RESEARCH

Effects of continuous straw return and fertilization on rice lodging resistance

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ABSTRACT

As a common problem in rice (*Oryza sativa* L.) production, lodging will not only increase harvest costs and reduce rice production, but also affect rice taste seriously and reduce its commercial value. There is still a lack of systematic research on the effect of lodging resistance of rice after returning wheat (*Triticum aestivum* L.) straw to the field. The study evaluated the effects of continuous straw returning and different fertilizer input levels on the lodging resistance of rice stalks based on years of experiments, using a split zone design with two factors including full return of straw to the field and straw removal, and three fertilization levels (conventional fertilization, 50% of conventional fertilization and no fertilization) under each factor, for a total of six treatments. Results suggested that under the same level of chemical fertilizer application, treatments of straw returning significantly increased stalk flexural resistance up to 33.74% as well as decreased the lodging index by a maximum of 33.86% compared with straw removal. Decrease of chemical fertilizer application increased significantly stalk flexural resistance, while decreased significantly lodging index. Rice plant height, center of gravity height, internode length, stem wall thickness and internode dry weight were main factors that influence rice lodging resistance. Compared with straw removal, straw returning combined with chemical fertilizers applying could significantly increase rice yield up to 19.62%. The increase in rice yield increased the risk of rice lodging. The continuous return of straw to the field combined with the application of chemical fertilizers reduced the risk of rice lodging to a certain extent, and meanwhile it achieved successive annual increase in rice production, which has a good promotion prospect.

Key words: Lodging index, *Oryza sativa*, returning straw to the field, rice, rice-wheat rotation, *Triticum aestivum*.

INTRODUCTION

With the rapid development of the national economy and the continuous improvement of people's living standards, Chinese people have higher and higher requirements for the quality of rice (*Oryza sativa* L.), and the demand for rice has changed from eating full to eating well (Peng et al., 2015). Lodging is a common problem in rice production. After rice lodging, it will not only increase harvest costs and reduce rice yield, but also seriously affect the taste of rice and reduce the commercial value of rice.

Therefore, it is of great significance to research the problem of rice lodging and take effective measures to improve rice lodging resistance and prevent or reduce the occurrence of lodging. There are two types of rice lodging: root lodging and stem lodging (Zhu et al., 2013). Root lodging mostly occurs in direct seeding fields, and stem lodging occurs mainly in rice transplanting fields. In addition to natural factors and the agronomic characteristics of rice varieties themselves (Zhu et al., 2013; Yamaguchi et al., 2018; Zhao et al., 2019), cultivation and management measures are also important influencing factors to rice lodging (Liu et al., 2018b). Zhang et al. (2017) showed that lodging resistance of rice is closely related to the physical properties of rice such as plant height, center of gravity height, stem length, stem thickness, stem dry weight, and stem wall thickness. In addition, the lodging resistance of rice stems is also affected by the content of chemical components such as Si, K, cellulose, lignin, starch, and soluble sugar in the stems (Sreeja et al., 2016; Zhang et al., 2016; Dorairaj et al., 2017; Gui et al., 2018).

Returning straw to the field can significantly increase the content of organic matter in the soil, improve the physical and chemical properties and biological characteristics of the soil (Wang et al., 2015). And also, the decomposition of straw can provide a large amount of nutrients for crop growth and reduce the input of chemical fertilizers (Wei et al., 2019). Returning straw to the field is one of the most direct and effective measures to fertilize the soil and implement the national strategy of "reserving grain on the ground" (Zhao et al., 2018), and it is also the most direct and effective way to realize the utilization of straw resources (Wang et al., 2021b). Regarding the influence of cultivation measures on the lodging resistance of rice stalks, existing studies (Hao et al., 2013; Adha et al., 2020; Wang et al., 2021a) mostly focused on planting methods and cultivation modes, fertilizer types and dosages, planting density and irrigation methods. There are few studies on the effect of straw returning to the lodging resistance of crops (Li et al., 2013a), and there is no report on the effect of returning wheat (*Triticum aestivum* L.) straw to the field on the lodging resistance of rice in the rice-wheat rotation area.

In this experiment, the high-stalk 'Jindao 263' and the short-stalk 'Shengdao 19' rices were selected. Relying on the straw return and fertilization positioning experiment started in 2013, the effects of different straw treatment methods and chemical fertilizer input levels on rice lodging resistance were studied. The purpose was to explore the lodging resistance of rice under different straw treatment methods and chemical conventional fertilizer input levels and its related mechanisms. The results of the study could provide a theoretical basis for the formulation of rice cultivation and management measures under the condition of straw returning to the field and the promotion of straw returning technology.

MATERIALS AND METHODS

Test location and test species

The test site is located at the Jining Comprehensive Test Base of Shandong Rice Research Institute (35°19' N, 116°37' E). It is located in the central area of the depression between the sloping plain of Taiyimeng Mountain in the central-south of Shandong and the yellow flood plain of southwest in Shandong province. The area has a warm temperate monsoon climate, with an average annual temperature of 13-14 °C, annual precipitation of 600-800 mm, annual sunshine duration of 2391.4 h, and a frost-free period of 200 d. The test soil is calcic Vertisols (FAO), which was formed by the de-swamping of the sediments of Nansi Lake, and its ability to retain fertilizer is poor. The experiment started in 2013, and the basic fertility data measured before the experiment were: organic matter content 18.8 g kg^{-1}, total N 1.22 g kg^{-1}, total P 0.65 g kg^{-1}, total K 10.55 g kg^{-1}, and alkaline hydrolysis N 72.98 mg kg^{-1}, available P 23.46 mg kg^{-1}, available K 135.00 mg kg^{-1}.

In 2018, the tested rice (*Oryza sativa* L.) variety was the high-stalk Jindao 263, and in 2019 tested variety was the dwarf and lodging resistant Shengdao 19.

Experimental design

Based on the "rice-wheat (*Triticum aestivum* L.)" crop rotation system, a split zone design was adopted, with two factors including full return of straw to the field and straw removal, and three fertilization levels under each factor, for a total of six treatments: conventional fertilization + straw full return to the field (HN1), 50% conventional fertilization + full straw return (HN4), no fertilization + full straw return (HN0), conventional fertilization + straw removal (N1), 50% conventional fertilization + straw removal (N4) and no fertilization + straw removal (N0). The plot area was 24 m^2 (4 m × 6 m), repeated three times. Each treatment plot had separate drainage and separate irrigation, with irrigation drainage ditch in the middle. Between the plots and drainage ditch, 30 cm ridges were built and coated with plastic film to prevent cross-irrigation.

After rice and wheat were harvested, for full straw return treatment all the straws were crushed to less than 5 cm and then plowed back to the field with a plowing depth of about 20 cm; and for straw removal treatment all the straws were removed from the experimental field.

Conventional fertilizer rate for rice: 276 kg N ha^{-1}, 135 kg P_2O_5 ha^{-1}, 78 kg K_2O ha^{-1}. Conventional fertilizer rate for wheat: 276 kg N ha^{-1}, 67.5 kg P_2O_5 ha^{-1}, 59 kg K_2O ha^{-1}. Other management measures for rice and wheat were carried out as usual.

Measurements

Twenty-five days after earing, 20 representative single stems were randomly selected from each plot in each treatment, and plant height, center of gravity height, length of each internode, thickness of the internode from the middle, thickness of the stem wall, flexural resistance of base 1, 2, 3, and 4 internodes (I1, I2, I3 and I4), as well as the length and fresh weight from the base of the internode to the top of the ear were measured.

Center of gravity height: The upper part of the fresh stalk (including ears, leaves and leaf sheaths) was horizontally placed on the knife edge, and moved it left and right until it lied on the knife edge in balance. At this time, the contact point with the knife edge was the center of gravity. The distance from the center of gravity to the base of the stalk is the height of the center of gravity (cm).

The calculation of the bending moment (BM), flexural resistance (BR) and lodging index (LI) from internodes at the base of rice with different planting methods referred to the method of Xing et al. (2017):

Bending moment (cm g) = Length from base of internode to top of ear (cm) × Fresh weight from base of this internode to top of ear (g)

Lodging index (cm g g^{-1}) = Bending moment (cm g)/Flexural resistance (g) ×100.

Internode flexural resistance was measured with YYD-1 stalk strength measuring instrument (Top Instrument, Hangzhou, China). Fixed the distance between the two fulcrums at 5 cm, placed the internodes horizontally on the two fulcrums, applied force at the midpoint of the internodes to break them, and the magnitude of the force was the flexural resistance of the internodes. If the internode length was less than 5 cm, adjusted the two fulcrums to an appropriate distance, and after measured the flexural resistance, converted the fulcrum distance to 5 cm (Xia et al., 2017).

Internode thickness and stem wall thickness: Digital vernier calipers were used to measure the outer diameter of the long axis and short axis of the internode, and obtain the average value as the thickness of the internode; internode was cut from the middle and thickness was measured of the four intersections of the long axis and short axis from the stem wall, and the average value was the stem wall thickness.

Internode volume: Considering the internode as an approximate hollow cylinder, the volume of the internode was $V = \pi L (DT - T^2)$; where D is the thickness of the internode, T is the thickness of the stem wall, and L is the length of the internode.

Dry weight per unit length and dry weight per unit volume: Dry weight per unit length = Dry weight of the internode/ Internode length; Dry weight per unit volume = Dry weight of the internode/Volume of the internode.

After completed the above determination items, each internode stalk and leaf sheath were bagged separately, placed in an oven, deactivated at 105 °C for 30 min, and then dried at 80 °C to a constant weight, and dry weight of each internode stem and leaf sheath was measured. Calculated the stalk substantial degree (dry weight of stalk per internode).

Yield and its components: At the maturity stage, 20 representative whole plants were taken from each plot to plant laboratory test, and number of effective panicles, total grains per panicle, seed setting rate, and 1000-grain weight were determined, and 5 m^2 of actual harvest were measured.

Statistical analysis

Excel 2013 software was used for data sorting. And SPSS 16.0 statistical programs package (IBM, Armonk, New York, USA) was used for multiple comparisons between treatments. The means of each treatments were compared with the least significant difference (LSD) test at the $p < 0.05$ and $p < 0.01$ probability levels.

RESULTS

Effect on lodging resistance of rice

The high-stalk 'Jindao 263' (2018) and the dwarf 'Shengdao 19' (2019) were used to research the lodging resistance of rice under different straw treatments and fertilizer rates. Under the same fertilizer input level (conventional fertilization and 50% fertilization), flexural resistance of the stalk in the treatment of returning straw to the field was significantly greater than that of removing the straw; flexural resistance of the first internode at the base in HN1 had an increase of 33.74% and 33.04% compared with N1 in 2018 and 2019, respectively (Table 1). The lodging index of the straw returning treatment was significantly lower than that of straw removal; lodging index of the first internode at the base of treatment HN1 decreased by 18.41% and 33.86% compared with treatment N1 in 2018 and 2019, respectively. Under the condition of no chemical fertilizer, the bending resistance of the stalk in the treatment of returning straw to the field was significantly reduced compared with the removal of straw, while the lodging index increased significantly. The resistance of rice stalks in the treatments of straw returning and straw removal showed different trends with the decrease of chemical fertilizer application; the treatment of straw returning to the field first increased and then decreased with the decrease of fertilizer amount, while the treatment of straw removal increased with the decrease of amount of fertilizer. The stalk bending moment of the straw returning and the straw removal treatments decreased with the decrease of the fertilization amount in 2018, while the stalk bending moment of the straw returning to the field and the straw removal treatments first increased and then decreased with the decrease of the fertilization amount in 2019. Generally speaking, the lodging index decreased with the decrease of fertilizer application.

This suggested that returning straw to the field combined with chemical fertilizer applying could reduce the lodging index by increasing the stalk bending resistance, but returning straw to the field without chemical fertilizer reduced the stalk bending resistance and increased the lodging index. Whether the straw was returned to the field or not had nonsignificant effect on the bending moment of the rice stalk. The bending moment of the rice 'Jindao 263' decreased with the decrease of the fertilizer rate, and the 'Shengdao 19' first increased and then decreased with the decrease of the fertilizer rate. The lodging index decreased with the decrease of fertilizer application.

Effect on stem structure characteristics

The effects of different straw treatment methods under the same fertilizer input level on rice stalk structure showed different trends in different years (Table 2). The length of first internodes of the base were significantly reduced in the straw returning treatment compared with the treatment of straw removal in 2018, among them, treatment HN1 reduced by 30.33% compared with treatment N1, and there was nonsignificant difference between the second, third, and fourth base internodes. Whether the straw was returned to the field or not had no obvious regularity on the effect of the internode length under the condition of no fertilizer.

The first internode of the stem base in the straw returning treatment became significantly longer compared with the straw removal treatment under the same fertilizer input level in 2019, and the second one was significantly shorter, there was nonsignificant difference between the third and fourth nodes of the stem base. Whether the straw was returned to the field or not had no obvious regularity on the effect of the length of internodes under the condition of no fertilizer. On the whole, plant height and center of gravity height were significantly increased in the straw returning treatment under

Table 1. Effects of different straw treatment methods and fertilizer rates on rice lodging resistance.

Year	Treatment	Flexural resistance				Bending moment				Lodging index			
		I1	I2	I3	I4	I1	I2	I3	I4	I1	I2	I3	I4
		g				cm g				cm g g^{-1}			
2018	HN1	1470.00a	968.67d	631.33d	450.00d	1185.12a	918.06a	591.60a	307.38a	87.63b	102.17a	97.54a	73.23a
	HN4	1425.83b	1175.33b	857.33b	675.83b	1009.73b	804.30c	515.57c	260.00c	77.71c	74.22b	64.57c	39.97d
	HN0	1285.83c	1028.67cd	790.00c	516.00c	848.12c	671.54e	461.94d	234.58d	66.77d	65.88b	58.50d	45.52c
	N1	1099.17d	840.67e	646.00d	439.33d	1183.30a	866.41b	568.49b	291.35b	107.40a	105.39a	87.86b	64.66b
	N4	1310.00c	1072.00c	872.67b	678.00b	1000.52b	703.86d	451.65d	221.95d	78.37c	71.31b	58.09d	37.38de
	N0	1574.44a	1412.00a	1123.33a	748.67a	817.20c	658.27e	457.48d	232.62d	54.29e	49.36c	45.87e	34.03e
2019	HN1	941.10b	826.98c	645.82d	441.02c	601.62c	519.64d	381.98bc	236.01b	63.93c	67.99a	67.29a	64.65a
	HN4	1185.41a	975.52b	704.96c	520.05b	627.22c	557.58b	391.48b	231.72b	52.93d	58.26b	55.85b	46.00c
	HN0	856.00c	1148.17a	996.60a	607.75a	473.13d	377.52e	261.17d	151.76d	55.27d	32.54c	25.99d	25.23d
	N1	707.38d	796.05c	688.64c	390.21d	682.92b	541.53c	377.74c	213.67c	96.66a	68.10a	54.86b	54.79b
	N4	898.48bc	955.81b	679.13c	499.32b	750.49a	598.24a	466.42a	309.59a	83.60b	62.59b	68.71a	62.04a
	N0	1131.81a	1111.48a	843.64b	607.07a	474.47d	331.07f	239.79e	138.05e	42.03e	36.97c	28.12c	23.29d

Different lowercase letters in the same column in the same year indicated a significant level of 5% difference respectively.
HN1: Conventional fertilization + straw full return to the field; HN4: 50% of conventional fertilization + full straw return; HN0: no fertilization + full straw return; N1: conventional fertilization + straw removal; N4: 50% of conventional fertilization + straw removal; N0: no fertilization + straw removal; I1: first internode of base; I2: second internode of base; I3: third internode of base; I4: fourth internode of base.

Table 2. Effects of different straw treatment methods and fertilizer rates on rice stalk structure characteristics.

Year	Treatment	Internodes length				Plant height	Center of gravity height	Relative center of gravity height
		11	12	13	14			
		cm				cm		%
2018	HN1	7.42c	13.88ab	19.61a	27.95b	97.36a	44.45b	45.66e
	HN4	8.96b	13.57b	19.73a	29.77a	91.77c	43.33c	47.23d
	HN0	7.96c	10.30c	17.87b	26.13c	79.53e	39.03d	49.04b
	N1	10.65a	14.45a	19.71a	28.45b	94.59b	45.45a	48.06c
	N4	10.04a	13.43b	19.43a	27.63b	89.53d	42.67c	47.66cd
	N0	7.08c	9.77c	17.20c	26.50c	77.30f	38.67d	50.04a
2019	HN1	3.83c	6.92c	12.90a	26.54ab	71.42a	36.04a	51.74a
	HN4	5.57a	7.13bc	11.73b	24.73b	68.25b	34.27b	50.22bc
	HN0	2.04e	4.55e	9.23d	22.10c	53.20c	26.27d	49.41c
	N1	2.61d	8.10a	13.43a	27.43a	67.93b	32.30c	47.49d
	N4	4.44b	7.77ab	12.93a	27.07ab	66.60b	33.93b	51.01ab
	N0	2.11e	5.97d	9.87c	21.93c	50.60c	25.37d	50.08c

Different lowercase letters in the same column in the same year indicated a significant level of 5% difference respectively.
HN1: Conventional fertilization + straw full return to the field; HN4: 50% of conventional fertilization + full straw return; HN0: no fertilization + full straw return; N1: conventional fertilization + straw removal; N4: 50% of conventional fertilization + straw removal; N0: no fertilization + straw removal; I1: first internode of base; I2: second internode of base; I3: third internode of base; I4: fourth internode of base.

the same fertilizer input level, and the relative height of the center of gravity was significantly reduced. The length of the base internodes of the straw returning treatments increased first and then decreased with the decrease of the fertilizer application. The length of the base internodes of the straw removal treatments generally decreased with the decrease of the fertilizer application. Plant height and center of gravity height showed a decreasing trend with the decrease of the fertilizer application.

This suggested that returning straw to the field and applying chemical fertilizers changed the structural characteristics of rice stalks, increased plant height and center of gravity height, while reduced the relative height of center of gravity. The effect of returning straw to the field combined with applying chemical fertilizers on the base internode length of 'Jindao 263' and 'Shengdao 19' was different; 'Jindao 263' had shorter base internodes and 'Shengdao 19' had longer base internodes.

Effect on thickness of internodes and stem wall thickness

On the whole, the thickness of stem internodes and stem wall thickness in the treatment of straw returning were significantly larger than that of straw removal under the same level of fertilizer input (conventional fertilization and fertilization reduced by half) (Table 3); among them, the thickness of the first internode and its stem wall at the base from HN1 were increased by 7.19% and 36.28% compared with N1 in 2018, respectively. The thickness of the stem internode and its stem wall in the treatment of straw returning to the field were reduced compared with the treatment of removing straw under the condition of no fertilizer.

The thickness of rice stalk internodes in the treatment of straw returning and straw removal showed different trends with the decrease of chemical fertilizer application. Thickness of the first and second internodes of the stalk base in the treatment of straw returning decreased with the decrease of fertilizer application, and the thickness of the third and fourth internodes of the stalk had no obvious change with the decrease of fertilizer application. The internode thickness of the stalk first decreased and then increased with the decrease of the fertilizer application in the straw removal treatments in 2018, and increased with the decrease of the fertilizer application in 2019. The thickness of rice stalks in the treatments of straw returning and straw removal with the decrease of fertilizer application showed a trend of first decreasing and then increasing in 2018. The thickness of the first internode at the base of the rice stalk increased with the decrease of fertilizer application under the condition of returning straw to the field in 2019, while the other internodes showed no obvious change. The thickness of the stem wall increased with the fertilizer application under the condition of straw removal.

Table 3. Effects of different straw treatment methods and fertilization rates on internode thickness and stem wall thickness.

Year	Treatment	Internodes thickness				Stem wall thickness			
		I1	I2	I3	I4	I1	I2	I3	I4
		mm				mm			
2018	HN1	6.26a	5.42a	4.28c	3.11bc	1.54a	1.27a	1.03a	0.89a
	HN4	5.58c	4.86bc	4.28c	3.01c	1.04d	0.92e	0.83d	0.70c
	HN0	5.34d	4.86bc	4.35bc	3.20ab	1.06d	0.97d	0.88c	0.69c
	N1	5.84b	5.29a	4.44a	3.24a	1.13c	1.02c	0.94b	0.77b
	N4	5.25d	4.70c	4.17d	3.03c	0.98e	0.88f	0.83d	0.68c
	N0	5.43c	4.98b	4.38ab	3.24a	1.21b	1.13b	0.96b	0.79b
2019	HN1	4.65e	4.84c	4.64a	3.21ab	1.22d	1.22b	1.12b	0.94a
	HN4	5.79a	5.28a	4.56ab	3.30a	1.39c	1.20b	1.01c	0.65d
	HN0	5.29c	4.98bc	4.29d	3.01c	1.59b	1.15c	1.00c	0.75c
	N1	5.07d	5.00b	4.41c	3.20ab	1.04e	1.00d	0.82d	0.69cd
	N4	5.13d	5.05b	4.33cd	3.20ab	1.16d	0.99d	0.85d	0.72c
	N0	5.49b	5.07b	4.52b	3.08bc	1.69a	1.44a	1.20a	0.83b

Different lowercase letters in the same column in the same year indicated a significant level of 5% difference respectively.
HN1: Conventional fertilization + straw full return to the field; HN4: 50% of conventional fertilization + full straw return; HN0: no fertilization + full straw return; N1: conventional fertilization + straw removal; N4: 50% of conventional fertilization + straw removal; N0: no fertilization + straw removal; I1: first internode of base; I2: second internode of base; I3: third internode of base; I4: fourth internode of base.

This suggested that straw returning to the field combined with chemical fertilizers increased thickness of the internodes and stem wall compared with the removal of straw, which was an important factor in improving the stem bending resistance of the straw returning treatments. The internode thickness and stem wall thickness of 'Jindao 263' and 'Shengdao 19' showed different trends with the decrease of fertilizer application.

Effects on dry weight of rice stalks

The dry weight of stalks, dry weight of internodes per unit length, and dry weight of internodes per unit volume from the first and second internodes of the stem base in straw returning treatments under the same fertilizer input level (conventional fertilization and 50% fertilization) were significantly increased compared with straw removal treatments (Table 4). Among them, dry weight of stalks, dry weight of internodes per unit length, and dry weight of internodes per unit volume in HN1 were increased by 16.41%, 37.41% and 10.15%, respectively, compared with N1 in 2018, and the former increased by 41.43%, 14.39% and 16.46%, respectively, compared with the latter in 2019. Dry weight of stalks,

Table 4. Effects of different straw treatment methods and fertilizer rates on the dry weight of stalks.

Year	Treatment	Dry weight per internode				Dry weight per unit length				Dry weight per unit volume			
		I1	I2	I3	I4	I1	I2	I3	I4	I1	I2	I3	I4
		g				mg cm^{-1}				mg cm^{-3}			
2018	HN1	0.298b	0.376b	0.401d	0.376cd	36.07b	27.14d	20.82e	13.87b	170.33e	173.83c	200.49d	227.23d
	HN4	0.296bc	0.386b	0.492b	0.429b	34.71c	28.43c	24.92c	14.35b	241.60c	247.79b	282.55b	289.26b
	HN0	0.288bc	0.349c	0.488b	0.435b	36.16b	34.02b	27.27b	16.80a	259.42b	305.10a	288.81b	326.91a
	N1	0.256d	0.336d	0.387e	0.391c	26.25e	24.16e	20.05e	14.13b	154.64f	168.95c	195.92d	245.66c
	N4	0.278c	0.358c	0.441c	0.371d	28.33d	26.17d	22.64d	13.42b	204.20d	248.97b	263.59c	278.61b
	N0	0.328a	0.418a	0.569a	0.465a	46.13a	42.88a	33.07a	17.50a	273.28a	309.32a	322.43a	291.64b
2019	HN1	0.099d	0.155e	0.250bc	0.334cd	28.38de	23.29cd	19.64d	12.94cd	212.87c	172.86d	165.30d	203.85e
	HN4	0.292a	0.248b	0.305a	0.362ab	52.42b	34.69b	26.36c	14.83ab	271.87b	225.11b	237.40b	280.85a
	HN0	0.090d	0.163de	0.259b	0.312d	45.00c	36.21b	28.44b	13.94bc	264.25b	263.68a	274.07a	268.56ab
	N1	0.070e	0.168d	0.234c	0.340bc	24.81e	20.77d	17.30e	12.62d	182.79c	175.48d	198.62c	236.05d
	N4	0.131c	0.196c	0.245bc	0.379a	29.86d	25.42c	18.98de	13.97bc	211.17c	204.72c	208.14c	246.11cd
	N0	0.149b	0.261a	0.317a	0.348bc	73.04a	43.15a	32.46a	15.69a	387.04a	268.26a	263.76a	256.67bc

Different lowercase letters in the same column in the same year indicated a significant level of 5% difference respectively.
HN1: Conventional fertilization + straw full return to the field; HN4: 50% of conventional fertilization + full straw return; HN0: no fertilization + full straw return; N1: conventional fertilization + straw removal; N4: 50% of conventional fertilization + straw removal; N0: no fertilization + straw removal; I1: first internode of base; I2: second internode of base; I3: third internode of base; I4: fourth internode of base.

dry weight of internodes per unit length, and dry weight of internodes per unit volume from the first and second internodes of the base in straw returning treatments were significantly reduced compared with the treatments of straw removal under the condition of no fertilizer.

The dry weight of stalks in the treatments of returning straw to the field with the decrease in chemical fertilizers showed different trends in 2018 and 2019. Dry weight of internodes per unit length and dry weight of internodes per unit volume increased with the decrease of fertilizer application in 2018; stem internodes dry weight first increased and then decreased with the decrease of fertilizer application in 2019, dry weight per unit length and dry weight per unit volume of the first internode at the stem base increased first and then decreased with the decrease of fertilizer application, and the remaining internodes increased with the decrease of fertilizer application. The dry weight of stalks, dry weight of internodes per unit length and dry weight of internodes per unit volume from the first and second internodes of the stem base in the straw removal treatments showed a trend of increasing with the decrease of the fertilizer application.

The above analysis suggested that returning straw to the field and applying chemical fertilizers increased dry weight of internodes at the base of the rice stalk. Reducing chemical fertilizers increased the dry weight of rice stalks to a certain extent.

Correlation between lodging index and main physical properties of stem

The main physical properties of rice stalks such as the height of the center of gravity, length of internodes, thickness of stem wall, dry weight of internodes, dry weight of internodes per unit length, dry weight of internodes per unit volume had the highest correlation with lodging index of the rice stalk, and some internodes were significantly or extremely and significantly related (Table 5). Some plant height, center of gravity height, internode length and lodging index were significantly or extremely significantly positively correlated. Some internodes stem wall thickness, internode dry weight, dry weight of internodes per unit length, dry weight of internodes per unit volume and lodging index showed a significant or extremely significant negative correlation. The relative height of the center of gravity and the thickness of internodes were not significantly correlated with the lodging index.

The above analysis suggested that the greater the value of rice plant height, center of gravity and internode length, the greater the risk of rice lodging. The greater the stem wall thickness, internode dry weight, internode dry weight per unit length and internode dry weight per unit volume, the lower the risk of lodging. The relative height of the center of gravity and the thickness of the internode had limited influence on the lodging index.

Table 5. Correlation between lodging index and main physical properties of rice stem.

		Number of base internodes			
Year	Items	I1	I2	I3	I4
2018	Plant height	0.853*	0.892*	0.862*	0.715
	Center of gravity height	0.926**	0.901*	0.828*	0.681
	Relative center of gravity height	-0.588	-0.736	-0.782	-0.652
	Internodes length	0.703	0.835*	0.700	0.219
	Internode thickness	0.590	0.756	0.132	0.191
	Stem wall thickness	0.146	0.304	0.558	0.708
	Dry weight per internode	-0.837*	-0.590	-0.870*	-0.582
	Dry weight per unit length	-0.824*	-0.817*	-0.829*	-0.444
	Dry weight per unit volume	-0.933**	-0.968**	-0.955**	-0.779
2019	Plant height	0.588	0.959**	0.939**	0.938**
	Center of gravity height	0.489	0.924**	0.964**	0.940**
	Relative center of gravity height	-0.406	0.087	0.368	0.281
	Internodes length	0.072	0.903*	0.921**	0.957**
	Internode thickness	-0.497	-0.125	0.281	0.735
	Stem wall thickness	-0.912*	-0.564	-0.415	0.055
	Dry weight per internode	-0.470	-0.319	-0.482	0.451
	Dry weight per unit length	-0.855*	-0.875*	-0.840*	-0.670
	Dry weight per unit volume	-0.849*	-0.962**	-0.881*	-0.647

*, **Significant at 0.05 and 0.01 level, respectively.
I1: First internode of base; I2: second internode of base; I3: third internode of base; I4: fourth internode of base.

Effect on rice yield and its composition

Continuous straw return and different fertilizer input levels had a significant impact on rice yield and its composition. On the whole, the primary branch number, secondary branch number and rice yield decreased significantly in 2019 compared with which in 2018 (Table 6). The effective panicle number, panicle grain number, primary branch number, and secondary branch number of straw-returning treatments were increased compared with straw removal treatments under the same chemical fertilizer input level (conventional fertilization and fertilization amount reduced by half), and the rice yield was also significantly increased. The number of effective panicles, number of grains per panicle, number of secondary branches, and yield of rice all decreased significantly with the decrease of fertilizer application under the same straw treatment method.

This suggested that the continuous return of straw to the field combined with chemical fertilizers applying improved rice yield by improving the number of effective panicles and grains per panicle. The level of fertilizer input was one of the decisive factors affecting rice yield. The yield potential of the lodging-resistant 'Shengdao 19' was significantly lower than that of 'Jindao 263'.

Correlation between lodging resistance index and rice yield and its components

The effective panicles number, number of grains per panicle, primary branches number, rice yield and rice stalk lodging index had the highest correlation, and some internodes had significant or extremely significant positive correlations (Table 7). The number of secondary branches, seed setting rate, 1000-grain weight and lodging index were not significantly correlated. It suggested that the increase in the number of effective panicles, grains per panicle, and rice yield would affect the lodging resistance of rice: the larger the value, the higher the risk of lodging.

Table 6. Effects of different straw treatment methods and fertilizer input levels on rice yield and its composition.

Year	Treatment	Effective panicle number	Total grains per panicle	Primary branch number	Secondary branch number	Seed setting rate	1000-grain weight	Yield
		Nr pot^{-1}	———	Nr	———	%	g	t ha^{-1}
2018	HN1	17.13a	120.00a	12.15a	17.80a	95.46b	27.40b	11.24a
	HN4	14.63b	119.27a	11.90a	18.35a	96.17ab	28.73a	9.19c
	HN0	10.08c	102.67ab	11.55ab	16.87a	96.70ab	28.60a	5.88e
	N1	16.28ab	115.73a	11.10ab	17.95a	96.36ab	28.11ab	10.09b
	N4	14.80b	101.09ab	11.15ab	14.55ab	97.20a	28.70a	7.78d
	N0	9.28c	86.45b	10.00b	12.40b	96.23ab	27.80ab	5.48e
2019	HN1	19.70a	116.33a	8.50ab	11.06bc	94.12ab	27.16a	8.78a
	HN4	12.90b	107.33bc	8.78a	11.94ab	95.46a	25.95b	5.09c
	HN0	4.80d	79.97d	7.75c	10.44cd	90.41c	27.05a	2.46d
	N1	18.20a	112.56ab	8.42ab	12.33a	95.82a	27.12a	7.34b
	N4	10.55c	112.17ab	8.70ab	10.89bcd	95.05a	27.05a	4.70c
	N0	6.85d	103.03c	8.19bc	9.86d	92.65b	27.36a	2.46d

Different lowercase letters in the same column in the same year indicated a significant level of 5% difference respectively.

HN1: Conventional fertilization + straw full return to the field; HN4: 50% of conventional fertilization + full straw return; HN0: no fertilization + full straw return; N1: conventional fertilization + straw removal; N4: 50% of conventional fertilization + straw removal; N0: no fertilization + straw removal.

Table 7. Correlation between lodging index and rice yield and its components.

		Number of base internodes			
Year	Items	I1	I2	I3	I4
2018	Effective panicle number	0.861*	0.884*	0.840*	0.693
	Total grains per panicle	0.761	0.829*	0.819*	0.692
	Primary branch number	0.436	0.580	0.624	0.531
	Secondary branch number	0.692	0.743	0.722	0.637
	Seed setting rate	-0.171	-0.429	-0.603	-0.625
	1000-grain weight	-0.109	-0.346	-0.504	-0.612
	Yield	0.834*	0.917*	0.919**	0.798
2019	Effective panicle number	0.549	0.911*	0.760	0.818*
	Total grains per panicle	0.457	0.873*	0.826*	0.803
	Primary branch number	0.328	0.790	0.844*	0.738
	Secondary branch number	0.633	0.745	0.570	0.585
	Seed setting rate	0.593	0.882*	0.801	0.754
	1000-grain weight	0.169	-0.182	-0.231	-0.097
	Yield	0.555	0.902*	0.784	0.853*

*, **Significant at 0.05 and 0.01 level, respectively.
I1: First internode of base; I2: second internode of base; I3: third internode of base; I4: fourth internode of base.

DISCUSSION

Effects on rice lodging resistance

Lodging is one of the main limiting factors for high yield and quality of rice (Corbin et al., 2016). In this study, continuous straw returning under the same level of chemical fertilizer input improved the stem bending resistance of rice stalks and reduced the risk of lodging significantly. Returning straw to the field under the condition of no fertilizer reduced the resistance of rice stalks significantly and increased lodging risk. This is due to the continuous return of straw to the field under the condition of application of chemical fertilizers, which improved the physical and chemical properties of the soil and its fertilizer supply capacity (Huang et al., 2017), and significantly increased the thickness of the stalk and its wall at the base of the rice (Table 3), increased the dry weight of rice stalks at the base of the internode, increased the compactness of rice stalks, and made the rice grow more robust while reducing the risk of lodging. However, when the straw was returned to the field under the condition of no fertilizer, the thickness of internodes and thickness of stem wall at the base of the rice stem were reduced, dry weight of stem was significantly reduced, and the risk of lodging increased. There were two possible reasons: The first one was that the straw was returned to the field under the condition of no fertilizer, which caused the straw to compete with rice seedlings for N during the decomposition process (Hu et al., 2020), which aggravated the problem of lack of nutrients required for the growth of rice; the second reason was that when the straw was returned to the field, the straw decomposed slowly under the condition of lack of nutrients, especially N (Dhaliwal et al., 2020), resulting in deterioration of soil properties and reduced fertilizer supply capacity of the soil.

In this study, the bending resistance of rice stalks under the condition of straw removal increased with the decrease of fertilizer application, which was consistent with the results of Zhang et al. (2016). This was because as the amount of fertilizer increased, the thickness of the stem wall and the dry weight of internodes decreased, and the compactness of rice stalks also decreased (Tables 3 and 4). Studies have shown (Li et al., 2013b; Zhang et al., 2014) that the dry weight of internode decreased significantly with the increase of fertilization, while the stem wall thickness did not change significantly. This is not completely consistent with the results of this study, which may be related to the characteristics of the *indica* and *japonica* rice varieties. In this study, the bending moment of rice showed different trends in different years with the decrease of fertilizer amount; it decreased with the decrease of fertilization amount in 2018, while it first increased and then decreased with the decrease of fertilization amount in 2019, this is due to the different trends of rice internode length and stem dry weight with the decrease of fertilizer amount in different years. The internode length and stem dry weight of rice decreased with the decrease of fertilization amount in 2018, while the internode length and stem dry weight of rice first increased and then decreased with the decrease of fertilization amount (Tables 2 and 3) in 2019, this may be related to the characteristics of the breed itself.

Relationship between rice lodging resistance and plant traits

Existing studies have suggested that rice lodging resistance is closely related to plant height, center of gravity height, base internode length, internode thickness, stem wall thickness internode dry weight, etc. (Li et al., 2011; Hao et al., 2013; Li et al., 2013b; Hu et al., 2015; Corbin et al., 2016). This is consistent with the results of this study. In this study, the removal of straw under conventional fertilization conditions reduced the strength of rice internodes, which may be due to its high alpha-amylase activity of internodes (Liu et al., 2012), resulting in low carbohydrate accumulation and low content, resulting in the arrangement of the tissue cells in the thick outer stem walls were loose (Zhang et al., 2016), lignification and silicification were reduced (Liu et al., 2018a), resulting in a reduction in the thickness of the stem wall, a reduction in the dry weight of the internodes and the deterioration of the stalk resistance.

Relationship between rice lodging resistance and yield traits

This study suggested that rice lodging resistance was closely related to rice yield, effective panicle number, grain number per panicle, and number of primary branches; the enhancement in rice yield increased the risk of rice lodging, this was in line with Li et al. (2013b). This study also showed that continuous straw return combined with chemical fertilizers made the rice growing population more reasonable and significantly increased the rice yield (Table 6); on the other hand, it significantly increased the flexural resistance of the rice base internodes and reduced the lodging index (Table 1). This was because the continuous straw returning to the field combined with the application of chemical fertilizers made the rice grow more robust, stem wall was thicker, stem was heavier, and flexural resistance was enhanced. These all showed the role and advantage of straw returning in enhancing the lodging resistance of rice.

CONCLUSIONS

In conclusion, under the condition of no fertilizer, thickness of stalk and thickness of stem wall at the base of the rice stalk were reduced, dry weight of stalk was significantly reduced while the lodging index increased, and the risk of lodging increased. Continuous straw return to the field combined with chemical fertilizers increased the dry weight of the stalks at the bases, and increased the compactness and bending resistance of the rice stalk, while reduced the lodging index of rice, improved the lodging resistance of rice by increasing the thickness of stalk and stalk wall at the base of the rice. Compared with straw removal, returning straw to the field and applying chemical fertilizers improved the composition of rice yield, and rice yield was significantly increased. Therefore, the continuous return of straw to the field combined with the application of chemical fertilizers reduced the risk of lodging of rice to a certain extent, and meanwhile realized the continuous increase in rice production, which had high application value.

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