

Effects of wheat straw returning and potassium application rates on the physicochemical properties and lodging resistance of different stem internodes in direct-seeded rice**

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Received June 21, 2022; accepted October 10, 2022

Abstract. This study aimed to evaluate the relationship between the physicochemical properties and lodging index of different stem internodes and the yield of direct-seeded rice. Two treatments of wheat straw returning (returning and non-returning) and five potassium application rates of 0, 62.5, 125, 187.5, and 250 kg ha⁻¹ were applied. Wheat straw returning combined with a potassium application rate of 125 kg ha⁻¹ significantly promoted potassium accumulation, increased total soluble sugar and lignin contents, improved breaking moment, reduced the flattening rate and lodging resistance index of different internode stems, and increased the yield. Correlation analysis revealed that compared with those of the 4th and 5th internodes, potassium content and accumulation and total soluble sugar and lignin contents of the 3rd internode were significantly positively correlated with yield ($r = 0.85^{**}$ - 0.93^{**}) and negatively correlated with the stem flat rate and lodging index ($r = -0.67^{*}$ - -0.79^{**}), which improved lodging resistance in collaboration with the 4th and 5th internodes ($r = 0.82^{**}$ - 0.95^{**}). Increasing potassium accumulation, total soluble sugar and lignin content, and reducing stem flatness of

the 3rd stem internodes are important factors for improving lodging resistance of direct-seeded rice and may provide a basis for improving the 4th and 5th stem internodes.

Keywords: straw returning, structural equation modeling, stem bending, lodging resistance, direct-seeded rice

INTRODUCTION

Wheat-rice rotation is a major cropping system in Chinese agriculture, with a planting area of 4.8 million ha. With scientific and technological developments and a declining pool of rural labour, traditional transplanted rice (TPR) can no longer be regarded as the optimal solution to sufficiently meet the needs of a growing population. Accordingly, European countries and the US have been gradually replacing manual or mechanized planting with mechanized direct seeding to improve agricultural production efficiency (Zhang *et al.*, 2020). However, a serious concern with this development is the incidence or occurrence of the lodging of direct-seeded rice (DSR), which impacts both rice yield and quality. DSR lodges more readily than TPR (Chaudhary *et al.*, 2022), in part because the larger culm number per area means that the stems are

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**This work was supported by the Research Program Foundation of Key Laboratory of Sichuan Province, China, the Cultivation of Green and Efficient Super Rice Varieties (2022ZDZX0012, 2022-2025); the Project Foundation of the State Key Laboratory of Crop Gene Exploration and Utilization in Southwest China (Grant No. SKL-ZY202228, 2022-2024); the Rice Breeding Project Foundation of Sichuan Provincial Science and Technology Department (Grant No. 2021YFYZ0005, 2021-2025).

thinner and this also makes root lodging more likely (Teng *et al.*, 2021). Stem bending resistance is an important measurement index for lodging resistance. Lodging is directly related to the height of the centre of gravity, internode lengths, the stem flatness rate, and the cavity sizes of rice stems (Zhang *et al.*, 2010; Duan *et al.*, 2004). A low centre of gravity leads to a strong or stable mass and consequently to a high level of lodging resistance (Katsuyuki *et al.*, 1997; Kashiwagi *et al.*, 2004).

Apart from genetic factors, rice cultivation measures are particularly important for building up lodging resistance, especially indirect or direct potassium (K) fertilizer application. As an indirect high-quality fertilizer, the return of straw to the soil gradually increases its K content (Dong *et al.*, 2019; Yan *et al.*, 2019; Wang *et al.*, 2020; Zhan *et al.*, 2016). Enhancing soil fertility, ensuring vegetative growth, promoting stem growth and improving the nutrient-absorption capacity of the roots of direct-seeded rice (Yan *et al.*, 2018), increases the lignin and soluble sugar contents of direct-seeded rice stems and other plant components to improve lodging resistance. By contrast, the direct application of quick-acting K fertilizer is a timely supplement for soil K deficiency, which is extremely important for the growth of rice stalks. Studies have shown that the appropriate application of K fertilizer increases both internode length and internode wall thickness and diameter (Li *et al.*, 2021). As the rice internodes rise from the base at ground level to the top of the spike, the internodes become longer, the diameter becomes smaller, and the wall thickness decreases. Fan *et al.* (2017) reported that combining silicon and K fertilizers in rice cultivation effectively improves the bending resistance of direct-seeded rice stems. An adequate soil K content results in the thickened stalks of direct-seeded rice, it improves their mechanical properties and promotes a higher level of lodging resistance (Yang *et al.*, 2004).

In addition to physical properties, the chemical components of the stems also contribute directly to their lodging resistance. K fertilizer increases the level of soluble sugar accumulation in rice stems in the form of non-structural carbohydrates, which serves to maintain the standing strength of the culm (Ishimaru *et al.*, 2008). Furthermore, lignin content is a key factor leading to varying stem strengths (Zhang J. *et al.*, 2017; Zhou *et al.*, 2012; Zhang W. *et al.*, 2017). Potassium fertilizer improves the degree of lignification of sclerenchyma cells in rice and promotes the thickening of horn histiocytes and cuticles, thereby effectively improving the lodging resistance of stems (He *et al.*, 2017; Yang *et al.*, 2011).

Previous studies have confirmed that a suitable regime of returning straw to the soil (Zhang *et al.*, 2021), K fertilizer management (Li *et al.*, 2021), and planting density (Sun *et al.*, 2012) can improve the lodging resistance and rice yield. However, at present there is a lack of reports concerning the breakage of different stem internodes.

Furthermore, there are also few reports concerning the relationship between the lodging resistance and the single culm of different stem internodes, previous studies mainly focused on the single-factor effects of returning straw to the soil and K fertilizer application on the lodging resistance and yield of rice. Potassium and available potassium fertilizer input through the return of straw to the field are two important sources that affect the absorption and utilization of K in rice, however, there is no clarity on how to improve the usage of the coupling effect of the two sources of K and synergistically enhance the difference between rice produced through straw returning and direct-seeded rice under the coupling of K fertilizer application. Furthermore, the relationship between the physicochemical properties of the internode stalk and the lodging resistance with rice yield is unclear, as only a few studies have been conducted on how the changes in the lodging resistance of stems affect yields. Therefore, this study aimed to analyse the differences in the physical and chemical properties of rice internodes and the effects of direct-seeded rice on lodging resistance in order to improve the resistance of directly seeded rice under rice-wheat rotation using structural equation modelling (SEM) under the conditions of direct seeding (Guo *et al.*, 2012; Miao *et al.*, 2013). This method allows for the effect of individual indicators and the relationship between them to be analysed, the effects of returning wheat straw to the soil and K fertilizer application on the overall outcome of the growth process was also analysed. The results of this study will provide a theoretical basis and technical support for improving the lodging resistance of direct-seeded rice and enhance the rational application of K fertilizer under rice-wheat rotation.

MATERIALS AND METHODS

The experiment was conducted in 2021 at the experimental farm of Sichuan Agricultural University, Chongzhou, Chengdu, China (30°33' N, 103°38' E; 520.6 m altitude). The preceding crop was wheat. The soil consisted of a sandy loam texture (0-20 cm), 14.71 g kg⁻¹ organic matter, 1.60 g kg⁻¹ total N, 86.45 mg kg⁻¹ of available N, 22.58 mg kg⁻¹ Olsen-P, and 100.31 mg kg⁻¹ of exchangeable K. Seeds of the F-you 498 rice variety (*Indica* three-line hybrid rice: average growth period of 150.2 day) were soaked and dried under shade with minimal handling using wet seeding and mechanical ploughing. The spacing between the sowing rows was set at 25 × 20 cm (200 thousand holes per ha), and a direct seeding machine 2BDXS-10CP (25) (Shanghai Shidaer Modern Agricultural Machinery Co., Ltd.) 4-5 seeds in a hole. The field experiment was conducted in the form of a two-factor split-plot design, with three replicates, 30 plots, and a 15 m² plot area. Ridges were heaped up between each cell and wrapped with plastic film to prevent the water and fertilizer from mixing. For the treatment of not returning the straw to the field, the straw

and underground parts were removed from the experimental field after the wheat grains had been harvested. For the treatment involving returning straw to the soil, the straw was crushed and returned to the field after the wheat grain had been harvested (returned amount, 5050 kg ha⁻¹; water content, 13.5%). The wheat straw contained: 9.74, 0.37, and 11.69 g kg⁻¹ N, P and K, respectively. Five K application rates of 0, 62.5, 125, 187.5, and 250 kg ha⁻¹ were applied in the subarea and were recorded as K₀, K_{62.5}, K₁₂₅, K_{187.5}, and K₂₅₀, respectively. Potassium chloride (KCl) was applied 1 day before sowing, 22 day after sowing, and 70 day after sowing (5:2:3), while N fertilizer (urea) was converted to pure nitrogen (120 kg ha⁻¹) and applied 1 d before sowing and 22 day after sowing (7:3). Phosphate fertilizer (superphosphate) was converted to P₂O₅ (90 kg ha⁻¹) and used as a base fertilizer. Other field management methods remained the same as those used for conventional field production.

Twenty days after heading, five rice paddies with similar growth patterns were selected in each plot, and five single stems with similar elongation internodes were selected from each hole. Afterwards, the lengths from the base of the 3rd, 4th, and 5th internodes to the top of the spike, fresh weight, and stem node buckling resistance were measured.

Force: Following the method of (Sun *et al.*, 2012) (Fig. 1), the stem internode with its leaf sheath was placed on the bracket, and a tensiometer (ZTS-500N; accuracy, ±0.2%) was used to pull down at the midpoint of the internode at a constant speed until the stem internode was broken.

Bending resistance: The long axis, short axis, and wall thickness of the stem nodes were measured using Vernier callipers, and the following indicators were calculated:

(1) Bending moment = length from the base of the internode to the top of the panicle (cm) × fresh mass from the base of the internode to the top of the panicle (g).

(2) Breaking moment (g cm⁻¹) = weight at the time of internode breaking (g) × bracket spacing / 4.

(3) Lodging index (%) = (bending moment/breaking moment) × 100%.

(4) Stem flatness rate (%) = (1 - outer diameter minor axis/outer diameter major axis) × 100%.

(5) Cavity area (mm²) = a × b × π/4, where a and b represent the long and short axes of the stem internode's inner diameter, respectively.

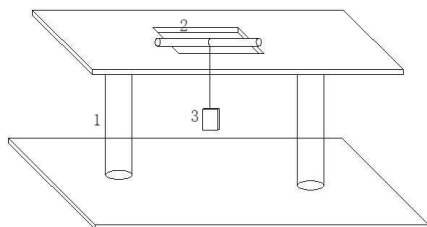


Fig. 1. Breaking moment measurement model. 1 – shelf, 2 – stem internode, 3 – tensiometer.

The stem nodes measured in a ratio of 2:2:1 were oven fixed at 105°C for 45 min, dried to a constant weight at 80°C, and ground with a ball mill (JXFSTPRP-64). The lignin content was determined by the micro-method using a Solarbio kit (BC4205). The anthracene ketone colorimetric method was used to determine the total soluble sugar content (Li *et al.*, 2000).

Each stem node ground in 1:2:2 (weight, 0.2000 g) was placed in a cooking tube and digested with H₂SO₄-H₂O₂. The potassium content was measured using flame photometry (Shanghai Yidian Analysis Instrument FP640), and the cumulative amount of K was calculated.

At the maturity stage, 50 representative rice plants were investigated in each plot, and the number of effective panicles was counted, the average value was then calculated. Ten rice plants were randomly selected (the number of stems and tillers in each plant was the average number of stems and tillers in each plot) as representative samples and their seeds were tested indoors, the number of grains per panicle were measured, as were the number of spikelets, the weight of 1000-grains, and the seed setting rate and other traits were also calculated. Each plot yield was calculated using the number of real plants collected (the standard moisture content of the grains was 13.5%). If there was lodging on the plots, the lodging plants were excluded from the yield observations.

The data were analysed using Excel 2010 and SPSS 24.0 software. Pathway analysis was performed across 3×5=15 treatments and a correlation was made across 2×3×5=30 treatments. An analysis of the least significant difference (LSD) method was used for multiple comparisons, and Origin 2018 was used for graphing. Structural equation modelling (SEM) was conducted using Amos 24.0 to fit the plot (Livote *et al.*, 2008).

RESULTS

The return of wheat straw to the soil, K application amount, and the interaction effect between the two factors significantly affected grain yield (Table 1). With the straw treatment, the average yield of wheat straw returned to the field increased significantly by 8.95% compared to the non-returning treatment. Additionally, straw returning resulted in an increased paddy rice yield and then in a decreasing yield when K application levels were increased, however, the optimal K fertilizer application rate differed under varying straw returning treatments. The yield with K fertilizer application was 187.5 kg ha⁻¹ and was higher under the treatment of the wheat straw not being returned, however, under the wheat straw-returning treatment, the amount of K fertilizer being applied can be reduced, and the highest yield may be achieved when the K fertilizer application rate is 125 kg ha⁻¹. Thus, this experiment highlights that the best method is to return straw to the field. Under the combined application of K fertilizer, continual increments in

Table 1. Effects of straw returning and K fertilizer application on the yield and components of direct-seeded rice

Treatment		Effective panicles ($\times 10^4 \text{ ha}^{-1}$)	Spikelets (No./panicle)	Total spikelets ($\times 10^6 \text{ ha}^{-1}$)	Seed setting rate (%)	1000 grain wt. (g)	Grain yield (kg ha^{-1})
M ₀	K ₀	204.8 c	133.1 c	272.6 d	82.00 b	31.90 a	7027 d
	K ₇₅	215.3 ab	139.0 c	299.3 c	80.40 c	32.10 a	7700 c
	K ₁₅₀	219.4 a	147.9 b	324.5 b	81.50 b	32.20 a	8485 b
	K ₂₂₅	219.7 a	154.9 a	340.3 a	81.90 b	32.20 a	8901 a
	K ₃₀₀	211.3 b	151.6 ab	320.3 b	82.90 a	32.40 a	8600 b
	Average	214.1	143.7	311.4	81.20	32.10	8143
M ₁	K ₀	210.4 c	138.8 c	292.0 d	82.70 ab	32.10 a	7569 d
	K ₇₅	217.3 b	154.2 b	335.0 c	81.40 c	31.90 a	8457 c
	K ₁₅₀	228.7 a	164.2 a	375.5 a	81.70 c	32.00 a	9703 a
	K ₂₂₅	223.1 ab	158.8 ab	354.2 b	82.60 b	32.20 a	9370 b
	K ₃₀₀	219.1 b	156.4 b	342.7 c	83.50 a	32.60 a	9257 b
	Average	219.7	152.4	339.9	82.18	32.03	8871
F value	M	4.39**	9.26**	15.90**	0.73	0.04	59.94**
F value	K	6.83**	13.49**	23.52**	4.65*	0.58	111.1**
	M×K	0.31	1.72	1.47	0.06	0.14	3.02*

M₀ – wheat straw not returned to the field, M₁ – straw returning. Different lowercase letters under the same straw-returning method in the same column indicate significant differences at the 5% level between treatments with different potassium application rates. Indicate significant effects at: * $p < 0.05$ and ** $p < 0.01$ levels.

K fertilizer input on this basis will lead to a reduced yield. Excessive K fertilizer application results in reduced yields and other traits, possibly due to the impact on soil nutrient balance, resulting in an unbalanced uptake by the roots of the plant (Zhan *et al.*, 2016).

The quantity of wheat straw quantity being returned to the field and the quantity of K being applied had a significant effect on the number of effective panicles, grains per panicle, and total spikelets (Table 1). The effects of K application and the seed setting rates on the total spikelet number were significantly greater than those of the wheat straw-returning treatment and the interaction effect of the two factors, thereby indicating that returning wheat straw to the field and the combination of suitable K fertilizers could serve to adjust yield components and achieve a better yield. Compared to those experiments with the non-returning treatment, the number of grains per panicle and total spikelets increased by 6.05 and 8.38%, respectively. The highest effective number, the number of grains per panicle, and the total number of spikelets were obtained under the non-returning treatment combined with 187.5 and 125 kg ha⁻¹ of K fertilizer application. It was found that excessive or insufficient K fertilizer application would reduce the effective panicle number, grain number per panicle, and also, the total spikelet number.

Except for the breaking moment of the 5th internode, the effects of wheat straw being returned to the field, K application, and also the effects of their interaction on the breaking moment and on the lodging index of the different internodes

were significant (Table 2). Compared with those under the non-returning treatment, the breaking moment and lodging index decreased under the straw-returning treatment. The breaking moments of the 3rd, 4th, and 5th internodes increased by 13.50, 10.26, and 5.70%, respectively. Additionally, the straw-returning treatment initially exhibited an increasing and then a decreasing breaking moment when the K application levels were increased, while the opposite was true for the lodging index. However, the optimal K fertilizer application rate was different under varying wheat straw-returning treatments. The best K application rate that improved the lodging resistance of the third internode under the non-returning straw treatment was 125 kg ha⁻¹, while the treatment that improved the lodging resistance between the fourth and fifth node was 187.5 kg ha⁻¹. Overall, a suitable K application rate for wheat straw not being returned to the field was 187.5 kg ha⁻¹, and a suitable K application rate for wheat straw being returned to the field was 125 kg ha⁻¹. However, excessive or insufficient K fertilizer application will reduce the breaking moment and increase the lodging index.

Returning wheat straw to the field, the K application amount, and their interaction effects on the K content of different internode stems all reached significant levels (Fig. 2A). Compared with the stem subjected to the non-returning straw treatment, under the wheat straw-returning treatment the K content of each internode increased, and the K application rate increments gradually led to higher K contents in the 3rd, 4th, and 5th internodes. The K contents of

Table 2. Effects of wheat straw returning and K fertilizer application on the bending moment and lodging index of stems in different internodes of direct-seeded rice

Treatment	Breaking moment (g cm ⁻¹)			Lodging index (%)			
	3th	4th	5th	3th	4th	5th	
M ₀	K ₀	1436c	1788b	3175d	113.7a	95.79a	62.42a
	K ₇₅	1437c	1825b	3404c	108.0a	93.22ab	60.14a
	K ₁₅₀	1983a	2175a	3996b	78.10c	85.60b	54.14c
	K ₂₂₅	1863ab	2354a	4554a	88.03bc	71.17c	47.12b
	K ₃₀₀	1763b	2350a	3496c	90.78b	100.6a	58.89a
Average	1696	2098	3725	95.72	89.27	56.54	
M ₁	K ₀	1554c	1917d	3275e	97.27a	97.10a	57.65a
	K ₇₅	1767b	2104c	3592d	90.99ab	97.93a	47.95b
	K ₁₅₀	2354a	2854a	4675a	70.27c	62.48c	45.56b
	K ₂₂₅	2254a	2596b	4317b	82.42b	79.53b	47.43b
	K ₃₀₀	1875b	2221c	3892c	98.66a	85.54b	51.95ab
Average	1961	2338	3950	87.92	84.88	50.11	
F value	M	37.61**	12.26**	13.31*	12.04**	6.55*	36.70**
F value	K	29.22**	25.11**	62.63**	19.53**	33.05**	9.94**
	M×K	6.38**	6.17**	1.27	8.64**	11.08**	11.34**

Explanations as in Table 1.

the different internode stems varied in the following order: 4th > 3rd > 5th. The K content of the 4th internode under the non-returning straw treatment was 1.95 and 21.67% higher than that of the 3rd and 5th internodes, respectively, while the K content of the 4th internode under the wheat straw-returning treatment was 8.56 and 19.12% higher than that of the 3rd and 5th internodes, respectively.

The wheat straw-returning treatment and the combined application of K fertilizer affected K accumulation at the different internodes to a significant extent, and also the K accumulation under different wheat straw returning to the field treatments occurs in the following order: 3rd > 4th > 5th (Fig. 2B). Under the same K fertilizer application, returning wheat straw to the field increased internode stem and overall K accumulation by 2.39-33.55%. The K application amount was proportional to the K accumulation amount under the non-returning straw treatment. With an increase in the K application amount under the wheat straw-returning treatment, the K accumulation amount initially increased and then decreased; when the K application rate was 125 kg ha⁻¹, then K accumulation reached its highest point. When the K application rate exceeded 187.5 kg ha⁻¹, no significant difference in K accumulation was observed in the 5th internode, and this was not conducive to K accumulation in the 3rd and 4th internodes.

Wheat straw being returned to the field, the K application amount, and the interaction effect between the two factors had significant effects on the stem gravity centre height and plant heights in the third, fourth, and fifth internodes (Table 3). Compared with those under the non-returning

straw treatment, the internode length increased by 7.04-25.55% and the average increase in the height of the centre of gravity and plant height under the wheat straw-returning treatment were 4.40 and 5.81%, respectively. Additionally, the internode stalk length, centre of gravity height, and plant height initially decreased and then increased with increasing K rates, and it was suitable for a combined K fertilizer application at 187.5 kg ha⁻¹. K fertilizer reduction and an application rate of 125 kg ha⁻¹ were most effective under the wheat straw-returning treatment. The height of the centre of gravity increased when the K application rate was insufficient, and the plant height increased when K was applied in excess, which was not conducive to the lodging resistance of the stem.

Under the wheat straw-returning treatment, the K application amount and the interaction between the two factors significantly impacted the flattening rate and cavity area of the different internodes (Table 4). The cavity area results indicated an initially decreasing and then increasing trends. After the wheat straw-returning treatment, the flat rates of the third, fourth, and fifth internodes decreased by 5.77-18.57% and the cavity area increased by 13.03-16.08%. When the wheat straw was returned to the field with a K fertilizer rate of 125 kg ha⁻¹, each internode had the lowest flat rate and cavity area, implying that this was the optimal fertilizer amount, and the area of the 5th internode cavity was at its lowest level.

The effects of wheat straw returning to the field, the K application amount, and their interaction effects on the soluble total sugar and lignin contents of each internode stem

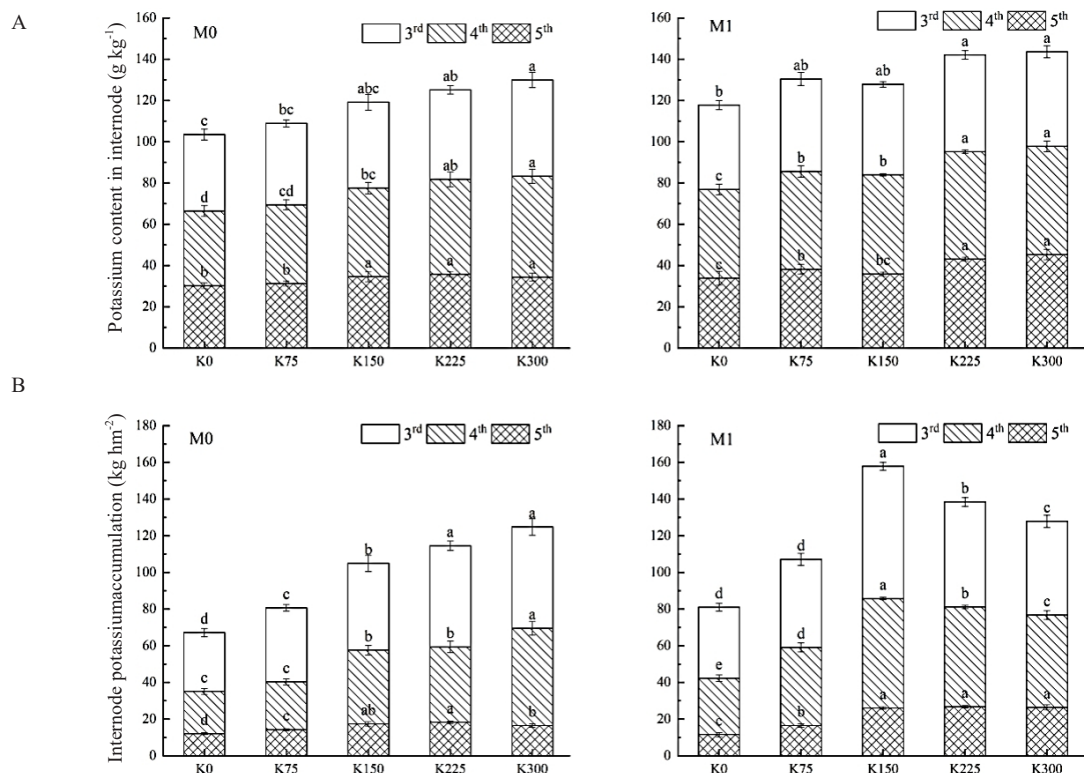


Fig. 2. Effects of wheat straw returning and potassium fertilizer application on K content (A) and K accumulation (B) in different stem internodes of direct seeding rice. Different lowercase letters in the same node under the same straw returning method indicate significant differences at the 5% level for different potassium application treatments.

Table 3. Effects of straw returning and K fertilizer application on stem length and the height of the centre of gravity in different internodes of direct-seeded rice

Treatment	Internode length (cm)					Height of centre of gravity (cm)	Plant height (cm)	
	1rd	2th	3th	4th	5th			
M ₀	K ₀	23.37a	17.90ab	11.40a	6.47a	3.47a	57.43a	90.93b
	K ₇₅	24.40a	18.07a	11.17ab	6.27a	3.20ab	58.10a	95.63a
	K ₁₅₀	23.33ab	16.13c	9.63bc	6.07ab	3.10ab	56.80a	84.80c
	K ₂₂₅	24.37a	16.70bc	8.77c	5.83b	2.67b	51.07b	88.77b
	K ₃₀₀	24.17a	17.03abc	10.53ab	6.37a	2.73b	56.67a	88.47b
Average	23.93	17.17	10.30	6.20	3.03	56.01	89.72	
M ₁	K ₀	24.00a	18.47bc	11.10a	8.13a	4.13ab	59.90a	94.40bc
	K ₇₅	23.93a	20.57a	11.90a	7.40b	4.33a	58.97a	96.47ab
	K ₁₅₀	24.27a	17.70bc	9.47b	6.87b	4.00ab	58.53a	92.63c
	K ₂₂₅	23.83ab	17.33c	10.80ab	7.40b	3.47b	55.53b	94.20bc
	K ₃₀₀	24.47a	19.13ab	12.13a	8.13a	4.43a	60.00a	98.57a
Average	24.10	18.64	11.08	7.59	4.07	58.59	95.25	
F value	M	0.55	4.16	3.83	42.33**	15.80**	6.58*	24.05**
F value	K	1.07	1.52	4.42**	0.95	0.26	4.09*	3.87*
	M×K	0.39	0.25	1.37	2.22	1.23	0.39	2.75

Explanations as in Table 1.

Table 4. Effects of straw returning and K fertilizer application on the stem flatness rate and cavity area of different internodes in direct-seeded rice

Treatment		Flat rate (%)			Cavity area (mm ²)		
		3th	4rd	5th	3th	4th	5th
M ₀	K ₀	20.48ab	19.65a	19.10a	16.46b	22.60a	19.38a
	K ₇₅	20.43ab	19.87a	16.31b	15.96bc	16.79b	17.41b
	K ₁₅₀	18.48bc	17.94a	15.87b	14.09c	13.55c	16.31bc
	K ₂₂₅	17.07c	15.26b	15.44b	17.74b	16.20b	14.46d
	K ₃₀₀	21.57a	19.13a	16.22b	21.18a	17.20b	15.49cd
Average		19.61	18.37	16.59	17.09	17.27	16.61
M ₁	K ₀	18.49a	15.73c	14.87b	20.61b	21.93a	18.24b
	K ₇₅	18.40a	15.13c	13.14c	17.48c	18.60b	18.13b
	K ₁₅₀	14.64b	14.96c	7.58d	16.84c	15.74c	17.34b
	K ₂₂₅	16.98ab	18.29b	16.73a	20.66b	23.07a	22.77a
	K ₃₀₀	16.50ab	22.44a	15.25b	22.68a	23.54a	22.36a
Average		17.00	17.31	13.51	19.65	20.58	19.77
F value	M	22.40**	7.04*	144.5**	53.47**	110.4**	121.4**
F value	K	2.76	22.53**	50.14**	27.24**	67.29**	28.50**
	M×K	4.83*	11.54**	39.71**	14.61**	21.39**	21.21**

Explanations as in Table 1.

Table 5. Effects of wheat straw returning and K fertilizer application on the total soluble sugar and lignin levels in different internode stems of direct-seeded rice

Treatment		Total soluble sugar (%)			Lignin (%)		
		3th	4rd	5th	3th	4th	5th
M ₀	K ₀	8.01c	3.94d	5.40c	2.62c	2.73c	3.05d
	K ₇₅	9.30b	4.97c	5.89bc	2.54d	2.55d	3.69b
	K ₁₅₀	9.95b	5.98b	6.39ab	2.50d	3.06b	3.74a
	K ₂₂₅	10.78a	7.85a	6.77a	3.61a	4.07a	3.46c
	K ₃₀₀	9.75b	7.26a	6.03abc	3.17b	3.04b	3.31c
Average		9.558	6.00	6.096	2.888	3.09	3.45
M ₁	K ₀	7.16c	5.77d	5.46c	2.24e	2.99c	2.80d
	K ₇₅	9.73.b	6.23cd	6.70b	2.75d	3.07c	3.30c
	K ₁₅₀	12.19a	7.57a	8.82a	3.85a	3.85a	4.33b
	K ₂₂₅	10.17b	6.67bc	7.76a	3.63b	3.40b	4.73a
	K ₃₀₀	9.83b	6.98b	6.29bc	3.31c	3.06c	3.33c
Average		9.816	6.644	7.006	3.156	3.274	3.698
F value	M	3.99	21.07**	22.23**	121.64**	83.44**	46.59**
F value	K	42.80**	14.59**	6.22*	319.12**	257.70**	142.64**
	M×K	57.46**	47.33**	15.17**	135.43**	215.72**	76.64**

Explanations as in Table 1.

reached significant levels (Table 5). With increases in the K application rate, the total soluble sugar and lignin contents in each internode stem showed a trend of first increasing and then decreasing. The total soluble sugar and lignin contents in the internodes under the wheat straw-returning

treatment increased by 2.65-12.98 and 5.50-8.54%, respectively. Under the non-returning straw treatment, the lignin content of the 5th internode stem was highest when the K application rate was 125 kg ha⁻¹, while the lignin and soluble total sugar contents of the other internode stems

Table 6. Correlation analysis of stem physicochemical properties, lodging resistance and rice yield in different internodes of direct-seeded rice under wheat straw returning and K fertilizer application

Index	Internode	Breaking moment			Lodging index			Grain yield
		3rd	4th	5th	3rd	4th	5th	
Breaking moment	3rd							0.92**
	4th	0.95**						0.91**
	5th	0.86**	0.82**					0.84**
Lodging index	3rd	-0.90**	-0.77*	-0.86**				-0.79**
	4th	-0.86**	-0.60*	-0.68*	0.64*			-0.60*
	5th	-0.75*	-0.80**	-0.73*	0.82**	0.74*		-0.77**
Internode potassium content	3rd	0.74*	0.65*	0.55	-0.57	-0.29	-0.60*	0.89**
	4th	0.72*	0.71*	0.61*	-0.58	-0.38	-0.65*	0.87**
	5th	0.58	0.49	0.55	-0.34	-0.48	-0.66*	0.73*
Internode potassium accumulation	3rd	0.97**	0.93**	0.78**	-0.84**	-0.47	-0.64*	0.93**
	4th	0.87**	0.89**	0.90**	-0.78**	-0.45	-0.68*	0.91**
	5th	0.86**	0.82**	0.78**	-0.60	-0.69*	-0.72*	0.90**
Internode length	3rd	-0.46	-0.52	-0.61*	0.63*	0.40	0.22	-0.35
	4th	-0.10	-0.05	-0.17	0.01	0.14	0.19	0.16
	5th	-0.09	-0.02	-0.17	0.03	0.08	0.29	0.11
Flat rate	3rd	-0.68*	-0.65*	-0.44	0.48	0.38	0.59	-0.67*
	4th	-0.29	-0.32	-0.29	0.53	0.01	0.34	-0.14
	5th	-0.59	-0.64*	-0.37	0.67*	0.12	0.51	-0.59
Cavity area	3rd	0.08	0.19	0.03	0.10	0.14	0.05	0.29
	4th	-0.19	-0.22	-0.21	0.49	0.09	0.17	-0.16
	5th	-0.33	-0.45	-0.32	0.62*	0.01	0.22	-0.25
Total soluble sugar content	3rd	0.85**	0.85**	0.79**	-0.78*	-0.51	-0.62*	0.86**
	4th	0.70*	0.81**	0.72*	-0.73*	-0.29	-0.52	0.83**
	5th	0.92**	0.91**	0.80**	-0.81**	-0.62*	-0.75*	0.80**
Lignin content	3rd	0.80**	0.88**	0.82**	-0.71*	-0.46	-0.46	0.85**
	4th	0.72*	0.79**	0.84**	-0.60*	-0.43	-0.51	0.72*
	5th	0.77**	0.74*	0.76*	-0.64*	-0.82**	-0.67*	0.68*

Indicate significant effects at: * $p < 0.05$ and ** $p < 0.01$ levels, respectively.

did not differ at a K application rate of 187.5 kg ha⁻¹. The contents of lignin and total soluble sugar in the 3rd and 4th internodes under the wheat straw-returning treatment were highest when the K application rate was 125 kg ha⁻¹, thereby indicating that returning the wheat straw to the field possibly saves K fertilizer and increases the total soluble contents of the stem and also the sugar and lignin contents.

The breaking moments of the 3rd and 4th internodes were significantly positively correlated to a significant extent with the K content of the corresponding internodes (Table 6), thereby indicating that increasing the K content of the 3rd and 4th internodes may increase the culm breaking moment. There was a very significant positive correlation between the breaking bending moment and K accumulation in the internodes ($r = 0.78^{**}$ - 0.97^{**}). The lodging indices of the other internodes were closely related

to each other except for the 4th internode. Potassium accumulation was negatively correlated to a significant extent. The longer stems in the third internode would reduce the bending moment of the fifth internode and also increase the lodging index of the third internode. The flattening rate of the 3rd internode was negatively correlated to a significant extent with the breaking bending moment of the 3rd and 4th internodes, thereby indicating that a reduction in the flattening rate of the third internode could increase the breaking moment. The total soluble sugar and lignin contents of each internode stem were significantly positively correlated with the bending moment at the breaking point ($r = 0.70^{*}$ - 0.92^{**}). The total soluble sugar and lignin contents of the 5th internode stem were negatively correlated to a significant extent with the lodging index of each internode stem. Additionally, the relationship between the

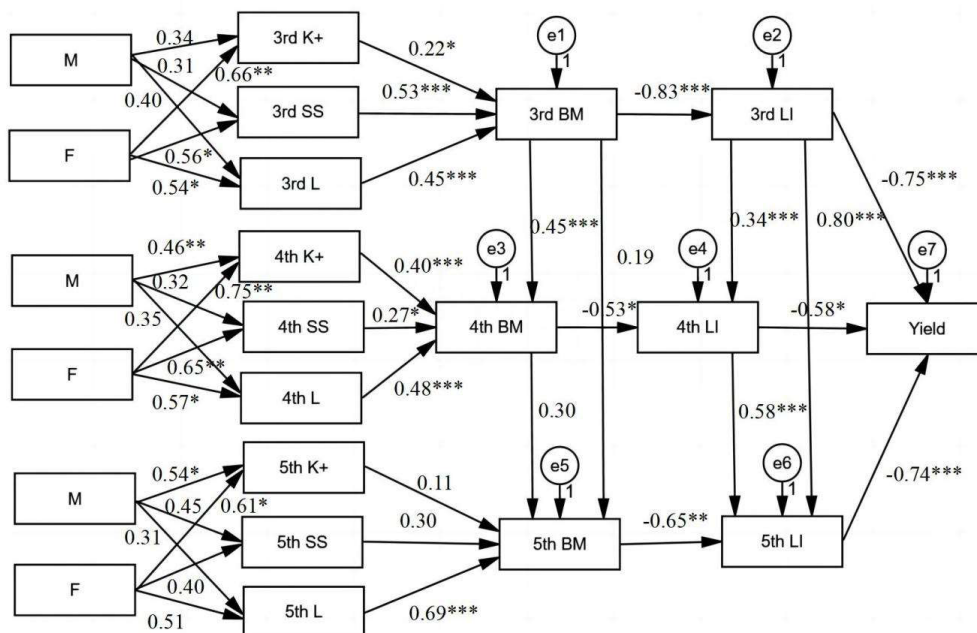


Fig. 3. Relationship between the content of the chemical constituents in different stem internodes and lodging and yield. M – straw returning, F – fertilization, K+ – potassium accumulation, SS – total soluble sugar content, L – lignin content, BM – breaking moment, LI – lodging index. Individual models are fitted for different internodes, and the interaction effects are fitted. The numbers represent standardized total influence coefficients, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

physicochemical properties, lodging index, and the yield of stems in different internodes varied. Compared with those in the 4th and 5th internodes, the accumulation of K and total soluble sugar and lignin contents in stems at the third internode were positively correlated ($r = 0.85^{**}$ – 0.93^{**}) to a very significant extent with the yield and negatively correlated to a significant extent with the stem flattening rate and lodging index ($r = -0.67^{*}$ – -0.79^{**}) and may synergistically improve the 4th internode. The 5th internode culm was comprehensively resistant to lodging ($r = 0.82^{**}$ – 0.95^{**}).

The wheat straw-returning treatment and K fertilizer application increased the breaking moment of stems at each internode to a significant extent, reduced the lodging index, and ultimately increased the yield of direct-seeded rice (Fig. 3). The wheat straw-returning treatment affected K accumulation, and the increase in K accumulation significantly increased the breaking moment of the stem at the 3rd and 4th internodes. ($p < 0.01$), it also had a significant effect on the contents of soluble sugar and lignin ($p < 0.05$). Potassium accumulation and the soluble sugar content mainly increased the breaking moment of the stems at the 3rd and 4th internodes, while the lignin content had a very significant promoting effect on the breaking moment of stems at different internodes. The breaking moment had a significant or extremely significant inhibitory effect on the lodging index; in particular, the inhibitory effect of the 3rd internode was extremely significant ($p < 0.001$). The lodging index at the 3rd internode had a very significant

effect on the 4th and 5th internodes, thereby suggesting that the breaking moment of the stems at different internodes not only correlated with K accumulation and soluble sugar and lignin contents but also correlates to a significant extent with each internode.

DISCUSSION

Transplanted rice plants from the seedling nursery undergo a transplantation shock that causes delayed biomass accumulation in transplanted rice, but none of these problems occur in direct-seeded rice as opposed to transplanted rice. Appropriate cultivation measures are the key to improving the yield of direct-seeded rice. Several studies have shown that straw returning and proper K fertilizer management can improve crop yields, but the techniques employed for straw returning and K fertilizer application to optimize crop yield are not consistent (He *et al.*, 2017; Bahmaniar *et al.*, 2007; Yang B. *et al.*, 2009). Returning straw to the field can improve rice yield by affecting the leaf area index and dry matter accumulation, optimizing the grain filling rate, and increasing the thousand-grain weight (Sun *et al.*, 2012; Zhao *et al.*, 2011). Furthermore, returning straw to the field increases the soil organic matter, improves nutrient absorption by the roots of direct seeding rice, and increases the number of effective panicles thereby increasing the yield of direct seeding rice. However, it does not affect the seed setting rate and 1000 grain weight (Yang *et al.*, 2010). The present study revealed that the number of effective panicles and the number of grains per panicle

are significantly increased by returning straw to the field, thereby increasing yields. However, compared with previous studies (Zhao *et al.*, 2011), returning wheat straw to the field in this study had no significant effect on the 1000 grain weight, while K fertilizer increased yield. Yang B. *et al.* (2009) reported that K fertilizer mainly increases the yield by increasing the number of spikelets and grains per panicle, but it has a certain inhibitory effect on the seed setting and panicle formation rates. The present study revealed that returning straw to the field and K fertilizer management had a significant interaction effect on the yield of direct-seeded rice and that exploiting these two factors together for increased yield was beneficial for increasing the number of effective panicles, the number of grains per panicle, and the total number of spikelets. In particular, K fertilizer had a significant promoting effect on the seed setting rate and optimized the factors affecting the yield, this further complemented the results of previous studies (Yang B. *et al.*, 2009; Lei *et al.*, 2014). Additionally, this study revealed that the excessive application of K fertilizer under the treatment in which straw was returned to the field reduced the number of effective panicles, grains per panicle, and the total spikelet number of direct-seeded rice, which resulted in a reduced yield. Therefore, the K fertilizer management of direct-seeded rice should be optimized further according to the soil fertility (Lei *et al.*, 2014) and the K content of the returning straw.

In addition to its genetic factors and cultivation methods, the lodging resistance of rice is closely related to the external environmental conditions of growth (Lei *et al.*, 2014). Using the evaluation indicators reported in previous studies, including the internode length, centre of gravity height, plant height, flat rate, cavity area, breaking moment, total soluble sugar, and lignin content, the lodging resistance of rice stems was measured (Zhang *et al.*, 2010; Duan *et al.*, 2004; Jiang *et al.*, 2020). Rice lodging occurs for the most part in the basal internodes, and the length of the basal internodes is positively correlated with the lodging index (Li *et al.*, 2009). The higher the plant height, the higher the height of the centre of gravity of the plant and its corresponding lodging probability (Torro *et al.*, 2011). The results of this study show that returning straw to the field has significant positive effects on the lengths of the 4th and 5th internodes at the base and is positively correlated with the lodging index, this finding is consistent with previous reports (Jiang *et al.*, 2020). Under the straw-returning treatment, the centre of gravity height, plant height, and cavity area increased, but the flat rate of the internodes decreased, and also, the breaking moment increased, which was beneficial for improving the lodging resistance of the base internodes. Therefore, reducing plant height and shortening the internode length of the stem improves the flat rate and cavity area, and consequently improves the lodging resistance of rice (Luo *et al.*, 2007). Zhao *et al.* (2022) showed that returning straw to the field improves the

stem wall thickness, stem thickness, and also the bending resistance of the basal internodes. Under the same fertilization treatment, returning straw significantly improved the bending resistance of stems (up to 33.74%), and also the lodging index was reduced by up to 33.86%. The results of this study showed that the fracture breaking moment of the base internodes increased after the return of the straw, with that of the 3rd internode increasing most and reaching 13.50%, while the lodging index decreased by 8.15%. Potassium fertilizer application promotes the lignification of the sclerenchyma cells and the thickening of the thick horn tissue of rice culms, making it stout, and increasing its mechanical strength, and consequently improving the lodging resistance of rice culms. Wu *et al.* (2019) showed that K application can enhance the unit internode dry weight, internode thickness, and stem wall thickness, thereby improving the lodging resistance of rice. An increased internode breaking moment at the base leads to a greater rice stem wall thickness, and also, an increased rice stem fullness can significantly improve stem bending resistance (Li *et al.*, 2021). The present study showed that under the straw-returning treatment, increased K fertilizer application led to an initial decrease and then an increase in the physical indexes of the base internodes, while the breaking moment first increased and then decreased. Moreover, it was found that applying 187.5 and 125 kg ha⁻¹ of K fertilizer to the field and after the return of wheat straw treatment, respectively, is suitable. A correlation analysis showed that reducing the length and flattening the rate of the 3rd internode significantly increased the breaking moment and reducing the cavity area of the 5th internode improved the lodging resistance. Lignin, which is a key cell wall polymer for rice lodging resistance, increases the mechanical strength of the basal stem (Liu *et al.*, 2019). The present study observed that the 5th internode had the highest lignin content and the shortest length as compared with the other internodes. Another study showed that lignin content was positively correlated with the breaking moment of rice stems, and that the lodging index was negatively correlated with lignin and the total soluble sugar contents (Zhao *et al.*, 2011; Yang S. *et al.*, 2009). When the lignin content is greatly reduced, a significantly low breaking moment and a high lodging index are observed (Weng *et al.*, 2017). The present study showed that under the straw-returning treatment, the chemical components in the stems were inconsistent in the different internodes, having significantly different correlations with the breaking moment and lodging index. A significant positive correlation exists between the breaking moment and K content, and the internode K accumulation has a very significant positive correlation with the breaking moment. Increasing the internode K content and accumulation can serve to reduce the lodging index of stems. This study also showed that the lodging index of the

3rd internode was the largest one and increasing the total soluble sugar and lignin contents in the 3rd internode could improve the lodging resistance of the basal internode.

The most direct impact of rice lodging is a reduction in the yield; therefore, it is one of the major determinants of the limited quality and yield of rice (Guo *et al.*, 2021). Several studies concerning rice lodging and yield enhancement methods exist; these include studies with the fertilization methods and amounts (Zhang *et al.*, 2017; Sun *et al.*, 2012), planting density (Xu *et al.*, 2015), stem mechanical strength and starch content (Liu *et al.*, 2012), and also rice lodging resistance genes (Liu *et al.*, 2018). Using structural equation modelling to analyse the effects of rice yield and its composition may provide important guidance. Miao *et al.* (2013) discussed the relationship between rice yield, water demand, and photosynthesis based on structural equation modelling. In addition, in the study of rice lodging resistance, the model was used to analyse the relationship between the mechanical strength of the rice stems and the thickness of the stem wall cells and vascular bundles (Zhou *et al.*, 2019). In the present study, under the rice-wheat rotation system, the effects of straw returning and K fertilizer application on the physicochemical characteristics and lodging resistance of different internodes were studied. A structural equation model analysis showed that there was a significant correlation between the physical and chemical properties of each internode and the lodging indexes of the stems. The breaking moment and lodging index of the third internode were affected most by the contents of the chemical components, which also influenced the remaining internodes. However, the effects of carbohydrates, such as cellulose and starch, on different internode lodging indices require further research. Additionally, the regulatory genes and their regulatory pathways which affect the absorption and transport of K ions under the conditions of returning wheat straw to the field and K fertilizer application require further study.

CONCLUSIONS

1. The interaction of returning wheat straw to the field and the quantity of K application had significant effects on the physicochemical properties and lodging index of different internode stems, and also on the grain yield in direct-seeded rice.

2. Under the conditions of this experiment, a K fertilizer application rate of 125 kg ha⁻¹ combined with wheat straw returning significantly promoted K accumulation in different internodes, increased the total soluble sugar and lignin contents, improved the bending moment at breakage, and reduced the stem flat rate and lodging resistance index, which are important factors for improving the lodging resistance and yield of direct-seeded rice.

3. Compared with those of the 4th and 5th internodes, K accumulation and the total soluble sugar and lignin contents of the 3rd internode were positively correlated to

a significant extent with the yield and negatively correlated with the culm flatness rate and lodging index. Therefore, these factors have the potential to synergistically improve stem lodging resistance between the 4th and 5th internodes.

4. Accordingly, the physicochemical properties and lodging resistance indexes of the 3rd internode stem may be used as evaluation indexes for the simultaneous improvement of the yield and lodging resistance of direct-seeded rice, thus representing an important regulatory approach to achieving coordination and unity between high yields and lodging resistance.

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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