Effects of Planting Method and Nitrogen Application Rate on Nitrogen Utilization Characteristics and Yield of Hybrid Indica Rice (Postprint)

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Abstract

Using hybrid indica rice 'F You 498' as experimental material, a two-factor split-plot design was adopted, with main plots being three planting methods: carpet seedling mechanical transplanting (mechanical transplanting), wet precision hill-direct seeding (direct seeding), and manual transplanting, and subplots being nitrogen application rates of 0 kg·hm^{-2}, 90 kg·hm^{-2}, 135 kg·hm^{-2}, and 180 kg·hm^{-2}, to investigate nitrogen accumulation and translocation, yield and its components, and nitrogen use efficiency in hybrid indica rice under different treatments. Planting method and nitrogen application rate had significant effects and interactive effects on nitrogen accumulation, translocation, and yield during the main growth stages of rice. Total plant nitrogen accumulation at heading and maturity stages followed the order: manual transplanting > mechanical transplanting > direct seeding; nitrogen accumulation rates during sowing-jointing and heading-maturity stages followed the order: direct seeding > mechanical transplanting > manual transplanting, while during jointing-heading stage the order was: manual transplanting > mechanical transplanting > direct seeding; under different planting methods, the maximum nitrogen accumulation rate occurred during the jointing-heading stage; nitrogen agronomic efficiency and nitrogen harvest index showed the pattern: manual transplanting > mechanical transplanting > direct seeding; nitrogen requirement per 100 kg grain was: direct seeding > manual transplanting > mechanical transplanting; the yield of manual transplanted rice showed no significant difference from that of mechanically transplanted rice; compared with manual transplanted rice, direct-seeded rice showed an average yield reduction of 13.04%. Plant nitrogen accumulation and panicle nitrogen accumulation increased significantly with increasing nitrogen application rate, while the contribution rate of leaf nitrogen to the panicle decreased with increasing nitrogen application rate. Planting method and nitrogen application rate had substantial effects on nitrogen use efficiency;

nitrogen agronomic efficiency in mechanically transplanted rice increased with nitrogen application rate but the difference was not significant, while nitrogen agronomic efficiency in direct-seeded and manually transplanted rice decreased with increasing nitrogen application rate; nitrogen recovery efficiency showed a quadratic relationship with nitrogen application rate under manual transplanting and mechanical transplanting, while it gradually decreased with increasing nitrogen level under direct seeding; nitrogen grain production efficiency and harvest index both decreased with increasing nitrogen application, with no significant differences among nitrogen treatments. In summary, a nitrogen application rate of 135 $kg \cdot hm^{-2}$ for direct-seeded rice, and 135–180 $kg \cdot hm^{-2}$ for mechanical transplanting and manual transplanting, could achieve stable yield while maintaining relatively high nitrogen use efficiency.

Full Text

Effects of Planting Methods and Nitrogen Application Rates on Nitrogen Utilization Characteristics and Yield of Indica Hybrid Rice

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Abstract

In recent years, rice planting methods have undergone a remarkable transition, with mechanical transplanting and direct seeding developing rapidly. Different planting methods inevitably affect rice growth and development differently, leading to variations in nutrient accumulation and utilization of thermal and light resources. Nitrogen application remains one of the most critical field management practices in rice cultivation. A field experiment was conducted to investigate nitrogen accumulation and utilization characteristics in indica hybrid rice under different planting methods and nitrogen rates using the widely planted Sichuan Basin cultivar 'F You 498'.

The experiment employed a two-factor split-plot design. The main plot comprised three planting methods: mechanical transplanting (T1), precision hill direct seeding (T2), and manual transplanting (T3). The subplot consisted of four nitrogen fertilizer rates: 0 kg hm^{-2} (N0), 90 kg hm^{-2} (N1), 135 kg hm^{-2} (N2), and 180 kg hm^{-2} (N3). Rice nitrogen accumulation and translocation, yield and yield components, and nitrogen use efficiency were analyzed across different treatment combinations.

Results showed that planting method and nitrogen rate significantly affected nitrogen accumulation, translocation, yield, and yield components. Total nitrogen accumulation at heading and maturity stages followed the order: manual transplanting > mechanical transplanting > direct seeding. Nitrogen accumulation rate under direct seeding was significantly higher than under mechanical transplanting and manual transplanting from sowing to jointing stage and from heading to maturity stage; however, the order reversed during the jointing-to-heading stage (manual transplanting > mechanical transplanting > direct seeding). Agronomic nitrogen efficiency and nitrogen harvest index followed the same pattern as total accumulation (T3 > T1 > T2). Nitrogen requirement per 100 kg grain ranked as direct seeding > manual transplanting > mechanical transplanting. Grain yield under manual transplanting was significantly higher than under precision hill direct seeding but did not differ significantly from mechanical transplanting.

Nitrogen accumulation in both total plant and panicle increased significantly with nitrogen fertilization rate, while leaf nitrogen contribution to panicle decreased. Planting method and nitrogen application rate significantly influenced nitrogen use efficiency. Agronomic nitrogen efficiency under mechanical transplanting increased with nitrogen rate, though not significantly. Conversely, it decreased with increasing nitrogen application under direct seeding and manual transplanting. Nitrogen recovery efficiency showed a quadratic relationship with nitrogen rate under manual transplanting and mechanical transplanting, but decreased gradually under direct seeding. Both nitrogen grain production efficiency and nitrogen harvest index decreased with increasing nitrogen rate, with no significant differences among nitrogen treatments. Integrating grain yield and nitrogen use efficiency, a nitrogen fertilizer rate of 135 kg hm^{-2} for direct seeding and 135–180 kg hm^{-2} for mechanical and manual transplanting achieved stable yields with high nitrogen use efficiency.

Keywords: Rice; Precision hill direct seeding; Mechanical transplanting; Nitrogen application rate; Nitrogen accumulation and translocation; Nitrogen use efficiency

Introduction

Nitrogen is the most sensitive element affecting rice (*Oryza sativa*) yield formation, and fertilization represents a primary pathway for soil nitrogen acquisition, contributing up to 50% of grain yield. Nitrogen application rate and management profoundly influence rice growth and development. However, over the past three decades, grain yield growth has slowed markedly while excessive nitrogen application has caused a sharp decline in nitrogen use efficiency. Current nitrogen use efficiency in Chinese rice production ranges from only 30–45%, far below that of other countries. Excessive nitrogen application may cause lodging, yield reduction, increased pest and disease pressure, reduced grain quality, higher production costs, intensified greenhouse gas emissions, and water eutrophication, severely limiting sustainable rice production. Therefore, rational nitrogen management is crucial for improving nitrogen use efficiency, reconciling the conflict between nitrogen input and yield, and increasing farmer income, making it a key focus for agricultural researchers.

Measures to improve rice nitrogen use efficiency mainly include two categories: genetic improvement through genotype or cultivar selection, and adjusting cultivation practices and environmental factors such as nitrogen management, water-nitrogen coupling, and tillage patterns. Planting method constitutes an essential component of rice cultivation management. In recent years, rice planting methods have been transitioning rapidly, with mechanical transplanting and direct seeding developing extensively. Different planting methods create different growth environments, leading to variations in nutrient and resource utilization that inevitably affect rice growth and development. While previous research has extensively examined how cultivation practices affect nitrogen absorption and utilization, most studies have focused on nitrogen application rates or specific planting methods in isolation. Few have investigated the combined effects of different planting methods and nitrogen rates on nitrogen absorption characteristics or the potential interaction effects between these factors.

Therefore, this study used the mid-late maturing indica hybrid rice combination 'F You 498' , widely promoted in the Sichuan Basin, to compare plant nitrogen accumulation, translocation, and use efficiency under different planting method and nitrogen rate combinations. The objective was to clarify how planting methods and nitrogen rates affect nitrogen absorption and utilization characteristics, providing theoretical and practical foundations for high-yield rice cultivation and efficient nitrogen use.

Materials and Methods

1.1 Experimental Materials and Site Description

The field experiment was conducted from May to September 2016 at the experimental field of the Rice Research Institute, Sichuan Agricultural University, located in Wenjiang District, Chengdu City, Sichuan Province (30°44 N, 103°52 E). The test cultivar was 'F You 498' , a mid-late maturing indica hybrid rice widely cultivated in the Sichuan rice region with a growth duration of 145–152 days. The experimental soil was sandy loam with a pH of 6.61, bulk density of 1.71 g cm^{-3}, total nitrogen of 1.07 g kg^{-1}, alkaline hydrolyzable nitrogen of 118.42 mg kg^{-1}, available phosphorus of 70.78 mg kg^{-1}, and available potassium of 49.70 mg kg^{-1}. Meteorological data during the rice growth period were obtained from the Sichuan Meteorological Bureau (Fig. 1).

1.2 Experimental Design

The experiment employed a two-factor split-plot design with planting method as the main plot and nitrogen application rate as the subplot. Three planting methods were established: blanket seedling mechanical transplanting (T1), wet precision hill direct seeding (T2), and manual transplanting (T3). Four nitrogen rates were applied: 0 kg hm^{-2} (N0), 90 kg hm^{-2} (N1), 135 kg hm^{-2} (N2), and 180 kg hm^{-2} (N3). Nitrogen fertilizer was applied in a 3:3:2:2 ratio as basal, tillering, panicle initiation, and spikelet fertility fertilizers. For manual and mechanical transplanting, tillering fertilizer was applied 7 days after transplanting; for direct seeding, it was applied at the 5-leaf-1-heart stage. Panicle initiation and spikelet fertility fertilizers were applied equally at the 4th and 2nd leaf positions from the top, respectively. Phosphorus (P_2O_5) at 75 kg hm^{-2} and potassium (K_2O) at 150 kg hm^{-2} were applied as basal fertilizers.

Each treatment had three replications. Plot dimensions were 6.4 m × 3.75 m (24 m^2). Plots were separated by ridges (40 cm wide, 30 cm high) wrapped with plastic film to prevent water and fertilizer movement between plots. Water management followed alternate wetting and drying irrigation with "sufficient seedlings sun-drying" in the middle stage, while other field management followed local high-yield rice cultivation practices.

For mechanical transplanting (T1), seedlings were raised in plastic soft trays on April 15 with 70 g dry seed per tray and transplanted on May 23 using a Toyo PF455S four-row transplanter. Seedlings were 38 days old with 4.5–5.5 leaves and no tillers, planted at 30 cm × 16 cm spacing. For precision hill direct seeding (T2), pre-germinated seeds were sown on May 23 at 33 cm × 16.5 cm spacing with a seeding rate of 22.5 kg hm^{-2}. For manual transplanting (T3), seeds were sown on April 15, raised through dry nursery, and transplanted on May 23 with 38-day-old seedlings at 4.5–5.5 leaf stage and no tillers, at 33 cm × 16.5 cm spacing. Mechanical and manual transplanting were harvested on September 12, while precision wet hill direct seeding was harvested on September 25. Main growth stages are shown in Table 1.

1.3 Measurement Items and Methods

1.3.1 Dry Matter Accumulation At jointing, heading, and maturity stages, three representative plants with uniform growth were selected from each plot and separated into stems, leaves, and panicles (at heading and maturity). Samples were killed at 105 °C for 30 minutes, then dried at 80 °C to constant weight and weighed.

1.3.2 Nitrogen Accumulation The dried and weighed stem, leaf, and panicle samples from Section 1.3.1 were ground and passed through a 0.2 mm sieve. Nitrogen content was determined using the concentrated H_2SO_4-H_2O_2 digestion method with a FOSS-8400 Kjeldahl nitrogen analyzer.

1.3.3 Yield Components and Grain Yield Before harvest, effective panicle number was investigated in each plot. Five representative plants (sampled according to average tiller number) were taken from each plot for yield component analysis, measuring 1000-grain weight, filled grains per panicle, and unfilled grains to calculate seed setting rate. For yield measurement, border rows were removed and yield was calculated based on actual harvested plants.

1.4 Data Calculations

The following formulas were used:

Organ nitrogen accumulation (kg hm^{-2}) = organ dry matter accumulation × nitrogen content (1)

Total nitrogen accumulation (kg hm^{-2}) = Σ organ nitrogen accumulation (2)

Nitrogen uptake rate (kg hm^{-2} d^{-1}) = (N_2 - N_1)/(t_2 - t_1) (3)

Stem (leaf) nitrogen translocation amount (kg hm^{-2}) = N accumulation in stem (leaf) at heading - N accumulation in stem (leaf) at maturity (4)

Stem (leaf) nitrogen translocation rate (%) = [Stem (leaf) nitrogen translocation amount / N accumulation in stem (leaf) at heading] × 100 (5)

Stem (leaf) contribution rate (%) = [Stem (leaf) nitrogen translocation amount / Panicle N accumulation at maturity] × 100 (6)

Panicle nitrogen increment (kg hm^{-2}) = N accumulation in panicle at maturity - N accumulation in panicle at heading (7)

Nitrogen harvest index (%) = [N accumulation in grain at maturity / Total N accumulation in plant at maturity] × 100 (8)

Nitrogen grain production efficiency (kg kg^{-1}) = Grain yield / N accumulation in plant at maturity (9)

Agronomic nitrogen use efficiency (kg kg^{-1}) = (Grain yield in N-applied plot - Grain yield in N0 plot) / N application rate (10)

Nitrogen recovery efficiency (%) = [(N accumulation in plant in N-applied plot - N accumulation in plant in N0 plot) / N application rate] × 100 (11)

Nitrogen requirement for 100 kg grain [kg · $(100kg)^{-1}$] = (N accumulation in plant at maturity / Grain yield) × 100 (12)

1.5 Data Processing and Analysis

Data were processed using Microsoft Excel 2007. Analysis of variance was performed using DPS v.7.05, and figures were prepared using Origin 9.0. Significance was tested using the least significant difference (LSD) method at $\alpha = 0.05$.

Results

2.1 Effects of Planting Method and Nitrogen Rate on Nitrogen Accumulation in Organs at Main Growth Stages

As shown in Table 2, planting method significantly or highly significantly affected nitrogen accumulation in stems, leaves, panicles, and whole plants at heading, as well as panicle nitrogen accumulation at maturity. Nitrogen rate highly significantly affected nitrogen accumulation in stems, leaves, panicles, and whole plants at both stages. The interaction between planting method and nitrogen rate significantly or highly significantly affected nitrogen accumulation in stems, leaves, and whole plants at heading.

Across planting methods, plant nitrogen accumulation at heading and maturity followed the order: manual transplanting > mechanical transplanting > direct seeding. Compared with manual transplanting, mechanical transplanting and direct seeding reduced plant nitrogen accumulation by 2.30% and 6.73% at heading, and 2.39% and 4.22% at maturity, respectively, demonstrating the advantage of manual transplanting for nitrogen accumulation.

Under different nitrogen rates, organ nitrogen accumulation at all growth stages increased with nitrogen application, with significant differences in plant nitrogen accumulation. Stem and leaf nitrogen content at heading increased with nitrogen rate under all planting methods, with significant differences among nitrogen levels for mechanical transplanting, but no significant differences between N2 and N3 for manual transplanting and direct seeding. This indicates that mechanical transplanting can more effectively absorb and accumulate nitrogen at high nitrogen levels during late growth stages.

2.2 Effects of Planting Method and Nitrogen Rate on Stage-Based Nitrogen Accumulation and Uptake Rate

Planting method significantly or highly significantly affected the proportion of pre-jointing nitrogen accumulation to total accumulation and nitrogen uptake rate. Nitrogen rate significantly or highly significantly affected nitrogen accumulation and uptake rate at different growth stages. The interaction between planting method and nitrogen rate highly significantly affected nitrogen accumulation and its proportion to total accumulation, as well as nitrogen uptake rate during the jointing-to-heading stage (Table 3).

Throughout the rice growth period, stage-based nitrogen accumulation, uptake rate, and their proportions to total accumulation were highest during the jointing-to-heading stage. Across planting methods, pre-jointing nitrogen uptake rate ranked as direct seeding > mechanical transplanting > manual transplanting, while the order reversed during jointing-to-heading. Post-heading nitrogen accumulation, its proportion, and uptake rate were higher under direct seeding than under mechanical transplanting and manual transplanting.

Regarding nitrogen rates, the proportions of pre-jointing and jointing-to-heading nitrogen accumulation to total accumulation increased with nitrogen level, though differences were not significant between medium and high nitrogen treatments. Nitrogen uptake rate during heading-to-maturity was highest under N1 treatment.

2.3 Effects of Planting Method and Nitrogen Rate on Nitrogen Absorption and Translocation from Heading to Maturity

Table 4 shows that planting method and nitrogen rate significantly or highly significantly affected translocation rate and amount, contribution rate, and panicle nitrogen increment in stems and leaves, with significant interactions between planting method and nitrogen rate for leaf nitrogen translocation amount and stem nitrogen translocation rate. From heading to maturity, leaf nitrogen translocation amount, rate, and contribution rate were markedly higher than those of stems.

Across planting methods, manual transplanting showed significantly higher stem nitrogen translocation amount, translocation rate, contribution rate, and panicle nitrogen accumulation than mechanical transplanting and direct seeding. In contrast, leaf nitrogen translocation amount, rate, and contribution rate were significantly higher under mechanical transplanting than under manual transplanting and direct seeding. Mechanical transplanting thus maintained stem nitrogen accumulation while enhancing leaf nitrogen content, improving leaf nitrogen translocation to fill panicle nitrogen accumulation and achieve high yield. This suggests that manual transplanting enhanced stem nitrogen translocation to the panicle after heading, mechanical transplanting increased leaf nitrogen translocation, while direct seeding showed lower translocation from both stems and leaves.

Regarding nitrogen rates, stem nitrogen translocation amount, rate, and contribution rate increased with nitrogen application under mechanical transplanting and direct seeding, while manual transplanting showed a trend of first increasing then decreasing (N2 > N3 > N1 > N0). Leaf nitrogen accumulation and translocation increased with nitrogen rate at low to medium levels but decreased at high nitrogen levels, indicating excessive nitrogen reduces leaf nitrogen translocation amount and rate. Leaf contribution rate decreased with increasing nitrogen rate. Panicle nitrogen increment increased with nitrogen application, with N3 showing 10.62–59.89% higher values than other nitrogen levels under mechanical transplanting, 11.53–94.19% higher under direct seeding, and 8.56–41.01% higher under manual transplanting.

2.4 Effects of Planting Method and Nitrogen Rate on Nitrogen Production and Use Efficiency

Table 5 shows that planting method and nitrogen rate significantly or highly significantly affected nitrogen grain production efficiency and nitrogen harvest index, with significant interaction effects on nitrogen harvest index. Across planting methods, agronomic nitrogen efficiency and nitrogen harvest index were highest under manual transplanting, being 15.62% and 0.32% higher than mechanical transplanting, and 64.90% and 6.51% higher than direct seeding, respectively. Direct seeding showed 8.64% and 27.36% higher nitrogen recovery efficiency than mechanical transplanting and manual transplanting, respectively. However, direct seeding' s high recovery efficiency did not translate to high agronomic efficiency or harvest index, possibly due to more ineffective tillers and lower panicle formation rate, causing nitrogen to remain in leaves and stems rather than translocating to panicles. Mechanical transplanting showed 11.35% and 2.61% higher nitrogen grain production efficiency than direct seeding and manual transplanting, respectively.

Regarding nitrogen rates, agronomic nitrogen efficiency under mechanical transplanting increased with nitrogen rate, though not significantly. Under direct seeding and manual transplanting, it was highest under N1. Nitrogen recovery efficiency showed a quadratic relationship with nitrogen rate under manual transplanting and mechanical transplanting, but decreased gradually under direct seeding. Nitrogen grain production efficiency and nitrogen harvest index decreased with nitrogen rate across planting methods, with no significant differences among nitrogen treatments. These results indicate that increasing nitrogen does not necessarily reduce nitrogen use efficiency significantly; reduction occurs only when increased nitrogen fails to enhance nitrogen accumulation and decreases the proportion allocated to grain.

2.5 Effects of Planting Method and Nitrogen Rate on Grain Yield and Yield Components

Except for the non-significant effect of planting method on 1000-grain weight, planting method and nitrogen rate significantly or highly significantly affected yield and yield components, with significant interaction effects on spikelets per panicle and seed setting rate (Table 6). Grain yield ranked as manual transplanting > mechanical transplanting > direct seeding, with T1 and T2 yielding 1.08% and 13.04% less than T3, respectively. Yield component analysis revealed that effective panicles were significantly higher under T1 and T2 than T3, while spikelets per panicle and seed setting rate showed the opposite trend. Direct seeding had significantly lower seed setting rate than mechanical transplanting and manual transplanting, while 1000-grain weight did not differ significantly among planting methods.

Increasing nitrogen rate improved yield, but the increase was not significant at high nitrogen levels (N3). Under T1, N1, N2, and N3 increased yield by 7.16–15.90% compared with N0; under T2, the increase was 7.17–11.16%; and under T3, 9.45–15.39%. Effective panicles increased gradually with nitrogen rate, while spikelets per panicle showed varying responses. The 1000-grain weight and seed setting rate were higher under N0 than under other nitrogen treatments, which did not differ significantly among themselves.

Planting method and nitrogen rate significantly or highly significantly affected nitrogen requirement per 100 kg grain for hybrid rice 'F You 498' . Direct seeding required 10.00% and 11.59% more nitrogen per 100 kg grain than manual transplanting and mechanical transplanting, respectively. Increasing nitrogen application raised grain nitrogen content, though differences were not significant between medium and high nitrogen treatments.

Discussion

3.1 Effects of Planting Method and Nitrogen Rate on Rice Nitrogen Absorption and Translocation

Nitrogen is crucial for rice growth, development, and yield formation, with distinct characteristics under different planting methods. Previous studies have reported inconsistent results regarding nitrogen accumulation under different planting methods. Xu et al. found that direct seeding had lower nitrogen accumulation than transplanting at tillering and panicle initiation stages, similar accumulation at heading, and higher accumulation at maturity. In contrast, Huo et al. reported that plant nitrogen accumulation at heading and maturity followed the order: manual transplanting > mechanical transplanting > direct seeding. Our results showed that at jointing stage, nitrogen accumulation ranked as mechanical transplanting > manual transplanting > direct seeding, while at heading and maturity, the order was manual transplanting > mechanical transplanting > direct seeding.

These differences may arise because direct-seeded rice has small seedlings with underdeveloped root systems after basal and tillering fertilizer application, limiting nitrogen absorption capacity while urea volatilizes and leaches from the soil, reducing nitrogen available for morphological construction during vegetative growth. After heading, direct-seeded rice exhibits inferior individual quality, smaller stems, lower panicle formation rate, and poor photosynthetic efficiency, resulting in lower stage-specific uptake rates and ultimately lower total plant nitrogen accumulation compared with manual and mechanical transplanting. Manual transplanting maintained higher plant nitrogen accumulation at heading and maturity, likely because its root activity declined more slowly after heading, facilitating continued nitrogen absorption and accumulation. The interaction between manual transplanting and nitrogen rate may also effectively regulate nitrogen distribution among organs.

Consistent with previous research, plant nitrogen accumulation increased with nitrogen application rate across planting methods. At maturity, panicle nitrogen accumulation depends primarily on translocation from stems and leaves. Huo et al. noted that maintaining stem nitrogen accumulation while increasing leaf nitrogen accumulation to enhance panicle nitrogen accumulation is beneficial for high yield. Our study found that from heading to maturity, manual transplanting showed higher stem nitrogen translocation amount, rate, contribution rate, and panicle nitrogen accumulation than mechanical transplanting and direct seeding. However, mechanical transplanting exhibited significantly higher leaf nitrogen translocation amount, rate, and contribution rate than the other methods. By maintaining stem nitrogen accumulation while increasing leaf nitrogen content and translocation, mechanical transplanting enhanced panicle nitrogen accumulation and achieved high yield.

3.2 Effects of Planting Method and Nitrogen Rate on Rice Nitrogen Use Efficiency

Many factors affect nitrogen use efficiency, including fertilizer type, application rate, soil background nitrogen, and field management. Liu et al. found that nitrogen grain production efficiency and nitrogen harvest index ranked as mechanical transplanting > conventional hand transplanting > mechanical precision hill direct seeding. Our results showed that agronomic nitrogen efficiency and nitrogen harvest index were highest under manual transplanting, being 15.62% and 0.32% higher than mechanical transplanting, and 64.90% and 6.51% higher than direct seeding, respectively. Direct seeding showed 8.64% and 27.36% higher nitrogen recovery efficiency than mechanical transplanting and manual transplanting, respectively. However, its high recovery efficiency did not translate to high agronomic efficiency or harvest index, likely due to more ineffective tillers, lower panicle formation rate, and nitrogen retention in leaves and stems rather than translocation to panicles.

Numerous studies have shown that increasing nitrogen rate decreases nitrogen agronomic efficiency and nitrogen harvest index. Our results revealed inconsistent relationships between nitrogen rate and use efficiency across planting methods. Agronomic nitrogen efficiency under mechanical transplanting increased with nitrogen rate, though not significantly, while it decreased with nitrogen application under direct seeding and manual transplanting. Nitrogen recovery efficiency showed a quadratic relationship with nitrogen rate under manual transplanting and mechanical transplanting, but decreased gradually under direct seeding. Nitrogen grain production efficiency and nitrogen harvest index decreased with nitrogen rate across planting methods, with no significant differences among nitrogen treatments. These findings indicate that increasing nitrogen does not necessarily reduce nitrogen use efficiency; reduction occurs only when increased nitrogen fails to enhance nitrogen accumulation and decreases the proportion allocated to grain. While nitrogen harvest index decreased with nitrogen rate under mechanical and manual transplanting, it increased slightly under direct seeding. Therefore, selecting appropriate nitrogen rates and management strategies for different planting methods provides an effective approach to improving nitrogen use efficiency.

3.3 Effects of Planting Method and Nitrogen Rate on Rice Grain Yield and Components

Numerous studies have shown that manual transplanting produces higher grain yield than mechanical transplanting. Yang et al. and Guo attributed this to lower spikelets per panicle and insufficient total spikelet number under mechanical transplanting, with no significant differences in seed setting rate or 1000-grain weight. Huang et al. suggested that direct seeding increases yield through higher effective panicle numbers. Our results showed that 'F You 498' achieved highest yield under manual transplanting, followed by mechanical transplanting with minimal difference, and lowest under direct seeding (13.04% reduction compared with manual transplanting). Lower seed setting rate limited direct seeding yield, possibly due to lower temperatures and insufficient light during late growth stages, combined with significantly higher effective panicles creating a larger sink but insufficient source capacity. Mechanical transplanting had significantly higher effective panicles but lower spikelets per panicle than manual transplanting, with no significant difference in seed setting rate, consistent with previous research.

The relationship between nitrogen rate and yield components also varied by planting method. Spikelets per panicle under mechanical and manual transplanting increased then decreased with nitrogen rate, while they increased continuously under direct seeding. Mechanical and manual transplanting showed higher spikelets per panicle at low to medium nitrogen levels, but reductions at high nitrogen levels, with yield increases driven primarily by effective panicle number. The 1000-grain weight and seed setting rate were higher under N0 than under other nitrogen treatments, which did not differ significantly among themselves.

Conclusion

Nitrogen absorption, translocation, and efficiency in indica hybrid rice are affected by planting method, nitrogen rate, and their interaction. The interaction between manual transplanting and nitrogen rate enhanced plant nitrogen accumulation at heading and maturity, particularly panicle nitrogen accumulation at maturity. Direct-seeded rice showed rapid growth and significantly higher nitrogen uptake rate during the sowing-to-jointing stage than mechanical and manual transplanting. Nitrogen requirement per 100 kg grain ranked as direct seeding > manual transplanting > mechanical transplanting. Planting method and nitrogen rate differentially affected nitrogen use efficiency: agronomic nitrogen efficiency under mechanical transplanting increased with nitrogen rate, while it decreased under direct seeding and manual transplanting; nitrogen recovery efficiency showed a quadratic relationship with nitrogen rate under manual transplanting and mechanical transplanting, but decreased gradually under direct seeding. Under our experimental conditions, the optimal nitrogen rate was 135 kg hm^{-2} for direct seeding and 135–180 kg hm^{-2} for mechanical and manual transplanting.

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