

Article

Effects of Sowing Mode on Lodging Resistance and Grain Yield in Winter Wheat

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Abstract: For improving lodging resistance and increasing grain yield in wheat in the Yellow-Huai River Basin in China, different sowing modes have been investigated. Conventionally, the small-flat-plot sowing mode has been adopted in wheat cultivation. However, this sowing mode leads to heavy lodging and low land use efficiency. In this study, a new sowing mode, high-low-plot sowing mode with two more rows sowed on the high plot, was investigated. Two cultivars, Hengguan 35 and Jimai 44 were used for two seasonal field experiments from 2018 to 2020. The results showed that grain yield improved with the high-low sowing mode by as much as 25% since more spikes per unit area were observed concomitant with reduced stem lodging. The grain yield increase was mainly due to the enhanced spike number per m², while the lodging resistance was improved through the lowered plant height and the center of gravity height. This research proves that the high-low-plot sowing mode is an improved sowing mode for producing greater grain yield with better lodging resistance in the wheat production area in northern China.

Keywords: grain yield; high-and-low-plot sowing mode; lodging resistance; small-flat-plot sowing mode; wheat

1. Introduction

Wheat (*Triticum aestivum* L.), as one of the most important staple crops along with rice [1], supplies about 20% of calories and protein for human consumption worldwide [2,3]. As the largest wheat producer and consumer in the world, wheat production in China is crucial for local markets and for the global wheat industries [4]. In particular, the North

China Plain (NCP) is playing an important role by producing over 50% of the national wheat harvest [5] from only 21% of the total wheat acreage in China. Thus, stability and improvement in wheat grain yield in NCP are very important for national food security, as well as for global food supply chains.

In NCP, the annual precipitation is about 400–500 mm. Each year, two crops of maize and wheat are planted in summer and winter, respectively. During the wheat growing season, the total rainfall is only about 200 mm [6,7]. About half of the water required for wheat cultivation is sourced from underground aquifers and is called well irrigation. An amount of 50–70 mm of water is applied at the tillering, jointing, and grain-filling stages, and the total amount of water used is about 150–210 mm [8]. On average, each farm comprises 1–3 ha of cultivated land. Winter wheat is conventionally sown with machinery in narrowly spaced rows on small flat plots (SFP, Figure 1a,d) (30–100 m long and 2–4 m wide) in the well-irrigated area of the Yellow River Delta, in the North China Plain. Probably due to irrigation and heavy nitrogen utilization, lodging has become a limiting factor reducing grain yield and grain quality in wheat. It also impairs the machine harvesting of wheat [9–13]. Thus, this problem needs to be solved for cost-effective wheat production [14,15]. Stem lodging is highly associated with the strength of the second basal internode [11,16–20]. For improving stem lodging resistance, a range of topics have been investigated including sowing modes, ways of irrigation and fertilization, and control of stem diseases and pests [13,21–24]. Among them, Shah et al. [23] reported that different methods of sowing and tillage showed a significant improvement in lodging resistance in wheat. As an example, compared with the flat sowing mode, raised-bed sowing resulted in over 50% less lodging [24,25]. Furthermore, raised-bed sowing significantly increased grain yield by reducing the lodging score. Si et al. [22] showed that the strength of the basal internodes in raised-bed cropping was greater than in the flat cropping method and that the grain yield in the raised beds increased by over 11%.

To date, the studies on wheat lodging in China have focused on different effects between raised-bed sowing and flat sowing [8,22,26–28]. For a long time, the small-flat-plot sowing mode has been used in the well-irrigated area of the Yellow River Delta (Figure 1a,d). Even though high-yielding, drought-tolerant wheat cultivars such as Heng-guan 35 are being used in this sowing mode, lodging and the low ratio of land utility remain limiting factors affecting yield performance [27]. For increasing yield and reducing lodging, a high-low-plot sowing mode (Figure 1b,e) with an increased land use rate has been developed at Binzhou Academy of Agricultural Sciences. To investigate how this mode increased grain yield and lodging resistance, two different sowing modes, high-low-plot sowing mode (HLP) and small-flat-plot sowing mode (SFP), were used in two seasonal field experiments in this study. The physiological and phenotypical results provided evidence that the HLP sowing mode reduced wheat lodging and achieved desirable grain yield with an increase in overall land usage in the North China Plain.

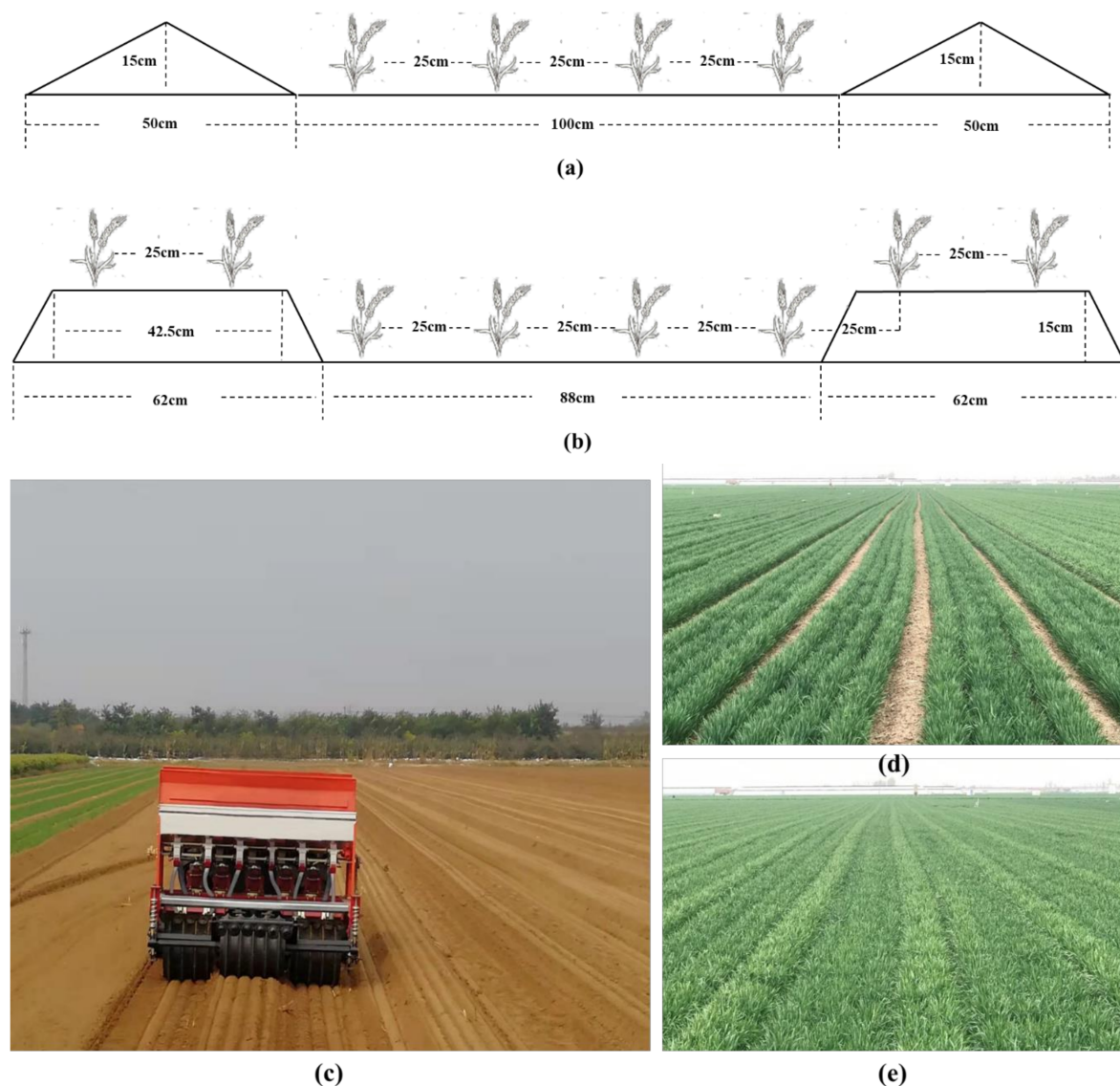


Figure 1. Sowing structures, sowing processes, and different field trials: (a) small-flat-plot mode; (b) high-low-plot mode; (c) sowing process by high-low border planter; (d) wheat plants grown in the small-flat-plot mode; (e) wheat plants grown in the high-low plot mode.

2. Materials and Methods

2.1. Experimental Site

Field experiments were carried out in 2018–2020 at Boxing Mazhuang experimental site (118.29° E, 37.06° N) of Binzhou Academy of Agricultural Sciences, which is located on the eastern side of the North China Plain, Shandong Province, China. The average annual precipitation of the experimental site is 580 mm and the average annual temperature is 12.5 °C. The total yearly sunshine duration is 2595 h and the nonfrost period is 180 days. The local soil type is silt loam containing organic matter (1.3%), alkali-hydrolyzable nitrogen (59.7 mg/kg), available phosphorus (10.7 mg/kg), and available potassium (127.6 mg/kg).

2.2. Materials and Experimental Design

Winter wheat cultivars, Hengguan 35 (HG35) and Jimai 44 (JM44), were used in the experiments. HG35 is a high-yielding cultivar with a relatively low height of 70–80 cm and high lodging resistance. JM44 is also a high-yielding cultivar with a high gluten level. The height of JM44 ranges from 70 to 90 cm.

Two sowing modes were applied: high-low-plot sowing (HLP) (high border of 42.5 cm width and low border of 88 cm width and 15 cm depth) and small-flat-plot sowing (SFP) (border of 100 cm width with 15 cm depth). For the HLP sowing mode, two rows of wheat were sowed in the high border and four rows were sowed in the low plot. For the SFP sowing mode, four rows of wheat were sowed in the small flat plot. In both HLP and SFP sowing modes, the row space between neighboring plants was 25 cm. A schematic diagram of the sowing modes is presented in Figure 1. For the HLP mode, a special sowing machine was designed, in which the height of the planter is able to be adjusted with the height of the border (Figure 1c). The HLP planter integrates five processes of making the high-low border, ditching, fertilizing, seeding, and suppression, and completes all the procedures at once. For the SFP mode, a normal sowing machine was used, and the above sowing processes were included except for making the high-low border.

The experiments were carried out in two wheat-growing seasons (2018/2019; 2019/2020). The two cultivars under two sowing modes with three replicates led to 12 large plots. The large plots were randomly located on 8000 m², with each plot area of 666.7 m². The seeding rate was 120 kg/ha. A total of 120 kg/ha nitrogen, 120 kg/ha superphosphate (P₂O₅), and 120 kg/ha potassium sulfate (K₂SO₄) were applied as basal fertilizer. An additional 120 kg/ha nitrogen was applied at the wheat jointing stage. Local standard procedures were used for irrigation and pests management [7,29]. Irrigation was applied (75 mm at each watering) at tillering, jointing, and grain-filling stages. Pesticide and fungicide were mainly applied at the jointing and booting stages. There was no pest incidence in the two growing seasons.

2.3. Measurements and Data Analysis

Before harvesting, a subplot of three m² (2.0 m × 1.5 m) was randomly selected in each large plot. Spike number (SN) per unit area (m²) was recorded before harvesting. A total of 20 spikes were randomly collected from each subplot and threshed. Grain number per spike (GNS) was recorded. Thousand kernel weight (TKW) was determined by the weight of 200 kernels. Grain yield (GY) was collected for each plot.

From each subplot, 30 main tillers were randomly collected at maturity for plant height and second basal internode measurements at the ripening stage according to the methods of Wei et al. [30]. Plant height (PH) was measured from the base of the plant to the tip of spikes excluding awns. After detaching the leaves together with the leaf sheath, the length, diameter, and wall thickness of the second basal internode were measured with a digital caliper with an accuracy of 0.001 mm (the midpoint of the internode was used for the diameter and wall thickness measurements). The dry weight of the second internode of subsamples was recorded after oven drying for 30 min at 105 °C, followed by 75 °C to constant weight. The stem-filling degree was scored with the formula: dry weight of second basal internode/length of second basal internode × 1000 [20].

A stalk strength tester (YDD-1; Zhejiang Top Instrument Co., Hangzhou, China) was used to measure the breaking strength of the second basal internode. The second basal internodes without sheath were placed on the groove of the support pillars at 50 mm and then set the tester perpendicular to the stem at the middle. The mechanical breaking strength was recorded based on the breaking point on the culm internode. The center of gravity height (COGH) refers to the distance from the culm (with spike, leaf, and sheath) base to the balance fulcrum. The culm lodging resistance index (CLRI) according to Li et al. [13] was calculated as follows: $CLRI = N/M \times 100$, where the values of N and M were the mechanical breaking strength and the center of gravity height, respectively.

Statistical analysis was performed using IBM SPSS Statistics 22 and GraphPad Prism 8 software [31,32]. The means and significant differences among different sowing modes, cultivars, and years were computed by analysis of variance (ANOVA), and Tukey's multiple range test was used for the equal variance analysis at the significant level of 0.05. Two-way and three-way ANOVA were performed using the multiple comparisons procedure under GraphPad Prism 8 software, where each trait was treated as the fixed effect, and sowing

modes, cultivars, years, and their interactions were all treated as random effects. The “rcorr” function in the R package Hmisc [33] was used for the pairwise correlation analysis.

3. Results

3.1. Sowing Mode Effects on Wheat Yield and Yield-Related Components

The effects of sowing mode and cultivar on yield and yield components were highly significant ($p < 0.001$) (Table 1), while there was no significant effect of year. The interactions between sowing mode and cultivar were also significant on SN, GNS, and TKW, whereas the interaction between year and cultivar was significant ($p < 0.01$) on SN only. The interactions between year and sowing mode were not significant.

Table 1. Analysis of variance for sowing modes, cultivars, and their interactions on wheat yield and yield components.

Years	Cultivars	Modes	GY (ton/ha)	SN (m ⁻²)	GNS	TKW (g)
2019	HG35	HLP	10.66 ± 0.16 aA	788.33 ± 8.61 aB	31.76 ± 0.27 aA	42.70 ± 0.26 aB
		SFP	9.60 ± 0.031 bA	696.67 ± 2.73 bA	31.96 ± 0.39 aA	42.75 ± 0.33 aB
	JM44	HLP	7.80 ± 0.11 aB	836.67 ± 6.77 aA	18.50 ± 0.37 bB	50.31 ± 0.66 aA
		SFP	6.25 ± 0.16 bB	607.78 ± 6.48 bB	22.09 ± 0.17 aB	46.47 ± 0.58 bA
2020	HG35	HLP	10.88 ± 0.13 aA	795.00 ± 3.88 aB	32.02 ± 0.67 aA	42.32 ± 0.11 aB
		SFP	9.63 ± 0.06 bA	690.00 ± 13.85 bA	33.47 ± 0.85 aA	41.52 ± 0.30 aB
	JM44	HLP	7.71 ± 0.047 aB	826.67 ± 2.60 aA	18.74 ± 0.10 bB	50.50 ± 0.38 aA
		SFP	6.33 ± 0.15 bB	573.46 ± 3.53 bB	23.50 ± 0.90 aB	47.06 ± 0.68 bA
F-value						
Year (Y)			0.531	0.041	0.042	0.528
Cultivar (C)			<0.001	<0.001	<0.001	<0.001
Mode (M)			<0.001	<0.001	<0.001	<0.001
Y × C			0.499	0.005	0.939	0.084
Y × M			0.982	0.076	0.135	0.731
C × M			0.129	<0.001	0.001	<0.001
Y × C × M			0.371	0.656	0.963	0.344

HG35: Hengguan 35; JM44: Jimai 44; HLP: high-low-plot sowing mode; SFP: small-flat-plot sowing mode; GY: grain yield; SN: spike number per m^2 ; GNS: grain number per spike; TKW: thousand kernel weight. The same lowercase letters indicate that the difference between sowing modes was not significant. The same uppercase letters mean the difference between cultivars was not significant.

Significantly higher grain yield and spike number per m^2 were observed in the HLP sowing mode in both cultivars across both growing seasons (Figure 2 and Table 1). Compared with SFP, grain yield was increased in HLP by 11.1–24.7% and 12.9–21.7% in 2019 and 2020, respectively. In both modes, the grain yield of HG35 was higher than JM44, with an increment of 36.6–53.4% and 41.1–52.1%, in 2019 and 2020, respectively.

Among the yield components, the spike number per m^2 (SN) was significantly higher in HLP mode in both cultivars and years. In 2019 and 2020, SN in HLP increased by 13.2–37.7% and 16.7–37.7% (Figure 2 and Table 1), respectively. No significant differences were observed in grain number per spike (GNS) and thousand kernel weight (TKW) between HLP and SFP in the case of HG35, while in JM44, GNS was reduced, and TKW was increased in HLP. Based on cultivars, SN and TKW of JM44 were significantly higher than those of HG35 in HLP, whereas GNS was significantly lower than that of HG35. In SFP, same as in HLP, the TKW of JM44 was significantly higher than that of HG35. The overall variations in yield-related traits in HLP and SFP were generally consistent over the two seasons.

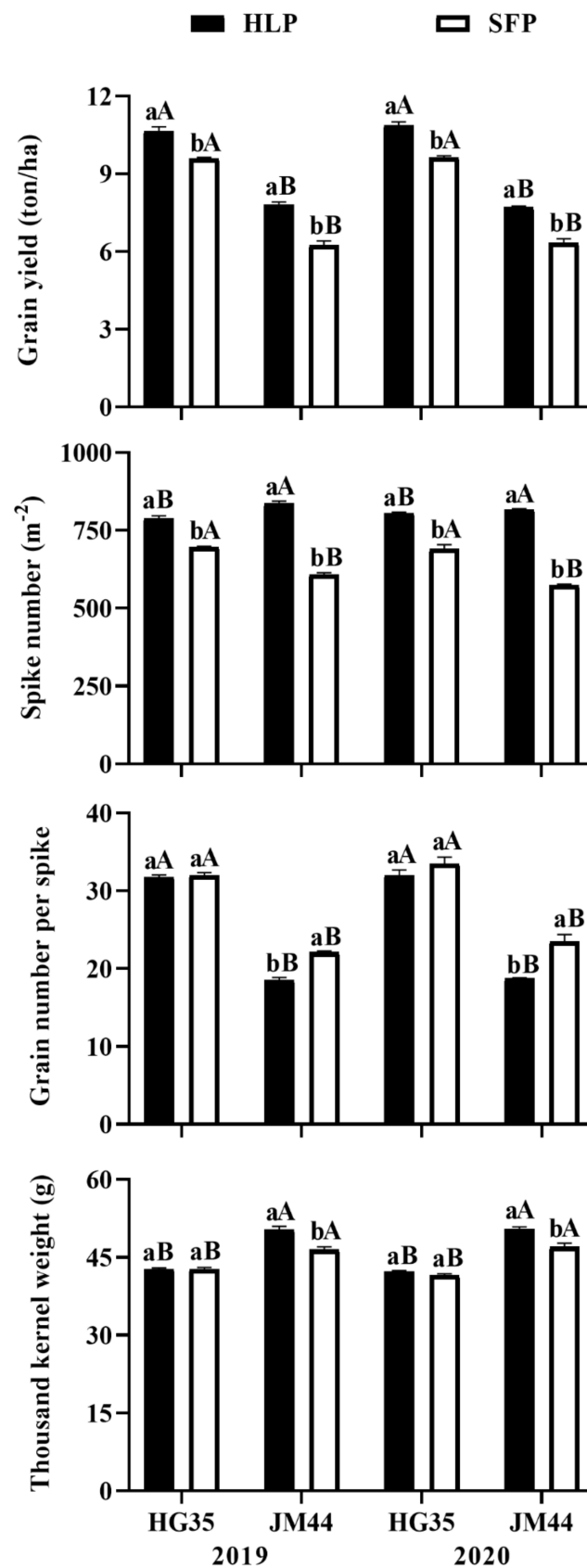


Figure 2. Effects of sowing modes, cultivars, and their interactions on wheat yield and yield components. HG35: Hengguan 35; JM44: Jimai 44; HLP: high-low-plot sowing mode; SFP: small-flat-plot sowing mode. The same lowercase letters indicate that the difference between sowing modes was not significant. The same uppercase letters mean the difference between cultivars was not significant.

3.2. Effects of Sowing Modes on Lodging Resistance

The culm lodging resistant index (CLRI) was used to measure plant lodging. Compared with SFP, the CLRI in HLP was increased in 2020, while the enhanced level did not reach a significant level in 2019. In 2020, the CLRI of plants in HLP was significantly higher than in SFP by 8.9 and 24.9% in HG35 and JM44, respectively (Figure 3). In HLP, samples from high plots (HP) and low plots (LP) were investigated further. The CLRI of plants in HP increased 23.0 and 29.8% in comparison to LP and SFP, respectively (Figure 3), while it was similar in LP and SFP. The increment of CLRI in HLP mode stems from the high CLRI levels of plants in HP. The CLRI levels of HG35 were significantly higher than JM44 in both HLP and SFP modes in 2020 (Figure 3).

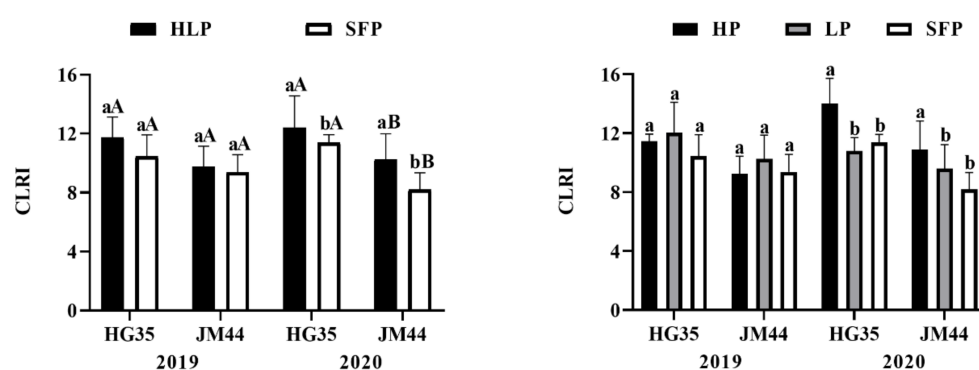


Figure 3. Effects of sowing modes on culm lodging resistance index (CLRI). HG35: Hengguan 35; JM44: Jimai 44. HLP: high-low-plot sowing mode; SFP: small-flat-plot sowing mode. The same lowercase letters indicate that the difference between sowing modes was not significant. The same uppercase letters mean the difference between cultivars was not significant.

3.3. Effects of Sowing Modes on Stem Strength

In both growing seasons, plant height and the center of gravity height (COGH) were lower in the HLP mode than in the SFP mode (Figure 4 and Table 2). Within the HLP mode, plant height and COGH in HP were reduced significantly by 1.8–21.6% and 0.3–21.8%, respectively, in comparison to the SFP mode plants (Figure 4). Plant mechanical strength levels were similar for the two sowing modes (Figure 4), but they were significantly higher in HG35 than in JM44 (Figure 4 and Table 2).

3.4. Effects of Sowing Modes on the Second Basal Internode

The strength of the second basal internode was identified to be highly associated with plant lodging. The internode length, diameter, wall thickness, dry weight, and stem-filling degree were measured. Based on the ANOVA analysis, the influence of sowing modes on internode diameter and dry weight were significant, and there was an interaction between cultivar and sowing mode for diameter (Table 3). Moreover, sowing mode affected internode diameter and dry weight in JM44 but not in HG35 (Figure 5 and Table 3). Plants of JM44 in HP had the lowest stem diameter and dry weight in the second basal internode, while the dry weight of HG35 was lower in HP in 2019, in comparison to LP and SFP (Figure 5).

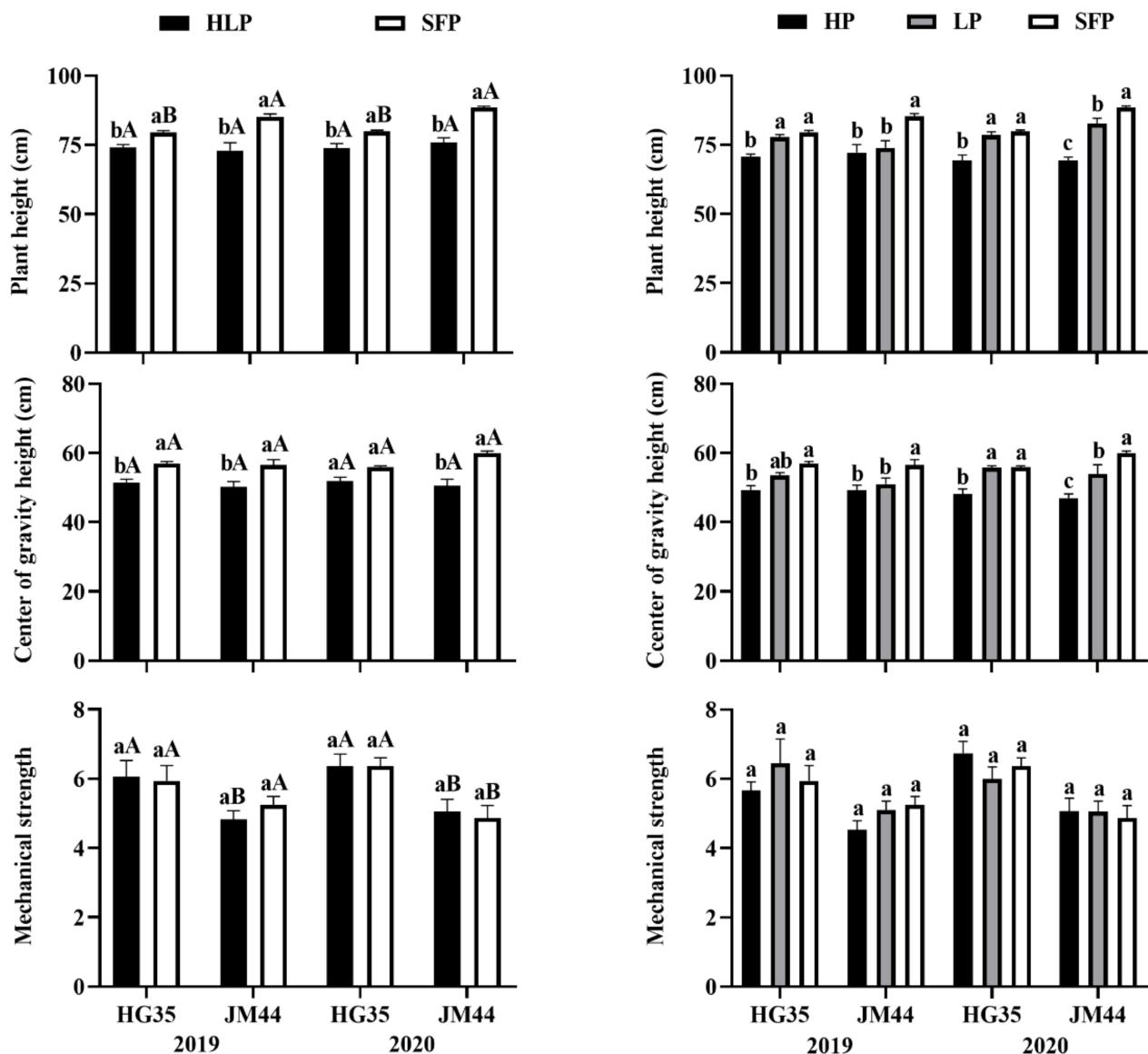


Figure 4. Effects of sowing modes, cultivars, and their interactions on plant height, the center of gravity of height, and mechanical strength. HG35: Hengguan 35; JM44: Jimai 44. HLP: high-low-plot sowing mode; SFP: small-flat-plot sowing mode. The same lowercase letters indicate that the difference between sowing modes was not significant. The same uppercase letters mean the difference between cultivars was not significant.

Table 2. Analysis of variance for sowing modes, cultivars, and their interactions on plant height, the center of gravity of height, and mechanical strength.

Years	Cultivars	Modes	PH (cm)	COGH (cm)	MS
2019	HG35	HP	70.57 ± 1.03 b	49.29 ± 1.25 b	5.67 ± 0.24 a
		LP	77.71 ± 0.97 a	53.51 ± 0.82 ab	6.45 ± 0.70 a
		HLP	74.14 ± 1.00 A	51.4 ± 1.035 A	6.06 ± 0.47 A
		SFP	79.54 ± 0.65 aB	56.93 ± 0.58 aA	5.94 ± 0.44 aA
	JM44	HP	72.19 ± 2.86 b	49.25 ± 1.45 b	4.53 ± 0.26 a
		LP	73.87 ± 2.61 b	51.03 ± 1.70 b	5.10 ± 0.26 a
		HLP	73.03 ± 2.74 A	50.14 ± 1.58 A	4.82 ± 0.26 B
		SFP	85.24 ± 0.98 aA	56.53 ± 1.53 aA	5.24 ± 0.25 aA
2020	HG35	HP	69.28 ± 1.96 b	48.13 ± 1.48 b	6.74 ± 0.34 a
		LP	78.37 ± 1.34 a	55.70 ± 0.57 a	6.00 ± 0.34 a

Table 2. Cont.

Years	Cultivars	Modes	PH (cm)	COGH (cm)	MS
		HLP	73.83 ± 1.65 A	51.92 ± 1.03 A	6.37 ± 0.34 A
		SFP	79.81 ± 0.53 aB	55.89 ± 0.36 aA	6.37 ± 0.23 aA
	JM44	HP	69.35 ± 1.27 c	46.94 ± 1.26 c	5.06 ± 0.38 a
		LP	82.58 ± 1.95 b	53.99 ± 2.63 b	5.05 ± 0.31 a
		HLP	75.97 ± 1.61 A	50.47 ± 1.95 A	5.06 ± 0.35 B
		SFP	88.48 ± 0.50 aA	59.99 ± 0.55 aA	4.87 ± 0.36 aB
F-value					
Year (Y)			0.123	0.383	0.37
Cultivar (C)			0.006	0.714	< 0.001
Mode (M)			< 0.001	< 0.001	0.84
Y × C			0.097	0.379	0.47
Y × M			0.02	0.085	0.13
C × M			0.008	0.128	0.81
Y × C × M			0.121	0.328	0.48

HG35: Hengguan 35; JM44: Jimai 44. HLP: high-low-plot sowing mode; SFP: small-flat-plot sowing mode. PH: plant height; COGH: the center of gravity height; MS: mechanical strength. The same lowercase letters indicate that the difference between sowing modes was not significant. The same uppercase letters mean the difference between cultivars was not significant.

Table 3. Analysis of variance for sowing modes, cultivars, and their interactions on the morphological characteristics of culm second basal internodes.

Years	Cultivars	Modes	Second Basal Internode				
			Length (mm)	Diameter (mm)	Wall Thickness (mm)	Dry Weight (mg)	Stem Filling Degree (mg/mm)
2019	HG35	HP	68.93 ± 4.53 a	3.55 ± 0.07 a	0.42 ± 0.00 a	85.85 ± 4.23 b	1.29 ± 0.09 a
		LP	77.33 ± 3.77 a	3.82 ± 0.09 a	0.48 ± 0.05 a	102.71 ± 5.12 a	1.35 ± 0.06 a
		HLP	73.13 ± 4.15 B	3.69 ± 0.08 A	0.45 ± 0.03 A	94.28 ± 4.68 A	1.32 ± 0.08 A
		SFP	79.4 ± 7.10 aB	3.83 ± 0.12 aB	0.45 ± 0.02 aA	96.51 ± 4.31 abB	1.25 ± 0.09 aA
	JM44	HP	99.60 ± 5.97 a	3.77 ± 0.06 b	0.37 ± 0.01 a	103.52 ± 6.32 b	1.06 ± 0.07 b
		LP	92.78 ± 7.68 a	3.99 ± 0.06 b	0.43 ± 0.02 a	113.81 ± 5.24 ab	1.31 ± 0.10 a
		HLP	96.19 ± 6.83 A	3.88 ± 0.06 A	0.40 ± 0.02 A	108.67 ± 5.78 A	1.19 ± 0.09 A
		SFP	101.33 ± 5.44 aA	4.46 ± 0.13 aA	0.37 ± 0.00 aB	128.17 ± 5.14 aA	1.22 ± 0.07 aA
2020	HG35	HP	71.07 ± 3.96 a	3.66 ± 0.06 a	0.44 ± 0.00 a	87.49 ± 3.63 a	1.26 ± 0.07 a
		LP	72.93 ± 2.61 a	3.67 ± 0.06 a	0.47 ± 0.03 a	98.62 ± 2.56 a	1.40 ± 0.03 a
		HLP	72.00 ± 3.29 B	3.67 ± 0.06 A	0.46 ± 0.02 A	93.06 ± 3.10 A	1.33 ± 0.05 A
		SFP	75.67 ± 2.88 aB	3.82 ± 0.05 aB	0.47 ± 0.00 aA	94.15 ± 4.23 aB	1.29 ± 0.05 aA
	JM44	HP	88.53 ± 2.97 b	3.65 ± 0.02 b	0.39 ± 0.01 a	101.81 ± 6.23 b	1.20 ± 0.05 a
		LP	98.67 ± 3.00 ab	4.09 ± 0.18 a	0.37 ± 0.02 a	118.19 ± 5.78 ab	1.20 ± 0.05 a
		HLP	93.60 ± 2.99 A	3.97 ± 0.10 A	0.38 ± 0.02 B	110.00 ± 6.01 A	1.20 ± 0.05 A
		SFP	104.93 ± 5.04 aA	4.18 ± 0.09 aA	0.37 ± 0.02 aB	128.49 ± 5.34 aA	1.26 ± 0.06 aA
F-value							
Year (Y)			0.66	0.64	0.96	0.81	0.81
Cultivar (C)			<0.001	<0.001	<0.001	<0.001	0.09
Mode (M)			0.07	<0.001	0.12	<0.001	0.07
Y × C			0.80	0.86	0.34	0.32	0.79
Y × M			0.72	0.26	0.15	0.92	0.71
C × M			0.76	0.02	0.53	0.09	0.25
Y × C × M			0.20	0.02	0.65	0.19	0.20

HG35: Hengguan 35; JM 44: Jimai 44. HLP: high-low-plot sowing mode; SFP: small-flat-plot sowing mode. The same lowercase letters indicate that the difference between sowing modes was not significant. The same uppercase letters mean the difference between cultivars was not significant.

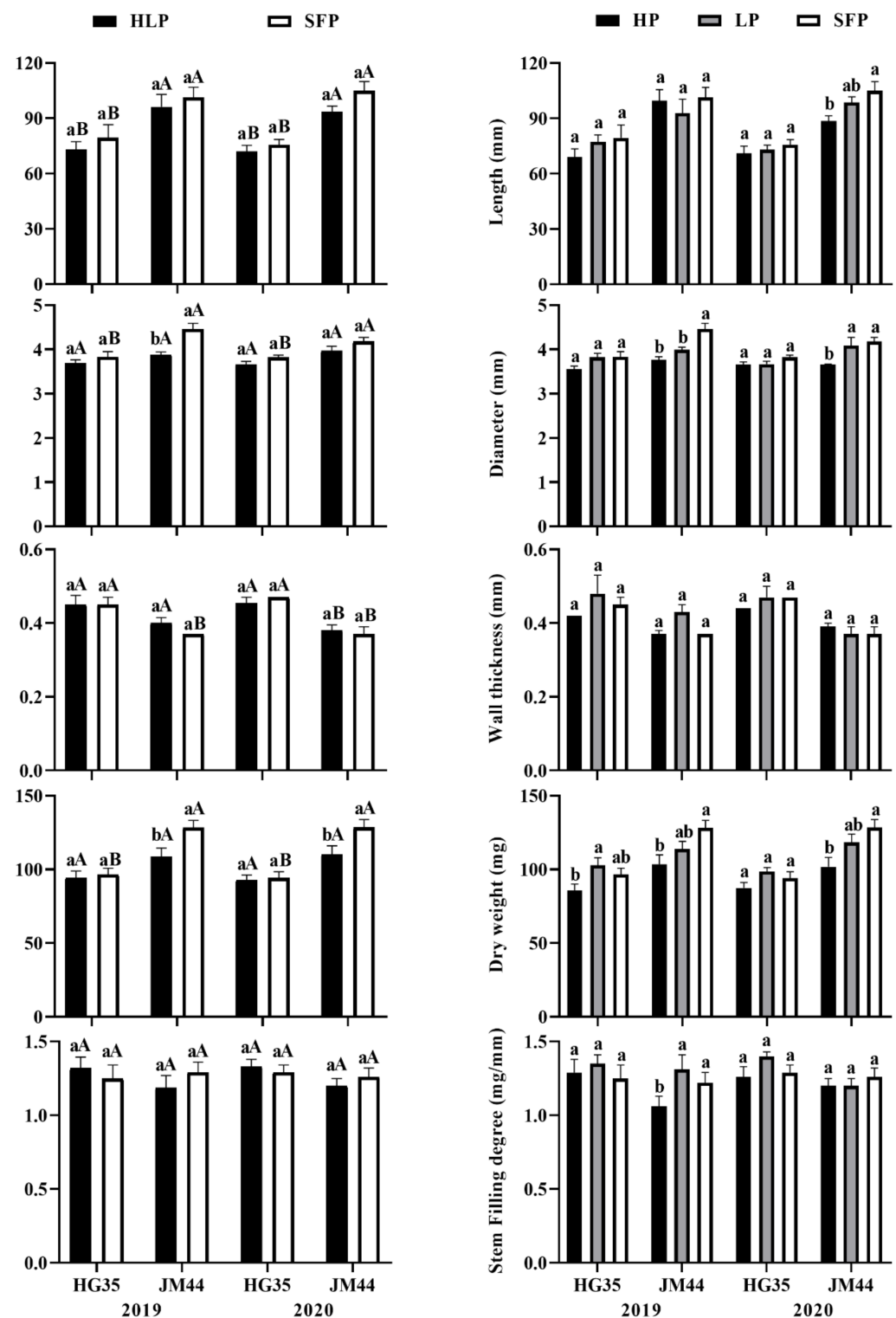


Figure 5. Effects of sowing mode, cultivars, and their interactions on the morphological characteristics of culm second basal internodes. HG35: Hengguan 35; JM44: Jimai 44. HLP: high-low-plot sowing mode; SFP: small-flat-plot sowing mode. The same lowercase letters indicate that the difference between sowing modes was not significant. The same uppercase letters mean the difference between cultivars was not significant.

3.5. Correlation of Morphological Parameters

Correlation analysis was performed between parameters (Figure 6). The stem mechanical strength in the second basal internode was significantly positively correlated with wall thickness, stem filling degree, and culm lodging resistance index (CLRI), and significantly negatively correlated with internode length and dry weight. The CLRI was positively and significantly correlated with wall thickness and the mechanical breaking strength of the second basal internode, while negatively associated with plant height, the center of gravity height, internode length, and dry weight. Significantly positive correlations were found between the center of gravity height and plant height, together with the second internode-related traits such as internode diameter and dry weight. Internode dry weight was positively associated with the internode length, internode diameter, and plant height. Correlation analysis demonstrated that the culm lodging resistance index of wheat was positively and significantly correlated with wall thickness and the mechanical breaking strength of the second basal internode and negatively and significantly correlated with plant height, the center of gravity height, and the length and dry weight of the second basal internode (Figure 6).

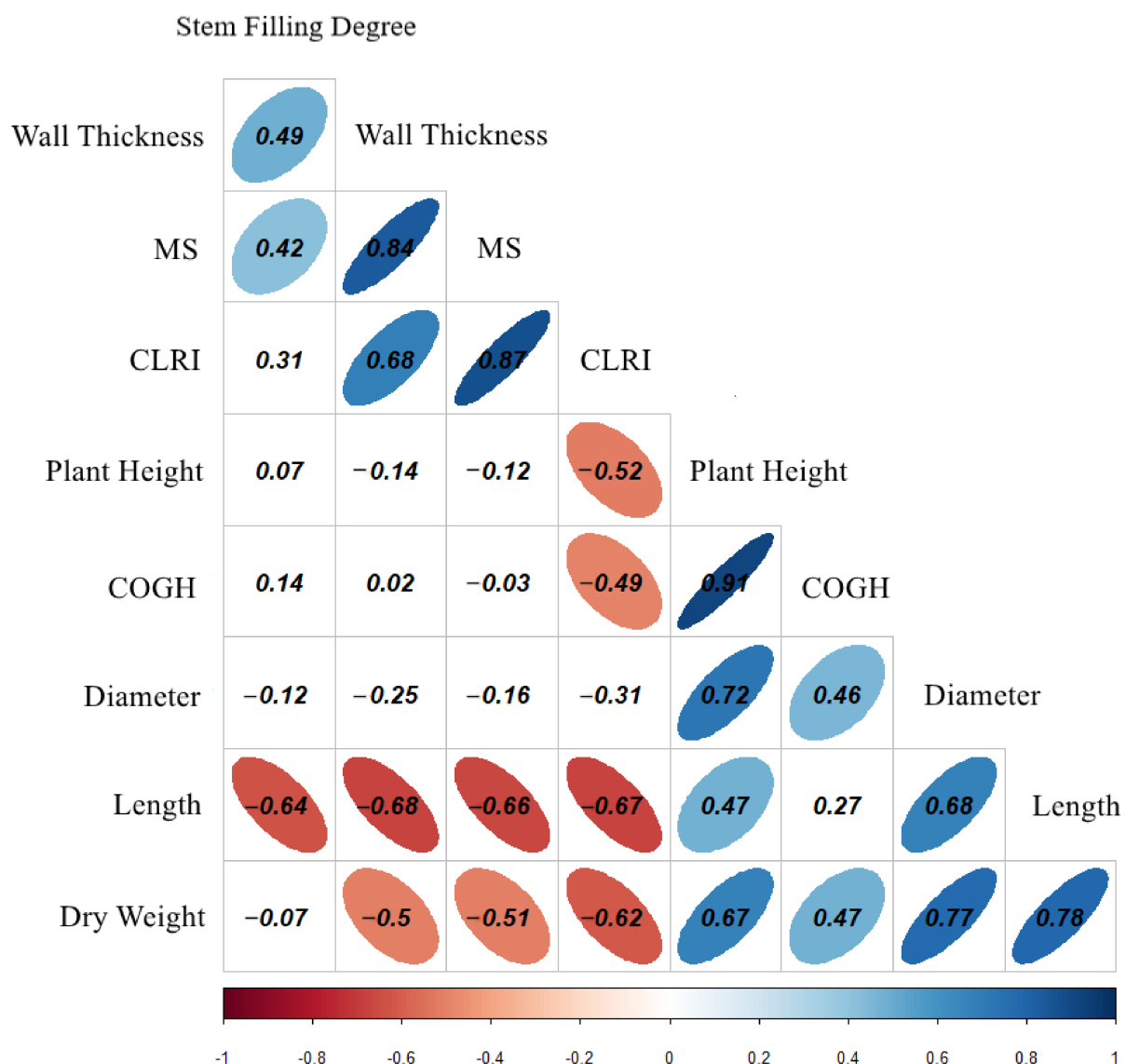


Figure 6. Correlation analysis of morphological characteristics. COGH: the center of gravity height; MS: mechanical strength; CLRI: culm lodging resistance index; ellipse indicates significant difference at 0.01 level.

4. Discussion

Increasing grain yield is a priority in wheat production in China [34,35]. The grain yield components mainly include spike number per unit area (SN), grain number per spike (GNS), and thousand kernel weight (TKW) [36–38]. These three components are influenced by a set of factors such as cultivar, seeding rate, fertilization, irrigation, and sowing mode [5,35,39,40]. Many researchers have suggested that effective sowing modes could enhance grain yield via the adjustment of field structure, such as the soil's physical status [8,22,41–43]. Raised-bed sowing is one of the sowing modes that can be used for the adjustment of field structure. The benefits of growing winter wheat using a raised-bed sowing mode, in comparison with flat sowing, were reported by Wang et al. [8], who suggested that raised beds can eliminate soil crusts and improve soil physical status. Soil structure has also been found to have an important effect on lodging, as it has been predicted to be directly proportional to the anchorage strength of the crop [44]. Other studies have shown that the bedding process can increase soil aggregate formation and maintain optimal ratios of solid, liquid, and gaseous phases in agricultural soil [43,45], as well as optimization of water holding capacity [46,47]. Based on field observations, HLP mode helps to improve soil physical characteristics such as soil bulk density and soil porosity, compared with the SFP mode. Meanwhile, we suggest that the HLP mode plays a positive role in the maintenance of soil moisture, water, and soil conservation. Indeed, these changes will all favor wheat growth. Additionally, the more favorable field microclimate in the HLP crop is likely to reduce the incidence of disease and pests as well as decrease lodging, which directly and indirectly improves grain yield.

For a long time, the flat sowing mode has been adopted in well-irrigated areas in wheat production along the Yellow River Basin. The disadvantages of flat sowing mode are land wastage and a high frequency of diseases, pests, and weeds, which reduce grain yield. Therefore, our research group proposed another sowing mode—the HLP mode, which has the same effect as the raised-bed sowing pattern. The HLP mode is a combination sowing system of high and low plots in order to increase the utilization of farmland, thus enhancing grain yield through an increase in spike number per unit area [48–50]. In this study, HG35 and JM44 in HLP from 2019 to 2020 produced significantly higher grain yield, (Figure 2 and Table 1). A number of studies have reported that increases in plant density (spike number per unit area) would result in a decrease in grain number per spike and thousand kernel weight [48,51–53]. However, high spike density did not cause any loss in TKW and grain number per spike in our study.

For improving the output of grain yield, producers in China prefer to use more nitrogen than in many other nations. The overuse of nitrogen fertilizer results in low nitrogen use efficiency and economic losses [54,55] and contributes to environmental pollution [56–58]. Meanwhile, the heavy application of nitrogen could increase the risk of lodging [18]. Controlling the soil nitrogen level under a certain limit could improve lodging resistance and ultimately reduce the likelihood of lodging [59]. Compared with the traditional flat bed, the raised bed improved grain yield and nitrogen use efficiency by 10% or more [8]. Wheat on the high plot would eliminate the luxury consumption of nitrogen taken by plants on the low plot, which could reduce plant lodging on the low plot. Similar findings were reported by Limon-Ortega et al. [41].

Culm morphological features and culm lodging resistance index (CLRI) have been the major physical parameters to evaluate wheat stem lodging resistance [19,20,30,60,61]. Significant positive correlations were evident between CLRI and other morphological traits of the second basal internode including wall thickness, and mechanical breaking strength (Figure 6), especially, the high correlation ($r = 0.87^{**}$) between CLRI and mechanical strength. These results are in agreement with previous studies, which reported that culm morphological characteristics are highly correlated with lodging resistance [60,62,63]. The results of the present study also showed that mechanical breaking strength was not affected by the sowing mode (Figure 4 and Table 2). In this study, the CLRI was significantly negatively correlated with plant height, the center of gravity height (COGH), the length

of the second basal internode, and its dry weight. The COGH plays an important role in improving lodging resistance among different sowing modes, and the decreases in COGH usually decrease the lodging rate. Therefore, the increased CLRI in HLP indicates a decrease in the lodging rate. Several studies have shown that shortening plant height is one of the most effective methods to reduce the risk of lodging [64,65]. Generally, plant height, as one of the lodging-related traits, is mainly affected by cultivars, years, sowing modes, and their interactions. Results of ANOVA showed that there were significant height differences between HG35 and JM44 in SFP, while no significance was detected in HLP. The plant height of both HG35 and JM44 was significantly reduced in HLP compared with SFP. Within the HLP mode, the plant height of JM44 was reduced significantly in both HP and LP, while the significant reduction in HG35 was only in HP. The results indicate that the reduced plant height in both cultivars under the HLP mode may also contribute to lodging resistance.

5. Conclusions

Comparison of two types of sowing modes (HLP and SFP) using two wheat cultivars revealed considerable improvements in lodging resistance and grain yield in the HLP sowing. An increase in spike number per unit area contributes to the grain yield in the HLP mode. Furthermore, an improvement on lodging resistance derived from the reductions in the center of culm gravity height and plant height benefited the efficient grain filling and effective mechanical harvesting. Therefore, this study showed that the high-and-low-combination plot sowing system is an optimized sowing mode in well-irrigated areas in the Yellow River Basin for increasing wheat production. Broadly, the HLP mode provides an option to similar worldwide agroecological zones to reduce the yield loss caused by lodging.

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