Effects of Nitrogen Fertilizer Management and Planting Pattern on Grain Filling and Yield of Hybrid Indica Rice (Postprint)

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Abstract

Using indica hybrid rice 'II You 498' as material, the effects of nitrogen fertilizer management strategies [with basal-tiller fertilizer to panicle fertilizer ratios of 9:1 (N1), 7:3 (N2), and 5:5 (N3)] and planting methods [wide-narrow row planting (C1), triangular planting (C2), expanded-row reduced-planting-density cultivation (C3), and broadcast seedling cultivation (C4)] on rice sink capacity, grain filling and plumpness, and yield were studied in Hanyuan and Wenjiang of Sichuan Province, where light and temperature conditions differ significantly, to clarify the relationships among light-temperature characteristics, nutrient regulation, and planting methods with rice grain filling and yield formation. The results showed that: 1) In Hanyuan with superior light and temperature conditions, rice grain sink capacity, plumpness degree, seed-setting rate, and 1000-grain weight were all better than those in Wenjiang, with lower initial growth potential of grains, delayed date to reach the filling peak, higher filling intensity in the early and middle stages, longer duration, larger proportion of growth amount, and longer active grain-filling period, making it easier to obtain high yield; 2) With the increase in the degree of postponed nitrogen fertilizer application, the maximum sink capacity of rice showed a decreasing trend, but the grain filling rate, plumpness index, effective sink plumpness degree, seed-setting rate, and 1000-grain weight all showed increasing trends, with reduced initial growth potential of grains, increased maximum grain-filling rate (Gmax) and average grain-filling rate (Gmean), delayed date to reach the filling peak, increased proportion of growth amount, and shortened grain-filling duration, with the moderate postponement of nitrogen fertilizer (N2) treatment yielding higher overall; 3) Different planting methods showed smaller differences in seed-setting rate and 1000-grain weight, but larger differences in biological yield, maximum sink capacity, grain-filling characteristic parameters, and plumpness indicators; each planting method exhibited similar grain-filling characteristics when achieving high yield, namely larger sink capacity, lower initial growth potential of grains, delayed date to reach the filling peak, larger proportion of growth amount, and higher Gmax and Gmean; wide-narrow row planting, triangular planting, expanded-row reduced-planting-density cultivation, and broadcast seedling cultivation achieved high yield under N1, N1, N2, and N3 conditions respectively, with triangular planting showing the optimal yield; 4) Correlation analysis indicated that as the maximum sink capacity increased, the initial growth potential of grains decreased, the filling peak period was delayed, the duration and intensity of grain filling in the early and middle stages increased, the proportion of growth amount at the filling peak period also increased, and high yield was more easily obtained when the filling intensity in the early and middle stages and the contribution rate to grain filling in the early stage showed significant advantages. Therefore, to improve rice yield, corresponding nitrogen fertilizer management measures should be adopted according to local ecological conditions and targeted at different planting methods.

Full Text

Effect of Nitrogen Management and Cultivation Method on Grain-Filling Characteristics and Grain Yield of Indica Hybrid Rice

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Abstract: Using indica hybrid rice 'II-you-498' as material, this study investigated the effects of nitrogen management [ratios of basal-tiller to panicle fertilizer were 9:1 (N1), 7:3 (N2) and 5:5 (N3)] and cultivation method [wide-narrow row cultivation (C1), triangular cultivation (C2), wide-row narrow-spacing cultivation (C3), and seedling-throwing cultivation (C4)] on sink capacity, grain-filling characteristics, and grain yield at two locations with significantly different light and temperature conditions (Hanyuan and Wenjiang in Sichuan Province). The objective was to clarify the relationships among ecological characteristics, nutrient regulation, cultivation method, and grain-filling and yield formation in rice. The results showed that: (1) In Hanyuan with superior light and temperature conditions, grain sink capacity, plumpness, seed setting rate, and 1000-grain weight were all superior to those in Wenjiang. The initial growth vigor was lower, the date to reach peak grain-filling rate was delayed, the grain-filling intensity in early and middle stages was higher with longer duration and greater growth proportion, and the active grain-filling period was longer, making high yield more achievable. (2) With increasing nitrogen application at later stages, maximum sink capacity decreased while grain plumpness, plumpness index, effective filling rate of sink, seed setting rate, and 1000-grain weight increased. The initial growth vigor decreased, while maximum and mean grain-filling rates (Gmax and Gmean) increased. The time to reach peak grain-filling was delayed with increased growth proportion, while the grain-filling duration shortened. Overall, moderate nitrogen postponement (N2) produced higher yields. (3) Different cultivation methods showed small differences in seed setting rate and 1000-grain weight but large differences in biomass yield, maximum sink capacity, grain-filling parameters, and filling indexes. High-yielding cultivation methods shared similar grain-filling characteristics: larger sink capacity, lower initial growth vigor, delayed time to peak grain-filling with larger growth proportion, and higher Gmax and Gmean. Wide-narrow row, triangular, wide-row narrow-spacing, and seedling-throwing cultivation achieved highest yields under N1, N1, N2, and N3 conditions respectively, with triangular cultivation producing the optimal yield. (4) Correlation analysis indicated that with increasing maximum sink capacity, initial growth vigor decreased and peak grain-filling period was delayed. The duration and intensity of grain-filling in early and middle stages increased, as did the growth proportion at peak grain-filling. High yields were more readily achieved when early and middle stage grain-filling intensity and early-stage contribution rate were significantly superior. Therefore, improving rice yield should integrate local ecological conditions with appropriate nitrogen management tailored to specific cultivation methods.

Keywords: Rice; Ecological condition; Nitrogen management; Cultivation method; Grain-filling characteristics; Sink capacity; Grain yield

Introduction

As global extreme climate events increase and natural resources decrease and become unevenly distributed, food security faces severe challenges. Developing rice (*Oryza sativa*) production and increasing grain yield are crucial for ensuring food security and maintaining social stability. Large panicles with numerous grains provide the necessary sink capacity advantage and high biological yield for rice production, while grain-filling degree constrains the expression of sink capacity and yield potential. Breeders have developed tall, large-panicle varieties through genetic improvement, giving rice the inherent advantages of sufficient "source" and large "sink." However, due to differences in ecological conditions, cultivation methods, and fertilizer management, stable high yields remain difficult to achieve through variety improvement alone. Research shows that suitable temperature and light conditions, rational water and fertilizer management, and locally-adapted cultivation methods can promote grain-filling, optimize yield component formation, and thereby increase production. Thus, ensuring smooth "flow" is also essential for high rice yield on the basis of sufficient "source" and large "sink." Previous studies have extensively investigated grain-filling from perspectives of nitrogen regulation, water-nitrogen coupling, and temperature-light management, but reports on the effects of different nitrogen management and cultivation methods on rice grain-filling under specific ecological conditions are scarce.

Sichuan Province has unique topographical conditions, with wide-narrow row cultivation, triangular cultivation, wide-row narrow-spacing cultivation, and seedling-throwing cultivation coexisting as long-standing rice cultivation practices. Nitrogen management also significantly affects rice yield in this region. This experiment was conducted at two locations with markedly different light and temperature conditions—Wenjiang and Hanyuan—under a locally high nitrogen application rate (180 kg · hm ^{2}) to investigate the effects of nitrogen management and cultivation method on rice grain-filling characteristics and yield. The study aimed to clarify the differential effects of light-temperature characteristics, nutrient regulation, and cultivation method on rice grain-filling and yield formation under different ecological conditions, explore the causes of these differences, and propose optimal nitrogen management and cultivation methods to provide theoretical and practical foundations for achieving high-yield, high-efficiency rice cultivation.

Materials and Methods

1.1 Experimental Design

The experiment was conducted in 2010 at two locations with significantly different light and temperature conditions: the experimental field of the Rice Research Institute of Sichuan Agricultural University in Wenjiang District, Chengdu City, Sichuan Province (103.87°E, 30.71°N) and at Dazhuang Village, Jiuxiang Town, Hanyuan County, Sichuan Province (102.63°E, 29.47°N). The test variety was the hybrid rice 'II-you 498.' The previous crop at both locations was garlic (*Allium sativum*), and the soil type was sandy loam. Basic soil nutrient contents and meteorological data during the rice growth period at both locations are shown in Table 1 .

A two-factor split-plot design was adopted at both locations, with nitrogen management as the main plot and cultivation method as the sub-plot. Nitrogen management treatments were established at a nitrogen rate of 180 kg · hm ^{2} with basal-tiller to panicle fertilizer ratios of 9:1 (N1), 7:3 (N2), and 5:5 (N3). Cultivation methods included: wide-narrow row cultivation [C1, planting pattern: (40+26.7) cm × 16.7 cm], triangular cultivation (C2, planting pattern: 40 cm × 40 cm with three plants per hill arranged triangularly at 10 cm spacing), wide-row narrow-spacing cultivation (C3, planting pattern: 33.3 cm × 16.7 cm), and seedling-throwing cultivation (C4, 1.8×10 plants · hm ^{2}). All four treatments had essentially the same plant density (1.8×10 plants · hm ^{2}). Each plot area was 15.0 m^{2}, with 30 cm wide ridges covered with plastic film between plots to prevent water and fertilizer movement. The experiment had three replications.

1.2 Field Management

Nitrogen (N), phosphorus (P O), and potassium (K O) application rates were 180 kg · hm ^{2}, 90 kg · hm ^{2}, and 180 kg · hm ^{2}, respectively. Phosphorus fertilizer was applied entirely as basal fertilizer, potassium fertilizer was applied at a basal to panicle ratio of 2:1, and nitrogen fertilizer was applied according to experimental design. Basal and tiller fertilizers were applied one day before transplanting and seven days after transplanting, respectively, while panicle fertilizer was applied 15 days after jointing. Dry nursery seedlings were raised on April 2 and March 25, and transplanting dates were May 11 and May 9 at Wenjiang and Hanyuan, respectively. Harvest dates were September 7 and September 16, respectively. Water management: For C1, C3, and C4, a 2–3 cm water layer was maintained from transplanting to ineffective tillering stage before sun-drying, then a 3 cm water layer was restored during panicle differentiation. For C2, a cycle of "1 cm water layer—natural drying—1 cm water layer" was repeated from transplanting until late tillering stage, followed by sun-drying, then a 1-2 cm water layer was maintained to heading stage. After heading, all treatments adopted alternate wetting and drying irrigation until drainage seven days before maturity. Water consumption was essentially the same across the four cultivation methods. Other field management practices were consistent across treatments.

1.3 Measurements

1.3.1 Grain-Filling Dynamics At initial heading stage, rice plants with consistent growth were selected and tagged. Every 3-6 days after flowering, eight panicles were randomly sampled from each plot, and 200-300 grains from the middle portion of panicles were randomly taken. After deactivation and drying, unfertilized empty grains were removed, and the remaining grains were hulled and weighed, recorded as W.

1.3.2 Yield Components and Grain Yield At maturity, 30 hills were randomly surveyed in each plot to calculate effective panicle number per unit area. Avoiding previous sampling points, five robust and uniformly growing rice plants were taken from each treatment according to average effective panicle number. After root removal, plants were deactivated at 105°C for 1 hour and dried to constant weight at 75°C to calculate aboveground dry matter accumulation. Another five uniformly growing plants were taken to investigate grains per panicle, 1000-grain weight, and seed setting rate. After removing border rows, the entire plot was harvested and sun-dried, and yield was calculated based on actual harvested plant number.

1.3.3 Grain Plumpness Analysis Based on the method of Liu et al. [12], filled grains from section 1.3.2 were graded using saline solution with specific gravity of 1.1 g · mL ^{1} into plump grains (specific gravity > 1.1) and partially plump grains (specific gravity < 1.1). Fertilized grains were counted as total filled grains. After grading and drying, 1000-grain weight of plump grains was measured, and plumpness rate and plumpness index were calculated based on the measured 1000-grain weight of filled grains from section 1.3.2.

1.4 Parameter Calculations

The Richards equation was used to analyze grain-filling processes following the method of Zhu et al. [13]:

$$W = \frac{A}{(1 + Be^{-Kt})^{1/N}} \quad (1)$$

where W represents the average grain weight after drying at each sampling time (dependent variable), t represents days from flowering (independent variable), and A, B, K, and N are parameters. Parameter A indicates the predicted maximum growth capacity, B is the initial value parameter, K is the growth rate parameter, and N is the shape parameter. The coefficient of determination (R^2) was used to test goodness of fit.

Taking the first derivative of equation (1) gives grain growth per unit time, recorded as growth rate G:

$$G = \frac{AKBe^{-Kt}}{N(1 + Be^{-Kt})^{(N+1)/N}} \quad \text{or} \quad G = \frac{KW}{N}\left[1 - \left(\frac{W}{A}\right)^{N}\right] \quad (2)$$

Taking the second derivative of equation (1) gives the rate of change of growth rate (G) over time (t):

$$\frac{G}{t} = \frac{(AK^2Be^{-Kt})(Be^{-Kt} - N)}{N^2(1 + Be^{-Kt})^{(2N+1)/N}} \quad (3)$$

Grain-filling characteristic indexes included: initial growth vigor (R), maximum grain-filling rate (Gmax) and time to reach Gmax (tmax·G). Substituting tmax·G into equations (2) and (1) yielded Gmax and growth capacity at that time (Wmax · G). I represents the percentage of Wmax · G to final growth capacity (A), Gmean is the mean grain-filling rate throughout the process, and D is the active grain-filling period.

Two time inflection points were obtained from the G/t equation, recorded as t and t , representing two distinct moments when the grain weight curve changed significantly during grain-filling. The day when final grain weight reached 99% was recorded as effective grain-filling period (t). These three points marked the end of early, middle, and late grain-filling stages. T , T , and T represented grain-filling duration in early, middle, and late stages, while W , W , and W represented grain weights at t , t , and t . Corresponding mean grain-filling rates in early, middle, and late stages (MGR , MGR , MGR) were calculated as:

$$MGR_1 = \frac{W_1}{T_1} \quad (4)$$

$$MGR_2 = \frac{W_2 - W_1}{T_2 - T_1} \quad (5)$$

$$MGR_3 = \frac{W_3 - W_2}{T_3 - T_2} \quad (6)$$

Following the method of Yang et al. [14], the contribution rates of grain-filling matter to total grain-filling matter in early, middle, and late stages (RGC , RGC , RGC) were calculated as:

$$RGC_1 = \frac{W_1}{A} \times 100\% \quad (11)$$

$$RGC_2 = \frac{W_2 - W_1}{A} \times 100\% \quad (12)$$

$$RGC_3 = \frac{W_3 - W_2}{A} \times 100\% \quad (13)$$

Formulas for calculating grain sink capacity and filling indexes were:

$$\text{Sink capacity (t} \cdot \text{hm }^{2}) = \text{panicles per unit area (hm }^{2}) \times \text{grains per panicle} \times \text{1000-grain weight of plump grain}$$

$$\text{Plumpness rate (\%)} = \frac{\text{1000-grain weight of fertilized grains (g)}}{\text{1000-grain weight of plump grains (g)}} \times 100\% \quad (15)$$

$$\text{Effective filling rate of sink (\%)} = \frac{\text{grain yield (t} \cdot \text{hm }^{2})}{\text{sink capacity (t} \cdot \text{hm }^{2})} \quad (16)$$

$$\text{Plumpness index (\%)} = \text{seed setting rate} \times \text{plumpness rate} \quad (17)$$

1.5 Data Analysis

Microsoft Excel 2007 and DPS 6.55 software were used for data analysis and table preparation. Least significant difference (LSD) test was used to examine significant differences among treatments.

Results

2.1 Effects of Nitrogen Management and Cultivation Method on Rice Yield at Two Locations

Rice grain yield, seed setting rate, 1000-grain weight, and biomass yield at Hanyuan were higher than those at Wenjiang (Table 2). Regarding nitrogen management, seed setting rate and 1000-grain weight at both locations increased with increasing panicle fertilizer ratio, while biomass and grain yield showed different responses. Overall, N2 treatment was more favorable for increasing rice grain yield and biomass yield. Cultivation method had minor effects on seed setting rate and 1000-grain weight at both locations but showed differential effects on grain yield and biomass yield depending on panicle fertilizer ratio. Under N1 condition, C1 and C2 treatments had the highest yield and biomass, with C2 significantly higher than C3 and C4. Under N2 condition, grain yield among cultivation methods showed C3 > C4 > C2 > C1, while biomass yield showed C4 > C3 > C2 > C1, with C3 significantly higher than C1. Under N3 condition, cultivation methods showed different trends between locations for grain yield, but both showed higher grain yield and biomass under C4. These results indicate that regardless of cultivation method, optimal nitrogen ratio combinations are required to achieve yield advantages.

2.2 Effects of Nitrogen Management and Cultivation Method on Rice Grain Sink Capacity and Filling Indexes

Grain sink capacity, plumpness rate, plumpness index, and effective filling rate of sink at Hanyuan were 2.06 t · hm ², 0.03, 5.29%, and 7.93% higher than Wenjiang, respectively (Table 3). Nitrogen management also significantly affected these indexes. With increasing nitrogen postponement, sink capacity decreased while plumpness rate, plumpness index, and effective filling rate of sink increased. At Hanyuan, plumpness rates exceeded 0.98. Additionally, different cultivation methods showed varying performances in sink capacity and filling indexes under different nitrogen managements. Under N1, location differences were significant: at Wenjiang, C1 and C2 significantly exceeded C3 and C4 in all indexes; at Hanyuan, all indexes except plumpness rate were particularly prominent under C2. Under N2 and N3 conditions, C3 and C4 showed significant sink capacity advantages, respectively, with smaller differences in filling indexes. These results demonstrate that nitrogen management substantially affected sink capacity across cultivation methods.

2.3 Effects of Nitrogen Management and Cultivation Method on Rice Grain-Filling Characteristics

Grain-filling characteristics of all treatments were fitted using the Richards equation, with determination coefficients (R^2) exceeding 0.975, indicating high feasibility of this equation for describing grain-filling (Table 4). Ecological conditions differentially affected parameters: initial growth vigor (R) and maximum grain-filling rate (Gmax) at Hanyuan were generally lower than Wenjiang, time to peak grain-filling (tmax · G) was delayed, growth proportion at Gmax (I) increased, active grain-filling period (D) was longer, and maximum grain growth capacity (A) was higher at Hanyuan. These results indicate that improved light-temperature conditions and increased sink capacity reduced initial growth vigor, delayed peak grain-filling, increased duration and intensity of early and middle grain-filling stages, and extended the active grain-filling period, ultimately providing more assimilates per grain.

With increasing nitrogen postponement, general trends in parameters were: R decreased; I, Gmax, and Gmean increased; tmax · G was delayed; D shortened; and A increased. Under different cultivation methods, parameter changes corresponding to different nitrogen managements showed similarities: C2, C3, and C4 treatments under N1, N2, and N3 conditions, respectively, had the lowest R , latest tmax · G, largest I, and higher Gmax and Gmean.

As shown in Table 5 , Hanyuan had longer grain-filling duration and higher mean grain-filling rate (MGR) than Wenjiang at all stages, with larger differences in middle and late stages for duration and in early stage for MGR. Grain-filling contribution rate (RGC) at Hanyuan was higher than Wenjiang in early stage, similar in middle stage, and lower in late stage.

Regarding nitrogen management, with increasing panicle fertilizer ratio, MGR showed decreasing trends in early stage, while in middle and late stages it first increased then decreased at Wenjiang and increased at Hanyuan, but differences were small. Grain-filling duration showed increasing trends in early stage and decreasing trends in middle, late, and total stages. RGC changes were consistent with duration trends, with the highest contribution rate in middle stage (all exceeding 59%). These results indicate that increasing panicle fertilizer ratio had minor effects on MGR but significant effects on grain-filling duration and RGC.

Regarding cultivation methods, RGC showed small differences in middle stage but large differences in early and late stages, showing opposite trends depending on nitrogen management. Under N1, C1 had the highest MGR in early stage, while C2 had obvious advantages in early-stage duration, with high RGC in early stage. Under N2 and N3 conditions, C3 and C4 showed greater comprehensive advantages in grain-filling process parameters.

2.4 Correlations Among Grain-Filling, Plumpness, and Yield

Correlation analysis among grain-filling, plumpness, and yield is shown in Table 6 . Maximum sink capacity and plumpness indexes were extremely significantly positively correlated with yield and seed setting indexes. Seed setting rate and 1000-grain weight were positively correlated with early and middle stage grain-filling duration (extremely significant in early stage), negatively correlated with late-stage duration, and significantly or extremely significantly positively correlated with MGR at all stages. Yield and biomass yield were positively correlated with grain-filling duration at all stages (extremely significant in middle stage) and positively correlated with MGR (extremely significant in early stage, significant in middle stage, not significant in late stage). All four yield indexes were positively correlated with RGC in early stage and negatively correlated in middle and late stages, with seed setting rate, 1000-grain weight, and grain yield being extremely significant and biomass yield being significant. These results indicate that duration and MGR at each grain-filling stage promoted yield formation to varying degrees, but relatively higher early-stage grain accumulation was more conducive to high yield.

As shown in Table 7 , sink capacity and plumpness rate were significantly or extremely significantly positively correlated with A, tmax · G, and D, significantly negatively correlated with R , and positively correlated with I (extremely significant for plumpness rate). Sink capacity was negatively correlated with grain-filling rates (Gmax and Gmean), while plumpness rate was positively correlated, though not significantly. These results indicate that sink capacity substantially affected grain-filling. With increasing sink capacity, initial growth vigor decreased, peak grain-filling was delayed (i.e., early and middle grain-filling duration and intensity increased), active grain-filling period extended, and maximum grain growth capacity increased, thereby improving seed setting rate, 1000-grain weight, and yield. However, the negative correlation between sink capacity and grain-filling rates (Gmax and Gmean) suggests that further coordinating sink capacity and grain-filling relationships through certain measures is important for yield increase.

Discussion

3.1 Effects of Ecological Conditions on Rice Grain-Filling and Yield

Plant material accumulation is based on photosynthesis, which can be significantly affected by light intensity, sunshine duration, temperature, and other factors. Under weak light, rice grain-filling rate decreases to varying degrees and empty grain rate increases substantially. When sunshine duration is insufficient, nutrients produced by photosynthesis cannot meet floret development needs, increasing partially filled grain rate. Insufficient light intensity and duration causing poor grain plumpness leads to substantial rice yield reduction. This study showed that overall, grain sink capacity, plumpness, seed setting rate, and 1000-grain weight at Hanyuan were superior to Wenjiang, ultimately producing higher yields. Meteorological data comparison revealed that Hanyuan had higher total solar radiation, longer total sunshine hours, and a rice growth period nearly 400 hours longer than Wenjiang, providing sufficient material basis and time guarantee for material accumulation and grain-filling. Additionally, Hanyuan had a longer active grain-filling period, delayed date to reach peak grain-filling, higher grain-filling intensity in early and middle stages with longer duration and greater growth proportion. Since early and middle stage grain-filling intensity significantly affects plumpness rate, seed setting rate, 1000-grain weight, and yield, improved grain-filling intensity provided more favorable conditions for high yield formation.

3.2 Effects of Nitrogen Management on Rice Grain-Filling and Yield

Nitrogen is the most important nutrient element for rice growth and development. Different growth stages have different fertilizer requirements, and rational fertilizer management not only meets rice growth needs and provides material guarantee for high yield but also improves fertilizer use efficiency for nitrogen saving. Previous studies show that among nitrogen applied at different stages, panicle fertilizer contributes most to rice nitrogen absorption and accumulation. Under the same nitrogen rate, increasing panicle fertilizer ratio can increase grain-filling rates (Gmax and Gmean), effectively promote panicle development, and increase grain weight. For different experimental treatments, nitrogen postponement degrees vary, with studies showing that basal-tiller to panicle fertilizer ratios of 7.5:2.5, 6:4, 5:5, and 4:6 can all potentially achieve high yields. This study showed that with increasing nitrogen postponement, maximum sink capacity tended to decrease while grain plumpness indexes, seed setting rate, and 1000-grain weight increased. Appropriate nitrogen postponement (N2, basal-tiller:panicle = 7:3) achieved higher grain yield. In this study, the yield increase resulted from grain-filling parameters developing in directions more conducive to grain plumpness and yield formation under appropriately increased panicle nitrogen: initial growth vigor decreased appropriately, grain-filling rates (Gmax and Gmean) increased, peak grain-filling was delayed, early and middle stage grain-filling duration and intensity increased, and growth proportion at peak grain-filling was effectively improved.

3.3 Nitrogen Management and Optimal Cultivation Method

Improved cultivation methods can provide better growth conditions for rice and make high yield possible. This study showed that under the same nitrogen management, cultivation methods had small differences in seed setting rate and 1000-grain weight but large differences in biomass yield, maximum sink capacity, grain-filling parameters, and plumpness indexes, ultimately causing yield differences. Wide-narrow row and triangular cultivation form field population structures with light-receiving advantages due to their unique row-hill configurations, making it easier to obtain advantageous populations in early stages. Under heavy basal-tiller fertilizer (N1) conditions, wide-narrow row and triangular cultivation increased biomass yield and expanded sink capacity, establishing the foundation of sufficient "source" and large "sink" for high yield formation. Simultaneously, triangular cultivation showed obvious advantages in grain-filling parameters and plumpness indexes, producing the highest yield among all treatments. With increasing nitrogen postponement, advantages of wide-narrow row and triangular cultivation gradually weakened. Previous studies also show that when rice row spacing is appropriately expanded, plant morphological characteristics are improved, making full use of mid- and late-stage production advantages. Ling (1997) reported that expanded row spacing combined with heavy panicle fertilizer application helps stabilize panicle number, form large panicles, and obtain advantageous populations. This study showed that compared with other cultivation methods, wide-row narrow-spacing cultivation under 30% panicle fertilizer (N2) had generally optimal yield formation indexes and obvious yield advantages. Seedling-throwing cultivation has rapid early growth and large populations due to its irregular planting pattern, but plants easily shade each other in late stages, resulting in poor ventilation and light penetration. This study showed that compared with other cultivation methods, seedling-throwing cultivation under higher nitrogen postponement (N3) was beneficial for optimizing biomass yield, sink capacity, and grain-filling indexes, with obvious yield advantages and prevention of excessive early population growth, consistent with previous research.

Under better light-temperature conditions at Hanyuan and appropriate nitrogen postponement, rice had sufficient "source" and large "sink" (high biomass yield and large sink capacity) with obvious grain-filling advantages (high grain-filling rates, strong early and middle stage grain-filling intensity, and long active grain-filling period), which was more conducive to high yield formation. Different nitrogen managements had substantial effects on grain-filling, plumpness, and yield formation under different cultivation methods. Under heavy basal-tiller fertilizer (basal-tiller:panicle = 9:1), wide-narrow row and triangular cultivation had greater sink capacity advantages and better grain plumpness, showing obvious yield advantages. Under appropriate nitrogen postponement (basal-tiller:panicle = 7:3), wide-row narrow-spacing cultivation had generally better indexes and greater yield potential. Under heavy panicle fertilizer (basal-tiller:panicle = 5:5), seedling-throwing cultivation could highlight yield advantages.

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