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Polymer-coated urea application can increase both grain yield and nitrogen use efficiency in *japonica-indica* hybrid rice

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Abstract

We investigated whether the one-time application of polymer-coated urea (PCU) before transplanting could simultaneously improve the grain yield and nitrogen use efficiency (NUE) of *japonica-indica* hybrid rice (JIHR) through a field experiment. The local high-yield JIHR cultivar Chunyou-927 was field grown during the rice-growing seasons in 2019 and 2020. The experiment consisted of three treatments: no nitrogen application (0N), application of conventional urea (CU), and the one-time application of PCU. Grain yield was 1.0–1.3 t/ha higher, and agronomic NUE (kg grain yield increase per kg N applied) was 5.2–5.9 kg/kg higher, respectively, under the PCU treatment compared with the CU treatment across the two study years. When compared with the CU treatment, the PCU treatment could (1) improve root morphological trait, (2) reduce redundant vegetative growth during the early growth period, (3) increase matter production during the mid and late growth period, and (4) increase plant activity during the grain-filling period. Overall, our findings indicate that one-time PCU application before transplanting of the JIHR cultivar holds great promise for increasing grain yield and NUE.

Introduction

Rice (*Oryza sativa* L.) is one of the most important sources of food in China, as it feeds more than half of the Chinese population (Peng *et al.*, 2009; Deng *et al.*, 2019). However, it is predicted that rice grain yields need to be increased by more than 70% by the year 2050 relative to the current level, with an annual growth rate of almost 2.5%, to meet the continually growing demand for food (Normile, 2008; Fan *et al.*, 2012; Song *et al.*, 2022). Therefore, there is an urgent need to breed new rice cultivars with stronger yield production potential and to improve crop management and enhance average farm yield (Mueller *et al.*, 2012; Yu *et al.*, 2012; Ray and Foley, 2013; Yuan, 2017).

Japonica and *indica* are the predominant subspecies of cultivated rice in Asia; however, these two varieties differ in their biological and ecological characteristics. It is generally accepted that cross-breeding between *japonica* and *indica* is an important approach for breeding new rice cultivars with stronger yield production potential (Zhang, 2020). Over the past 10 years, several high-yielding *japonica-indica* hybrid rice (JIHR) cultivars have been successfully bred in China, and these cultivars can produce a higher grain yield and have higher nitrogen use efficiency (NUE) than *japonica* or *indica* hybrid rice cultivars, these cultivars have now become more prevalent in the lower Yangtze River plain (Wei *et al.*, 2016, 2018; Chu *et al.*, 2019, 2022; Zhu *et al.*, 2020).

The application of nitrogen (N) fertilizer is the most important practice in crop management, and it has contributed greatly to increases in rice grain yield (Ju *et al.*, 2009; Vitousek *et al.*, 2009). However, given that N fertilizer application methods lack a scientific basis in China, more than 50% of the N fertilizer is wasted, and this has caused several environmental problems. Controlled-release urea (CRU) has been developed to reduce these losses by delaying the release of urea from the fertilizer granule. Applying CRU instead of conventional urea (CU) is considered as a more effective measure for reducing N loss and increasing NUE (Geng *et al.*, 2015; Chu *et al.*, 2018; Ke *et al.*, 2018; Li *et al.*, 2018; Zhang *et al.*, 2021). Polymer-coated urea (PCU) is a currently used CRU (Golden *et al.*, 2009; Lyu *et al.*, 2015; Bhatt and Singh, 2021). The release of N by PCU is controlled compared with that of CU, and this allows crop N requirements to be met for longer periods (Lyu *et al.*, 2015; Chu *et al.*, 2018; Bhatt and Singh, 2021). Previous studies have indicated that PCU can significantly enhance grain yield and NUE and reduce greenhouse gas emissions compared with either CU or other modified N fertilizers when applied at the same N rate (Lyu *et al.*, 2015; Chu *et al.*, 2018; Bhatt and Singh, 2021; Zhang *et al.*, 2021). A recent meta-analysis has shown that the application of PCU at an equal N rate can increase crop yield by 9.2% compared with the application of CU (Zou *et al.*, 2022). These observations suggest that the application of

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PCU is a more effective approach for providing the N needed for rice growth and reducing N loss. No information is currently available regarding whether the one-time application of PCU before transplanting can increase both grain yield and NUE in newly bred JIHR cultivars.

The main objective of this study was to compare the effects of applying CU and PCU on grain yield and NUE in JIHR cultivars. Some agronomic and physiological traits that are closely associated with rice growth were investigated to understand the biological mechanisms underlying the effects of PCU application on rice yield and NUE.

Materials and methods

Plant materials and growth conditions

The experimental site was located in Buqiao Village of Fuyang City, Zhejiang Province, China ($3\overset{\circ}{0}5'$ N, $11\overset{\circ}{9}4'$ E). The experiment was conducted during the rice-growing season in 2019 and 2020. Figure 1 shows the weather conditions during the two rice growing seasons, and weather data were recorded from a weather station located near the experimental field. The soil of the plough layer (0–20 cm) was classified as clay loam, and the main soil physical and chemical properties are listed in Table 1.

A local high yielding JIHR cultivar Chunyou-927 was grown during both study years. In 2019 and 2020, the pre-germinated seeds were manually sown in a seedbed on May 20. Twenty-five days later, the seedlings were manually transplanted into the experimental field at a hill spacing of 25 cm × 16 cm with two seedlings /hill. The heading dates of these cultivars ranged from 2 to 3 September, and rice was harvested on 31 October. Diseases, insect pests and weeds were strictly controlled to avoid yield losses.

Treatments

The experiment was conducted in a randomized complete block design with three replicates. Each plot (6.0 m × 8.0 m) was separated from the others by 1 m. There were three N application treatments: (1) 0N, no N fertilizer was applied during the entire growth period; (2) CU, application of conventional urea (N 46%, Zhejiang Julong Fertilizer Co. Ltd.; Huzhou, China) at a rate of 180 kg N/ha. Urea was applied in two doses following the practices of local farmers: 70% as a basal dressing one day before transplanting, and the other 30% as a topdressing 10 days after transplanting (DAT). In the (3) PCU treatment, polymer-coated urea (N 44%, longevity was 3 months, Shanghai Jinshengmei Fertilizer Co. Ltd.; Shanghai, China) was applied at a rate of 180 kg N/ha at 1 day before transplanting. Potassium was applied at a uniform rate of 180 kg K_2O/ha, and potassium was applied in two doses: 60% as a basal dressing one day before transplanting, and the remaining 40% was applied as a topdressing at the panicle initiation stage. Phosphorous was applied as superphosphate (12% P_2O_5) at a uniform rate of 90 kg P_2O_5/ha in each experimental plot as a basal dressing one day before transplanting. After the seedlings were manually transplanted, flooded conditions were maintained in the field until 10 days before the final harvest.

Sampling and measurements

To characterize variation in the number of tillers, 20 plants were manually tagged at 10 DAT, and then the number of tillers was determined at the jointing (44–45 DAT), heading (83–84 DAT), and physiological maturity (138–139 DAT) periods.

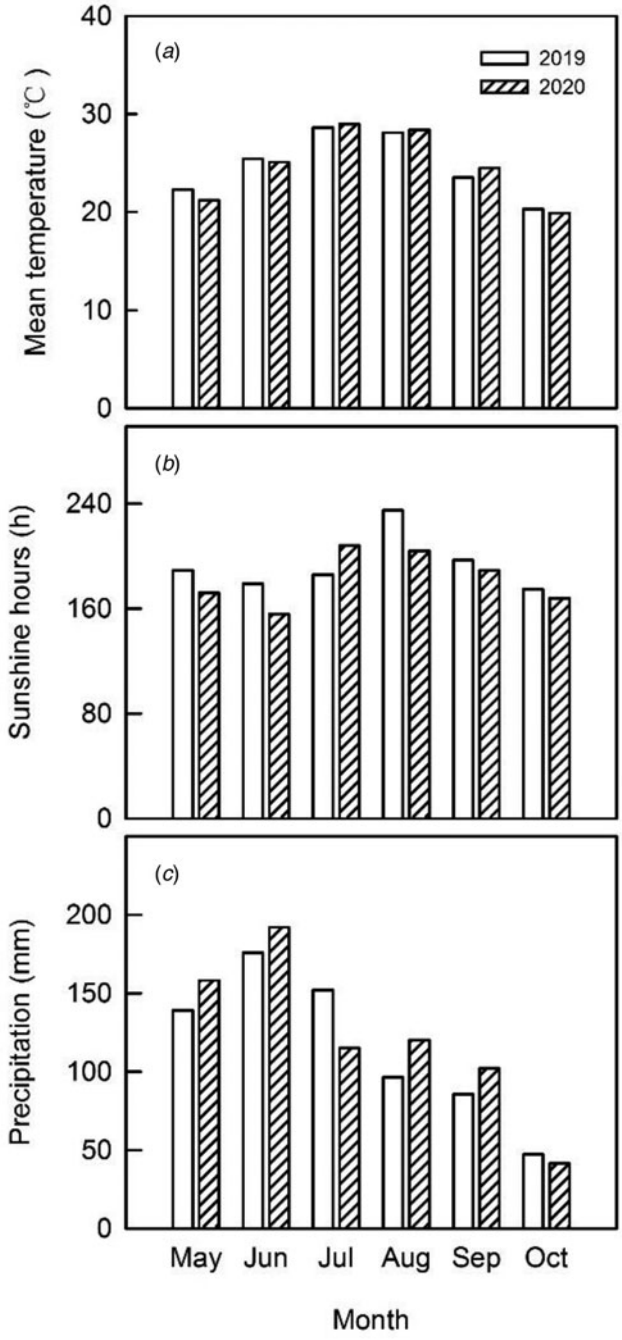

Fig. 1. Monthly average temperature (a), and total sunshine hours (b) and precipitation (c) for the 2019 and 2020 growing seasons for the experimental site in Fuyang, southeast China..

Using the method described by Chu *et al.* (2019), five representative hills from each plot were sampled to measure the green leaf area and shoot biomass at the jointing, heading, and physiological maturity periods with an LAI metre (Li-3100, Li-Cor, Lincoln, USA), and the leaf area index (LAI) was calculated. The leaf area duration (LAD) and crop growth rate (CGR) were calculated as follows:

$$\text{LAD}\ (\text{m}^2/\text{m}^2\text{d}) = \frac{1}{2}\,(LAI_1 + LAI_2) \times (t_2 - t_1) \qquad (1)$$

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Table 1. Soil physical and chemical properties in the experiment field in 2019 and 2020

Year	PH	Total *N* content (g/kg)	Organic matter content (g/kg)	alkali-hydrolysable *N* (mg/kg)	Olsen-P (mg/kg)	exchangeable *K* (mg/kg)
2019	6.3	2.57	37.5	195	16.9	70.4
2020	6.2	2.51	37.2	201	17.2	71.5

$$\mathrm{CGR}\,(\mathrm{g/m^2/d^1}) = (DW_2 - DW_1)\,/\,(t_2 - t_1) \qquad (2)$$

where LAI_1 and LAI_2 are the first and second LAI measurements (m^2/m^2), respectively; DW_1 and DW_2 are the first and second shoot biomass measurements (g/m^2), respectively; and t_1 and t_2 are the first and second (d) measurements, respectively.

Root biomass was measured at the heading stage. Using a core sampler, three soil cubes (25 cm × 16 cm × 20 cm) around each hill from each plot were carefully extracted. The three soil cubes were then divided into two parts, a 0–10 cm part and a 10–20 cm part. The roots were rinsed thoroughly using a hydropneumatic elutriation device and then dried in a forced-air oven at 80°C for 72 h to determine the root biomass. The root sampling method was used to sample three hills of roots, which were used to measure root oxidation activity (ROA) at three periods after heading: early grain filling (95–96 DAT), mid-grain filling (107–108 DAT), and late grain filling (119–120 DAT). ROA was determined according to the method of Chu *et al.* (2019). The flag leaf net photosynthetic rate was also measured at the early, mid- and late grain filling periods with a portable photosynthesis system (Li-6400XT, Li-Cor, Lincoln, USA).

Following the method described by Chu *et al.* (2022), the activity of sucrose synthase (SuSase, EC 2.4.1.13) and adenosine diphosphoglucose pyrophosphorylase (AGPase, EC 2.7.7.27) in grains was determined at the three periods after heading: early, mid-, and late grain filling.

The grain yield of each plot was determined from 100 plants and adjusted to a moisture content of 14%. The N content in the plants was determined using the Kjeldahl method, and the methods for calculating NUE were based on those of Xue *et al.* (2013).

Statistical analysis

The results of this study were evaluated using analysis of variance (*ANOVA*) with SPSS 25.0 software (SPSS Inc., Chicago, USA). Data from each sampling date were analysed separately. The significance of differences between means was determined using the least significant difference test at the 5% probability level.

Results

Root biomass

The root dry weight at heading was significantly higher in both N fertilizer application treatments than in the 0N treatment (Fig. 2). The root dry weight at heading was significantly higher in the PCU treatment than in the CU treatment (Fig. 2A, B). The study divided the roots into two parts, and there was no significant difference in root dry weight in the 0–10 cm soil layer between the CU and PCU treatment (Fig. 2C, D). However, the root dry weight in the deep soil layer (10–20 cm soil layer) was significantly higher in the PCU treatment than in the CU treatment (Fig. 2E, F).

Number of tillers and percentage of productive tillers

The number of tillers was significantly lower in the 0N treatment than in the CU and PCU treatment during the three periods in which measurements were taken (Table 2). At the jointing period, the number of tillers was significantly higher in the CU treatment than in the PCU treatment (Table 2). However, the difference in the number of tillers was not significant between the CU and PCU treatment at the heading and maturity periods (Table 2). The percentage of productive tillers was significantly higher in the 0N treatment than in the CU treatment, and the difference in the percentage of productive tillers was not significant between the 0N and PCU treatment (Table 2). The percentage of productive tillers was significantly higher in the PCU treatment than in the CU treatment (Table 2).

Shoot dry weight and CGR

The shoot dry weight was significantly lower in the 0N treatment than in the CU and PCU treatment at the jointing, heading and maturity periods (Fig. 3A, B). The shoot dry weight was significantly lower in the PCU treatment than in the CU treatment at the jointing period, and the difference in the shoot dry weight between the PCU and CU treatment at the heading stage was not significant (Fig. 3A, B). However, the shoot dry weight was significantly higher in the PCU treatment than in the CU treatment at the maturity stage (Fig. 3A, B). CGR from transplanting to jointing was significantly higher in the CU treatment than in the PCU treatment, and the CGR was significantly increased from jointing to heading and from heading to maturity in the PCU treatment compared with the CU treatment (Fig. 3C, D).

LAI and LAD

The LAI and LAD were significantly lower in the 0N treatment than in the CU and PCU treatment throughout the growth period (Table 3). The LAI was significantly lower in the PCU treatment than in the CU treatment at the jointing period, and the difference in the LAI between the PCU and CU treatment was not significant at the heading stage (Table 3). However, the LAI was significantly higher in the PCU treatment than in the CU treatment at maturity (Table 3). LAD from transplanting to jointing was significantly higher in the CU treatment than in the PCU treatment (Table 3). The difference in LAD from jointing to heading between the CU and PCU treatment was not significant (Table 3). During the grain-filling period, LAD was significantly higher in the PCU treatment than in the CU treatment (Table 3).

Plant activity during the grain-filling period

ROA was significantly lower in the 0N treatment than in the two N fertilizer application treatments. ROA was higher throughout the grain filling period in the PCU treatment than in the CU

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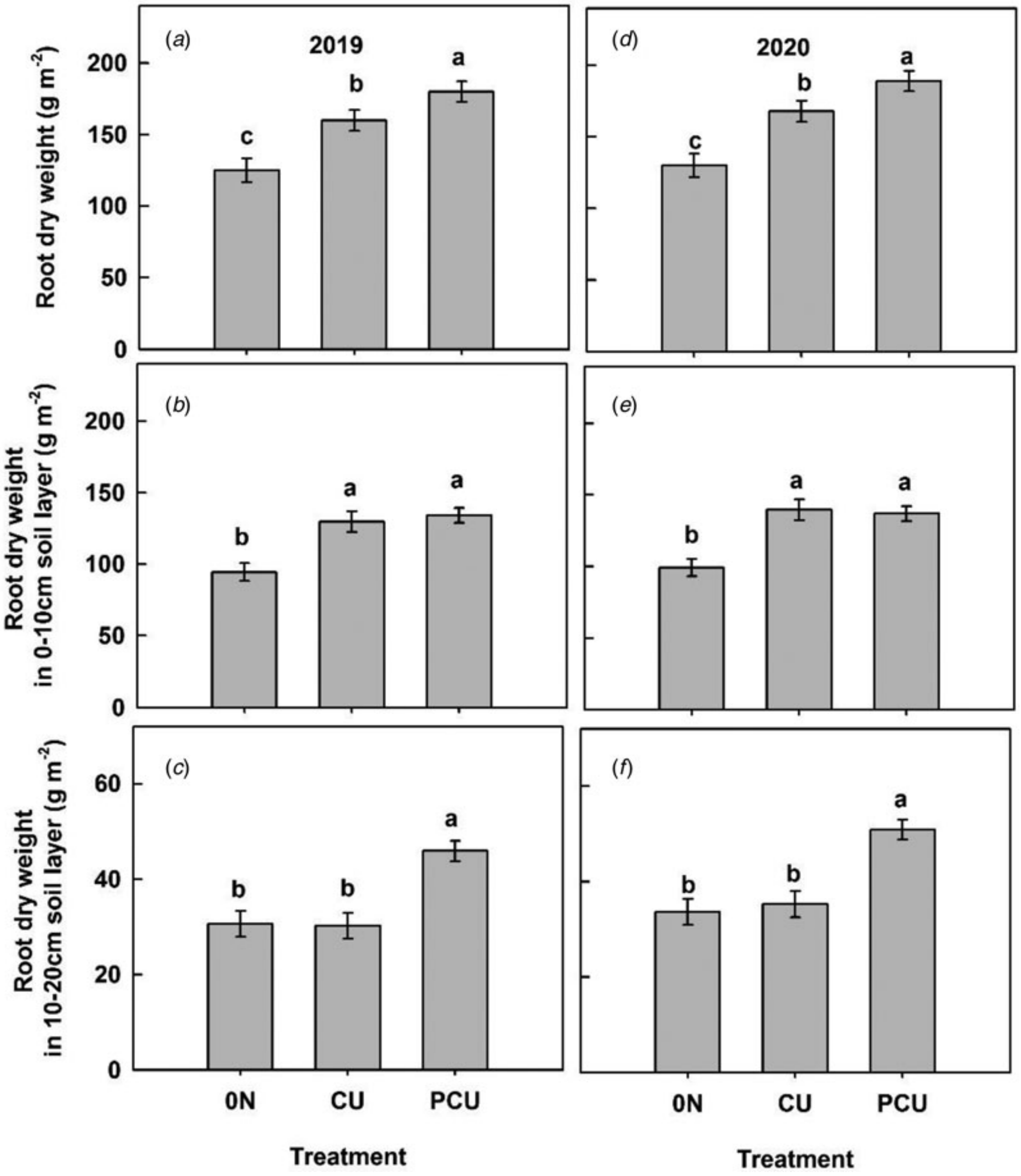

Fig. 2. Root dry weight (A and B), root dry weight in the 0–10 cm soil layer (C and D), and root dry weight in the 10–20 cm soil layer (E and F) of rice grown under different treatments at heading in 2019 and 2020. 0N, CU and PCU represent no N application, conventional urea application (CU) and polymer-coated urea application (PCU), respectively. Vertical bars represent ± standard error of the mean ($n = 3$) (which in some cases does not exceed the size of the symbol). Different letters above the column indicate statistical significance at the $P = 0.05$ level within the same stage.

treatment, indicating that the application of PCU could increase the physiological activity of the root system (Fig. 4A, B). Similar patterns were observed in the flag leaf photosynthetic rate and the activity of SuSase and AGPase in grains during the grain-filling period (Figs 4C, D and 5). A correlation analysis revealed that ROA was significantly positively correlated with the flag leaf net photosynthetic rate and the activity of SuSase and AGPase in grains ($r = 0.79^{**} \sim 0.90^{**}$). These findings indicated the existence of a root–shoot interaction (Table 4).

Grain yield and NUE

The grain yield was significantly increased in the CU and PCU treatments compared with the 0N treatment (Table 5). The grain yield was 1.0–1.3 t/ha higher under the PCU treatment compared with the CU treatment across both study years (Table 5). The difference in productive tillers between the PCU and CU treatment was not significant (Table 5). The total spikelet number per m^2 under the PCU treatment was 5.74×10^4–5.85×10^4, which was significantly higher than that in the CU treatment (Table 5). The increase in the total spikelet number per m^2 under the PCU treatment was mainly attributed to the increase in the number of spikelets per panicle (Table 5). Furthermore, the number of filled grains and grain weight were significantly higher in the PCU treatment than in the CU treatment, suggesting that the higher yield performance in the PCU treatment was not attributed exclusively to the larger sink capacity but also to the greater sink strength (Table 5).

The total N uptake by plants at maturity was significantly higher in the PCU treatment than in the CU treatment

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(Table 6). Furthermore, NUE, including IE_N, PFP_N and AE_N, was significantly higher in the PCU treatment than in the CU treatment (Table 6).

Discussion

Simultaneously increasing grain yield, NUE, and utilizing minimal labour input in China may be challenging when there is an urgent need to increase total crop production due to a rapidly growing human population and scarce human resources. The findings of this study suggest that the one-time application of PCU before transplanting in JIHR cultivars could achieve the dual goal of increasing both grain yield and NUE. However, the mechanism underlying these effects is not fully understood. Our observations in the present study suggest several possible explanations.

Improved root morphological trait

The roots are a critical organ in rice plants that anchor the aboveground part of plants, absorb resources from the soil, and synthesize plant growth regulators (Yang *et al.*, 2012). Root biomass is considered the most important root morphological trait because this trait is closely associated with the nutrient- and water-absorbing ability of roots and aboveground biomass (Chu *et al.*, 2014; Meng *et al.*, 2018). The current study results showed that root dry weight at the heading period was significantly higher in the PCU treatment than in the CU treatment Fig. 2A, B). Furthermore, it was found that deep root (roots in the 10–20 cm

Table 2. The number of tillers and percentage of productive tillers of rice grown under different treatments in 2019 and 2020

	Number of tillers per m^2			
Year/Treatment[a]	Jointing	Heading	Maturity	Productive tillers %[b]
2019				
0N	128^{c}	106^{b}	104^{b}	81.5^{a}
CU	201^{a}	140^{a}	138^{a}	68.7^{c}
PCU	178^{b}	138^{a}	135^{a}	75.7^{b}
2020				
0N	122^{c}	105^{b}	102^{b}	83.4^{a}
CU	205^{a}	147^{a}	144^{a}	70.1^{c}
PCU	182^{b}	145^{a}	140^{a}	76.8^{b}
Analysis of variance				
Year (Y)	NS[d]	NS	NS	NS
Treatment (T)	**	**	**	**
$Y \times T$	NS	NS	NS	NS

[a] 0N, CU and PCU represent no N application, conventional urea application (CU), and polymer-coated urea application (PCU), respectively.

[b] The number of panicles developed from tillers (tillers at maturity)/the number of tillers at the jointing stage.

[c] Different letters indicate statistical significance at the $P = 0.05$ level within the same column and the same year.

[d] NS, not significant at the $P = 0.05$ level.

*Significant at the $P = 0.05$ level.

**Significant at the $P = 0.01$ level.

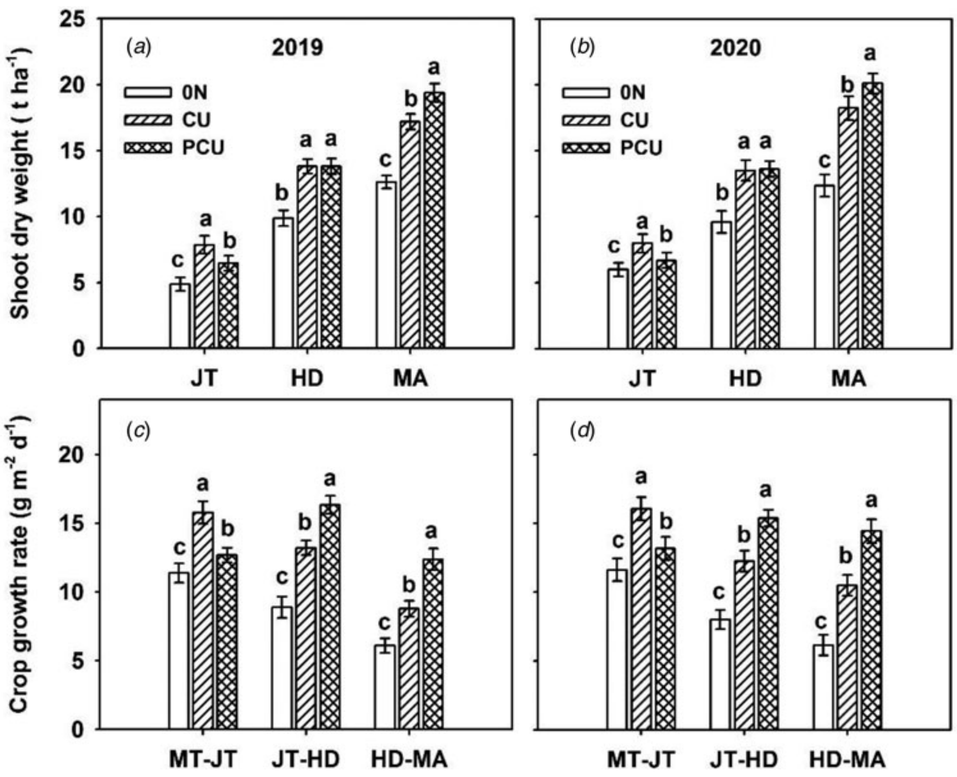

Fig. 3. Shoot dry weight (A and B) and crop growth rate (C and D) of rice grown under different treatments in 2019 and 2020. 0N, CU and PCU represent no N application, conventional urea application (CU) and polymer-coated urea application (PCU), respectively. JT, HD and MA represent jointing (44–45 DAT), heading (83–84 DAT) and physiological maturity (138–139 DAT), respectively. Vertical bars represent ± standard error of the mean ($n = 3$) (which in some cases does not exceed the size of the symbol). Different letters above columns indicate statistical significance at the $P = 0.05$ level within the same stage.

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Table 3. Leaf area index (LAI) and leaf area duration (LAD) of rice grown under different treatments in 2019 and 2020

	LAI			LAD		
Year/Treatment[a]	Jointing	Heading	Maturity	Transplanting-Jointing	Jointing- Heading	Heading-Maturity
2019						
0N	3.83^{c}	5.44^{b}	0.94^{c}	103^{c}	209^{b}	144^{c}
CU	5.98^{a}	7.99^{a}	1.28^{b}	151^{a}	314^{a}	209^{b}
PCU	4.79^{b}	8.11^{a}	2.18^{a}	138^{b}	308	236^{a}
2020						
0N	3.89^{c}	5.22^{b}	0.92^{c}	104^{c}	205^{b}	138^{c}
CU	5.87^{a}	7.91^{a}	1.22^{b}	149^{a}	310^{a}	205^{b}
PCU	4.66^{b}	8.04^{a}	2.13^{a}	135^{b}	302^{a}	231^{a}
Analysis of variance						
Year (Y)	NS[c]	NS	NS	NS	NS	NS
Treatment (T)	**	**	**	**	**	**
$Y \times T$	NS	NS	NS	NS	NS	NS

[a] 0N, CU and PCU represent no N application, conventional urea application (CU) and polymer-coated urea application (PCU), respectively.
[b] Different letters indicate statistical significance at the $P = 0.05$ level within the same column and the same year.
[c] NS, not significant at the $P = 0.05$ level.
*Significant at the $P = 0.05$ level.
**Significant at the $P = 0.01$ level.

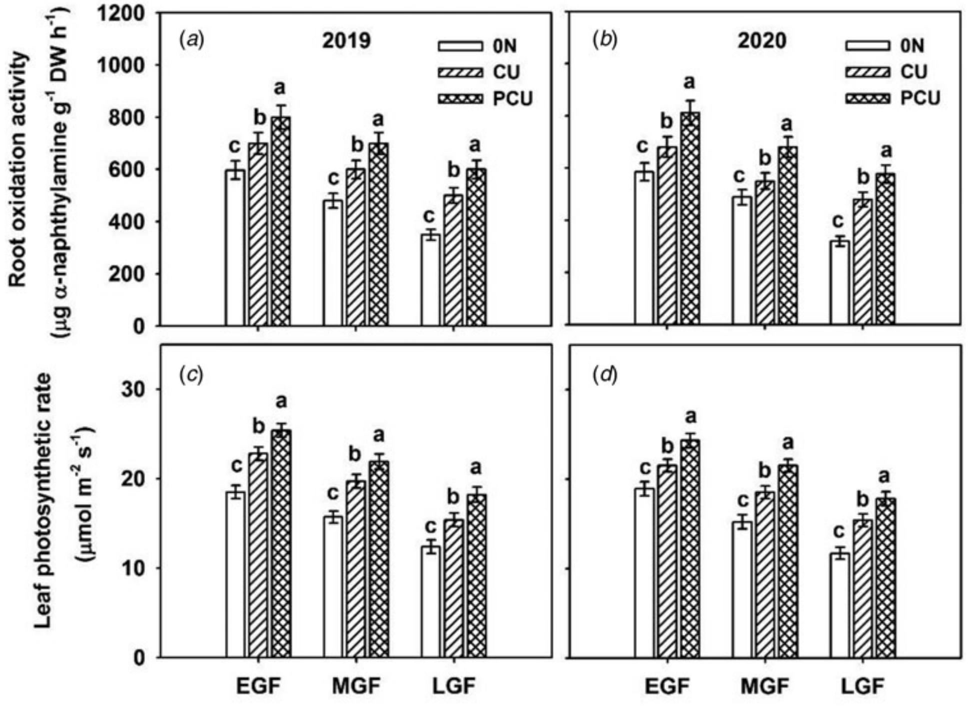

Fig. 4. Root oxidation activity (A and B) and leaf photosynthetic rate (C and D) of rice grown under different treatments during the grain filling period in 2019 and 2020. 0N, CU and PCU represent no N application, conventional urea application (CU) and polymer-coated urea application (PCU), respectively. EGF, MGF and LGF denote the stages of early grain filling (95–96 DAT), mid-grain filling (107–108 DAT) and late grain filling (119–120 DAT). Vertical bars represent ± standard error of the mean ($n = 3$) (which in some cases does not exceed the size of the symbol). Different letters above the column indicate statistical significance at the $P = 0.05$ level within the same stage.

soil layer) biomass was significantly higher in the PCU treatment than in the CU treatment (Fig. 2E, F), suggesting that PCU could promote the entry of the roots into deeper soil layers. The absorption of water and nutrients is thought to be enhanced when the roots penetrate more deeply into the soil (Ju *et al.*, 2015; Meng *et al.*, 2018; Chu *et al.*, 2022). Thus, greater root biomass and a deeper root distribution might have contributed to increased yield performance and NUE in the PCU treatment.

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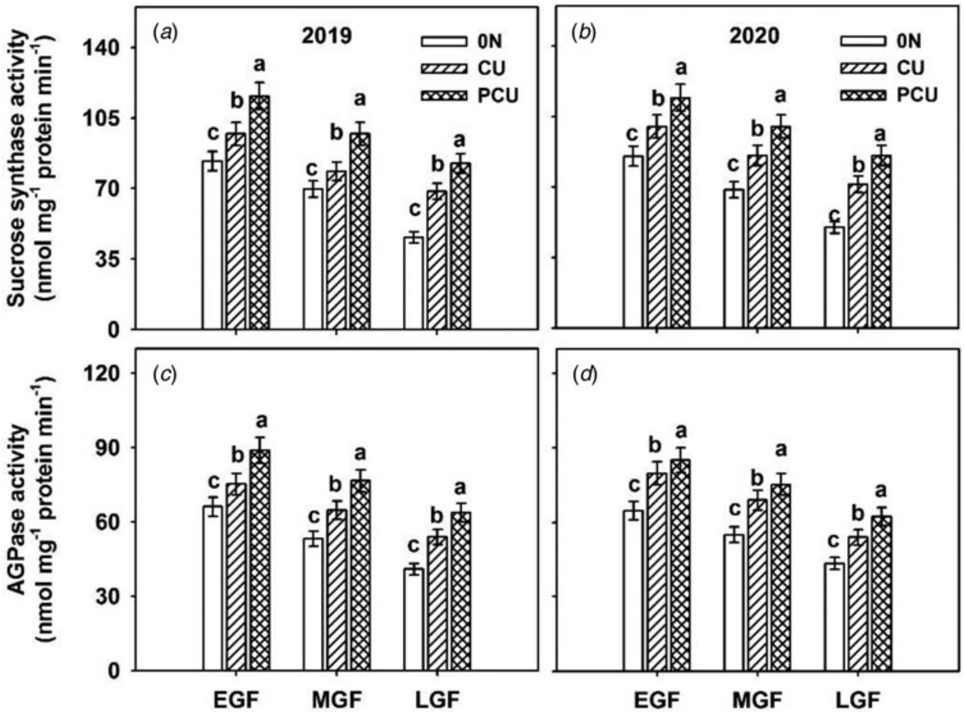

Fig. 5. The activity of SuSase (A and B) and AGPase (C and D) in rice grains under different treatments during the grain filling period in 2019 and 2020. 0N, CU and PCU represent no N application, conventional urea application (CU) and polymer-coated urea application (PCU), respectively. EGF, MGF and LGF denote the stages of early grain filling (95–96 DAT), mid-grain filling (107–108 DAT) and late grain filling (119–120 DAT). Vertical bars represent ± standard error of the mean ($n = 3$) (which in some cases does not exceed the size of the symbol). Different letters above the column indicate statistical significance at the $P = 0.05$ level within the same stage.

Table 4. Correlation coefficients of root oxidation activity (ROA) with leaf photosynthetic rate (Pr) and activity of sucrose synthase (SuSase) and adenosine diphosphate glucose pyrophosphorylase (AGPase) in rice grains

Year	Pr	SuSase	AGPase
2019	0.89**	0.81**	0.79**
2020	0.90**	0.85**	0.87**

**Correlation significant at the $P = 0.01$ level.

Less redundant vegetative growth during the early growth period

Previous studies have indicated that less redundant growth during the vegetative growth phase can reduce the consumption of resources (including N and water) and improve canopy structure (Wang *et al.*, 2016; Zhou *et al.*, 2017; Chu *et al.*, 2019). It was found that the number of tillers at the jointing period was significantly higher in the CU treatment compared with the PCU treatment (Table 2), which was mainly attributed to the large amount of N fertilizer applied during the early vegetative stage. However, there was no significant difference in the number of tillers at the heading and maturity periods between the CU and PCU treatment, and the percentage of productive tillers was significantly lower in the CU treatment than in the PCU treatment (Table 2), which indicates that the application of PCU can reduce redundant growth. Therefore, we suspected that less redundant vegetative during the early growth period of JIHR cultivars under PCU treatment might have contributed to the lower resource use for nonessential tissues and improved the quality of the canopy, thereby leading to higher grain yield and NUE.

Greater higher matter production during the mid and late growth period

Increasing the sink capacity of rice is important for enhancing rice grain yield (Cheng *et al.*, 2007; Yuan, 2017). It was found that the total spikelet number per m^2 was higher in the PCU treatment than in the CU treatment (Table 5). Furthermore, the greater number of spikelets per unit area in the PCU treatment was mainly attributed to an increase in the spikelet number per panicle (Table 5). It was found that the CGR was significantly higher in the PCU treatment than in the CU treatment from jointing to heading (Fig. 3C, D), suggesting that the one-time PCU application before transplanting can enhance shoot biomass accumulation during the reproductive period compared with traditional urea application. Previous studies have indicated that the stronger shoot biomass accumulation ability from jointing to heading not only promotes spikelet differentiation but also reduces spikelet degeneration, thereby increasing the spikelet number per panicle (Ju *et al.*, 2015; Chu *et al.*, 2019). Thus, we suspected that the greater aboveground biomass production during the reproductive period in the PCU treatment might contribute to the strengthened sink capacity, which resulted in a higher grain yield and NUE.

Higher plant activity during the grain-filling period

Grain-filling efficiency has been reported to be negatively related to the sink capacity (Fageria, 2007). In our study, the yield sink capacity and grain filling were enhanced in the PCU treatment compared with the CU treatment (Table 5). Greater activity of the key enzymes involved in the conversion of sucrose to starch in grains can increase sink activity and enhance grain filling (Yang *et al.*, 2003; Zhang *et al.*, 2012). It was found that the activity of SuSase and AGPase was

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Table 5. Grain yield and yield components of rice under different treatments in 2019 and 2020

Year/Treatment^{a}	Grain yield (t/ha)	Panicles per m^{2}	Spikelets per panicle	Total spikelets 10^{4} /m^{2}	Filled grains (%)	Grain weight (mg)
2019						
0N	7.19^{c}	154^{b}	208^{c}	3.20^{c}	90.5^{a}	24.8^{a}
CU	10.0^{b}	188^{a}	298^{b}	5.59^{b}	75.8^{c}	23.5^{c}
PCU	11.0^{a}	185^{a}	310^{a}	5.74^{a}	80.2^{b}	24.0^{b}
2020						
0N	7.04^{c}	152^{b}	202^{c}	3.07^{c}	92.1^{a}	24.9^{a}
CU	10.2^{b}	194^{a}	291^{b}	5.62^{b}	77.2^{c}	23.5^{c}
PCU	11.5^{a}	190^{a}	308^{a}	5.85^{a}	81.2^{b}	24.1^{b}
Analysis of variance						
Year (Y)	NS^{d}	NS	NS	NS	NS	NS
Treatment (T)	**	**	**	**	**	**
$Y \times T$	NS	NS	NS	NS	NS	NS

[a] 0N, CU and PCU represent no N application, conventional urea application (CU) and polymer-coated urea application (PCU), respectively.
[b] Different letters indicate statistical significance at the $P = 0.05$ level within the same column and the same year.
[c] NS, not significant at the $P = 0.05$ level.
*Significant at the $P = 0.05$ level.
**Significant at the $P = 0.01$ level.

Table 6. Nitrogen uptake at maturity and N use efficiency of rice under different treatments in 2019 and 2020

Year/Treatment^{a}	N uptake g/ha	IE$_{N}$ kg/kg^{b}	PFP$_{N}$ kg/kg^{c}	AE$_{N}$ kg/kg^{d}
2019				
0N	119^{c,e}	60.5^{a}	–	–
CU	199^{b}	50.8^{c}	56.2^{b}	16.2^{b}
PCU	208^{a}	53.1^{b}	61.3^{a}	21.4^{a}
2020				
0N	114^{c}	61.7^{a}	–	–
CU	203^{b}	51.2^{c}	57.7^{b}	18.6^{b}
PCU	211^{a}	54.3^{b}	63.6^{a}	24.5^{a}
Analysis of variance				
Year (Y)	NS^{f}	NS	NS	NS
Treatment (T)	**	**	**	**
Y × T	NS	NS	NS	NS

[a] 0N, CU and PCU represent no N application, conventional urea application (CU) and polymer-coated urea application (PCU), respectively.
[b] PFP$_{N}$ = Grain yield in N application plots (kg) / N rate (kg).
[c] IE$_{N}$ = grain yield (kg) / N uptake of plants (kg).
[d] AE$_{N}$ = (grain yield in N application plots – grain yield in N omission plots (kg)) / N rate (kg).
[e] Different letters indicate statistical significance at the $P = 0.05$ level within the same column and the same year.
[f] NS, not significant at the $P = 0.05$ level.
*Significant at the $P = 0.05$ level.
**Significant at the $P = 0.01$ level.

significantly higher in grains in the PCU treatment than in the CU treatment (Fig. 5). Therefore, the PCU treatment could significantly enhance the sink strength by increasing the activity of key enzymes involved in the conversion of sucrose to starch in grains, which can increase grain filling efficiency and thus grain yield and NUE.

ROA is an important root physiological trait, and the greater ROA observed during the grain-filling period might keep the physiological activity of plants high and enhance grain-filling (Osaki *et al.*, 1997; Yang *et al.*, 2012). It was found that ROA was significantly higher in the PCU treatment than in the CU treatment during the grain filling period (Fig. 4A, B). Furthermore, correlation analysis revealed that ROA was significantly positively correlated with the flag leaf net photosynthetic rate and the activity of SuSase and AGPase in grains during the grain-filling period (Table 4). The root and shoot have an interdependent relationship wherein active shoots ensure an abundance of carbohydrates, and this facilitates the development and maintenance of root functions. This activation of root functions can enhance shoot characteristics by providing sufficient nutrients, water and plant hormones to increase crop productivity (Osaki *et al.*, 1997; Yang *et al.*, 2012). Therefore, the application of PCU significantly increased root physiological activity, which contributes to increases in aboveground physiological activity, grain filling, and both the grain yield and NUE.

Conclusion

PCU application could increase grain yield by 1.0–1.3 t/ha, and agronomic NUE by 5.2–5.9 kg/kg compared with CU treatment in JIHR cultivar. The better yield performance and higher NUE were mainly attributed to the higher percentage of productive tillers, greater CGR from jointing to maturity, greater LAD from heading to maturity, larger root biomass and deeper root distribution at heading, higher activity of the key enzymes involved in the conversion of sucrose to starch in grains, higher ROA, and higher net photosynthetic rate of the flag leaves during the grain filling period. PCU application holds great promise for increasing the yield and NUE of JIHR cultivars, as well as reducing labour inputs.

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Ethical standard. Not applicable.

References

Bhatt R and Singh M (2021) Comparative efficiency of polymer-coated urea for lowland rice in semi-arid tropics. *Communications in Soil Science and Plant Analysis* **52**, 2331–2341.

Cheng SH, Cao LY, Zhuang JY, Chen SG, Zhan XD, Fan YY, Zhu DF and Min SK (2007) Super hybrid rice breeding in China: achievements and prospects. *Journal of Integrative Plant Biology* **49**, 805–810.

Chu G, Chen TT, Wang ZQ, Yang JC and Zhang JH (2014) Morphological and physiological traits of roots and their relationships with water productivity in water-saving and drought-resistant rice. *Field Crops Research* **162**, 108–119.

Chu G, Chen TT, Chen S, Xu CM, Zhang XF and Wang DY (2018) Polymer-coated urea application could produce more grain yield in "super" rice. *Agronomy Journal* **110**, 246–259.

Chu G, Chen S, Xu CM, Wang DY and Zhang XF (2019) Agronomic and physiological performance of *indica/japonica* hybrid rice cultivar under low nitrogen conditions. *Field Crops Research* **243**, 107625.

Chu G, Xu R, Chen S, Xu CM, Liu YH, Abliz B, Zhang XF and Wang DY (2022) Root morphological-physiological traits for *japonica/indica* hybrid rice with better yield performance under low N conditions. *Food and Energy Security* **3**, e355.

Deng NY, Grassini P, Yang HS, Huang JL, Cassman KG and Peng SB (2019) Closing yield gaps for rice self-sufficiency in China. *Nature Communications* **10**, 1725.

Fageria NK (2007) Yield physiology of rice. *Journal of Plant Nutrition* **30**, 843–879.

Fan MS, Shen JB, Yuan LX, Jiang RF, Chen XP, Davies WJ and Zhang FS (2012) Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. *Journal of Experimental Botany* **63**, 13–24.

Geng J, Sun Y, Zhang M, Li C, Yang Y, Liu Z and Li S (2015) Long-term effects of controlled release urea application on crop yields and soil fertility under rice-oilseed rape rotation system. *Field Crops Research* **184**, 65–73.

Golden BR, Slaton NA, Norman RJ, Wilson CE and DeLong RE (2009) Evaluation of polymer-coated urea for direct-seeded, delayed-flood rice production. *Soil Science Society of America Journal* **73**, 375–383.

Ju CX, Buresh RJ, Wang ZQ, Zhang H, Liu LJ, Yang JC and Zhang JH (2015) Root and shoot traits for rice varieties with higher grain yield and higher nitrogen use efficiency at lower nitrogen rates application. *Field Crops Research* **175**, 47–55.

Ju XT, Xing GX, Chen XP, Zhang SL, Zhang LJ, Liu XJ, Cui ZL, Yin B, Christie P, Zhu ZL and Zhang FS (2009) Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proceedings of the National Academy of Sciences of the United States of America* **106**, 3041–3046.

Ke J, He RC, Hou PF, Ding C, Ding YF, Wang SH, Liu ZH, Tang S, Ding CQ, Chen L and Li GH (2018) Combined controlled-released nitrogen fertilizers and deep placement effects of N leaching, rice yield and N recovery in machine-transplanted rice. *Agriculture Ecosystems & Environment* **265**, 402–412.

Li P, Lu J, Wang Y, Wang S, Hussain S, Ren T, Cong R and Li X (2018) Nitrogen losses, use efficiency, and productivity of early rice under controlled-release urea. *Agriculture Ecosystems & Environment* **251**, 78–87.

Lyu XX, Yang YC, Li YC, Fan XH, Wan YS, Geng YQ and Zhang M (2015) Polymer-coated tablet urea improved rice yield and nitrogen use efficiency. *Agronomy Journal* **107**, 1837–1844.

Meng TY, Wei HH, Li XY, Dai QG and Huo ZY (2018) A better root morpho-physiology after heading contributing to yield superiority of *japonica/indica* hybrid rice. *Field Crops Research* **228**, 135–146.

Mueller ND, Gerber JS, Johnston M, Ray DK, Ramankutty N and Foley JA (2012) Closing yield gaps through nutrient and water management. *Nature* **490**, 254–257.

Normile D (2008) Reinventing rice to feed the world. *Science (New York, N.Y.)* **321**, 330–333.

Osaki M, Shinano T, Matsumoto M, Zheng T and Tadano T (1997) A root-shoot interaction hypothesis for high productivity of field crops. *Soil Science and Plant Nutrition* **43**, 1079–1084.

Peng SB, Tang QY and Zou YB (2009) Current status and challenges of rice production in China. *Plant Production Science* **12**, 3–8.

Ray DK and Foley JA (2013) Increasing global crop harvest frequency: recent trends and future directions. *Environmental Research Letters* **8**, 044041.

Song KF, Zhang GB, Ma J, Peng SB LVSH and Xu H (2022) Greenhouse gas emissions from ratoon rice fields among different varieties. *Field Crops Research* **277**, 108423.

Vitousek PM, Naylor R, Crews T, David MB, Drinkwater LE, Holland E, Johnes PJ, Katzenberger J, Martinelli LA, Matson PA, Nziguheba G, Ojima D, Palm CA, Robertson GP, Sanchez PA, Townsend AR and Zhang FS (2009) Nutrient imbalances in agricultural development. *Science (New York, N.Y.)* **324**, 1519–1520.

Wang ZQ, Zhang WY, Beebout SS, Zhang H, Liu LJ, Yang JC and Zhang JH (2016) Grain yield, water and nitrogen use efficiencies of rice as influenced by irrigation regimes and their interaction with nitrogen rates. *Field Crops Research* **193**, 54–69.

Wei HY, Zhang HC, Blumwald E, Li HL, Cheng JQ, Dai QG, Huo ZY, Xu M and Guo BW (2016) Different characteristics of high yield formation between inbred *japonica* super rice and inter-sub-specific hybrid super rice. *Field Crops Research* **198**, 179–187.

Wei HY, Hu L, Zhu Y, Xu D, Zheng LM, Chen ZF, Hu YJ, Cui PY, Guo BW, Dai QG and Zhang HC (2018) Different characteristics of nutrient absorption and utilization between inbred *japonica* super rice and inter-sub-specific hybrid super rice. *Field Crops Research* **218**, 88–96.

Xue YG, Duan H, Liu LJ, Wang ZQ, Yang JC and Zhang JH (2013) An improved crop management increases grain yield and nitrogen and water use efficiency in rice. *Crop Science* **53**, 271–284.

Yang JC, Zhang JH, Wang ZQ, Zhu QS and Liu LJ (2003) Activities of enzymes involved in sucrose-to-starch metabolism in rice grains subjected to water stress during filling. *Field Crops Research* **81**, 69–81.

Yang JC, Zhang H and Zhang JH (2012) Root morphology and physiology in relation to the yield formation of rice. *Journal of Integrative Agriculture* **11**, 920–926.

Yu YQ, Huang Y and Zhang W (2012) Changes in rice yields in China since 1980 associated with cultivar improvement, climate and crop management. *Field Crops Research* **136**, 65–75.

Yuan LP (2017) Progress in super-hybrid rice breeding. *Crop Journal* **5**, 100–102.

Zhang GQ (2020) Prospects of utilization of inter-subspecific heterosis between *indica* and *japonica* rice. *Journal of Integrative Agriculture* **19**, 1–10.

Zhang H, Li HW, Yuan LM, Wang ZQ, Yang JC and Zhang JH (2012) Post-anthesis alternate wetting and moderate soil drying enhances activities of key enzymes in sucrose-to-starch conversion in inferior spikelets of rice. *Journal of Experimental Botany* **63**, 215–227.

Zhang WY, Yu JX, Xu YJ, Wang ZQ, Liu LJ, Zhang H, Gu JF, Zhang JH and Yang JC (2021) Alternate wetting and drying irrigation combined with the proportion of polymer-coated urea and conventional urea rates increases grain yield, water and nitrogen use efficiencies in rice. *Field Crops Research* **268**, 108165.

Zhou Q, Ju CX, Wang ZQ, Zhang H, Liu LJ, Yang JC and Zhang JH (2017) Grain yield and water use efficiency of super rice under soil water deficit and alternate wetting and drying irrigation. *Journal of Integrative Agriculture* **16**, 1028–1043.

Zhu KY, Zhou Q, Shen Y, Yan JQ, Xu YJ, Wang ZQ and Yang JC (2020) Agronomic and physiological performance of an *indica-japonica* rice variety with a high yield and high nitrogen use efficiency. *Crop Science* **60**, 1556–1568.

Zou HT, Ba C, Hou ZH, Guo NX, Yang M and Sun D (2022) How optimizing application of coated controlled-release urea affects crop yield in China. *Agronomy Journal* **114**, 991–999.

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