findings indicate that split fertilization combined with inhibitors better met rice P demand, reduced P allocation to stems and leaves, and increased P accumulation in panicles.

2.4 Effects of Biochemical Inhibitor Combinations and Fertilization Models on K Absorption and Distribution

2.4.1 K Absorption Fertilization model showed significant or highly significant effects on K accumulation (TKA) at all growth stages (except panicle initiation) and on K harvest index (KHI) ($P < 0.05$ or 0.001). Biochemical inhibitor combinations had significant or highly significant effects on TKA at mid-tillering and panicle initiation stages and on KHI ($P < 0.05$ or 0.001), and the interaction significantly affected KHI ($P < 0.01$). Total K accumulation followed an S-shaped curve throughout the growing season, peaking at heading stage, with CK showing the lowest values at all stages, confirming that nitrogen application promoted TKA accumulation. At mid-tillering, TKA was highest in U and U3 treatments, with minimal differences among other treatments. Differences among N treatments were negligible at panicle initiation and heading stages.

The U3 treatment increased TKA at maturity by 4.2% compared with the U treatment, indicating that split fertilization better met rice K demand and increased TKA accumulation at maturity. Under one-off application, N treatments increased TKA at maturity by 50.8-63.5% compared with CK. Compared with U treatment, U+NBPT, U+NPPT, U+CP, U+NBPT+CP, and U+NPPT+CP treatments increased TKA by 8.1%, 8.2%, 8.4%, 6.8%, and 5.6%, respectively. Under split application, N treatments increased TKA by 57.1-73.0% compared with CK. Compared with U3 treatment, U3+NBPT, U3+NPPT, U3+CP, U3+NBPT+CP, and U3+NPPT+CP treatments increased TKA by 5.9%, 6.5%, 8.0%, 4.8%, and 10.1%, respectively. These results demonstrate that urea with inhibitors prolonged soil N supply and increased TKA, establishing the foundation for high yield.

2.4.2 K Distribution At maturity, K accumulation in rice plants followed the pattern: stem and leaf > panicle [Figure 4: see original paper]. Split application resulted in higher K accumulation in panicles and leaves but lower accumulation in stems compared with one-off application, indicating that split fertilization better met rice K demand, promoted K translocation from stems, and increased K accumulation in panicles.

2.5 Relationships Between N, P, K Uptake and Grain Yield Under different fertilization models, N, P, and K uptake showed highly significant positive correlations with grain yield, increasing with yield level [Figure 5: see original paper]. These relationships indicate that adequate N, P, and K supply forms the basis for high-yield rice cultivation. The correlation coefficients between N, P, K uptake and grain yield were higher under split application (rN = 0.972**, rP = 0.985**, rK = 0.988**) than under one-off application (rN = 0.951**, rP = 0.936**, rK = 0.929**), demonstrating that split fertilization better met rice N, P, and K demand, improved nutrient accumulation, and thereby achieved higher yields.

3. Discussion

3.1 Effects of Fertilization Model on Rice Nitrogen Use Efficiency Large sink capacity and high biological yield are decisive factors for super hybrid rice productivity, and ideal cultivation techniques should facilitate smooth carbohydrate transport and distribution from "source" to "sink". Panicle fertilizer N, required for late reproductive growth in high-yielding rice, depends on accurate ratios determined by soil physicochemical properties, fertilizer types (slow-release or organic), climate conditions affecting fertilizer loss, and rice cultivar characteristics. Research has shown that nitrogen absorption peaks occur at the initial panicle differentiation stage in cold-region rice, with rapid absorption and large quantities absorbed from panicle differentiation to meiosis and from meiosis to heading. Studies on super hybrid rice have demonstrated that high nitrogen absorption during late growth stages (heading to maturity) benefits grain filling, improves seed-setting rate, and increases NHI. Our results showed that split fertilization increased post-heading N accumulation by 8.2% compared with one-off application, effectively increasing nitrogen reserves during late growth stages. The highly significant positive correlation between N uptake at maturity and grain yield (one-off: rN = 0.972**; split: rN = 0.951**) established the foundation for high yield. During early growth, underdeveloped root systems limit nitrogen absorption capacity and accumulation, resulting in minimal differences among nitrogen ratios. As plants developed and nutrient demand increased rapidly, increasing mid-to-late stage nitrogen application aligned nitrogen supply with peak demand, enhancing nitrogen accumulation and absorption, consistent with previous research.

Studies have found that increasing panicle fertilizer ratio at the same nitrogen level can improve nitrogen recovery efficiency, total accumulation, and translocation efficiency while reducing nitrogen production efficiency. Other research demonstrated that shifting nitrogen application later and increasing panicle fertilizer provides balanced nitrogen supply throughout the growth period, promoting nitrogen absorption and increasing seasonal utilization efficiency with higher panicle fertilizer proportions. Increased basal fertilizer rates have been shown to reduce nitrogen content in functional leaves during late growth stages, decreasing nitrogen accumulation at maturity and panicle nitrogen allocation coefficient, while significantly reducing NAE and NRE and showing quadratic relationships between nitrogen translocation rate and basal fertilizer rate. Research on double-cropping rice indicated that when basal and tiller fertilizers accounted for 60–70% of total nitrogen, rice achieved higher dry matter accumulation, nitrogen accumulation, NRE, and NAE with coordinated population carbon-nitrogen metabolism. Other studies found that appropriate panicle fertilizer application improved nitrogen productivity for grain and biomass, increased nitrogen absorption ratio and TNA. Our results demonstrated that split fertilization significantly increased N, P, and K uptake at maturity and improved NRE, NAE, and NPFP compared with one-off application. Excessive early nitrogen supply with high basal and tiller fertilizer proportions leads to luxury consumption, producing numerous ineffective tillers, increasing nitrogen absorption during jointing stage and by ineffective tillers, enlarging pre-jointing populations, increasing ineffective growth, weakening effective tillers, reducing spikelet numbers and sink capacity, and ultimately decreasing late-stage nitrogen absorption and yield, consistent with related studies.

3.2 Effects of Inhibitors on Rice Nitrogen Use Efficiency Nitrification inhibitor application in paddy soils maintains more nitrogen in NH -N form in surface water. As rice prefers NH -N, its presence promotes nitrogen absorption and utilization. Combined application of urease/nitrification inhibitors (hydroquinone/dicyandiamide) increases NH -N content in soil, promotes nitrogen absorption in NH -N form, simultaneously increases phosphorus uptake, and enhances crop growth. Research has shown that adding 3,4-dimethylpyrazole phosphate (DMPP) to urea increases nitrogen uptake in rice shoots and grains, improves nitrogen nutrition, and increases yield. Other studies found that 100% CP treatment significantly increased NRE by 27.3% and 78.3% in early and late rice, respectively. NBPT has been shown to slow urea hydrolysis in paddy fields, significantly reduce ammonia volatilization, increase rice yield and nitrogen uptake, and enhance soil nitrogen residue. Application of 0.75% NBPT in red soil increased double-cropping rice yield by 14.75% and improved NAE by 18.41%. Our results demonstrated that combining biochemical inhibitors with fertilization models increased post-heading dry matter and nitrogen accumulation and their proportions of total accumulation, maintaining post-heading nitrogen assimilation and absorption capacity. Under one-off application, inhibitor treatments increased NRE, NAE, and NPFP by 22.8–47.4%, 100.2–128.7%, and 20.1-25.8%, respectively, compared with U treatment. Under split application, inhibitor treatments increased NRE, NAE, and NPFP by 8.3–41.4%, 36.0–52.6%, and 10.8–15.8%, respectively, compared with U3 treatment.

Urease inhibitors slow urea hydrolysis and nitrogen loss during rice tillering stage, increase soil NH -N content at panicle initiation, and significantly increase rice yield and nitrogen use efficiency. Nitrification inhibitors reduce nitrogen loss by inhibiting NH -N transformation to NO -N, decreasing nitrous oxide emissions. Synergistic effects exist between urease and nitrification inhibitors, with combined application more effectively improving nitrogen recovery efficiency and reducing nitrogen loss in the rice rhizosphere than single applications. Research has shown that CP addition increased ^{1} N recovery efficiency by 25.0% [at 180 kg(N) · hm ^{2}] and 12.1% [at 240 kg(N) · hm ^{2}]. Compared with conventional nitrogen application [180 kg(N) · hm ^{2}], reducing nitrogen by 25% plus NBPT increased nitrogen use efficiency by 6.78% and 9.46% in early and late rice, respectively. Stabilized nitrogen fertilizer (hydroquinone + dicyandiamide) at equal nitrogen rates significantly promoted rice nitrogen absorption and accumulation compared with farmer practice, particularly under split application. Our results demonstrate that across different fertilization models, inhibitor combinations (NBPT, NPPT/+CP) significantly increased rice N, P, and K uptake, promoted dry matter production and nitrogen accumulation after heading, improved nutrient allocation to grains, and enhanced nitrogen use efficiency.

Integration of biochemical inhibitor combinations and fertilization models in yellow clayey paddy fields provides balanced nitrogen supply throughout the rice growth period, promotes rice growth, and facilitates N, P, and K absorption and utilization as well as post-heading nitrogen accumulation, thereby increasing nutrient accumulation in panicles and improving seasonal nitrogen use efficiency (NRE, NAE, and NPFP), biomass production, and yield.

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Note: Figure translations are in progress. See original paper for figures.