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RESEARCH ARTICLE

Optimized application of controlled-release nitrogen improves grain yield, nitrogen use efficiency, and lodging resistance in rice

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Highlights

- Controlled-release nitrogen (CRN)-urea integration improves rice yield, nitrogen use efficiency (NUE) and lodging resistance concurrently.
- CRN-urea strengthens rice stems by increasing vascular bundles, silicon layer and carbohydrates.
- 70%CRN with 30% basal urea optimizes rice yield, NUE and lodging resistance.

Abstract

Lodging is a primary factor limiting rice grain yield. Achieving synergistic improvements in grain yield and nitrogen use efficiency (NUE) without increasing lodging risk has been a global research priority. In this study, two rice cultivars — Yongyou 2640 (*indica–japonica* hybrid rice) and Jinxiangyu 1 (inbred *japonica* rice) — were evaluated in field experiments conducted over two growing seasons. Six nitrogen management strategies were implemented: no nitrogen (T1), conventional urea (T2), controlled-release nitrogen (CRN) (T3), reduction of CRN (T4), CRN combined with single basal application of conventional urea (T5), and CRN combined with split applications of conventional urea (T6). Compared with T2, the integrated nitrogen strategies (T5 and T6) increased NUE by 4.89–5.69% and grain yield by 3.41–4.65%. These treatments also enhanced structural integrity of the second basal internode, evidenced by increased carbohydrate content, internode breaking strength, epidermal silicon layer thickness, number of large and small vascular bundles, and thickness of both parenchymatous and mechanical tissues. Concurrently, internode length, bending moment, and lodging index were reduced. Collectively, these findings indicate that integrating CRN with conventional urea improves morphological, mechanical, physicochemical, and anatomical properties of the second basal internode, thereby enhancing stem strength and enabling high yield and NUE without compromising lodging resistance.

Keywords: rice (*Oryza sativa* L.), nitrogen use efficiency, controlled-release nitrogen, stem, lodging resistance

1. Introduction

Rice (*Oryza sativa* L.) plays a critical role in global food security and is cultivated in over 95 countries worldwide (Chen *et al.* 2021). In China, rice accounts for 32% of total grain production and serves as a primary dietary staple for more than half of the world's population (Liu *et al.* 2023). Nitrogen (N) management is essential for achieving high rice yields (Wang *et al.* 2022; Hoang *et al.* 2023). Excessive nitrogen application results in nitrogen loss, reduced nitrogen use efficiency (NUE), environmental degradation, and increased risk of rice lodging (Wu *et al.* 2023). Lodging complicates mechanical harvesting, and prolonged exposure of lodged plants to high surface humidity increases susceptibility to pest infestations and disease outbreaks (Salassi *et al.* 2013). Furthermore, stem breakage from lodging damages the vascular bundles, impedes the translocation of carbon, nitrogen, and organic matter to the panicle, and ultimately reduces grain yield (Kashiwagi and Ishimaru 2004).

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Rice exhibits two distinct peaks in nitrogen uptake: one from transplanting to panicle initiation and another from panicle initiation to heading (Wang *et al.* 2021). Effective N management strategies should therefore align with these critical periods of nitrogen demand. Controlled-release nitrogen (CRN), due to its engineered coating, releases nutrients at a rate that better matches plant requirements across the growing season, thereby minimizing nitrogen losses and enhancing NUE (Ransom *et al.* 2020; Guo *et al.* 2022). These fertilizers typically display a continuous nutrient release pattern governed by a multi-stage diffusion mechanism, often following a single-peak "J" or "S" shaped curve. Consequently, combining CRN with conventional urea represents a more efficient strategy, balancing nitrogen supply to sustain high yields. Controlled-release fertilizers employ various polymer coatings and are classified by material type into sulfur-coated, resin-coated, and urease inhibitor-coated formulations. Based on manufacturing methods, they can also be categorized as compound, blended, or mixed types. While most studies focus on the effects of CRN on soil organic matter, greenhouse gas emissions, and rice yield, research on its impact on lodging resistance remains limited.

Generally, two types of lodging occur in rice. Root lodging arises from root plate tilting and typically occurs during the wax ripening stage. Stem lodging poses the greater threat to yield, occurring when the basal internodes bend or fracture, usually after heading (Zhang *et al.* 2016b). Thus, a key challenge in increasing grain yield while maintaining lodging resistance lies in strengthening the lower stem internodes (Zhang *et al.* 2014). Rice lodging resistance is strongly influenced by plant height and the length, diameter, wall thickness, and plumpness of basal internodes (Fan *et al.* 2018). Among morphological traits, the outer diameter and cross-sectional thickness of basal internodes significantly determine stem breaking strength (Hirano *et al.* 2014). Additionally, cellulose, lignin, and non-structural carbohydrates in cell walls contribute to mechanical strength and lodging resistance (Zhao *et al.* 2019). Previous studies suggest that both high grain yield and lodging resistance can be achieved by moderately shortening basal internodes while increasing the length and plumpness of internodes beneath the panicle (Jing *et al.* 2017; Liu *et al.* 2018). Mechanical tissue thickness, along with the number and cross-sectional area of vascular bundles in the stem, are also closely associated with lodging resistance (Gui *et al.* 2018; Gao *et al.* 2022). In inbred japonica varieties and *indica–japonica* hybrids, the lodging index (LI) increases slightly with higher nitrogen rates, yet no actual lodging occurs under high nitrogen due to low and stable leaf angles. A significant interaction exists between genotypes and nitrogen levels; varieties with smaller top-three leaf angles exhibit resistance to lodging even under high nitrogen conditions (Ding *et al.* 2021). Increased nitrogen application reduces stem bending resistance by promoting greater plant height, raising the center of gravity, and elongating basal internodes (Zhang *et al.* 2016b). CRN has been shown to enhance lodging resistance in early-maturing rapeseed (*Brassica napus* L.) (Tian *et al.* 2016). When applied at equivalent or lower rates than urea, CRN improves rice uptake of potassium (K) and silicon (Si), which strengthens stems and enhances lodging resistance. Moreover, reductions in lodging index indicate that CRN further improves structural resilience (Zhang S G *et al.* 2019). Excessive nitrogen downregulates genes involved in lignin biosynthesis, leading to insufficient lignin deposition in secondary cell walls, weakened mechanical tissues, and reduced lodging resistance (Zhang *et al.* 2017).

In this study, we investigated whether and how an optimized application strategy for CRN in rice could achieve the triple objective of increasing grain yield, NUE, and lodging resistance. Special emphasis was placed on the morphological, mechanical and physicochemical properties, and anatomical indicators of stem. The relationships of yield, NUE, and lodging resistance and stem characteristics were analyzed. We demonstrate that a combined application strategy using CRN fertilizer can achieve relatively high yields while preserving strong lodging resistance. This study provides a theoretical foundation and practical guidance for optimizing nitrogen management in rice production to simultaneously improve yield, resource use efficiency, and crop resilience.

2. Materials and methods

2.1. Rice cultivation and experimental design

A field study was conducted at the Research Farm of Yangzhou University, Jiangsu Province, China (32°30´N, 119°25´E) during the rice growing season from May to October in both 2022 and 2023. The soil was classified as sandy loam (Typic fluvaquents, Entisols, U.S. Soil Taxonomy). The preceding crop in the experimental field was wheat. The tested varieties were Yongyou 2640 (YY2640, *indica–japonica* hybrid rice) and Jinxiangyu 1 (JXY1, inbred *japonica* rice). Seedlings were raised using trays. Meteorological data for the rice growing season over the two years were recorded by a weather station near the experimental site and are presented in Table 1.

The experiment followed a randomized complete block design with three replications. Each plot measured 20 m² and was separated by a 1-m-wide alley. Plastic film was inserted 0.50 m deep into the soil to serve as a barrier between plots. Phosphorus (30 kg P ha^{-1} as single superphosphate) and potassium (40 kg K ha^{-1} as KCl) were applied and incorporated into the soil prior to transplanting as basal fertilization. Six nitrogen management treatments were implemented as described below.

T1: 0N (no nitrogen application). Planting spacing was 10.7 cm×30 cm. Irrigation was managed using alternate wetting and moderate soil drying (AWD). AWD was applied from 10 days after transplanting until maturity, following the protocol of Zhang *et al.* (2021).

T2: Conventional urea (CK). Nitrogen was applied at 270 kg N ha^{-1} in a 4:2:2:2 ratio at pre-transplanting, mid-tillering, panicle initiation, and spikelet differentiation stages. Row spacing and water management were identical to those in T1.

T3: 100% CRN. The nitrogen content of the product was 44.5% (Product: Maoshi Agricultural Technology Co., Ltd., www.moith.com). The controlled-release fertilizer used in

Table 1 Meteorological data for the rice growing season in the experimental area[1)]

Month	Precipitation (mm mon^{-1})		Solar radiation (MJ m^{-2} mon^{-1})		Mean temperature (°C)	
	2022	2023	2022	2023	2022	2023
May	14.32	74.09	635.97	424.13	20.80	21.03
June	92.46	126.41	616.04	413.75	27.42	24.68
July	160.71	199.59	594.25	325.64	29.60	27.94
August	40.07	79.65	557.83	435.29	30.00	27.15
September	54.76	56.76	429.92	290.57	23.10	23.92
October	69.05	7.58	414.91	355.48	16.85	18.56

[1)] Precipitation value is monthly total; solar radiation value is monthly total; mean temperature value is the monthly average.

this study was resin-coated, with a nutrient release duration of 120 days. A total of 270 kg N ha^{-1} was applied as a single basal application at pre-transplanting. All other management practices were the same as in T2.

T4: Reduction of CRN. Nitrogen application was reduced by 11.1%, resulting in a total of 240 kg N ha^{-1}, applied as a single basal application at pre-transplanting. All other management practices were consistent with T2.

T5: CRN combined with single basal application of conventional urea (70% CRN+30% conventional urea). Total nitrogen application was 240 kg N ha^{-1}. Both CRN and conventional urea were applied together as a single basal application at pre-transplanting. Other management measures matched those in T2.

T6: CRN combined with split applications of conventional urea (70% CRN+30% conventional urea). Total nitrogen input was 240 kg N ha^{-1}. CRN was applied as a single basal dose at pre-transplanting, while conventional urea was split in a 5:5 ratio, with half applied at pre-transplanting and half at panicle initiation. All other management practices were identical to those in T2.

2.2. Morphological properties of stem

Thirty days after heading, 15 representative main stems were selected from each plot for morphological assessment. Measured traits included plant height, center of gravity height, panicle length (N0), and lengths of the basal internodes: first (N1), second (N2), third (N3), fourth (N4), and fifth (N5).

2.3. Mechanical properties of stem

Thirty days after heading, 15 representative main stems from each plot were sampled to determine mechanical strength. For each stem, length and center of gravity height were recorded. The breaking force of the second basal internode (N2), including the leaf sheath, was measured using a plant lodging tester (YYD-1, Top Instrument Co., Ltd.). The inner and outer diameters along the long and short axes of the hollow oval stem were measured with a vernier caliper. Mechanical parameters were calculated according to the methodology of Zhang *et al.* (2014).

2.4. Physicochemical properties of stem

Thirty days after heading, 15 representative main stems were collected from each plot, and the second basal internodes (N2) were excised. All N2 samples were oven-dried at 75°C until constant weight was achieved. Dried samples were ground into powder, passed through a 100-mesh sieve, stored, and used for physicochemical component analysis. Non-structural carbohydrate (NSC) and cellulose contents were determined using the anthrone colorimetric method (Li *et al.* 2017). Lignin content was quantified *via* the acetyl bromide lignin assay (Syros *et al.* 2004).

2.5. Anatomical indicators of stem

Thirty days after heading, 15 main stems were sampled from each plot. Sample preparation for anatomical analysis followed the procedure described by Chen C *et al.* (2023). Image analysis software (Axio-vision Rel.4.6) was used to quantify the number and area of large and small vascular bundles, parenchyma cell thickness and layer count, mechanical tissue thickness and layer count, and the distance between adjacent vascular bundles. Microscale distributions of phosphorus (P), silicon (Si), magnesium (Mg), and calcium (Ca) in the stem were analyzed using scanning electron microscopy coupled with energy dispersive X-ray spectroscopy (Gemini SEM 300 with Aztec EDS, Carl Zeiss, Germany).

2.6. Final harvest

Yield components — including number of panicles per square meter, percentage of filled grains, and grain weight — were determined from 50 randomly selected plants per plot, excluding border rows. Grain yield was assessed from all plants within a 5 m^2 area per plot, also excluding border plants.

2.7. Statistical analysis

The bending moment of the whole plant applied to the basal internode (WP, g cm) was calculated as WP=SL×FW, where SL is the distance from the basal internode break site to the top of the main stem (cm), and FW is the fresh weight from the break site to the top of the spike (g).

Breaking moment (M, g cm) was calculated as M=F×L/4, where F is the force (g) required to break the basal internode segment, and L is the distance between the two fulcrum points (cm).

The section modulus (Z, mm^3) of the basal elliptic hollow internode cross-section was calculated as $Z=\pi/32\times(a_1^3b_1-a_2^3b_2)/a_1$; where a_1 and a_2 represent the outside and inside diameters of the short axis, and b_1 and b_2 represent the outside and inside diameters of the long axis (unit: mm).

Bending stress of stem material strength (BS, g mm^{-2}) was computed as BS=M/Z.

Lodging index (LI, %) was determined as LI=WP/M.

Agronomic NUE (AE, kg kg^{-1}) was calculated as the difference between grain yield in nitrogen-applied and zero-nitrogen plots, divided by the amount of nitrogen applied.

Apparent recovery efficiency of nitrogen (RE, %) was calculated as: [(Nitrogen uptake in above-ground biomass in nitrogen-applied plots–Nitrogen uptake in zero-nitrogen plots)/Nitrogen applied]×100.

Physiological NUE (PE, kg kg^{-1}) was calculated as the difference in grain yield between nitrogen-applied and zero-nitrogen plots, divided by the difference in nitrogen uptake in above-ground biomass.

Partial factor productivity of nitrogen (PFP, kg kg^{-1}) was computed as grain yield divided by the amount of nitrogen applied.

All data were compiled using Microsoft Office Excel 2021 (Microsoft Corp., Redmond, WA, USA). Analysis of variance (ANOVA) was performed using IBM SPSS Statistics 26 (IBM Corp., Armonk, NY, USA). Graphs were generated using Origin 2021 software (OriginLab Corp., Northampton, MA, USA) and R version 4.2.1 (R Core Team, 2022, Vienna, Austria). Mean difference significance test was conducted by P=0.05 minimum significant range method ($LSD_{0.05}$). Correlation and Path coefficients for stem characteristics, lodging index, yield, and NUE under CRN were analyzed using linear stepwise regression models. Path coefficients and coefficients of determination (R^2) were used to assess the strength and direction of relationships among variables and to evaluate the proportion of variance explained.

3. Results

3.1. Grain yield and its components

Among the six treatments, T5 produced the highest grain yield for both YY2640 and JXY1. Under a total nitrogen (N) application rate of 270 kg N ha^{-1}, the average grain yield for YY2640 and JXY1 under T3 increased by 2.31 and 3.19%, respectively, compared to CK across two years. In contrast, grain yields under T4 decreased by 3.55 and 3.97% for the two varieties relative to T3. Compared with CK, T5 and T6 increased grain yield by 5.86 and 4.16% in 2022, and by 4.72 and 3.78% in 2023, respectively. For the same treatment, grain yield was consistently higher in YY2640 than in JXY1 (Table 2).

Regarding yield components, the increased yield under T5 and T6 was attributed to greater total spikelet production, which resulted from simultaneous improvements in panicle number and spikelets per panicle. Compared with CK, T5 significantly increased panicle number by 3.10–6.00%, spikelets per panicle by 0.03–1.86%, and total spikelets by 4.87–6.28%. Similarly, T6 significantly increased panicle number by 1.39–4.61%, spikelets per panicle by 1.29–7.69%, and total spikelets by 2.70–10.34% (Table 2).

3.2. N uptake and NUE of rice

Compared with CK, AE increased by 22.83 and 26.59% for YY2640 and JXY1 under T5 across two years, and by 19.83 and 23.95% under T6, respectively. Partial factor productivity of nitrogen (PFP) increased by 18.02 and 18.89% under T5, and by 16.34 and 17.71% under T6. Under a total N rate of 240 kg N ha^{-1}, PE increased by 6.35 and 6.37% under T5, and by 3.57 and 3.86% under T6 compared to T4. Apparent recovery RE increased by 5.03 and 7.93% under T5, and by 5.21 and 17.76% under T6, respectively (Table 3).

3.3. Stem morphology properties

Plant height and center of gravity height were the highest under T2 and the lowest under T5 at 30 days after heading. Reduced N application treatments (T4, T5, and T6) reduced both plant height and center of gravity height. Compared with CK, plant height for YY2640 and JXY1 decreased by 8.68 and 15.34% under T5 in 2022, and by 4.91 and 14.84% in 2023, respectively. Center of gravity height decreased by 8.50 and 6.09% for YY2640 and JXY1 in 2022, and by 17.23 and 5.16% in 2023. Across treatments, plant height and center of gravity height were higher in YY2640 than in JXY1 (Fig. 1).

The length of the second basal internode was greatest under T2, while reduced N treatments (T4, T5, and T6) suppressed its elongation. Compared with CK, the second basal internode length decreased by 15.64 and 28.55% under T5, and by 16.96 and 26.59% under T6 for YY2640 and JXY1, respectively, across two years. Under the same treatment, the second basal internode was shorter in JXY1 than in YY2640 (Fig. 2).

3.4. Stem mechanics properties

Compared with CK, controlled-release N (T3, T4, T5, and T6) significantly enhanced stem breaking strength and breaking resistance, while significantly reducing bending moment and lodging index. These effects were more pronounced under reduced N treatments (T4, T5, and T6), with T5 showing superior performance compared to T6. Stem mechanical properties were generally better in JXY1 than in YY2640 under identical treatments. Significant differences were observed among years, varieties, and treatments (Table 4). Linear regression analysis revealed that LI was inversely correlated with stem breaking resistance (F) and breaking strength (M), and positively correlated with bending moment (WP) (Fig. 3).

3.5. Physicochemical properties of stem

Compared with CK, total soluble sugar (Fig. 4-A and C) and starch (Fig. 4-B and D) contents in the stem and sheath of the second basal internode were significantly elevated under T5 for both YY2640 and JXY1 across two years. Total soluble sugar content increased by 43.70 and 28.17% for YY2640 and JXY1, respectively, while starch content increased by 30.11 and 31.03%. The highest total soluble sugar and starch contents across both years were observed under T1.

Lignin (Fig. 5-A and C) and cellulose (Fig. 5-B and D) contents in the stem and sheath of the second basal internode were substantially higher than those of total soluble sugar and starch under the same treatment. Compared with CK, controlled-release N (T3–T6) increased lignin and cellulose contents, with the most pronounced effect under T5. Lignin content increased by 13.27 and 11.25% for YY2640 and JXY1, respectively, while cellulose content increased by 16.71 and 11.95% under T5 across two years.

Table 2 Effects of controlled-release nitrogen on rice yield and associated yield components

Year/Variety	Treatment[1)]	Number of anicles ($\times10^4$ ha^{-1})	Spikelets per panicle	Total spikelets ($\times10^6$ ha^{-1})	1,000-grain weight (g)	Filled grains (%)	Yield (t ha^{-1})
2022							
YY2640	T1	180 c	183 e	328 e	24.91 a	66.9 e	3.74 e
	T2	248 b	221 d	548 d	24.12 c	84.4 a	10.19 cd
	T3	262 a	234 b	614 a	23.35 f	80.5 d	10.41 bc
	T4	256 a	225 c	576 c	24.02 e	80.4 d	9.97 d
	T5	260 a	224 c	581 bc	24.27 b	83.7 b	10.76 a
	T6	246 b	238 a	586 b	24.06 d	82.5 c	10.56 ab
JXY1	T1	192 d	123e	237 e	24.86 a	69.0 d	3.56 d
	T2	282 c	148 d	416 d	24.46 b	77.8 a	7.50 bc
	T3	294 b	152 b	447 b	24.16 e	75.7 b	7.76 ab
	T4	297 b	148 d	439 c	24.18 d	74.3 c	7.43 c
	T5	306 a	149 c	457 a	24.24 c	77.8 a	7.96 a
	T6	295 b	156 a	459 a	24.24 c	77.1 a	7.87 a
2023							
YY2640	T1	129 e	238 d	307 c	25.33 a	90.4 a	6.81 d
	T2	222 b	255 c	566 b	24.51 d	88.3 d	12.20 bc
	T3	218 c	269 a	586 a	24.64 c	88.8 c	12.50 abc
	T4	215 d	258 c	554 b	24.72 bc	89.2 b	12.14 c
	T5	225 a	261 bc	587 a	24.83 b	89.0 bc	12.71 a
	T6	219 c	267 ab	584 a	24.84 b	88.7 c	12.59 ab
JXY1	T1	208 f	124 d	258 d	26.28 a	87.4 a	5.42 d
	T2	287 c	155 c	445 b	25.62 b	81.7 e	8.95 bc
	T3	274 d	162 a	444 b	25.51 cd	82.3 d	9.21 ab
	T4	270 e	157 b	424 c	25.32 e	83.4 c	8.87 c
	T5	297 a	154 c	457 a	25.54 c	83.7 b	9.42 a
	T6	291 b	157 b	457 a	25.47 d	83.6 b	9.34 a
Analysis of variance							
Year (Y)		**	**	NS	**	**	**
Variety (V)		**	**	**	**	**	**
Treatment (T)		**	**	**	**	**	**
Y×V		**	**	**	**	**	**
Y×T		**	*	**	**	**	**
V×T		**	NS	**	**	**	**
Y×V×T		**	**	**	**	**	NS

[1)] T1, no nitrogen; T2, conventional urea; T3, controlled-release nitrogen; T4, reduction of controlled-release nitrogen; T5, controlled-release nitrogen combined with single basal application of conventional urea; T6, controlled-release nitrogen combined with split applications of conventional urea.
In the same year, different treatments within the same variety with different letters indicate statistically significant differences at P=0.05. * and ** indicate significant differences at $P\leq0.05$ and $P\leq0.01$, respectively; NS indicates no significant difference at $P\leq0.05$.

3.6. Anatomical indicators of stem

Compared with CK, T3 slightly increased the number and cross-sectional area of large and small vascular bundles in the second basal internode, with a more noticeable effect under T4. The greatest values were recorded under T5 and T6. Specifically, under T5, the number of large vascular bundles increased by 86.00 and 49.16%, and small vascular bundles by 49.14 and 54.36% for YY2640 and JXY1, respectively, compared to CK. Both the number and area of vascular bundles were greater in JXY1 than in YY2640 under the same treatment (Table 5).

T3 increased parenchyma tissue thickness and the number of cell layers, with cells arranged more compactly. Reduced N treatments (T4–T6) induced more substantial increases, with T5 having the most significant effect. Trends in mechanical tissue thickness and cell layer number paralleled those of parenchyma tissue, with no marked difference between varieties. No significant annual variation was observed in stem anatomical structure, but treatment effects were significant (Table 5).

According to SEM-EDS mapping, P, Mg, and Ca were uniformly distributed in the second basal internode, with no notable differences among treatments. Phosphorus content in the stem wall was significantly higher than Si, Mg, and Ca. Compared with 0N, all treatments reduced Si enrichment in the epidermis of stem internodes. However, compared with CK, controlled-release N (T3–T6) increased the thickness of the epidermal Si layer, with more pronounced Si accumulation under T5 and T6 (Figs. 6 and 7).

3.7. Relationships among yield, AE and stem strength

Physicochemical properties (total soluble sugar, starch, lignin, and cellulose contents) and anatomical traits (vascular bundle area, parenchyma tissue) of the second basal internode were mostly positively correlated with PE, PFP, and RE. Bending moment, lodging index, and the length of the second

Table 3 Effects of controlled-release nitrogen on nitrogen uptake and nitrogen use efficiency of rice

Year/Variety	Treatment[1)]	N uptake (kg N ha^{-1})	Agronomic nitrogen use efficiency (kg kg^{-1})	Physiological nitrogen use efficiency (kg kg^{-1})	Apparent recovery efficiency of nitrogen (%)	Partial factor productivity of nitrogen (kg kg^{-1})
2022						
YY2640	T1	73.54 d				
	T2	190.19 c	23.87 d	55.21 a	43.29 d	37.72 c
	T3	205.27 a	24.69 cd	50.54 b	48.88 c	38.54 c
	T4	196.99 b	25.97 b	50.42 b	51.54 b	41.56 b
	T5	203.17 a	29.24 a	54.06 a	54.11 a	44.83 a
	T6	200.41 ab	28.41 a	53.64 a	52.96 ab	43.99 a
JXY1	T1	67.50 d				
	T2	151.49 c	14.59 c	47.17 ab	31.00 b	27.78 c
	T3	168.29 a	15.55 bc	41.69 c	37.33 a	28.73 c
	T4	157.00 bc	16.14 b	43.29 bc	37.29 a	30.97 b
	T5	162.64 ab	18.33 a	46.34 ab	39.64 a	33.16 a
	T6	160.49 b	17.94 a	46.36 ab	38.75 a	32.78 a
2023						
YY2640	T1	104.47 d				
	T2	223.77 bc	19.96 c	45.25 a	44.19 c	45.19 c
	T3	232.72 a	21.07 bc	44.38 a	47.50 bc	46.30 c
	T4	220.48 c	22.21 b	45.97 a	48.34 ab	50.58 b
	T5	226.36 abc	24.58 a	48.49 a	50.79 ab	52.96 a
	T6	229.36 ab	24.08 a	46.31 a	52.04 a	52.46 a
JXY1	T1	93.88 e				
	T2	186.43 b	13.07 b	38.18 b	34.28 bc	33.15 c
	T3	198.24 a	14.04 b	36.33 b	38.65 a	34.11 c
	T4	168.25 d	14.38 b	46.50 a	30.99 c	36.96 b
	T5	175.36 cd	16.67 a	49.14 a	33.95 bc	39.25 a
	T6	178.56 bc	16.33 a	46.79 a	35.28 ab	38.92 a
Analysis of variance						
Year (Y)		**	**	**	**	**
Variety (V)		**	**	**	**	**
Treatment (T)		**	**	**	**	**
Y×V		*	**	**	NS	**
Y×T		**	NS	**	**	NS
V×T		NS	NS	NS	NS	**
Y×V×T		NS	NS	NS	NS	NS

[1)] T1, no nitrogen; T2, conventional urea; T3, controlled-release nitrogen; T4, reduction of controlled-release nitrogen; T5, controlled-release nitrogen combined with single basal application of conventional urea; T6, controlled-release nitrogen combined with split applications of conventional urea.

In the same year, different treatments within the same variety with different letters indicate statistically significant differences at P=0.05. * and ** indicate significant differences at P≤0.05 and P≤0.01, respectively; NS indicates no significant difference at P≤0.05.

basal internode were significantly negatively correlated with starch, lignin, and cellulose contents; vascular bundle number and area; mechanical tissue thickness; and cell layer count. Conversely, breaking strength and stem breaking resistance were positively correlated with these structural and compositional factors. Mantel's analysis confirmed significant correlations among grain yield, lodging index, AE, and bending moment, breaking strength, breaking resistance, second basal internode length, vascular bundle number, and cellulose content (Fig. 8).

Correlation and path coefficient analyses indicated that CRN directly improved NUE, explaining 92.5% of its variation, and indirectly enhanced grain yield. It also significantly influenced morphological, mechanical, physicochemical properties and anatomical indicators, accounting for 39.2, 57.4, 87.0, and 46.4% of their respective variations. By improving stem characteristics, CRN reduced lodging index and thereby increased yield (Fig. 9).

4. Discussion

4.1. Effects of CRN on yield and NUE

Applying nitrogen fertilizer is widely recognized as the primary method for enhancing rice yield. However, conventional nitrogen application presents several challenges, including high labor requirements, difficulty in timing fertilization accurately, and sensitivity to seasonal precipitation patterns in rice production (Chen C *et al.* 2023). CRN can reduce environmental nitrogen losses — such as leaching and ammonia volatilization — while improving nitrogen availability to plants (Zhang W S *et al.* 2019). The use of CRN has been shown to enhance both NUE and grain yield in rice (Sun *et al.* 2019). Nevertheless, some studies have reported that CRN may reduce effective panicle number and grain yield (Trinh *et al.* 2015; Zhang S G *et al.* 2019). In this study, under the same total nitrogen application rate, CRN (T3) increased grain yield compared to the control (Table 2). Cheng *et al.*

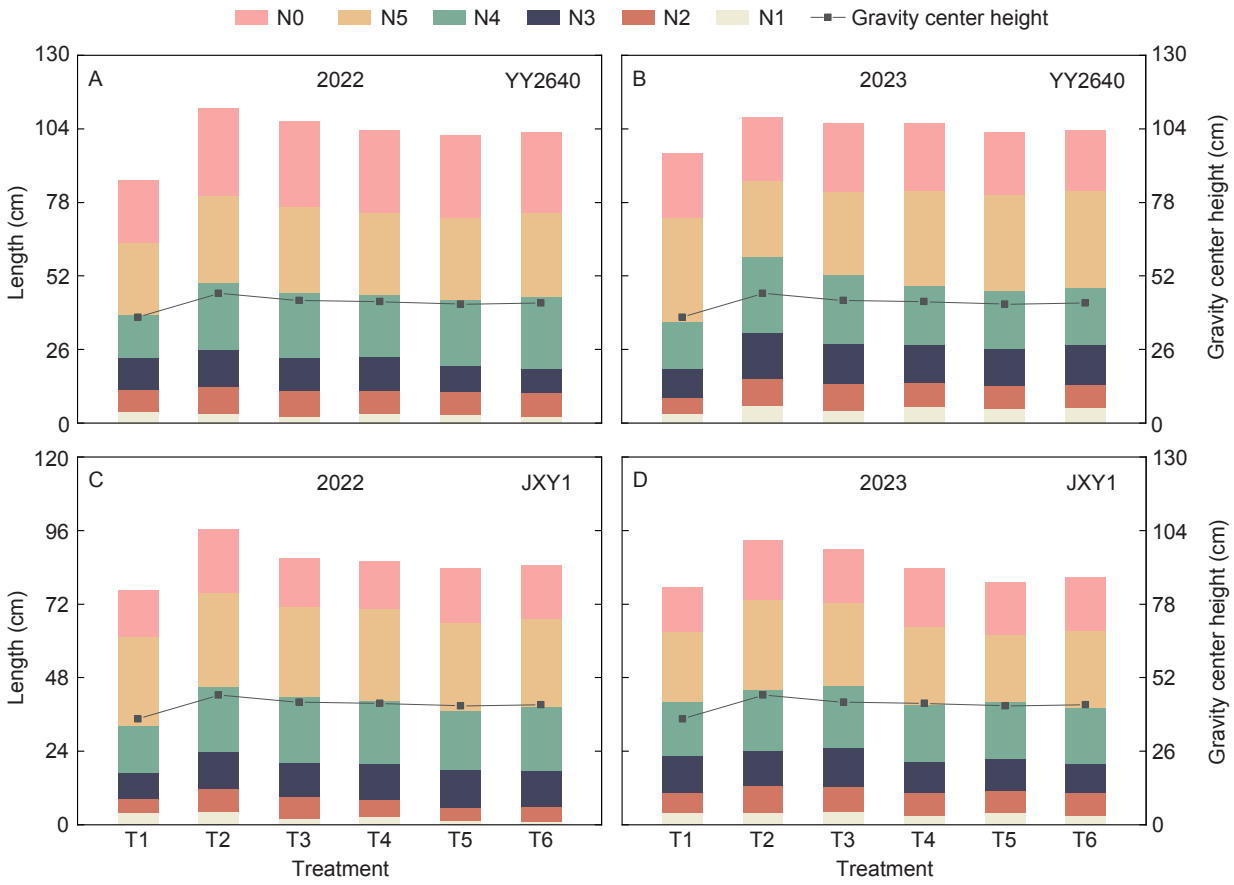


Fig. 1 Effects of controlled-release nitrogen on internode length and center of gravity height. T1, no nitrogen; T2, conventional urea; T3, controlled-release nitrogen; T4, reduction of controlled-release nitrogen; T5, controlled-release nitrogen combined with single basal application of conventional urea; T6, controlled-release nitrogen combined with split applications of conventional urea. N0, panicle length; N1, first basal internode length; N2, second basal internode length; N3, third basal internode length; N4, fourth basal internode length; N5, fifth basal internode length.

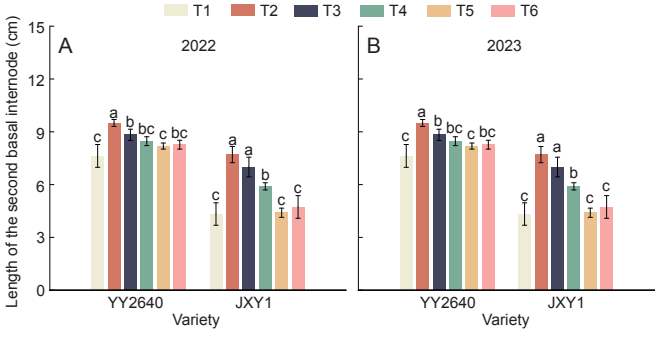


Fig. 2 Effects of controlled-release nitrogen on the length of the second basal internode. T1, no nitrogen; T2, conventional urea; T3, controlled-release nitrogen; T4, reduction of controlled-release nitrogen; T5, controlled-release nitrogen combined with single basal application of conventional urea; T6, controlled-release nitrogen combined with split applications of conventional urea. Bars mean SD (n=3). Different letters above the columns indicate statistical significance (P≤0.05) within the same variety.

(2022) found that, relative to conventional urea, CRN can maintain high rice yields under moderate nitrogen reduction, although excessive nitrogen reduction leads to yield decline — likely due to insufficient nitrogen supply. In our experiment, yield under T4 decreased by 11.1% compared to the control (CK, T2), supporting this conclusion. Recent evidence indicates that combining CRN with conventional urea improves grain yield by meeting nitrogen demands across all growth stages (Yuan *et al.* 2022; He *et al.* 2023; Su *et al.* 2024). Even under the condition of N reduction, the combined application of CRN and conventional urea (T5 and T6) significantly enhanced yield, with T5 showing the greatest improvement. This yield increase was primarily attributed to a higher number of total spikelets. Although T6 also improved yield, it was slightly lower than T5 (Table 2). Therefore, compared to conventional urea alone, an equivalent rate of CRN can increase yield. Moreover, integrating CRN with urea enables higher yields under reduced nitrogen inputs. It is noteworthy that substantial interannual variability in grain yield was observed under identical treatments, likely due to climatic anomalies during the 2022 growing season — including elevated temperatures, increased solar radiation, and reduced rainfall. These conditions contributed to a lower percentage of filled grains, ultimately reducing overall yield (Table 1). As a widely cultivated variety, the *indica–japonica* hybrid rice exhibits high yield potential, superior grain quality, and strong environmental adaptability. The results also indicate that, under identical management, YY2640 achieved higher yields than JXY1.

Table 4 Effects of controlled-release nitrogen on the mechanical properties of the second basal internode

Year/Variety	Treatment[1)]	Bending moment (g cm)	Breaking strength (g cm)	Section modulus (mm^3)	Bending stress (g mm^{-2})	Lodging index (%)	Stem breaking resistance (g)
2022							
YY2640	T1	1,427.60 d	3,380.67 a	13.65 b	279.93 a	42.29 e	1690.33 a
	T2	2,793.52 a	1,661.33 e	14.91 ab	111.95 b	168.43 a	830.67 e
	T3	2,602.55 a	1,876.67 d	14.74 ab	128.11 b	138.55 b	938.33 d
	T4	2,219.99 b	2,376.67 c	13.83 b	178.05 b	93.43 c	1,188.33 c
	T5	2,012.07 c	2,712.00 b	19.58 a	139.96 b	74.18 d	1,356.00 b
	T6	1,981.63 c	2,594.00 b	17.03 ab	152.35 b	76.41 d	1,297.00 b
JXY1	T1	1,126.67 d	4,348.67 a	13.17 a	461.48 a	25.84 e	2,174.33 a
	T2	2,051.07 a	2,505.33 e	6.79 a	394.82 a	81.90 a	1,252.67 e
	T3	1,950.31 a	3,036.00 d	7.21 a	438.15 a	64.28 b	1,518.00 d
	T4	1,739.25 b	3,272.00 c	8.58 a	419.78 a	53.16 c	1,636.00 c
	T5	1,518.27 c	3,529.33 b	7.60 a	464.80 a	43.03 d	1,764.67 b
	T6	1,541.62 c	3,476.00 b	7.09 a	492.81 a	44.33 d	1,738.00 b
2023							
YY2640	T1	1,768.93 e	3,087.20 a	23.57 a	136.86 a	58.09 e	1543.60 a
	T2	2,879.27 a	1,921.20 d	24.24 a	85.69 a	150.26 a	960.60 d
	T3	2,587.50 b	2,137.60 cd	20.40 a	119.01 a	122.00 b	1,068.80 cd
	T4	2,306.62 c	2,276.40 c	17.96 a	141.33 a	101.37 c	1,138.20 c
	T5	1,977.20 d	2,594.00 b	22.48 a	195.41 a	76.23 d	1,297.00 b
	T6	2,058.05 d	2,440.80 bc	18.07 a	229.52 a	84.31 d	1,220.40 bc
JXY1	T1	1,320.01 f	4,201.33 a	11.74 a	361.80 a	31.47 f	2,100.67 a
	T2	2,262.99 a	2,438.67 e	11.66 a	210.89 b	92.78 a	1,219.33 e
	T3	2,126.19 b	2,677.33 d	11.69 a	229.82 b	79.54 b	1,338.67 d
	T4	1,970.17 c	2,906.67 c	12.62 a	234.38 b	67.79 c	1,453.33 c
	T5	1,711.23 e	3,230.67 b	14.52 a	229.18 b	52.96 e	1,615.33 b
	T6	1,809.90 d	3,106.00 b	13.74 a	239.67 b	58.28 d	1,553.00 b
Analysis of variance							
Year (Y)		**	**	**	*	**	**
Variety (V)		**	**	**	*	**	**
Treatment (T)		**	**	NS	*	**	**
Y×V		*	**	NS	**	**	**
Y×T		NS	*	NS	**	**	*
V×T		**	*	NS	NS	**	NS
Y×V×T		NS	NS	NS	NS	**	NS

[1)] T1, no nitrogen; T2, conventional urea; T3, controlled-release nitrogen; T4, reduction of controlled-release nitrogen; T5, controlled-release nitrogen combined with single basal application of conventional urea; T6, controlled-release nitrogen combined with split applications of conventional urea.
In the same year, different treatments within the same variety with different letters indicate statistically significant differences at P=0.05. * and ** indicate significant differences at P≤0.05 and P≤0.01, respectively; NS indicates no significant difference at P≤0.05.

The improvement in NUE associated with CRN application is likely attributable to better synchronization between nitrogen release and plant demand, along with increased activity of key nitrogen-metabolizing enzymes in leaves — such as glutamine 2-oxoglutarate aminotransferase, nitrate reductase, and glutamine synthetase (Yang *et al.* 2012; Sun *et al.* 2019). In this study, AE, apparent recovery efficiency of N, and partial factor productivity of N were significantly higher under T5 (Table 3). Additionally, under the same treatment, YY2640 exhibited greater nitrogen uptake and NUE compared to JXY1. Previous research has shown that excessive nitrogen application during early vegetative growth promotes the formation of ineffective tillers and diverts nitrogen toward leaves and stems. In the middle stage, the lack of nitrogen led to the discoordination of plant photosynthesis, root activities, N absorption, transport and distribution, which decreased the translocation rate of stems and leaves, eventually caused the decrease of NUE (Huang *et al.* 2023; Sun *et al.* 2023). The current findings suggest that combining CRN with conventional urea enhances NUE by promoting more efficient nitrogen uptake and utilization, while ensuring adequate nitrogen supply throughout rice development (Table 3).

4.2. Effects of CRN on morphological and mechanical properties of stem

Lodging primarily results from an imbalance between the upper biomass and lower structural support, most commonly occurring at the stem. Excessive nitrogen application promotes elongation of all internodes, particularly the basal internodes, leading to increased plant height and center of gravity, and reduced stem diameter. These morphological changes compromise stem structural integrity and lodging resistance (Lv *et al.* 2022; Li *et al.* 2023; Liao *et al.* 2023). Reducing nitrogen input can decrease plant height and improve lodging resistance (Zhang *et al.* 2016b). In this study, poor lodging resistance under the control treatment (CK) was primarily due to longer basal internodes, higher

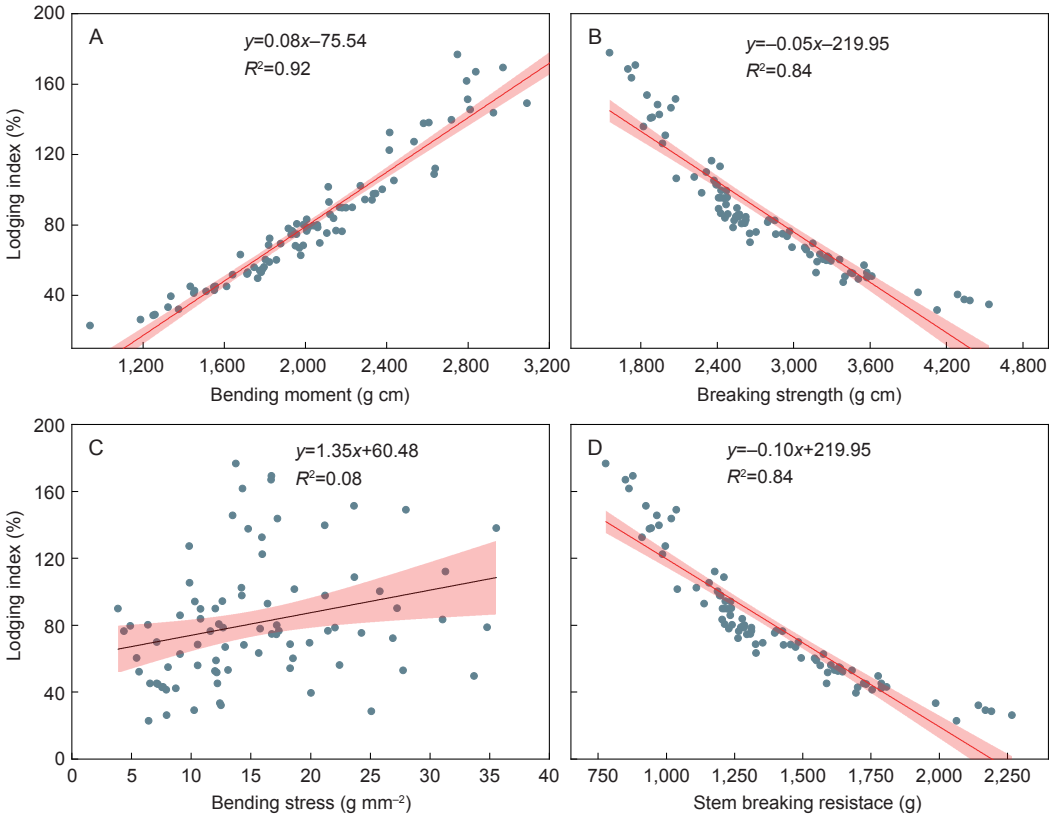


Fig. 3 Relationships between the lodging index and mechanical properties.

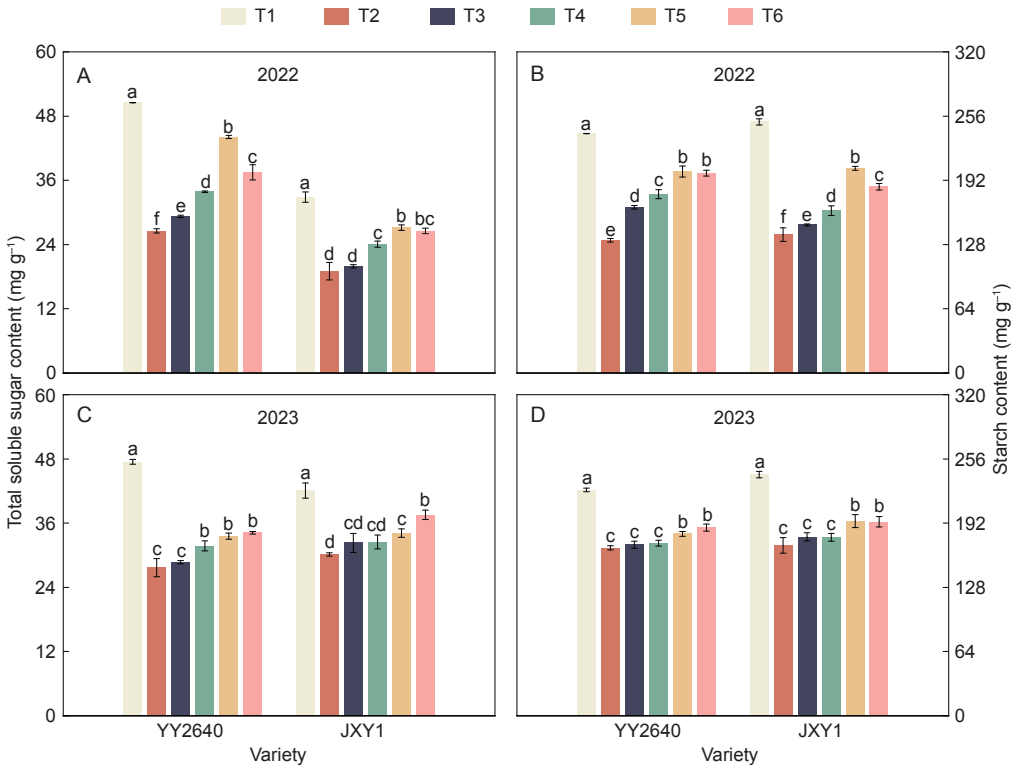


Fig. 4 Effects of controlled-release nitrogen on total soluble sugar content (A and C) and starch content (B and D) in the stem and sheath of the second basal internode. T1, no nitrogen; T2, conventional urea; T3, controlled-release nitrogen; T4, reduction of controlled-release nitrogen; T5, controlled-release nitrogen combined with single basal application of conventional urea; T6, controlled-release nitrogen combined with split applications of conventional urea. Bars mean SD (n=3). Different letters above the columns indicate statistical significance (P≤0.05) within the same variety.

plant height and center of gravity, and thinner basal internodes. The application of CRN (T4–T6) improved stem morphological properties under the condition of N reduction (Figs. 1 and 2).

Our results suggest that reduced nitrogen (N) application (T4–T6) enhances lodging resistance by improving the mechanical properties of the stem (Table 4). Previous studies have reported that excessive N increases tiller number during early rice growth, leading to higher population density and intensified competition for nutrients. This competition promotes thinner basal stem internodes and internode elongation (Corbin *et al.* 2016; Zhang *et al.* 2016a). Additionally, controlled-release N has been shown to reduce the lodging index, thereby improving lodging resistance (Zhang S G *et al.* 2019). In this study, controlled-release N under N-reduced conditions (T4–T6) increased stem breaking resistance (F) and breaking strength (M), while decreasing bending moment (WP) (Table 4). Correlation analysis indicated that reducing the LI is achievable by increasing F and M and decreasing WP, ultimately enhancing rice lodging resistance (Fig. 3). Plant height and center of gravity were higher in YY2640 than in JXY1, and under identical treatments, JXY1 exhibited superior stem mechanical properties. This difference may be attributed to a higher nutrient translocation rate in YY2640, which directs more resources toward grain yield formation at the expense of stem strength compared to JXY1.

4.3. Effects of CRN on physicochemical and anatomical properties of stem

Stem lodging primarily occurs at the basal internode and is closely associated with its chemical composition (Okuno *et al.* 2014). Enhanced accumulation of total soluble sugars in the stem during early grain filling has been linked to improved lodging resistance in rice (Kashiwagi and Ishimaru 2004). Conversely, excessive N application impedes carbohydrate accumulation in the basal stem, resulting in slender internodes and elevated lodging risk. In this study, applying controlled-release N (T3–T6) increased carbohydrate contents — including total soluble sugars, starch, lignin, and cellulose — in the second basal internode, with more pronounced effects under N-reduced treatments (T4–T6) compared to CK (Figs. 4 and 5). Correlation analysis revealed significant or highly significant negative relationships between these carbohydrate contents and bending moment (Fig. 8), while lodging index was positively correlated with bending moment (Fig. 3). These findings indicate that controlled-release N improves stem physicochemical properties by increasing carbohydrate accumulation in the second basal internode, thereby strengthening lodging resistance.

The lodging index of rice stems is strongly negatively associated with vascular bundle area, which was an important trait affecting lodging of stem (Gui *et al.* 2018). Our data show that smaller vascular bundle area is associated with reduced stem strength (Table 5). Moreover, vascular bundle

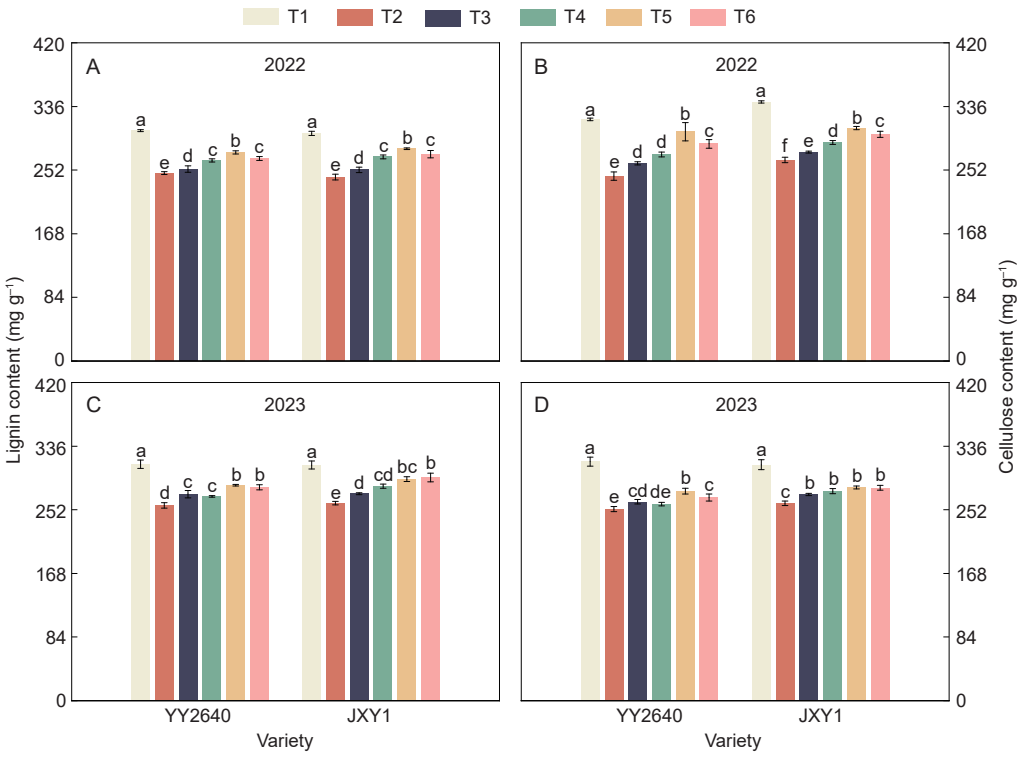


Fig. 5 Effects of controlled-release nitrogen on the lignin contents (A and C) and cellulose contents (B and D) in stem and sheath of the second basal internode. T1, no nitrogen; T2, conventional urea; T3, controlled-release nitrogen; T4, reduction of controlled-release nitrogen; T5, controlled-release nitrogen combined with single basal application of conventional urea; T6, controlled-release nitrogen combined with split applications of conventional urea. Bars mean SD (n=3). Different letters above the columns indicate statistical significance (P≤0.05) within the same variety.

Table 5 Effects of controlled-release nitrogen on the anatomical properties of the second basal internode

Year/ Variety	Treatment[1)]	Large vascular bundles		Small vascular bundles		Parenchymatous tissue		Mechanical tissue	
		Number (mm^{-2})	Area (mm^2 mm^{-2})	Number (mm^{-2})	Area (mm^2 mm^{-2})	Thickness (μm)	Cell layers	Thickness (μm)	Cell layers
2022									
YY2640	T1	12.23 ab	0.298 a	13.35 a	0.068 a	670.94 a	19.5 a	143.44 a	4.5 a
	T2	7.91 c	0.218 b	6.95 b	0.046 b	523.58 d	13.0 c	80.31 a	2.5 a
	T3	10.50 bc	0.263 ab	7.51 ab	0.058 a	546.22 cd	13.5 bc	91.43 a	3.5 a
	T4	11.21 bc	0.284 a	9.56 ab	0.062 a	572.21 bc	14.5 bc	111.41 a	3.5 a
	T5	15.26 a	0.291 a	11.28 ab	0.063 a	595.92 b	15.5 b	121.01 a	3.5 a
	T6	11.52 b	0.273 ab	9.02 ab	0.061 a	584.28 b	15.0 bc	109.07 a	3.5 a
JXY1	T1	18.57 a	0.333 a	17.73 a	0.054 a	729.50 a	20.5 a	153.94 a	6.0 a
	T2	10.99 c	0.222 d	7.99 e	0.046 a	374.50 e	13.0 bc	59.97 c	3.5 a
	T3	11.70 c	0.246 cd	9.25 de	0.047 a	465.29 d	13.0 bc	104.66 b	4.5 a
	T4	13.06 c	0.261 bcd	10.23 cd	0.041 a	553.27 c	13.0 bc	91.33 bc	4.5 a
	T5	16.47 ab	0.305 ab	13.13 b	0.055 a	648.44 b	16.0 b	120.78 ab	5.5 a
	T6	15.82 b	0.277 bc	11.86 bc	0.054 a	530.13 cd	12.5 c	105.22 b	5.0 a
2023									
YY2640	T1	10.81 c	0.295 a	12.46 a	0.067 a	638.89 a	18.5 a	138.27 a	5.0 a
	T2	8.41 d	0.230 c	7.84 e	0.056 c	528.41 c	11.0 e	87.33 c	2.5 c
	T3	9.88 cd	0.239 bc	8.05 de	0.060 bc	534.07 c	12.5 d	89.44 c	3.5 bc
	T4	11.60 bc	0.260 abc	9.08 cd	0.063 ab	555.57 bc	14.0 c	97.11 bc	4.0 ab
	T5	15.06 a	0.275 ab	10.66 b	0.063 ab	570.92 b	15.0 c	105.92 bc	4.5 ab
	T6	13.31 ab	0.277 ab	9.58 bc	0.065 a	579.44 b	16.5 b	115.45 ab	4.5 ab
JXY1	T1	17.39 a	0.335 a	13.90 a	0.071 a	697.31 a	19.5 a	146.99 a	5.5 a
	T2	10.09 d	0.234 c	8.29 d	0.054 d	547.49 cd	12.0 c	74.45 d	4.0 cd
	T3	12.12 c	0.245 c	9.05 d	0.055 d	537.79 d	13.5 bc	94.30 c	3.5 d
	T4	14.31 b	0.256 bc	10.27 c	0.058 cd	559.95 bcd	13.0 bc	90.12 c	4.5 bc
	T5	14.98 b	0.288 b	11.97 b	0.062 bc	574.26 bc	15.5 b	110.95 b	5.0 ab
	T6	15.76 ab	0.298 ab	10.76 bc	0.067 ab	590.69 b	14.5 bc	111.27 b	5.5 a
Analysis of variance									
Year (Y)		NS	NS	NS	**	NS	NS	NS	NS
Variety (V)		**	NS	**	**	NS	NS	NS	**
Treatment (T)		**	**	**	**	**	**	**	**
Y×V		NS	NS	NS	*	**	NS	NS	NS
Y×T		NS	NS	NS	NS	**	*	NS	NS
V×T		**	NS	NS	NS	**	*	NS	NS
Y×V×T		NS	NS	NS	NS	**	NS	NS	NS

[1)] T1, no nitrogen; T2, conventional urea; T3, controlled-release nitrogen; T4, reduction of controlled-release nitrogen; T5, controlled-release nitrogen combined with single basal application of conventional urea; T6, controlled-release nitrogen combined with split applications of conventional urea.

In the same year, different treatments within the same variety with different letters indicate statistically significant differences at P=0.05. * and ** indicate significant differences at P≤0.05 and P≤0.01, respectively. NS indicates no significant difference at P≤0.05.

number is positively correlated with mechanical strength: a greater number corresponds to stronger lodging resistance (Figs. 8 and 9). Excessive top-dressed N has previously been shown to reduce both large and small vascular bundle areas (Zhang *et al.* 2016a). Our results demonstrate that the combined application of controlled-release N and conventional urea under the condition of N reduction (T5 and T6) increases the number and cross-sectional area of both large and small vascular bundles, as well as the thickness of parenchyma and mechanical tissues (Table 5). Silicon (Si) is widely recognized for promoting lignification and silicification of plant cells, which enhances structural integrity and lodging resistance (Zhang *et al.* 2022). Due to its slow and sustained release pattern, controlled-release N maintains stable nutrient availability throughout the rice growth period (Su *et al.* 2024). This steady supply supports overall plant health and vigor, enhancing the uptake and utilization of essential elements such as Si. Silicon is known to play a critical role in strengthening plant cell walls, particularly through the process of silicification, where silicon deposits contribute to the formation of a thicker and more robust epidermal layer (Etesami and Jeong 2018). The improved nutritional status from controlled-release N likely stimulates metabolic activity, facilitating enhanced translocation and deposition of Si into stem tissues. Consequently, the thickness of the epidermal Si layer increases (Zhang *et al.* 2022), reinforcing stem structural integrity and reducing susceptibility to breakage under wind or rain stress (Hong *et al.* 2022). Furthermore, the controlled nature of nitrogen release from controlled-release N might also reduce the risk of nitrogen-induced lodging, which can occur when excessive nitrogen leads to overly rapid growth and elongation of the stem, making it more susceptible to lodging (Zhang *et al.* 2016b). Thus, controlled-release N enables more regulated Si accumulation in stems, contributing to greater structural stability. In summary, controlled-release N not only optimizes NUE but

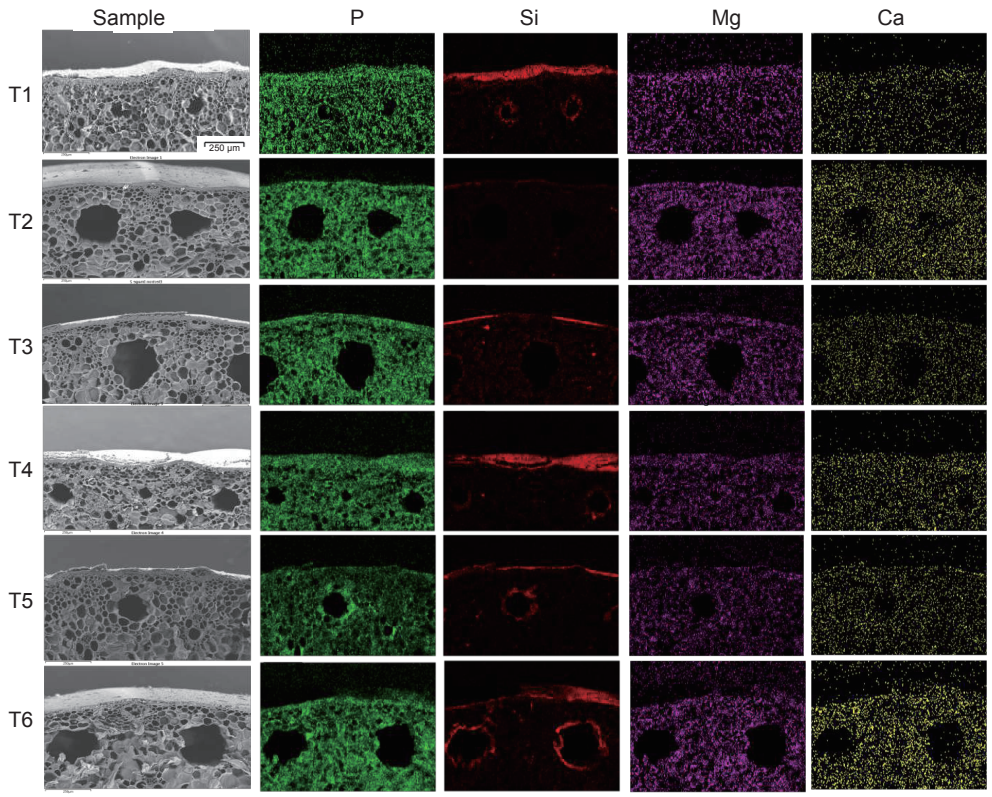


Fig. 6 Energy spectrum analysis of the second basal internode in YY2640. T1, no nitrogen; T2, conventional urea; T3, controlled-release nitrogen; T4, reduction of controlled-release nitrogen; T5, controlled-release nitrogen combined with single basal application of conventional urea; T6, controlled-release nitrogen combined with split applications of conventional urea. Detected elemental signals include P (phosphorus), Si (silicon), Mg (magnesium), and Ca (calcium).

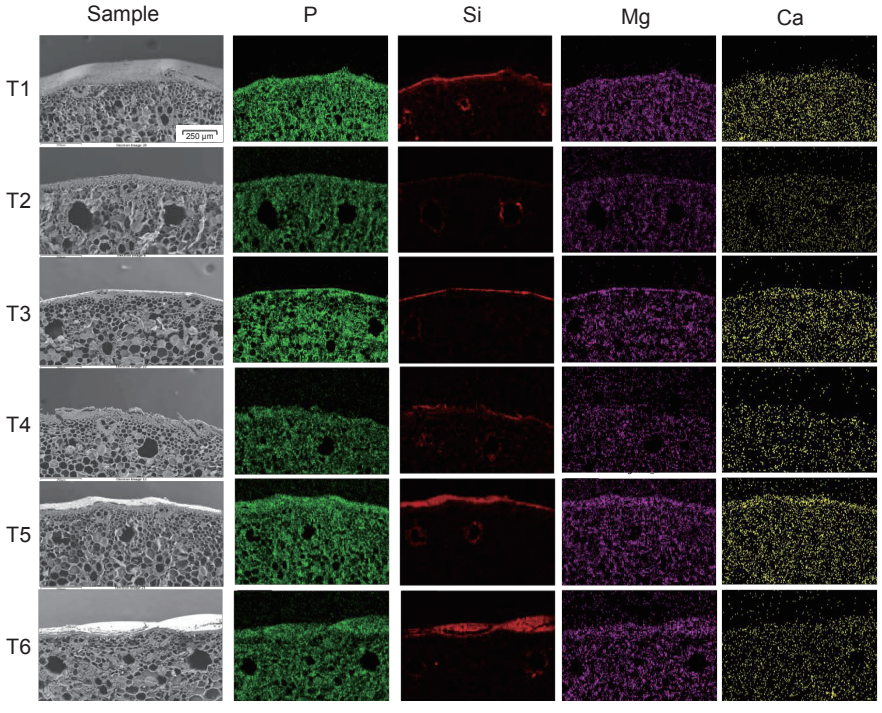


Fig. 7 Energy spectrum analysis of the second basal internode in JXY1. T1, no nitrogen; T2, conventional urea; T3, controlled-release nitrogen; T4, reduction of controlled-release nitrogen; T5, controlled-release nitrogen combined with single basal application of conventional urea; T6, controlled-release nitrogen combined with split applications of conventional urea. Detected elemental signals include P (phosphorus), Si (silicon), Mg (magnesium), and Ca (calcium).

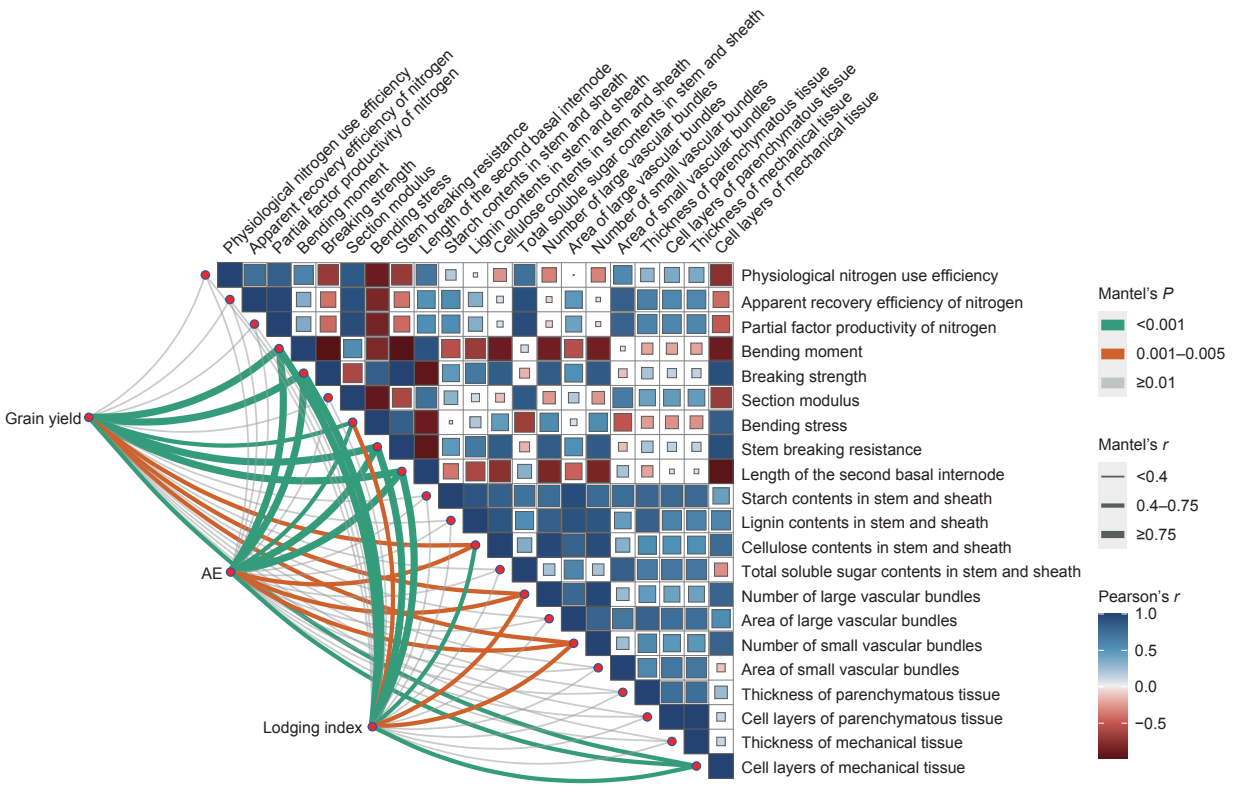


Fig. 8 Correlation analysis among yield, nitrogen use efficiency, and stem properties. AE denotes agronomic nitrogen use efficiency. The heatmap displays the Pearson correlation coefficients for selected phenotypic traits, where the intensity of blue signifies positive correlations and the intensity of red indicates negative correlations, reflecting the strength and direction of each. Separate color indicators correspond to ranges of Mantel's *P*-values: green for $P<0.001$, orange for $0.001 \le P \le 0.005$, and gray for $P \ge 0.01$. Below the heatmap, the network diagram highlights trait associations, where edge thickness reflects the magnitude of Mantel's *r*: thin lines represent $r<0.4$, medium lines $0.4 \le r<0.75$, and thick lines $r \ge 0.75$.

also indirectly strengthens the stem's Si layer, significantly improving lodging resistance. These multifaceted benefits highlight its potential as a key component in sustainable and resilient rice production systems.

Energy dispersive spectroscopy mapping *via* scanning electron microscopy revealed that the combined application of controlled-release N and conventional urea (T5 and T6) enhanced the thickness of the epidermal Si layer (Figs. 6 and 7). Correlation analysis showed significant negative correlations between the lodging index and both the number and area of large and small vascular bundles in the second basal internode (Fig. 8). Pathway analysis further indicated that anatomical indicators significantly influence the lodging index, accounting for 13.9% of its variation (Fig. 9). Collectively, these results suggest that the controlled-release N strategy improves stem anatomical properties by increasing vascular bundle number and area and enriching Si deposition in the epidermal layer, thereby enhancing lodging resistance.

5. Conclusion

The combined application strategy of controlled-release nitrogen — particularly 70% controlled-release nitrogen combined with 30% one-time basal conventional urea — can achieve the synergistic benefits of high grain yield, enhanced nitrogen use efficiency, and strong lodging resistance. It was found that increased breaking strength, stem breaking resistance, carbohydrate content, epidermal silicon layer thickness, and the number of large and small vascular bundles in the second basal internode — along with reduced internode length — contributed primarily to improvements in grain yield, agronomic nitrogen use efficiency, and lodging resistance under this strategy. This study advances sustainable and efficient nitrogen fertilizer management in rice cultivation by providing practical strategies for producing high-yielding, resilient crops.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

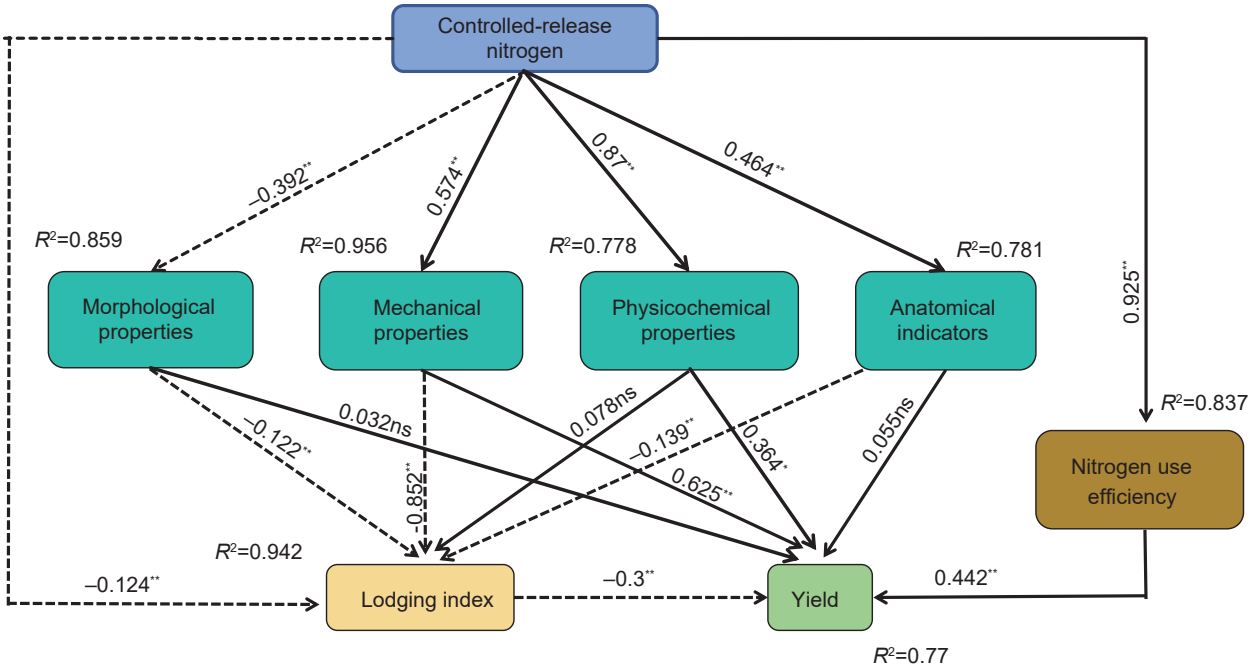


Fig. 9 Correlation coefficients and path coefficients among stem characteristics, lodging index, yield, and nitrogen use efficiency under controlled-release nitrogen. Solid and dashed arrows indicate positive and negative relationships, respectively. The proportion of variance explained is indicated by R^2. * and ** indicate significant differences at $P \leq 0.05$ and $P \leq 0.01$, respectively; NS indicates no significant difference at $P \leq 0.05$.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that they did not use AI in the preparation and writing of this manuscript.

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