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Management of Seeding Rate and Nitrogen Fertilization for Lodging Risk Reduction and High Grain Yield of Mechanically Direct-Seeded Rice under a Double-Cropping Regime in South China

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Abstract: Precision hill-drop direct seeding using mechanical drilling is a unique direct seeding technique employed in south China that offers advantages such as excellent grain yield and high lodging resistance. Improving yield and lodging-related traits is essential for efforts to improve mechanically direct-seeded rice (MDSR) production. Seeding rates (SR) and nitrogen (N) fertilization rate are two of the main factors affecting grain yield and lodging resistance under MDSR production. However, little information about double-season MDSR production in south China is available. Here, we evaluated yield and lodging risk for two rice cultivars Huanghuazhan, HHZ, lodging-resistant; Xiangyaxiangzhan, XYXZ, lodging-susceptible across two consecutive growing seasons under two under two seeding rates (LSR, 30 cm × 18 cm; HSR, 30 cm × 12 cm) and three N fertilization rates (N1 = 100 kg ha⁻¹, reduced N; N2 = 150 kg ha⁻¹, normal N; and N3 = 200 kg ha⁻¹, enhanced N). We found that increased SR and N fertilization rate improved grain yield and increased lodging risk. SR and N were consistently and positively related to plant height (PH), gravity center height (GCH), the length from the broken basal internode to the panicle tip (SL), the fresh plant weight of the plant part above the broken point (FW), and the length of the two basal internodes. SR and N decreased breaking force (F) and breaking strength (BM), driving increased lodging risk as reflected by increases in lodging index (LI) values. Culm diameter (CD) and culm wall thickness (CWT) did not respond consistently to SR and N treatments. Correlation analysis revealed that PH, GCH, the length of first and second basal internodes, FW, and bending moment for the whole plant (WP) were positively correlated with LI, while F and BM were negatively associated with LI. These findings suggest that the increased lodging risk resulting from high SR could be mitigated by applying appropriate rates of N; that is, this work suggests that grain yield can be maximized and lodging risk minimized by increasing SR while decreasing N fertilization rate. Seasonal differences in the effects of SR and N fertilization should be considered to achieve a high grain yield and maintain high lodging resistance. Our study suggests that increasing SR and decreasing N fertilization can enhance rice grain yield while improving lodging resistance for both varieties. Optimizing grain yield by increasing SR while reducing lodging risk by lowering N application rates may maintain lodging resistance and improve grain yield.

Keywords: rice; lodging resistance; nitrogen regulation; seeding rate regulation; direct seeding



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1. Introduction

Rice is a major food crop in China, and high yield and yield stability are of great importance for ensuring food security, both within China and globally. In recent years, worsening labor shortages in rural areas have prompted a shift away from traditional intensive rice farming techniques toward simpler and more efficient approaches. To reduce costs, many farms have begun to replace rice transplantation with direct-seeded rice (DSR) or, in south China, mechanically direct-seeded rice (MDSR) approaches [1]. Because lodging can result in lower grain yields, reduced grain quality, more difficult mechanical harvesting, lower harvest efficiency, and increasing production costs, it is one of the most important factors influencing DSR grain yield potential [2–4]. Previous studies have shown that lodging can be caused by many internal and external factors, including rice variety, wind, rain, planting patterns, seeding rates, N fertilization approach, light, any phytohormones [5–10].

In recent years, the direct-seeded and double-season rice (DDR) approach has become the subject of increasing interest due to its lower labor and resource requirements [11,12]. It is well known that crop management plays an important role in regulating both grain yield and lodging resistance [13,14]. N application and plant density (i.e., seeding rate) are regarded as the two most important crop management practices that can influence yield stability and lodging resistance [14,15]. In general, farmers employing DDR aim to increase germination rates and grain yield via N fertilization and seeding rate (SR). However, conventional farming approaches use large amounts of exogenous chemical fertilizers to increase yield; such practices are associated with environmental hazards, such as elevated greenhouse gas emissions, nitrate leaching, water eutrophication, and soil acidification [16–18], as well as with increased lodging risk under transplantation-based systems. Therefore, previous research has attempted to demonstrate that increasing planting density while reducing N application rate can increase grain yield under transplanted conditions [19].

Presently, N fertilization recommendations for DSR focus on fertilizer type; the fertilizer rate or ratio, especially coupled with SR, is less well-researched. Additionally, excessive N application not only causes serious environmental problems such as soil acidification and water eutrophication [16,17], but also increases crop lodging risk [5–8,10]. Farmers employing a DSR approach often combine high SR with high N fertilization rates, both of which result in higher lodging risk. However, limited information is available regarding grain yield and lodging resistance under different SR and N fertilization rates for DDR. We hypothesized that the negative effects associated with high seeding density can be mitigated by reasonable N fertilization and that increasing SR and reducing exogenous N application can improve lodging resistance and stabilize grain yield under DDR.

It is not clear whether differences between transplantation and DDR can affect how grain yield and lodging resistance are influenced by SR and N application. This work aimed to (1) determine the effects of SR and N on grain yield and lodging resistance, (2) compare how grain yield and lodging resistance respond to SR and N application in the early and late season under DDR, and (3) compare how grain yield and lodging resistance of two different DDR cultivars respond to SR and N application.

2. Materials and Methods

2.1. Experimental Sites

Field experiments were carried out at the Dafeng station of the Rice Research Institute at Guangdong Academy of Agricultural Sciences, China (23°09' N, 113°22' E), during the early (March–July) and late (July–November) growing season in 2020 and 2021. Soil in the area is classified as yellow soil, and samples were collected from the top 20 cm to assess physicochemical properties: pH, 5.34; organic matter, 36.2%; total N, 2.15 g kg^{−1}; available phosphorus, 50.8 mg kg^{−1}; and available potassium, 102.0 mg kg^{−1}. Meteorological data are presented in Figure 1. Average temperature during both the early and late seasons was lower in 2020 than in 2021, and rainfall was much higher in the early season than in the late season.

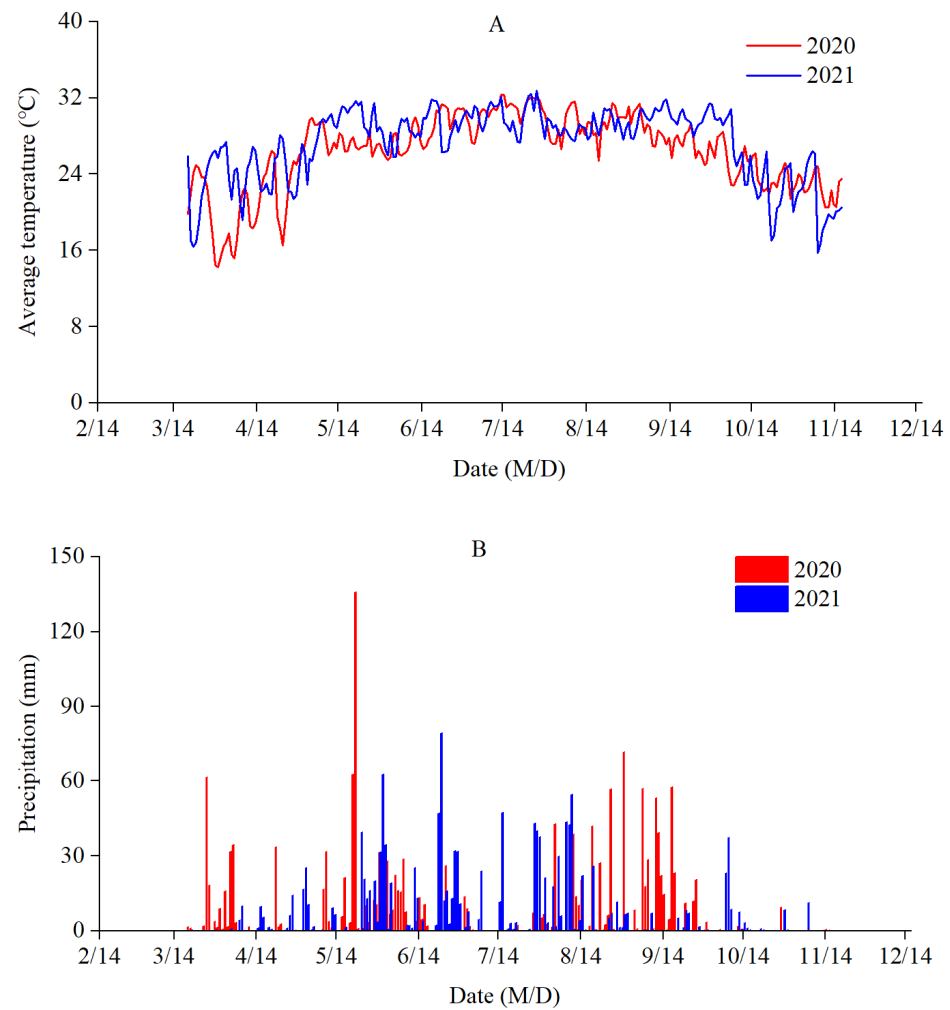


Figure 1. Daily average temperature (A) and precipitation (B) across the 2020 and 2021 growing seasons.

2.2. Experimental Design

Experiments were conducted using a split plot arrangements with three replicates during the early and late season in both 2020 and 2021. Main plots received one of two SR treatments (LSR: 30 cm × 18 cm; HSR: 30 cm × 12 cm), and split plots received one of three pure N treatments (N1, 100 kg ha⁻¹; N2, 150 kg ha⁻¹; N3, 200 kg ha⁻¹). Each plot had an area of 17.2 m² (4.3 m × 4.0 m). Two rice cultivars commonly grown in the region were used: Huanghuazhan (HHZ, conventional indica rice, lodging-resistant) and Xiangyaxiangzhan (XXYZ, conventional indica rice, lodging-susceptible).

Urea (i.e., the N source) was applied three times throughout each growing season: during the weaning stage (50%), tillering stage (30%) and the young panicle differentiation stage (20%). Superphosphate (i.e., the phosphorus source) was used as a basal fertilizer and was applied at a rate of 50.0 kg ha⁻¹. Potassium chloride (i.e., the potassium source) was applied at two different times at a rate of 90 kg ha⁻¹: basal fertilizer (50%) and panicle initiation fertilizer (50%).

To reduce biomass and yield loss, insects weed and diseases were chemically controlled in accordance with local practices.

2.3. Observations and Measurements

At the physiological maturity stage, rice plants of 50 holes were harvested to measure yield. The grain yield was adjusted to a moisture content of 13.5% by using a moisture detector.

At 20 days after heading, ten representative rice plants were selected from each replicate plot to measure stem breaking force (F, kg). F was measured by breaking the

basal culm, using a digital stem-strength-measuring instrument (YYD-1, Zhejiang Top Instruments Co., Ltd., Hangzhou, China). The lodging-related variables and index values were measured and calculated using the procedures described by Ookawa [20]:

- (1) SL (cm) = length from the broken basal internode to the panicle tip;
- (2) Fresh weight (FW, g) = fresh plant weight of the plant part above the broken point;
- (3) Bending moment for the whole plant (WP, g cm) = SL (cm) × FW (g);
- (4) Breaking strength (BM, g.cm) = $1/4 \times F$ (breaking force) × L (distance between two points (cm) × 10^3);
- (5) Lodging index (LI, %) = WP (g.cm)/BM (g.cm) × 100.

A vernier caliper was used to determine the morphological characteristics including the culm diameter (CD) and culm wall thickness (CWT) at the second basal internodes, and the calculation formulas were as follows:

- (6) Culm diameter (CD, mm) = (long axis diameter + short axis diameter)/2;
- (7) Culm wall thickness (CWT, mm) = axis outer diameter – axis inner diameter.

The length of the two basal internodes was measured by a ruler.

2.4. Statistical Analyses

Data were analyzed using SPSS 19.0, and the least significant difference (LSD) test was used to assess significance at the probability level of $p < 0.05$. Tables and figures were generated using Origin 2021pro and Microsoft Excel 2020.

3. Results

3.1. Grain Yield

Grain yield was influenced by SR and N fertilization rate (Figure 2, Table 1). In the late seasons of 2020 and 2021 and the early season in 2021, high seeding rate (HSR) resulted in yield that were 55.0%, 10.6%, and 22.0% higher than those of the low seeding rate (LSR) for HHZ, and these differences were statistically significant. A similar pattern was observed for XYXZ, where grain yields were 18.3%, 19.1%, 22.3%, and 28.2% higher for HSR than for LSR in both early and late seasons in 2020 and 2021. These differences were also statistically significant. Overall, increasing SR was associated with significant increases in yield for both cultivars in both years, though no significant differences were observed in the early season of 2020 for HHZ. Likewise, increasing N fertilization intensity increased grain yield for both cultivars in both years, though these differences were not statistically significant.

Table 1. Grain yield of direct-seeded rice for both cultivars.

Cultivar	Treatment	2020 Early Season	2020 Late Season	2021 Early Season	2021 Late Season
HHZ	LSR	8.48 A	6.98 B	9.58 B	7.32 B
	HSR	8.18 A	10.82 A	10.60 A	8.93 A
	N1	8.13 a	8.79 a	9.65 a	7.93 a
	N2	8.23 a	8.88 a	10.06 a	8.15 a
	N3	8.62 a	9.02 a	10.57 a	8.30 a
XYXZ	LSR	6.76 B	6.39 B	7.93 B	6.78 B
	HSR	8.00 A	7.61 A	9.70 A	8.69 A
	N1	7.02 a	6.88 a	8.58 a	7.56 a
	N2	7.20 a	7.01 a	8.77 a	7.82 a
	N3	7.92 a	7.11 a	9.10 a	7.83 a
ANOVA					
Seeding rate (SR)		*	**	**	**
Nitrogen (N)		ns	ns	ns	ns
SR × N		**	ns	ns	*

Note: LSR, low seeding rate; HSR, high seeding rate; HHZ, Huanghuazhan; XYXZ, Xiangyaxiangzhan; N1, N2, N3 represent nitrogen fertilization rates of 100 kg/ha, 150 kg/ha, 200 kg/ha, respectively. Different capital letters indicate significant differences between the two seeding rate treatments. Different lowercase letters indicate significant differences among different nitrogen treatments.; ns, not significant; *, $p < 0.05$, **, $p < 0.01$).

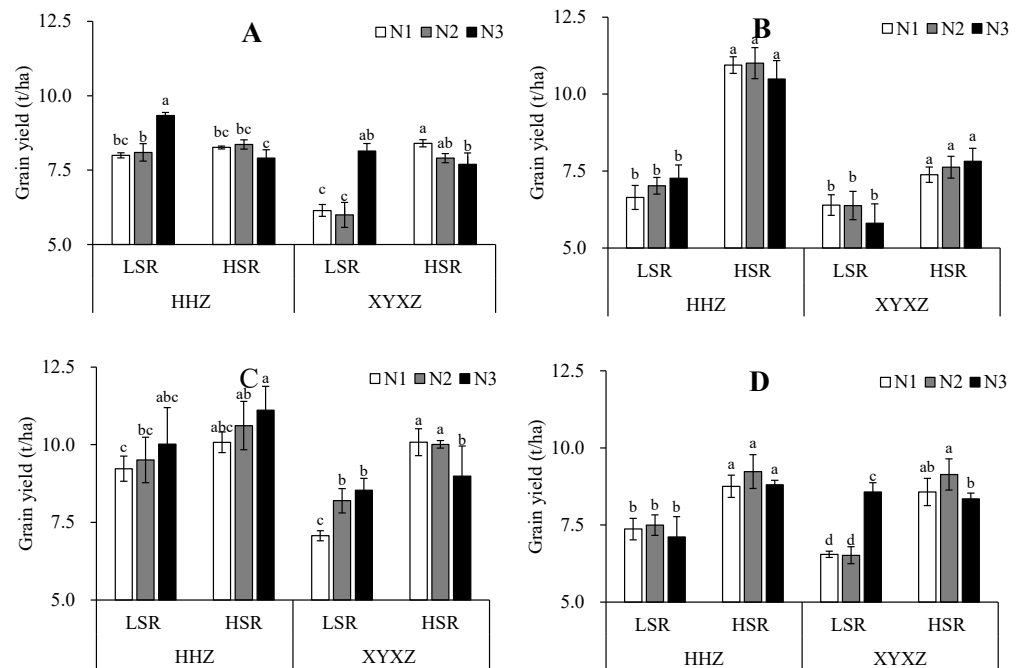


Figure 2. Rice grain yield under different seeding rates and nitrogen application rates in direct-seeded and double-season rice. (A–D) represent 2020 early season, 2020 late season, 2021 early season and 2021 late season, respectively. LSR, low seeding rate (30 cm × 18 cm); HSR, high seeding rate (30 cm × 12 cm); N1, nitrogen fertilization at 100 kg/ha; N2, nitrogen fertilization at 150 kg/ha; N3, nitrogen fertilization at 200 kg/ha; HHZ, Huanghuazhan; XYXZ, Xiangyaxiangzhan. Different lowercase letters indicate statistical significance between treatments ($p < 0.05$).

With the increase in nitrogen application at the LSR, the rice grain yield of HHZ showed an overall increase, although a fluctuating trend was observed in late season for 2021. In the case of XYXZ, there was a general increase in yield, with a minor decrease observed in late season for 2020 that was not statistically significant. With the increase in the nitrogen rate at the HSR, differences were observed between the two cultivars. The rice grain yield of HHZ showed an initial increase followed by a decrease except for an increase in early season of 2021. On the other hand, the rice grain yield of XYXZ displayed a decreasing trend in early season, an increasing trend in late season of 2020 and an initial increase followed by a decrease in late season of 2021.

The impact of the source of variation on grain yield was analyzed, with significant effects observed for SR and N (Table 1). SR showed a significant effect on grain yield for both early and late season rice across two years. Additionally, there was a significant interaction effect between SR and N on grain yield, particularly in the early season of 2020 and late season of 2021.

3.2. Lodging Index

Seeding rates had a significant impact on the LI, as shown in Tables 2 and 3. In 2020, for early season, late season, and in 2021 for both early and late season, the HSR resulted in LI values that were 24.1%, 12.5%, 12.4% and 11.8% higher than those obtained with the LSR for HHZ. A similar pattern was observed in XYXZ, with the LI values under the HSR being 16.9%, 6.0% and 40.2% higher compared to those for LSR for early season of 2020, early season of 2021, and late season of 2021, respectively, and these differences were statistically significant. However, no significant difference was observed in late season of 2020.

Table 2. Lodging-related characteristics of direct-seeded rice for both cultivars in 2020.

Cultivar	Treatment	SL (cm)	FW (g)	Early Season		BM (g.cm)	LI (%)	SL (cm)	FW (g)	Late Season		BM (g.cm)	LI (%)
				WP (g.cm)	F (kg)					WP (g.cm)	F (kg)		
HHZ	LSR	91.5 A	15.7 A	1435.8 A	2.18 A	2724.0 A	52.9 B	89.1 A	11.9 B	1057.4 A	1.35 A	1690.4 A	62.9 B
	HSR	92.7 A	16.1 A	1488.1 A	1.79 B	2275.1 B	65.7 A	89.3 A	12.6 A	1128.7 A	1.27 A	1603.9 A	70.7 A
	N1	91.6 a	14.7 b	1345.9 b	1.88 a	2348.8 a	57.4 a	88.3 a	11.9 b	1051.6 b	1.26 a	1576.3 a	66.8 a
	N2	91.6 a	16.5 a	1511.5 a	1.98 a	2502.6 a	61.0 a	89.6 a	11.9 b	1065.9 b	1.34 a	1663.1 a	62.9 a
	N3	93.1 a	16.4 a	1528.5 a	2.10 a	2647.4 a	59.6 a	89.7 a	13.0 a	1161.8 a	1.33 a	1702.0 a	70.6 a
XYXZ	LSR	98.7 A	14.9 A	1473.8 A	1.58 A	1978.4 A	75.5 B	97.5 B	10.5 A	1026.9 A	0.99 A	1222.4 A	84.3 A
	HSR	101.2 A	13.7 B	1383.8 B	1.25 B	1581.4 B	88.3 A	103.9 A	10.6 A	1099.7 A	0.97 A	1196.9 A	92.1 A
	N1	98.1 b	13.6 b	1331.7 b	1.45 ab	1813.7 a	73.7 b	97.3 b	10.3 a	1007.2 a	1.00 a	1241.5 a	81.0 b
	N2	99.5 ab	14.9 a	1477.9 a	1.54 a	1925.5 a	78.6 b	101.6 ab	10.6 a	1080.6 a	0.99 a	1238.0 a	87.4 b
	N3	102.2 a	14.5 ab	1476.75 a	1.26 b	1600.5 a	93.4 a	103.2 a	10.7 a	1102.1 a	0.94 a	1149.5 a	96.3 a
ANOVA													
Seeding rate (SR)		ns	ns	ns	**	**	*	ns	ns	**	ns	ns	**
Nitrogen (N)		ns	**	**	ns	ns	ns	ns	ns	**	ns	ns	ns
SR × N		ns	ns	*	ns	ns	**	ns	ns	*	ns	ns	ns

Note: LSR, low seeding rate (30 cm × 18 cm); HSR, high seeding rate (30 cm × 12 cm); N1, nitrogen fertilization at 100 kg/ha; N2, nitrogen fertilization at 150 kg/ha; N3, nitrogen fertilization at 200 kg/ha; HHZ, Huanghuazhan; XYXZ, Xiangyaxiangzhan. Different capital letters indicate significant differences between the two seeding rates; different lowercase letters indicate significant differences among the three nitrogen rates ($p < 0.05$). ns, not significant; *, $p < 0.05$, **, $p < 0.01$.

Table 3. Lodging-related characteristics of direct-seeded rice for both cultivars in 2021.

Cultivar	Treatment	SL (cm)	FW (g)	Early Season		BM (g.cm)	LI (%)	SL (cm)	FW (g)	Late Season		BM (g.cm)	LI (%)
				WP (g.cm)	F (kg)					WP (g.cm)	F (kg)		
HHZ	LSR	95.3 A	16.6 B	1583.7 A	2.05 A	2528.7 A	62.6 B	94.9 A	15.2 B	1439.0 B	1.90 A	2374.8 A	60.6 B
	HSR	96.9 A	17.6 A	1710.3 A	2.00 A	2438.4 A	70.3 A	96.0 A	17.1 A	1639.9 A	1.94 A	2426.1 A	67.8 A
	N1	93.9 b	16.1 b	1516.7 b	1.96 a	2356.5 a	64.2 a	95.8 a	15.1 a	1448.3 a	1.95 a	2441.4 a	59.2 b
	N2	96.5 ab	17.4 a	1682.3 a	2.10 a	2577.4 a	65.4 a	96.5 a	16.5 a	1616.8 a	1.94 a	2419.6 a	66.9 a
	N3	98.0 a	17.8 a	1742.1 a	2.01 a	2516.8 a	69.8 a	94.1 a	16.7 a	1553.3 a	1.87 a	2340.2 a	66.5 a
XYXZ	LSR	106.6 A	15.4 A	1645.6 A	1.33 A	1681.0 A	97.9 B	104.1 B	13.1 B	1362.4 B	1.43 A	1796.3 A	76.4 B
	HSR	107.6 A	15.2 A	1638.7 A	1.27 A	1584.7 A	103.8 A	112.3 A	16.0 A	1792.3 A	1.32 A	1680.9 A	107.1 A
	N1	106.5 a	14.9 a	1582.7 a	1.29 a	1639.2 a	96.6 a	106.6 a	13.7 a	1458.5 a	1.35 a	1837.1 a	84.4 a
	N2	107.4 a	15.4 a	1650.3 a	1.29 a	1612.2 a	102.4 a	108.8 a	14.4 a	1569.9 a	1.46 a	1806.3 a	88.1 a
	N3	107.4 a	15.8 a	1693.4 a	1.31 a	1647.1 a	103.5 a	109.1 a	15.5 a	1703.7 a	1.31 a	1672.4 a	102.7 a
ANOVA													
Seeding rate (SR)		ns	ns	*	ns	ns	**	ns	**	**	ns	ns	**
Nitrogen (N)		ns	*	**	ns	ns	ns	ns	**	**	ns	ns	**
SR × N		ns	*	**	ns	ns	ns	ns	ns	ns	ns	ns	*

Note: LSR, low seeding rate (30 cm × 18 cm); HSR, high seeding rate (30 cm × 12 cm); N1, nitrogen fertilization at 100 kg/ha; N2, nitrogen fertilization at 150 kg/ha; N3, nitrogen fertilization at 200 kg/ha; HHZ, Huanghuazhan; XYXZ, Xiangyaxiangzhan. Different capital letters indicate significant differences between the two seeding rates; different lowercase letters indicate significant differences among the three nitrogen rates ($p < 0.05$). ns, not significant; *, $p < 0.05$, **, $p < 0.01$.

Nitrogen fertilization increased the LI of both cultivars overall. The LI values were ranked as follows: N3 > N2 > N1, except for HHZ which showed N2 > N3 > N1 in early season of 2020. A slight decrease in the LI was noticed under N2 compared to N1 for HHZ in late season of 2020, with the ranking being N3 > N1 > N2. Additionally, the LI of HHZ with N2 and N3 in the late season of 2021, as well as the LI of XYXZ with N3 in both the early and late season of 2020, showed a significant increase compared to N1.

The different treatments had an impact on the LI. As shown in Figure 3, it is evident that for HHZ, at the LSR, the LI initially increased and then decreased with the rising nitrogen application in the early season of 2020 and late season of 2021; conversely, an increasing trend was observed in the early season of 2021, while a reverse decreasing trend was observed in the late season of 2020. For XYXZ, at the LSR, the LI of N2 decreased compared to N1, but increased with N3 in the early season of 2020 and late season of 2021; an increasing trend was observed in the late season of 2020, while a pattern of an initial increasing and then decreasing trend was observed in early season of 2021. At the HSR, a trend of a consistent increasing trend in the LI was observed for both cultivars over the two years with an increase in nitrogen application.

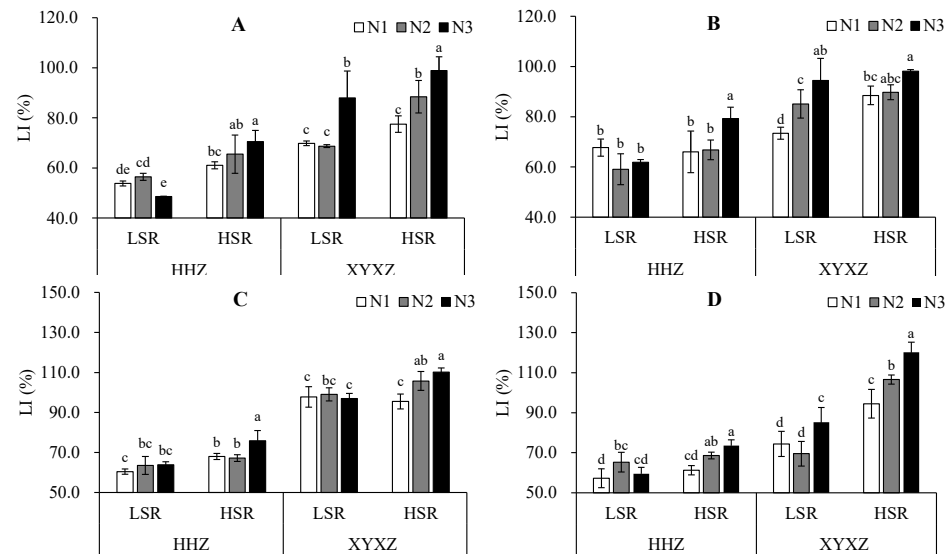


Figure 3. Lodging index (LI) under different seeding rates and nitrogen application rates in direct-seeded and double-season rice. (A–D) represented early season 2020, late season 2020, early season 2021, and late season 2021, respectively. LSR, low seeding rate (30 cm × 18 cm); HSR, high seeding rate (30 cm × 12 cm); N1, nitrogen fertilization at 100 kg/ha; N2, nitrogen fertilization at 150 kg/ha; N3, nitrogen fertilization at 200 kg/ha; HHZ, Huanghuazhan; XYXZ, Xiangyaxiangzhan. Different lowercase letters indicate statistical significance between treatments ($p < 0.05$).

SR, N and SR × N had effects on the LI, as shown in Tables 2 and 3. The LI was significantly affected by the SR in both the early season and late season over two years, and the LI was significantly affected by N in the late season of 2021. Additionally, there were interaction effects of SR × N on the LI in the early season of 2020 and late season of 2021.

3.3. Lodging-Related Characteristics

The lodging-related characteristics, including SL, FW, WP, F and BM, were associated with the LI (Tables 2 and 3). In both cultivars over two years, the HSR exhibited a higher SL compared to the LSR, with the differences in SL not being significant between the LSR and HSR of HHZ. However, for XYXZ, the SL was consistently higher than that of LSR by 2.6%, 6.6%, 1.0% and 7.8% with significant differences except for the early season in both years. Increased nitrogen application led to an increase in SL compared to the N1 treatment for both cultivars over two years except for HHZ in the late season of 2021. Furthermore, the SL of N3 was significantly higher than that of N1 for XYXZ in both the early and late seasons of 2020, and a significant increasing trend was observed for HHZ in the early season of 2021. Variance analysis revealed that SR and N had no significant effect on SL, and there were no significant interaction effects.

The HSR resulted in higher FW compared to the LSR for both cultivars over two years, except for the early season of XYXZ. For HHZ, FW was approximately 2.4%, 6.6%, 6.5% and 12.7% higher under the HSR than under the LSR in early season of 2020, late season of 2020, early season of 2021, and late season of 2021, respectively, with statistical significance except in 2020 early season. A similar increasing trend for XYXZ was only observed in the late season with a significant difference, while a decreasing trend was observed in the early season, with a significant decrease.

With the increase in nitrogen application, the FW of N2 and N3 showed an upward trend compared to N1 in both cultivars and years. In the case of HHZ, compared to N1, the FW of N2 and N3 saw a significant increase of 12.2%, 11.7%, 8.1% and 10.2% during the early season of 2020 and 2021, respectively. Moreover, a notable 8.8% difference was observed in the FW of N3 compared to N1 during the late season of 2020. Conversely, for XYXZ, the FW only showed a significant increase of 9.6% under N2 compared to N1 in the early season of 2020. Upon analyzing the sources of variation, it was found that FW was

significantly influenced by N in all seasons except for the late season of 2020. Furthermore, in the early season of 2021, there was an interaction effect between SR and N on FW.

The HSR exhibited a higher WP compared to the LSR for HHZ in both years. However, there were variations in XYXZ, with WP decreasing in the early season but increasing in the late season. Furthermore, there was a significant decrease in WP in the early season of 2020. The differences in WP were particularly notable in the late season of 2021, with an increase of 14.0% and 31.6% for HHZ and XYXZ, respectively.

The WP was increasing with nitrogen application. In the case of HHZ, the WP of N2 and N3 significantly increased compared to N1, with N3 showing a significant increasing trend in the late season of 2020 and early season of 2021. On the other hand, for XYXZ, the WP of N2 and N3 only showed a significant increase in the early season of 2020 when compared to N1. An analysis of the sources of variation revealed that both SR and N had a significant effect on WP across both cultivars and years, except for SR in 2020. Additionally, there was a significant interaction between SR and N on WP, except in the late season of 2021.

Overall, F was lower for the HSR compared to the LSR across two cultivars and years. Specifically, for the HHZ cultivar, the F was lower under the HSR than under the LSR in both early and late season of 2020, and early season of 2021. However, a slight increase was observed in the late season of 2021, although it was not statistically significant.

There was a significant decrease in XYXZ during the early season of 2020. When compared with N1, the application of nitrogen at levels of N2 and N3 showed no significant difference in two cultivars over the two years. Analyzing the source of variation, it was found that SR had a significant effect on F during the early season of 2020.

In both two cultivars and years, the HSR resulted in a lower BM compared to the LSR. Specifically, for the HHZ cultivar, the BM under the HSR was consistently lower than that under the LSR, except for the late season in 2021. Furthermore, the BM under the HSR was significantly lower than that in the early season of 2020. On the other hand, for the XYXZ cultivar, the BM under the HSR was lower than that under the LSR only in the early season of 2020, with no significant differences observed in other seasons.

As demonstrated in Tables 2 and 3, nitrogen application has an impact on BM. In the case of HHZ, an increasing in nitrogen application led to a corresponding increasing in BM in both seasons of 2020, although the difference was not statistically significant. Furthermore, a trend of an initial increasing followed by a decreasing trend was observed in both seasons of 2021, without significant differences. Conversely, for XYXZ, there was no significant effect on BM with the increment in nitrogen. In an analysis of the sources of variation, it was found that SR had a significant effect on BM in the early season of 2020.

3.4. Culm Characteristics

The PH and GCH were increased under the HSR compared to the LSR, with no significant differences found in the PH and GCH of HHZ. However, there were significant differences in XYXZ in the late season of both years, and the PH of XYXZ was also significantly increased in the early season of 2020.

The PH and GCH were positively influenced by higher nitrogen rates. In the early season of 2021, there was a significant increment of PH for HHZ with N2 and N3 compared to N1, whereas significant differences were only seen in the early season of 2020 for XYXZ. Additionally, the GCH of N3 showed a significant increased only in the early season of 2020 for HHZ compared to N1, while significant differences were observed in the late season of 2020 and early season of 2021 for XYXZ.

The CD and CWT exhibited a decreasing trend under the HSR compared to the LSR, as shown in Tables 4 and 5. While CD was significantly reduced only in the 2020 early season of HHZ, the sole significant difference was observed in the 2020 late season of XYXZ. No significant differences were observed for CWT.

Table 4. Culm characteristics of direct-seeded rice for both cultivars in 2020.

Cultivar	Treatment	PH (cm)	GCH (cm)	Early Season				PH (cm)	GCH (cm)	Late Season			
				CD (mm)	CWT (mm)	1st (cm)	2nd (cm)			CD (mm)	CWT (mm)	1st (cm)	2nd (cm)
HHZ	LSR	97.9 A	43.1 A	5.24 A	0.66 A	2.53 A	7.42 A	95.0 A	44.7 A	5.24 A	0.66 A	2.35 A	6.83 A
	HSR	98.9 A	44.0 A	5.02 B	0.66 A	2.84 A	7.23 A	96.0 A	45.4 A	5.22 A	0.65 A	2.52 A	7.06 A
	N1	97.7 a	42.6 b	5.13 a	0.66 a	2.47 a	7.10 a	94.7 a	44.4 a	5.33 a	0.65 a	2.23 b	6.69 a
	N2	98.0 a	43.4 b	5.17 a	0.66 a	2.71 a	7.35 a	95.4 a	45.2 a	5.26 ab	0.68 a	2.18 b	7.02 a
	N3	99.4 a	44.7 a	5.10 a	0.66 a	2.88 a	7.53 a	96.4 a	45.5 a	5.10 b	0.64 a	2.90 a	7.13 a
XYXZ	LSR	104.9 B	44.2 A	5.13 A	0.61 A	3.11 A	7.59 A	104.1 B	47.3 B	5.11 A	0.60 A	2.84 A	7.12 A
	HSR	107.9 A	45.8 A	5.03 A	0.62 A	3.18 A	8.46 A	110.8 A	50.1 A	4.96 B	0.59 A	3.19 A	7.31 A
	N1	104.1 b	44.1 a	5.06 a	0.62 a	2.74 a	7.45 a	105.4 a	46.6 b	5.03 a	0.61 a	2.78 a	7.00 a
	N2	106.6 ab	44.9 a	5.07 a	0.62 a	3.30 a	8.10 a	108.0 a	48.2 b	5.06 a	0.62 a	2.95 a	7.04 a
	N3	108.6 a	46.0 a	5.11 a	0.61 a	3.40 a	8.52 a	109.0 a	51.3 a	5.01 a	0.55 b	3.32 a	7.61 a
ANOVA													
Seeding rate (SR)		ns	*	**	*	*	*	ns	*	ns	ns	ns	ns
Nitrogen (N)		ns	**	ns	ns	ns	ns	ns	*	ns	*	*	ns
SR × N		ns	ns	**	*	ns	ns	ns	ns	ns	ns	ns	ns

Note: LSR, low seeding rate (30 cm × 18 cm); HSR, high seeding rate (30 cm × 12 cm); N1, nitrogen fertilization at 100 kg/ha; N2, nitrogen fertilization at 150 kg/ha; N3, nitrogen fertilization at 200 kg/ha; HHZ, Huanghuazhan; XYXZ, Xiangyaxiangzhan. Different capital letters indicate significant differences between the two seeding rates; different lowercase letters indicate significant differences among the three nitrogen rates ($p < 0.05$). ns, not significant; *, $p < 0.05$, **, $p < 0.01$.

Table 5. Culm characteristics of direct-seeded rice for both cultivars in 2021.

Cultivar	Treatment	PH (cm)	GCH (cm)	Early Season				PH (cm)	GCH (cm)	Late Season			
				CD (mm)	CWT (mm)	1st (cm)	2nd (cm)			CD (mm)	CWT (mm)	1st (cm)	2nd (cm)
HHZ	LSR	101.2 A	44.5 A	5.47 A	0.75 A	2.39 A	6.35 A	101.1 A	44.0 A	5.57 A	0.73 A	2.35 A	6.39 A
	HSR	102.0 A	45.1 A	5.50 A	0.72 A	2.76 A	6.49 A	101.3 A	44.4 A	5.89 A	0.71 A	2.72 A	6.38 A
	N1	99.0 b	43.7 a	5.46 a	0.73 a	2.09 b	5.99 a	100.9 a	43.9 a	5.63 a	0.72 a	2.11 b	6.13 a
	N2	102.0 a	45.1 a	5.43 a	0.72 a	2.71 ab	6.49 a	101.3 a	44.1 a	5.64 a	0.75 a	2.62 ab	6.42 a
	N3	103.9 a	45.8 a	5.56 a	0.75 a	2.95 a	6.78 a	101.5 a	44.5 a	5.47 a	0.69 a	2.88 a	6.60 a
XYXZ	LSR	112.9 A	48.3 A	5.36 A	0.66 A	3.54 A	8.49 A	110.4 B	46.0 B	5.23 A	0.66 A	3.77 B	6.83 B
	HSR	115.0 A	49.3 A	5.19 A	0.64 A	3.95 A	8.60 A	118.3 A	48.6 A	5.12 A	0.65 A	4.81 A	8.48 A
	N1	113.1 a	47.5 c	5.30 a	0.65 a	3.64 a	8.40 a	112.4 a	47.0 a	5.20 a	0.66 a	3.71 a	7.07 a
	N2	114.2 a	48.8 b	5.24 a	0.66 a	3.77 a	8.64 a	114.1 a	47.2 a	5.28 a	0.66 a	4.58 a	7.51 a
	N3	114.6 a	50.1 a	5.30 a	0.65 a	3.83 a	8.40 a	116.5 a	47.7 a	5.04 a	0.65 a	4.58 a	8.38 a
ANOVA													
Seeding rate (SR)		ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	*
Nitrogen (N)		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
SR × N		ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns

Note: LSR, low seeding rate (30 cm × 18 cm); HSR, high seeding rate (30 cm × 12 cm); N1, nitrogen fertilization at 100 kg/ha; N2, nitrogen fertilization at 150 kg/ha; N3, nitrogen fertilization at 200 kg/ha; HHZ, Huanghuazhan; XYXZ, Xiangyaxiangzhan. Different capital letters indicate significant differences between the two seeding rates; different lowercase letters indicate significant differences among the three nitrogen rates ($p < 0.05$). ns, not significant; *, $p < 0.05$, **, $p < 0.01$.

In the late season of 2020, the CD of HHZ significantly decreased with the increasing of nitrogen application from N1 to N3. For XYXZ, the CD increased in the early season and then showed an initial increasing followed by a decreasing trend in the late season for both years. No significant differences were observed in the CD of both cultivars over the two years.

With the nitrogen application increased, no significant differences were observed in the CWT of HHZ between the two cultivars and years. In the case of XYXZ, the CWT decreased in the early season of 2020 and the late season of 2021, while it initially increased and then decreased in the late season of 2020 and the early season of 2021. However, a significant reduction was only observed with N3 compared to N1 in the late season of 2020.

The length of the basal internodes, such as the first (1st) basal internode and the second (2nd) basal internode, were higher under the HSR compared to the LSR for two cultivars and years. There were no significant differences were observed for HHZ. Significant difference was only observed in the 2021 late season of XYXZ. Overall, with the nitrogen application increased, the length of the first and second internodes were increased. In comparison to N1, the first internode of N3 was significantly higher for HHZ, except in the early season of 2020, and no significant difference was found for the second internode.

An analysis of the sources of variation in culm characteristics revealed that there was no significant difference observed in the PH. The GCH was significantly affected by SR

in both seasons of 2020 and in the late season of 2021, as well as by N in both seasons of 2020. No interaction effects were observed for GCH. CD was significantly affected by SR and SR $\times$ N in the early season of 2020. Similarly, CWT was significantly affected by SR and SR $\times$ N in the early season of 2020 and by N in the late season of 2020. The basal first internode was significantly affected by SR in the early season of 2020 and by N in the late season of 2020. The basal second internode was significantly affected by SR in the early season of 2020 and in the late season of 2021.

3.5. Correlation Analysis

A significant positive correlation was found between the LI and SL ($r = 0.815$), WP ($r = 0.262$), PH ($r = 0.825$), GCH ($r = 0.779$), the first internode ($r = 0.634$) and the second internode ($r = 0.594$). Conversely, there was a significant negative correlation between the LI and F ($r = -0.689$), BW ($r = -0.691$), CD ($r = -0.815$) and CWT ($r = -0.815$) (Table 6).

Table 6. Correlation analysis of LI and lodging-related characteristics.

Indices	LI	SL	FW	WP	F	BM	PH	GCH	CD	CWT	1st	2nd
LI	1											
SL	0.815 **	1										
FW	−0.084 ns	0.076 ns	1									
WP	0.262 **	0.469 **	0.914 **	1								
F	−0.689 **	−0.374 **	0.727 **	0.482 **	1							
BM	−0.691 **	−0.371 **	0.739 **	0.494 **	0.990 **	1						
PH	0.825 **	0.965 **	0.042 ns	0.428 **	−0.412 **	−0.406 **	1					
GCH	0.779 **	0.711 **	−0.233 **	0.079 ns	−0.595 **	−0.601 **	0.720 **	1				
CD	−0.386 **	−0.149 ns	0.445 **	0.338 **	0.572 **	0.562 **	−0.194 *	−0.291 **	1			
CWT	−0.475 **	−0.228 **	0.561 **	0.408 **	0.710 **	0.702 **	−0.269 **	0.401 **	0.744 **	1		
1st	0.634 **	0.721 **	0.106 ns	0.392 **	−0.289 **	−0.275 **	0.758 **	0.560 **	−0.234 **	−0.262 **	1	
2nd	0.594 **	0.550 **	0.004 ns	−0.235 **	−0.345 **	−0.337 **	0.597 **	0.475 **	−0.363 **	−0.404 **	0.658 **	1

Notes: LI: lodging index; SL: length from the broken basal internode to the panicle tip; FW: fresh plant weight of the plant part above the broken point; WP: bending moment for the whole plant; F: breaking force; BM: breaking strength; PH: plant height; GCH: gravity center height; CD: culm diameter; CWT: culm wall thickness; 1st and 2nd represent the basal first internode and the basal second internode. ns, not significant; *, $p < 0.05$, **, $p < 0.01$.

4. Discussion

Increasing rice production by expanding the total area occupied by paddies is not feasible. To meet the increasing global demand for rice, it is necessary to improve overall rice production. DSR represents a simplified cultivation technique that can mitigate the impact of labor shortages while saving time and improving the sustainability of rice planting systems. Thus, quantifying the yield stability, potential yield, and lodging resistance associated with DSR supports efforts to ensure global food security.

4.1. Yield Difference between Seeding Rates and Nitrogen Rates

Lodging is an important factor that impacts rice yield and mechanical harvesting. Rice grain yield is strongly influenced by factors such as planting density and N fertilization rate, and evidence-based management of both factors can maintain rice grain yield and lodging resistance. Generally, rice yield can be improved by increasing seeding rates or N fertilization. Previous studies have indicated that adjustments in fertilization rates or planting density can influence rice grain yield [21,22]. Moreover, increasing nitrogen application or seeding rates can enhance crop yields in most cases [23–25]. Rice yield tends to increase with increasing N application, while grain yield may initially increase before decreasing with increasing direct-sowing density. Therefore, managing direct-sowing densities and N fertilization rates can improve rice yield [21]. Consistent with previous studies, we found that grain yield was significantly impacted by seeding rate [21,26]. This finding suggests that high seeding rates have the potential to generate relatively high grain yield. Furthermore, previous research has found that increasing N fertilization can enhance yield to a point, but excessive fertilization can reduce it [27,28]. Similarly, we found that increased N application rates generally boost rice grain yield, with yields increasing initially before declining. This study also highlighted the effects of SR, N, and their interactions on the grain yield as-associated with DDR.

4.2. Culm Morphology Characteristics

Increasing planting density or N fertilization can increase crop grain yield, but these strategies also increase lodging risk [29,30]. Relatively low GCH or GCH/PH ratios indicated stronger lodging resistance [31]. Previous studies have reported that extremely high planting densities and excessive N application result in increased PH and GCH, longer basal internodes, and thinner culms, all of which increase the risk of lodging [5,32]. Consistent with these findings, our study found that increasing seeding or N fertilization rates resulted in higher PH and GCH, thinner rice culms, and longer basal internodes. We observed inconsistent variation between the two cultivars with increasing SR. For instance, PH and GCH increased significantly for XYXZ but not for HHZ. Furthermore, N fertilization affected GCH significantly in both seasons in 2020. These findings suggest that seeding and N fertilization rates can increase PH and GCH.

Culm characteristics, such as weak culms or longer basal internodes, can increase the risk of lodging [33–35]. Previous studies have shown that increasing rates of N fertilization can weaken stems by altering morphological traits [6], reducing stem diameter and thickness and thus increasing lodging risk [5,36]. Furthermore, increased plant density can lead to greater competition for resources, which may result in greater plant height, thinner stems, longer basal internodes, and higher lodging risk [37]. Here, CD and CWT decreased with increasing seeding rate (Tables 5 and 6). Seeding rate significantly impacted these variables in the early season of 2020. CWT varied significantly with N fertilization rate in the late season of 2020. The interaction between SR and N had a significant effect on CD in the early seasons of 2020 and 2021 and on CWT during the early season of 2020. There were notable differences in the response of each cultivar to N fertilization across seasons.

Previous work has shown that higher CWT can improve the lodging resistance of japonica rice stems [38] and that excessively high N levels and high plant density can decrease CD and CWT, thereby increasing lodging risk [5,8,37]. Here, the effect of N fertilization on CD and CWT varied, with these metrics sometimes increasing, sometimes decreasing, and sometimes increasing before decreasing. This suggests that the impact of nitrogen fertilizer on CD and CWT is influenced by SR.

Basal internode length is closely correlated with lodging resistance [35]. Previous research suggests that N fertilization and high plant density can increase internode length, thereby reducing lodging resistance [5,39]. Other work demonstrates that PH and lodging risk are positively associated [40] and that increasing N fertilization rates and plant density can increase PH and GCH [14]. Consistent with this research, we found that the length of the first and second basal internodes increased when either SR or N application rate increased [41]. Additionally, correlation analysis revealed that PH, GCH, and basal internode length were positively and closely correlated with LI, while CD and CWT were negatively correlated with LI. Furthermore, SR and N interacted to influence CD and CWT. Our findings suggest that manipulating SR and N together to regulate culm morphology may represent a better strategy for managing rice cultivars than manipulating SR or N in isolation. This suggests that rice management practices should include recommendations for both seeding rates and N fertilization to optimize culm morphology and lodging resistance under DDR.

4.3. Mechanical Characteristics of Culms

Basal culm breaking strength and stiffness are the two primary regulators of culm lodging resistance, which can be improved by increasing the mechanical strength of basal culms. Rice lodging risk is usually assessed using LI, in which higher values correspond to greater risk [42]. Many studies have found positive correlations between F, BM, and rice lodging resistance [5,6,43] and tight, negative correlations between SL, FW, WP, and LI and lodging resistance [5,6]. Other work has demonstrated that high plant density and high N application rates increase lodging risk [32]. Our results are consistent with these findings and suggest that higher seeding or N application rates can increase LI and lodging risk.

Furthermore, FW and SL increased with increasing seeding or N application rates, resulting in large plant stem loads. Decreased F of basal internodes resulted in lower BM, contributing to higher LI and lodging risk. Additionally, higher rates of seeding or N application may also increase plant height and biomass production to a degree, thereby reducing light interception and driving subsequent deterioration of the rice canopy. These results imply that employing appropriate seeding density and N application rates can maintain stable grain yield and lodging resistance.

Factorial analysis showed that seeding rate mainly affected FW, WP, F, and BM and that N fertilization rate mainly affected FW and WP (Tables 2 and 3). In addition, we found that the interaction between N and SR had a significant impact on WP, except in the late season of 2021, and on FW in the early season of 2021. This implies that mechanical characteristics may be related to seasonal variation in weather conditions. Consistent with previous work, our correlation analysis showed that SL, FW, and WP were positively correlated with LI, while F and BM were negatively correlated with LI under DDR [5,10]. Together, these results suggest that mechanical characteristics varied with SR, N, and their interaction. Our findings are in accordance with previous re-search demonstrating that lodging resistance is regulated by culm mechanical characteristics, which are themselves strongly influenced by N fertilization or plant density.

5. Conclusions

Decreasing N fertilization rates to 100 kg/ha can mitigate the enhanced lodging risk caused by increasing SR to 30 cm × 12 cm. This work suggests that complementary advantages can be realized by manipulating N fertilization rates to improve the lodging resistance and yield of MDSR. Our work can help inform fertilization and seeding rate strategies for direct-seeded rice to maintain stable grain yields and reduce lodging resistance.

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Abbreviations

MDSR	mechanically direct-seeded rice;
DDR	direct-seeded and double-season rice;
DSR	direct-seeded rice;
F	breaking force;
SL	length from the broken basal internode to the panicle tip;
FW	fresh plant weight of the plant part above the broken point;
WP	bending moment for the whole plant;
BM	breaking strength;
LI	lodging index;
CD	culm diameter;
CWT	culm wall thickness;
PH	plant height;
GCH	gravity center height.

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