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Nitrogen Use Traits of Different Rice for Three Planting Modes in a Rice-Wheat Rotation System

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Abstract: At present, there is a limited understanding of nitrogen (N) accumulation, translocation, and utilization in different types of rice grown using different planting methods in a rice–wheat rotation system. Systematic experiments were conducted with six rice cultivars, including two *japonica-indica* hybrids (JIHR), two *japonica* conventional rice (JCR) cultivars, and two indica hybrid rice (IHR) cultivars, to study the effects on N use of plants in three transplanting modes: (1) the pothole seedling machine transplanting mode (PM), (2) the carpet seedling machine transplanting mode (CM), and (3) the mechanical direct seeding mode (DM). Results showed that at stem elongation stage, for N content and uptake, the planting methods were ranked in the order PM < CM < DM, and at heading and maturity the order was PM > CM > DM. After stem elongation the rankings for N accumulation, ratio of N accumulation to total N, and N uptake rate were PM > CM >DM. Thus, on the basis of a certain amount of N accumulation in the early growth phase, increasing the N uptake rate and N accumulation in the middle and late growth phases are ways to increase total N uptake for the PM and CM modes compared to DM. In addition, the PM/JIHR treatment had the highest N uptake at maturity. The N contents of leaves, stem-sheaths, and panicles at heading and maturity for the three planting modes were ranked PM > CM > DM. Moreover, the N translocation amount, apparent N translocation rate, and translocation conversion rate of leaves under PM were significantly higher than for CM and DM, which would increase N accumulation in the grain. The N uptake per 100 kg grain and the partial factor productivity of applied N under PM were larger than for CM and DM, but the N use efficiency of grain yield and biomass were smaller for PM than for CM and DM. In conclusion, rice grown using PM, especially JIHR, had higher total N uptake and N utilization compared to the CM and DM modes, and cultivation measures to improve the N use efficiency of grain yield and biomass could be appropriately applied to further improve N use in a rice–wheat rotation system.

Keywords: rice; agricultural machinery; planting method; N use

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1. Introduction

Since the 1860s, the production and application of chemical nitrogen (N) fertilizer has greatly improved the yield of rice [1]. In recent years, with the increases in the amount of applied N, the increases in rice yield are not as significant as in the past, and they have caused many cultivation and environmental problems, such as poor rice quality, water eutrophication, and soil hardening, none of which are conducive to sustainable and healthy agricultural development [2,3]. The data show that the N used for rice cultivation in China accounts for 37% of the world's total N consumption for rice. Compared with the other main rice producing countries, the amount of N used on rice in China was higher, and the N utilization rate was far lower, than the world average [3]. For example, rice grown in Jiangsu province is mainly *japonica* rice, which has a stronger fertilizer tolerance than *indica* rice. To realize high grain yields in *japonica* varieties to produce more food, 20% more N is applied compared to *indica* varieties, and the average nitrogen use efficiency (NUE) of rice grown in Jiangsu Province is far lower than the world average [3,4]. Nitrogen is not only an indispensable element of rice, but also a major contributor to the cultivation cost. Excessive blind application of N will fail to achieve the expected yield, and it will increase cultivation costs and decrease grower incomes. Therefore, reducing N application rates while retaining stable yields, stabilizing N rates with increased yield, and stabilizing N rates to give high NUE are important scientific problems to be solved for sustainable, high quality, high-yielding, and highly efficient rice cultivation [5].

Previous studies have made important progress in researching strategies for high yields and high NUE in rice by selecting efficient rice varieties, using appropriate fertilizer application technology, and practicing efficient planting and cultivation methods [6,7]. Cheng [8] found that a strategy involving multiple N topdressings could increase yield, improve NUE, and reduce input costs. Li [9] showed that high-yielding and high-efficiency rice varieties not only had high N utilization efficiency, but were also very efficient at using phosphorus and potassium. Zhang [10] suggested that the application of N fertilizer at the panicle differentiation stage can increase the yield and N utilization efficiency of small-panicle rice. For large-panicle rice, high yields could be obtained by applying N fertilizer at the initial stage of floret differentiation or heading. For middle-panicle rice, there were no significant differences in the effect of N fertilizer whether it was applied at panicle differentiation, spikelet differentiation, or heading. It was also found that N in *japonica* rice plants is stored more in organs than in the grains, while N in *indica* rice is stored more in grains than in organs [11]. The N harvest index for *indica* rice is higher than for *japonica* rice, and the total amount of N accumulation in *japonica* rice is higher than in *indica* rice. Huo [12] showed that scientific selection of planting methods was of great significance for efficient N utilization in rice. The NUE, N uptake per 100 kg grain, and grain yield of rice that was planted manually were significantly higher than for transplanting and direct-seeding methods. Moreover, while mechanized sowing and planting methods can reduce the total carbon content and carbon-nitrogen ratio of the plants at the stem elongation stage, they can significantly increase the N content of the plants at the stem elongation and the maturity stages, and increase N accumulation at maturity. This has been shown to be conducive to the efficient absorption and utilization of N in hybrid rice and the balance of carbon and N metabolism in the plant, resulting in high yields and high efficiency [13]. Therefore, N uptake and utilization in rice differ significantly in the different rice types and between cultivation measures, of which planting modes were also determined to have significant effects on rice yield and N utilization [14,15]. By regulating the population structure of rice, improving the photosynthetic characteristics of leaves, and regulating the physiological metabolism of the plants, planting modes can affect the source-sink characteristics of rice, change the grain filling characteristics, and promote the absorption and utilization of N and other nutrients, which greatly affects the final grain yield. Reasonable selection of planting modes has been an important way to achieve high rice yields, realize efficient use of nutrients, and reduce costs and environmental pollution. In recent years, the main rice planting modes have been the carpet seedling machine transplanting mode (CM), the mechanical direct seeding mode (DM), and the pothole seedling machine transplanting mode (PM). The high-yield cultivation techniques for each planting mode have gradually improved. However, comparative systematic studies on the characteristics and differences in N use in rice for different planting modes under high-yield cultivation are lacking, and the evaluation and analysis of the response of N use among rice varieties for different planting modes have not been reported.

This study was performed with six rice varieties of three types using three mechanized planting modes in a rice–wheat rotation system. Following the cultivation practice of the rice–wheat rotation system, the seedlings of PM and CM and the seeds of DM could only be planted in the field after the wheat harvest. Accordingly, this study included the high-yield cultivation test method, i.e., different high-yield cultivation measures were used for the different planting modes and rice types in the experiment [14,16,17]. In this test method, if different types of rice grown using different planting modes realized the highest possible yield, then the differences in N use traits among the treatments could be of practical significance for production. The main objectives of this study were: (1) to observe the N use traits of the different types of rice grown using different planting modes under high-yield cultivation test methods in a rice–wheat rotation system, and (2) to recommend methods to improve N use from the perspective of rice types and planting modes. Our findings will provide scientific data and support for high-yielding, high-efficiency mechanized cultivation in rice.

2. Materials and Methods

2.1. Experimental Site and Plant Materials

The experiment was conducted in 2014 and 2015 at the Diaoyu experimental site (33°05′ N, 119°58′ E) in Jiangsu province. This area belongs to the north subtropical humid climate zone with an annual average temperature of 15 °C, annual total sunshine of 2305.6 h, annual precipitation of 1024.8 mm, and an annual frost-free period of 227 days. The soil is clay loam with an organic matter content of 27.2 mg kg^{-1}, total nitrogen of 1.8 g kg^{-1}, available nitrogen of 114.5 mg kg^{-1}, available phosphorus of 13.9 mg kg^{-1}, available potassium of 152.8 mg kg^{-1}, and pH of 7.23 in the 0–20 cm soil layer. A typical rice–wheat rotation system is used here, and all of the wheat straw is returned to the field before rice is planted.

The six rice varieties of three types used in the experiment were the *japonica-indica* hybrid rice (JIHR) cultivars 'Yongyou 2640′ and 'Yongyou 1640′, the *japonica* conventional rice (JCR) cultivars 'Nanjing 9108′ and 'Wuyunjing 27′, and the *indica* hybrid rice type (IHR) cultivars 'Xinliangyou 6380′ and 'II You 084′. The used six varieties are of high yield potential, regional representation, and large-scale application. The pedigree information was list in Table 1.

Table 1. The pedigree information of the test rice varieties.

Type	Variety	Parental Information
JIHR	Yongyou 2640	Yongjing 26A × F7540
	Yongyou 1640	Yongjing 16A × F7540
JCR	Nanjing 9108	Wuxiangjing 14 × Guandong 194
	Wuyunjing 27	(Jia 45×9520) × Wuyunjing 21
IHR	Xinliangyou 6380	03S × D208
	II you 084	II-32A × Zhenhui 084

Note: JIHR, *japonica-indica* hybrid rice; JCR: *japonica* conventional rice; IHR: *indica* hybrid rice.

2.2. Experimental Design and Field Management

A split-plot experimental design was used in the experiment with machine planting mode as the main plot and rice varieties as the split plots. The three machine planting modes included the pothole seedling machine transplanting mode (PM), the carpet seedling machine transplanting mode (CM), and the mechanical direct seeding mode (DM). We designed the representative high-yield cultivation measures for each treatment based on the results of previous studies of high-yield cultivation measures in different rice types with different planting modes. Considering the applicability and scientific comparison of treatments, the detailed designs of the treatments are described below.

For the PM treatment, seedlings were grown in pothole seedling trays using the pothole seedling raising technique. There were three seedlings per pothole for JCR and two seedlings per pothole for JIHR and IHR during the seedling raising period. The seedlings were transplanted to the field using a 2ZB-6A (RXA-60T) pothole seedling transplanter (Ya Meike Machinery and Equipment Co., Ltd., Changzhou, China) at a hill spacing of 33.0×12.0 cm (Table 2). For the CM treatment, carpet seedling trays and the carpet seedling raising technique were used to raise the seedlings. The seedlings were transplanted to the field using a PD-60 carpet seedling transplanter (Dongyang Machinery Co., Ltd., Suzhou, China) at a hill spacing of 30.0×13.2 cm with three seedlings per hole for JCR and two seedlings per hole for JIHR and IHR. For the DM treatment, the DF 151 row-sowing machine (Dongfeng Agricultural Machinery Group Co., Ltd., Changzhou, China) and the germinated seed direct-sowing technique were used. The seedlings in the field were thinned to the numbers required for each treatment at the one-leaf stage (Table 2). After transplanting or sowing, three test replicates in 30 m^2 plots were planted in each treatment, and the seedlings were manually replenished in each plot. Soil mounds covered with plastic film were built between plots to ensure separation of fertilizer and water management treatments.

Table 2. The differential measures for different rice types under different planting modes.

Mode	Type	Sowing Date	Transplanting Date	Basic Seedling ($\times 10^4$ ha^{-1})	Applied Nitrogen (kg ha^{-1})
PM	JIHR			50.5	270
	JCR	May 18th	June 15th	75.8	270
	IHR			50.5	225
CM	JIHR			50.5	270
	JCR	May 28th	June 15th	75.8	270
	IHR			50.5	225
DM	JIHR			60.0	270
	JCR	June 13th	-	90.0	270
	IHR			60.0	225

Note: PM, pothole seedling machine transplanting mode; CM, carpet seedling machine transplanting mode; DM, mechanical direct seeding mode; JIHR, *japonica-indica* hybrid rice; JCR: *japonica* conventional rice; IHR: *indica* hybrid rice.

Considering the differences in the N uptake per 100 kg grain and the N fertilizer tolerance between *japonica* rice and *indica* rice, a lower amount of N was applied to the *indica* cultivars compared to the *japonica* cultivars to gain relative higher yield and ensure a reliable experimental outcome with scientifically useful data [14]. Of the total amount of N applied, 30%, 30%, 20%, and 20% was applied before sowing or transplanting, at the early tillering stage, at the inverted fourth leaf elongation stage, and at the penultimate leaf elongation stage, respectively. For each plot, 135 kg ha^{-1} P_2O_5 and 135 kg ha^{-1} K_2O were applied as ground fertilizer, and 135 kg ha^{-1} K_2O was applied to each plot at the inverted fourth leaf elongation stage. The chemical herbicides were used to control weeds in each plot. The prevention and control of sheath blight, rice blast, rice false smut, planthopper, rice stem borer, rice leaf roller and other diseases and insects were conducted using biotic pesticide based on the high-yield rice cultivation requirements.

2.3. Sampling and Measurements

At stem elongation, heading, and maturity stages, five representative holes of plants were sampled based on the mean number of tillers in the plot. The samples were divided into leaves, stem-sheaths at stem elongation stage, and leaves, stem-sheaths and panicles at heading and maturity stages. In addition, the samples were dried to a constant weight at 80 °C to determine the dry matter. After that, the samples were crushed and digested by H_2SO_4-H_2O_2 method. The Kjeldahl method was used to determine the nitrogen content of each digested sample [18]. Then, other parameters were obtained with the determined dry matter and N content, using the following calculation methods.

2.4. Calculation method and Data Analysis

$$\text{Nitrogen uptake (kg ha}^{-1}\text{)} = \text{nitrogen content} \times \text{aboveground dry matter weight} \quad (1)$$

$$\text{Nitrogen accumulation in a determined growth phase (kg ha}^{-1}\text{)} = \text{nitrogen uptake at later stage} - \text{nitrogen uptake at previous stage} \quad (2)$$

$$\text{Nitrogen uptake rate in a determined growth phase (kg ha}^{-1}\text{ d}^{-1}\text{) = nitrogen accumulation in the determined growth phase} \div \text{growth days in the determined growth phase} \quad (3)$$

$$\text{Nitrogen uptake per 100 kg grain (kg) = nitrogen uptake at maturity stage} \div \text{yield} \quad (4)$$

$$\text{The NUE of grain yield (kg kg}^{-1}\text{) = yield} \div \text{nitrogen uptake at maturity stage} \quad (5)$$

$$\text{The NUE of biomass (kg kg}^{-1}\text{) = aboveground dry matter weight at maturity} \div \text{nitrogen uptake at maturity stage} \quad (6)$$

$$\text{Partial factor productivity of applied nitrogen (kg kg}^{-1}\text{) = yield} \div \text{applied nitrogen amount} \quad (7)$$

$$\text{Nitrogen harvest index = nitrogen uptake of grain} \div \text{total nitrogen uptake at maturity stage} \quad (8)$$

$$\text{Nitrogen translocation amount (NTA, mg) of leaf or stem-sheath = nitrogen uptake of leaf or stem-sheath at heading stage} - \text{nitrogen uptake of leaf or stem-sheath at maturity stage} \quad (9)$$

$$\text{Apparent nitrogen translocation rate (ANTR, \%) of leaf or stem-sheath = the NTA of leaf or stem-sheath} \div \text{nitrogen uptake of leaf or stem-sheath at heading stage} \times 100\% \quad (10)$$

$$\text{Translocation conversion rate (NTCR, \%) of leaf or stem-sheath = the NTA of leaf or stem-sheath} \div \text{nitrogen uptake of leaf or stem-sheath at maturity stage} \times 100\% \quad (11)$$

$$\text{Nitrogen accumulation in panicle after heading (NAPH, kg ha}^{-1}\text{) = nitrogen uptake in panicle at maturity stage} - \text{nitrogen uptake in panicle at heading stage} \quad (12)$$

$$\text{Net nitrogen absorbed conversion rate after heading (NNCH, \%) = (total nitrogen uptake at maturity stage} - \text{total nitrogen uptake at heading stage)} \div \text{the NAPH} \times 100\% \quad (13)$$

Data were analyzed using the statistical package SPSS 20.0 (International Business Machines, Co., Ltd., Armonk, NY, USA) for Windows [19], and graphs were drawn using Excel 2013 (Microsoft, Co., Ltd., Redmond, WA, USA) for Windows. A significance level 5% was used to determine statistical significance by the least significant difference (LSD) test. Analyses of variance (ANOVA) was performed using Duncan's new multiple-range test. Because the data for the two rice varieties within the same type showed similar trends in the two experimental years, we averaged the data for the two varieties from two years in order to make the data less complicated in the table.

3. Results

3.1. Nitrogen Content and Nitrogen Uptake Traits

The N content and N uptake in the JIHR, JCR, and IHR treatments showed the same ranking order of PM < CM < DM at stem elongation stage and PM > CM > DM at heading and maturity (Table 3). Compared with DM, the N contents of PM and CM were 8.9% and 6.7% higher at heading and 11.1% and 8.1% higher at maturity, respectively. The N uptake of PM at heading and maturity was 19.6% and 29.8% higher than in DM, respectively, and the N uptake of CM at heading and maturity was higher than in DM by 13.0% and 19.2%, respectively. In the same planting mode, the N contents at stem elongation, heading, and maturity for IHR were significantly lower than in JIHR and JCR. Moreover, compared with JIHR and JCR, N uptake for IHR was 13.1% and 15.3% higher at stem elongation, 16.4% and 12.9% lower at heading, and 20.8% and 16.7% lower at maturity, respectively. The PM/JIHR treatment had significantly higher N content and N uptake at maturity.

Table 3. The nitrogen content and uptake of rice among planting modes at main growth stage.

Type	Mode	Trait	Nitrogen Content (%)			Nitrogen Uptake (kg ha^{-1})		
			SE	HE	MA	SE	HE	MA
JIHR	PM	Mean	1.94 c	1.52 a	1.22 a	88.8 de	197.4 a	261.0 a
		CV (%)	2.0	1.6	0.8	1.7	1.8	1.7
	CM	Mean	2.04 b	1.48 b	1.18 b	90.9 d	182.5 b	236.8 b
		CV (%)	2.4	1.1	1.3	1.1	0.9	2.9
	DM	Mean	2.19 a	1.37 d	1.07 d	93.5 c	157.2 d	193.1 e
		CV (%)	2.1	1.1	1.3	1.8	2.3	1.5
JCR	PM	Mean	2.05 b	1.51 a	1.19 b	88.4 e	182.1 b	236.2 b
		CV (%)	1.7	1.0	0.8	0.7	1.2	1.5
	CM	Mean	2.09 b	1.49 b	1.17 b	89.1 de	175.6 c	224.2 c
		CV (%)	0.6	1.0	1.1	0.8	0.4	1.4
	DM	Mean	2.15 a	1.39 c	1.11 c	90.5 de	156.4 d	194.2 e
		CV (%)	0.8	1.5	1.4	0.4	0.7	0.6
IHR	PM	Mean	1.83 d	1.24 e	1.09 c	100.8 b	159.7 d	205.8 d
		CV (%)	1.6	1.7	1.6	1.5	2.5	1.7
	CM	Mean	1.88 d	1.21 f	1.06 d	102.6 b	151.1 e	185.8 f
		CV (%)	1.8	1.0	1.4	2.3	2.3	1.3
	DM	Mean	1.96 c	1.16 g	0.98 e	105.6 a	136.7 f	155.3 g
		CV (%)	2.4	1.5	2.4	1.8	2.5	2.5
				ANOVA				
	Mode (M)		**	**	**	**	**	**
	Type (T)		**	**	**	**	**	**
	M × T		**	**	**	NS	**	**

Note: JIHR, *japonica-indica* hybrid rice; JCR: *japonica* conventional rice; IHR: *indica* hybrid rice; PM, pothole seedling machine transplanting mode; CM, carpet seedling machine transplanting mode; DM, mechanical direct seeding mode; SE, stem elongation stage; HE, heading stage; MA, maturity stage; CV, coefficient of variation; **, significant at p = 0.01 level; NS, no significant at the p = 0.05 level. Data followed by different letters were significantly different at the 5% probability level by LSD test.

3.2. Nitrogen Accumulation and Nitrogen Uptake Rate

The three planting modes ranked in the order PM < CM < DM for N accumulation, the ratio of accumulated N to total N, and the N uptake rate from sowing to the stem elongation stage, and the order was PM > CM > DM from stem elongation to heading and from heading to maturity (Tables 3 and 4). Compared with DM, the N accumulation for PM and CM was 67.4% and 43.7% higher from stem elongation to heading, respectively, and 89.4% and 55.5% higher from heading to maturity, respectively. The ratios of N accumulation to total N for PM and CM were 25.8% and 18.1% lower than for DM from sowing to stem elongation, respectively, 28.8% and 20.6% higher than DM from stem elongation to heading, respectively, and 45.2% and 30.2% higher than DM from heading to maturity, respectively. For the same planting mode, the N accumulation and the ratio of N accumulation to total N from stem elongation to heading and from heading to maturity for the three rice types were JIHR > JCR > IHR.

Compared with DM, the N uptake rates for PM and CM were 28.8% and 17.0% lower from sowing to stem elongation, respectively, 42.6% and 29.7% higher from stem elongation to heading, respectively, and 37.7% and 23.2% higher from heading to maturity, respectively (Table 4). In the PM treatments, N uptake rates of JIHR were higher than for JCR and IHR. Thus, a large amount of accumulated N, a high ratio of N accumulation to total N, and a high N uptake rate after stem elongation would be important traits for a high N uptake in PM or JIHR at maturity. In addition, the PM/JIHR treatment had the highest N accumulation, ratio of N accumulation to total N, and N uptake rate after the stem elongation stage.

Table 4. The nitrogen accumulation and uptake rate of rice among planting modes in main growth phases.

Type	Mode	Trait	Nitrogen Accumulation (kg ha^{-1})		Ratio of Nitrogen Accumulation to Total (%)			Nitrogen Uptake Rate (kg ha^{-1} d^{-1})		
			SE-HE	HE-MA	SO-SE	SE-HE	HE-MA	SO-SE	SE-HE	HE-MA
JIHR	PM	Mean	108.5 a	63.7 a	34.0 g	41.6 a	24.4 a	1.33 e	3.02 a	1.16 a
		CV (%)	2.7	7.6	1.5	3.2	6.6	3.0	2.8	7.5
	CM	Mean	91.6 b	54.3 b	38.4 ef	38.7 b	22.9 ab	1.57 c	2.59 b	0.99 b
		CV (%)	1.0	9.9	2.2	2.1	6.9	4.7	4.1	10.0
	DM	Mean	63.7 d	35.8 d	48.4 cd	33.0 c	18.6 c	1.91 a	1.86 c	0.68 c
		CV (%)	3.5	6.9	1.9	2.3	7.0	3.1	10.0	6.4
JCR	PM	Mean	93.7 b	54.2 b	37.5 f	39.7 b	22.9 ab	1.20 f	2.76 b	1.02 b
		CV (%)	2.5	5.8	2.2	1.9	4.7	4.4	5.0	5.5
	CM	Mean	86.6 c	48.6 c	39.7 e	38.6 b	21.7 b	1.39 d	2.51 b	0.92 b
		CV (%)	1.0	5.4	1.8	0.8	4.0	5.2	4.8	5.4
	DM	Mean	65.9 d	37.8 d	46.6 d	33.9 c	19.5 c	1.68 b	1.94 c	0.74 c
		CV (%)	1.2	5.4	0.7	1.7	5.0	4.0	4.4	5.1
IHR	PM	Mean	58.9 e	46.1 c	49.0 c	28.7 d	22.4 b	1.39 d	1.56 d	1.03 b
		CV (%)	5.8	3.7	1.1	4.8	4.0	2.1	10.9	10.2
	CM	Mean	48.5 f	34.7 d	55.2 d	26.1 e	18.7 c	1.59 c	1.27 e	0.77 c
		CV (%)	6.5	4.2	2.4	5.4	5.0	2.9	12.4	10.3
	DM	Mean	31.1 g	18.6 e	68.1 e	20.0 f	12.0 d	1.91 a	0.79 f	0.43 d
		CV (%)	9.6	7.6	2.8	7.2	6.8	4.2	12.9	10.6
					ANOVA					
	Mode (M)		**	**	**	**	**	**	**	**
	Type (T)		**	**	**	**	**	**	**	**
	M × T		**	**	**	**	**	*	**	**

Note: JIHR, *japonica-indica* hybrid rice; JCR: *japonica* conventional rice; IHR: *indica* hybrid rice; PM, pothole seedling machine transplanting mode; CM, carpet seedling machine transplanting mode; DM, mechanical direct seeding mode; SO, sowing date; SE, stem elongation stage; HE, heading stage; MA, maturity stage; CV, coefficient of variation; **, significant at p = 0.01 level; *, significant at p = 0.05 level; Data followed by different letters were significantly different at the 5% probability level by LSD test.

3.3. The NUE Traits

Compared with DM, the N uptake per 100 kg grain in the PM and CM treatments were 9.6% and 7.4% higher (Table 5). The N uptake per 100 kg grain in IHR was 9.0% lower than in JCR, and 9.2% lower than in JIHR. Moreover, the PM/JIHR treatment had the largest N uptake per 100 kg grain among the treatments. The N use efficiencies of grain yield and biomass for DM were higher than for CM and PM and higher in IHR than in JCR and JIHR. The partial factor productivity of applied N for PM and CM were 18.1% and 11.0% higher than for DM, and 4.8% and 9.8% higher in IHR than in JIHR and JCR. No significant differences were found in the N harvest index among planting modes, and the N harvest index for IHR was 22.2% and 23.1% higher than for JIHR and JCR.

3.4. Nitrogen Contents of Leaves, Stem-Sheaths, and Panicles

At the heading stage, the N contents of leaves, stem-sheaths, and panicles for the planting modes ranked PM > CM > DM, and IHR had a lower N content than JIHR and JCR (Table 6). Compared with DM, the leaf N contents for the PM and CM modes were higher by 12.9% and 10.5%, the stem-sheath N contents were higher by 3.9% and 2.6%, and the panicle N contents were higher by 3.0% and 2.3%, respectively. The PM/JIHR treatment had the highest N contents in leaves, stem-sheaths, and panicles among all treatments. At maturity, with the exception of leaf N content in IHR, which ranked the planting modes PM < CM < DM, the rankings for the other factors were all in the order PM > CM > DM. The N contents of leaves and stem-sheaths for IHR were smaller than for JIHR and JCR, but the panicle N content of IHR was higher than in JIHR and JCR.

Table 5. The nitrogen use efficiency traits of rice among planting modes.

Type	Mode	Trait	Nitrogen Uptake per 100 kg Grain (kg)	Nitrogen Use Efficiency of Grain Yield (kg kg^{-1})	Nitrogen Use Efficiency of Biomass (kg kg^{-1})	Partial Factor Productivity of Applied Nitrogen (kg kg^{-1})	Nitrogen Harvest Index
JIHR	PM	Mean	2.08 a	48.0 f	82.5 f	46.4 b	0.67 b
		CV (%)	0.6	0.7	0.9	1.2	1.5
	CM	Mean	2.04 b	49.1 ef	84.8 e	43.1 d	0.66 b
		CV (%)	1.2	1.1	1.5	1.9	1.4
	DM	Mean	1.86 de	53.8 bc	93.3 bc	38.5 g	0.64 b
		CV (%)	1.5	1.5	1.3	0.5	0.8
JCR	PM	Mean	2.03 b	49.2 e	83.9 e	43.1 d	0.65 b
		CV (%)	1.2	1.1	1.0	1.1	2.3
	CM	Mean	2.01 b	49.7 e	85.1 e	41.3 e	0.65 b
		CV (%)	1.4	1.3	1.0	1.4	2.3
	DM	Mean	1.91 c	52.3 d	90.3 d	37.6 h	0.65 b
		CV (%)	0.9	0.9	1.1	0.7	3.3
IHR	PM	Mean	1.89 cd	52.9 cd	91.5 cd	48.4 a	0.81 a
		CV (%)	1.6	1.6	1.6	1.3	1.6
	CM	Mean	1.83 e	54.6 b	94.7 b	45.1 c	0.80 a
		CV (%)	1.3	1.5	1.5	1.0	2.4
	DM	Mean	1.71 f	58.7 a	102.6 a	40.5 f	0.80 a
		CV (%)	2.5	2.4	2.6	1.0	4.2
				ANOVA			
	Mode (M)		**	**	**	**	**
	Type (T)		**	**	**	**	*
	M × T		**	**	**	**	NS

Note: JIHR, *japonica-indica* hybrid rice; JCR: *japonica* conventional rice; IHR: *indica* hybrid rice; PM, pothole seedling machine transplanting mode; CM, carpet seedling machine transplanting mode; DM, mechanical direct seeding mode; CV, coefficient of variation; **, significant at p = 0.01 level; *, significant at p = 0.05 level; NS, no significant at the p = 0.05 level. Data followed by different letters were significantly different at the 5% probability level by LSD test.

3.5. Nitrogen Translocation Traits

Compared with DM, the N translocation amount (NTA), apparent N translocation rate (ANTR), and translocation conversion rate (NTCR) of leaves for the PM mode were 67.2%, 16.6%, and 20.9% higher, respectively, and were 43.0%, 10.5% and 13.8% higher, respectively for CM (Table 7). Moreover, the leaf NTA, ANTR, and NTCR for IHR were higher than for JCR and JIHR. The planting modes for stem-sheath NTA ranked PM > CM > DM, and the modes for stem-sheath ANTR, and NTCR ranked PM < CM < DM. The stem-sheath NTA in the DM mode was 16.6% and 10.5% higher than in the PM and CM modes, respectively. The stem-sheath ANTR and NTCR in the DM mode were 4.1% and 19.7% lower than for PM, and 2.4% and 13.7% lower than for CM. The NTA, ANTR, and NTCR for IHR were higher than for JIHR and JCR under the same planting modes.

For the three planting modes, the N accumulation in panicles after heading (NAPH) ranked in the order PM > CM > DM (Table 7). Compared with DM, the NAPH increased by 44.4% and 28.0% for PM and CM, respectively. The NAPH in JCR was lower than in JIHR and IHR for the PM mode, and NAPH in JCR and IHR was significantly lower than in JIHR for CM. There were no significant differences in NAPH among the rice types for the DM mode. The planting mode rankings for net N absorbed conversion rate after heading (NNCH) in JIHR and IHR showed the same order, PM > CM > DM, and there were no significant differences in NNCH for JCR among the planting modes. IHR had the lowest NNCH in the three planting modes.

3.6. Relationship between Yield and N Accumulation or N Translocation

A previous study showed that grain yield had the same significant planting mode ranking of PM > CM > DM for a given rice type and JIHR > JCR > IHR for the same planting mode [14]. Under the influence of planting modes and rice varieties, the N accumulation from sowing to the stem elongation stage was significantly negatively correlated with yield, and from stem elongation to the heading stage or from heading to maturity it was positively correlated with yield (Figure 1). There was no significant positive correlation between N transport amount in leaves and stem-sheaths after heading and yield, but there was a significant positive correlation between N accumulation in the panicle and yield (Figure 2).

Table 6. The nitrogen contents of leaf, stem-sheath, and panicle of rice among planting modes at heading and maturity stages.

Type	Mode	Trait	Heading Stage			Maturity Stage		
			Leaf	Stem-Sheath	Panicle	Leaf	Stem-Sheath	Panicle
JIHR	PM	Mean	2.27 ab	1.14 a	1.19 a	1.49 a	0.73 bc	1.39 b
		CV (%)	3.0	0.7	1.8	2.5	5.5	1.8
	CM	Mean	2.21 b	1.12 ab	1.17 ab	1.45 a	0.71 c	1.35 bc
		CV (%)	2.3	1.1	1.6	3.8	3.7	2.3
	DM	Mean	1.94 d	1.10 b	1.15 ab	1.32 b	0.71 c	1.20 e
		CV (%)	2.9	0.9	2.1	4.9	6.6	1.6
JCR	PM	Mean	2.31 a	1.13 ab	1.16 ab	1.45 a	0.80 a	1.33 bc
		CV (%)	1.4	1.8	1.7	2.8	8.3	1.9
	CM	Mean	2.28 ab	1.12 ab	1.15 ab	1.43 a	0.79 a	1.31 cd
		CV (%)	1.7	2.2	1.5	3.0	7.8	1.7
	DM	Mean	2.04 c	1.09 b	1.13 b	1.28 b	0.76 ab	1.24 de
		CV (%)	3.8	1.8	0.9	4.1	8.5	2.7
IHR	PM	Mean	1.80 e	0.93 c	1.04 c	0.67 d	0.44 d	1.52 a
		CV (%)	1.9	3.5	4.7	4.4	13.4	1.9
	CM	Mean	1.75 e	0.92 cd	1.04 c	0.74 cd	0.44 d	1.48 a
		CV (%)	2.4	3.4	4.2	14.5	10.2	3.7
	DM	Mean	1.65 f	0.89 d	1.01 c	0.79 c	0.41 d	1.36 bc
		CV (%)	3.1	1.9	1.7	13.9	13.0	5.7
	ANOVA							
	Mode (M)		**	**	**	**	**	**
	Type (T)		**	**	**	**	**	**
	M × T		**	NS	NS	**	NS	**

Note: JIHR, *japonica-indica* hybrid rice; JCR: *japonica* conventional rice; IHR: *indica* hybrid rice; PM, pothole seedling machine transplanting mode; CM, carpet seedling machine transplanting mode; DM, mechanical direct seeding mode; CV, coefficient of variation; **, significant at $p = 0.01$ level; NS, no significant at the $p = 0.05$ level. Data followed by different letters were significantly different at the 5% probability level by LSD test.

Table 7. The nitrogen translocation traits of leaf, stem-sheath, and panicle of rice after heading among planting modes.

Type	Mode	Trait	NTA (mg)		ANTR (%)		NTCR (%)		NAPH (kg ha^{-1})	NNCH (%)
			L	S	L	S	L	S		
JIHR	PM	Mean	20.2 b	13.4 a	52.5 d	42.0 bc	29.1 bc	19.3 ef	150.5 a	40.1 a
		CV (%)	10.7	13.7	1.3	7.4	4.5	6.9	3.2	5.0
	CM	Mean	16.9 c	12.7 ab	49.5 de	43.3 b	27.8 c	20.8 de	132.7 b	38.9 ab
		CV (%)	8.1	12.1	2.3	5.5	5.0	4.4	4.8	4.0
	DM	Mean	10.9 f	11.2 c	42.1 f	43.4 b	24.0 d	24.6 b	98.8 d	36.6 b
		CV (%)	9.8	11.2	9.1	7.4	11.3	8.4	2.3	3.7
JCR	PM	Mean	12.9 e	7.9 d	51.5 de	37.5 d	30.2 b	18.4 f	130.9 b	39.8 a
		CV (%)	4.3	15.2	2.4	12.0	3.6	10.5	3.9	3.0
	CM	Mean	11.2 ef	7.6 d	48.2 e	38.2 d	28.9 bc	19.6 ef	120.3 c	39.1 a
		CV (%)	4.8	13.5	3.4	10.7	4.2	9.1	4.0	3.7
	DM	Mean	7.9 g	7.0 d	42.3 f	39.6 cd	24.8 d	22.0 cd	99.2 d	39.5 a
		CV (%)	6.2	14.9	7.0	11.2	4.4	12.0	3.8	3.7

Table 7. *Cont.*

Type	Mode	Trait	NTA (mg)		ANTR (%)		NTCR (%)		NAPH (kg ha^{-1})	NNCH (%)
			L	S	L	S	L	S		
IHR	PM	Mean	22.3 a	13.6 a	79.3 a	59.3 a	36.5 a	22.1 cd	146.3 a	30.3 c
		CV (%)	8.3	17.9	1.6	9.6	4.0	11.5	1.7	4.4
	CM	Mean	19.3 b	12.7 ab	74.9 b	59.7 a	36.1 a	24.0 bc	126.0 bc	26.8 d
		CV (%)	8.0	16.5	3.9	7.4	4.2	8.4	2.7	3.8
	DM	Mean	14.8 d	11.7 bc	68.2 c	61.9 a	34.9 a	28.2 a	98.2 d	21.5 e
		CV (%)	12.1	12.9	6.2	7.1	5.3	7.5	5.5	5.3
					ANOVA					
Mode (M)			**	**	**	**	**	**	**	**
Type (T)			**	**	**	**	**	**	**	**
M × T			**	*	NS	NS	**	*	**	**

Note: JIHR, *japonica-indica* hybrid rice; JCR: *japonica* conventional rice; IHR: *indica* hybrid rice; PM, pothole seedling machine transplanting mode; CM, carpet seedling machine transplanting mode; DM, mechanical direct seeding mode; NTA, nitrogen translocation amount; ANTR, apparent nitrogen translocation rate; NTCR, translocation conversion rate; NAPH, nitrogen accumulation in panicle after heading; NNCH, net nitrogen absorbed conversion rate after heading; L, leaf; S, stem and sheath; CV, coefficient of variation; **, significant at p = 0.01 level; *, significant at p = 0.05 level; NS, no significant at the p = 0.05 level. Data followed by different letters were significantly different at the 5% probability level by LSD test.

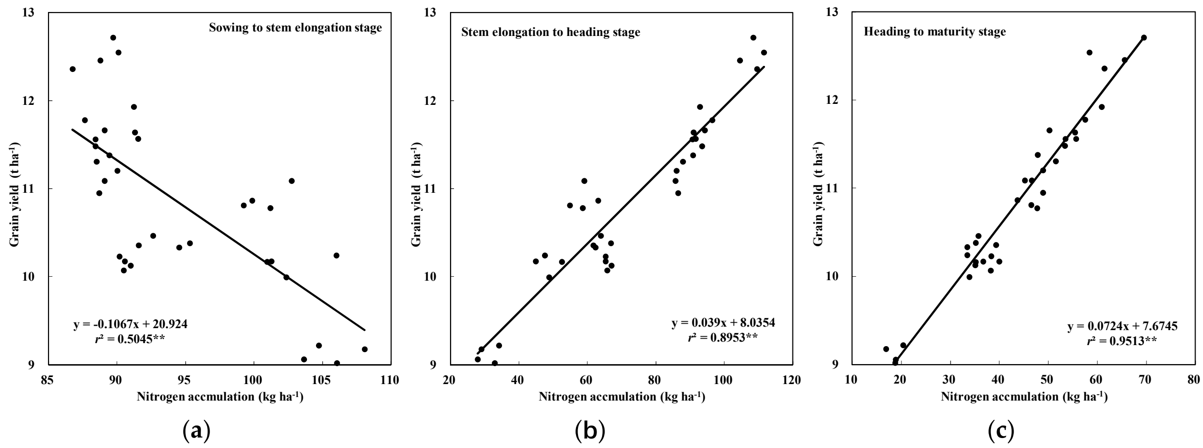

Figure 1. Relationships between nitrogen accumulation during main growth phases and yield. (**a**) Relationships between nitrogen accumulation during sowing to stem elongation stage and yield; (**b**) Relationships between nitrogen accumulation during stem elongation to heading stage and yield; (**c**) Relationships between nitrogen accumulation during heading to maturity stage and yield.

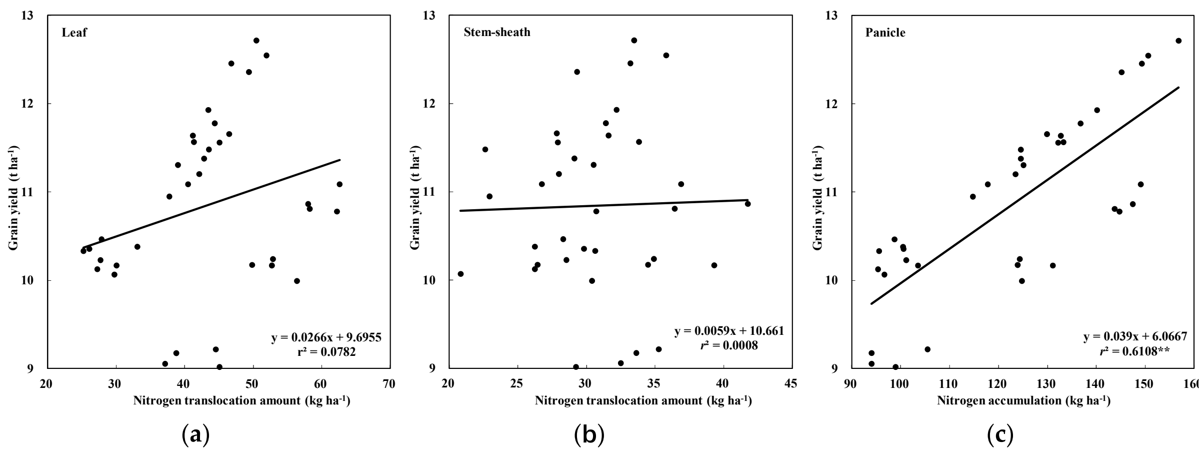

Figure 2. Relationships between nitrogen translocation amount in leaf and stem-sheath, nitrogen accumulation in panicle after heading and yield. (**a**) Relationships between nitrogen translocation amount

in leaf after heading and yield; (**b**) Relationships between nitrogen translocation amount in stem-sheath after heading and yield; (**c**) Relationships between nitrogen accumulation in panicle after heading and yield.

4. Discussion

N is the most sensitive factor affecting the growth of rice plants, and the highly efficient uptake and accumulation of N are usually indicators of a high rice yield. Most previous studies have shown that low N accumulation during the early phase of rice plant growth and higher N accumulation during the middle and late rice plant growth phases are important characteristics of N accumulation for high rice yield compared to low rice yield [6,20]. The above characteristics are especially true for super high-yielding rice [21,22]. In addition, promoting the stem-sheath N transfer after heading was conducive to improving rice yield, which was more obvious in JIHR [23,24]. However, the N contents at different growth stages of high yielding rice have maximum values, and N contents outside of the appropriate range at a critical stage will cause a reduction in rice yield [25,26]. Previous research has shown that the combination of planting mode and rice varieties can regulate N uptake and accumulation during rice growth to not only use more N, but also increase grain yield [12–17]. Huo [12] showed that, compared with transplanted and direct-seeded rice, manually planted rice had lower N content and N accumulation at the stem elongation stage and higher N content and N accumulation at heading and maturity, and the differences in these factors among treatments after stem elongation became large. The characteristics of N accumulation and N utilization in hybrid rice differ between the different sowing and transplanting methods. The direct sowing and transplanting methods with lower seedling numbers per hill were effective in controlling and regulating the N uptake and transfer in rice, maintaining a relatively high N accumulation during the entire rice growing period, thus leading to a high N requirement for 100 kg of grain production and a high yield [13,27].

In this experiment, compared with DM, the N content and N accumulation of the PM and CM planting modes were lower at stem elongation and higher at heading and maturity. The higher N accumulation before stem elongation and the higher N content at stem elongation for DM may be related to the fact that the rice plants in the DM mode were not subjected to seedling raising, and the seedlings in the field were smaller, with lower inter-individual competitiveness for N compared to CM and PM seedlings, while the base N and N applied at tillering in the field were the same among the three planting methods. In addition, the dry matter accumulation of rice plants for DM at stem elongation was insignificantly less than in the CM and PM planting modes [12,14,17]. Thus, a higher N content might predict higher rice N accumulation for DM at stem elongation. After the stem elongation stage, both the number of non-bearing tillers and the tiller senescence rate for the DM mode were higher than for CM and PM, which resulted in more N loss for DM compared to CM and PM [28,29]. Moreover, the weaker morphological traits and physiological functions of the leaves and roots of plants in the DM and PM treatments led to reduced N accumulation from stem elongation to heading and from heading to maturity for DM compared to CM and PM [14,30]. The difference in N uptake rates for the different growth periods among the three planting modes also tends to support the above results. The correlation analysis showed that rice yield was significantly negatively correlated with N accumulation from sowing to stem elongation and significantly positively correlated with N accumulation from stem elongation to heading and from heading to maturity. Moreover, plants in the DM treatments had higher ratios of N accumulation to total N before the stem elongation stage, and lower ratios of N accumulation to total N after stem elongation. Therefore, this suggests that lower levels of accumulated N before stem elongation and higher N accumulation after stem elongation (especially after heading) are important factors that contribute to the higher yield of plants in the PM treatments compared to CM and DM [11,20,31,32]. Because the different types of rice cultivars varied with respect to their N contents and N uptake traits, and significant differences were found for N content and N uptake in the interaction between planting mode and rice variety, further improvements in N uptake efficiency, N utilization, and high yields in rice can be realized by the appropriate selection of rice varieties and planting modes. The PM/JIHR treatment showed such advantages, for the reason that the JIHR was of the three-line *indica-japonica* heterosis and the PM was beneficial to develop the rice production potential. Thus, the N accumulation in PM/JIHR treatment was greater [32,33].

After heading, compared with DM, the higher N content and N translocation number of leaves and stem-sheaths and the higher apparent N translocation rate and translocation conversion rate of leaves in the PM and CM planting modes could indicate a stronger leaf function and more N absorption in the plant. In addition, the lower apparent N translocation rate and the translocation conversion rate of stem-sheaths in the PM and CM treatments would lead to more enriched stem-sheaths and increased lodging resistance [34,35]. Therefore, improving the apparent N translocation rate and N translocation conversion rate of the stem-sheath after heading can be considered a way to further increase the N uptake and utilization and grain yield in the PM and CM treatments [5,36]. For the same planting modes, the IHR cultivars had lower apparent N translocation rates and translocation conversion rates of the stem-sheath than did JCR and JIHR, which could be one way to explain the weak stem-sheath support and lodging susceptibility of IHR during the grain filling phase [37,38]. On the contrary, the lower apparent N translocation rate and translocation conversion rate of the stem-sheath, and the higher N accumulation in the panicles after heading would be important traits for the PM/JIHR treatment to increase the N uptake and for stronger stem-sheath support, which would also lead to higher yields. However, the N uptake of PM/JIHR treatment was higher than others, and the long-term N output of soil might lead to barren soil. Thus, measures to improve soil fertility in PM/JIHR should be taken into consideration.

Based on the analysis of N use traits in high-yield rice in different regions, the high yields and higher yields are often associated with high N fertilizer and higher N fertilizer inputs, respectively. Finding a way to achieve both high grain yield and efficient N utilization has long been a scientific problem that urgently needs to be solved for sustainable and environmentally friendly rice cultivation [2,39]. The NUE traits were significantly affected by planting modes and rice types. In this experiment, the N uptake per 100 kg grain and the partial factor productivity of applied N in the three planting modes were ranked in the order PM > CM > DM, while the NUE of grain yield and the NUE of biomass were ranked PM > CM > DM. This indicated that, compared with DM, the PM and CM planting modes could be more conducive to N uptake and utilization in rice, but that the lower NUE of grain yield and biomass would more efficiently limit N uptake and utilization [40,41]. Compared with IHR, the JIHR and JCR cultivars had stronger tolerance for N fertilizer with higher N uptake per 100 kg grain. This was one reason why less N was applied to IHR than to JIHR and JCR, and why IHR had higher NUEs of grain yield and biomass and partial factor productivity of applied N [42]. These data show that more attention should be directed toward increasing NUE to develop cultivars with higher NUE and higher yields using the new cultivation technology.

5. Conclusions

The results of our study show that selecting suitable mechanized planting modes can improve the N use in different rice types under high-yield cultivation conditions in a rice–wheat rotation system. Compared with DM, plants from the PM and CM planting modes had significantly lower N contents and N uptake at the stem elongation stage and higher N contents at heading and maturity, with higher N uptake rates and N accumulation after stem elongation. In addition, the N uptake at maturity for the three planting modes showed a significant difference, and the order was PM > CM > DM. Therefore, on the basis of the amount of N accumulated in the early phases of rice growth, increasing the N uptake rate and N accumulation in the middle and late phases of growth may be important for plants grown under the PM and CM planting modes to achieve higher total

N use. Machine transplanting of *indica-japonica* hybrid rice cultivars (PM/JIHR) would be a suitable combination for a rice–wheat rotation system with high N use and high rice grain yield.

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