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Improving Stem Lodging Resistance, Yield, and Water Efficiency of Wheat by Adjusting Supplemental Irrigation Frequency

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Abstract: Optimizing supplemental irrigation (SI) measures and enhancing stem lodging resistance can be the keys to achieving a high and stable yield and high efficiency in wheat. The experiment was established as a two-factor field trial in 2018–2020. We used four SI combinations at different stages: rain-fed (T0), SI at jointing (T1), SI at jointing + anthesis (T2), and SI at regreening + jointing + anthesis (T3) with ‘Bainong4199’ (BN4199) and ‘Zhoumai18’ (ZM18) as experimental materials. We researched the effects of different SI combinations on the stem characteristics, stem vigor, grain filling, and yield of winter wheat. The results suggest that the basal internode at the anthesis stage grew with the increase in SI amount, but the stem fracture resistance of T1 and T2 was higher than that of T0 and T3. As grain filling continued, the lodging index increased and stem vigor decreased. In comparison with T3, the average stem lodging index of T2 decreased by 21.92% for ‘BN4199’ and 36.63% for ‘ZM18’, but the WUE increased by 29.76% and 14.92%, respectively. The grain yield increased with the increase in irrigation times during the growth period; there was no significant difference between T2 and T3 in 2018–2019. In a biennial comparison, the grain yield of all treatments in 2019–2020 was significantly lower than those in 2018–2019, and the grain yield of ‘ZM 18’ was lower than that of ‘BN 4199’. Correlation analysis displayed that there were significant positive correlations between post-anthesis stem vigor and the dry matter contribution rate of post-anthesis to grains and between the grain filling rate at 21–28 days after anthesis (DAA) and stem strength at 30 DAA. In summary, selecting a high-yield lodging-resistant wheat variety with SI at jointing and anthesis was beneficial for forming strong stems and maintaining higher stem vigor at the later growth stage for grain filling, which reduced lodging risk and ensured high yield and high WUE.

Keywords: supplemental irrigation; stem vigor; stem strength; grain yield; WUE



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1. Introduction

Stem lodging is a universal phenomenon in the field cultivation of wheat. Lodging can reduce both yield and grain quality and hinder mechanized harvesting efficiency [1,2]. Previous studies have revealed that lodging leads to 10–57% of potential grain yield loss in the Huang-Huai region of China ([3], Figure 1). Therefore, it is of great significance to take practical cultivation measures and further study the relationship between stem characteristics, lodging resistance, and grain yield in wheat to reduce lodging risk [4,5].

In previous breeding work, the dwarfing degree was always used as an evaluation criterion to measure the lodging resistance of wheat. However, the total biomass obtained by dwarf plants was low, so it was difficult to achieve bivariate improvements in grain yield and stem lodging resistance by reducing plant height [5]. Tripathi et al. [6] showed that a shorter internode length is not an effective criterion for breeding lodging-resistant varieties. To meet the increasing food demand, the biological yield of wheat must be

increased, but the lodging risk increases with an increase in plant height. Through many years of research, we believe that increasing the plant height and strengthening the basal internode to improve lodging resistance is an important approach to achieving a high and stable yield of wheat [7]. Therefore, increasing stem strength is an important guarantee of high-yield wheat breeding [8].

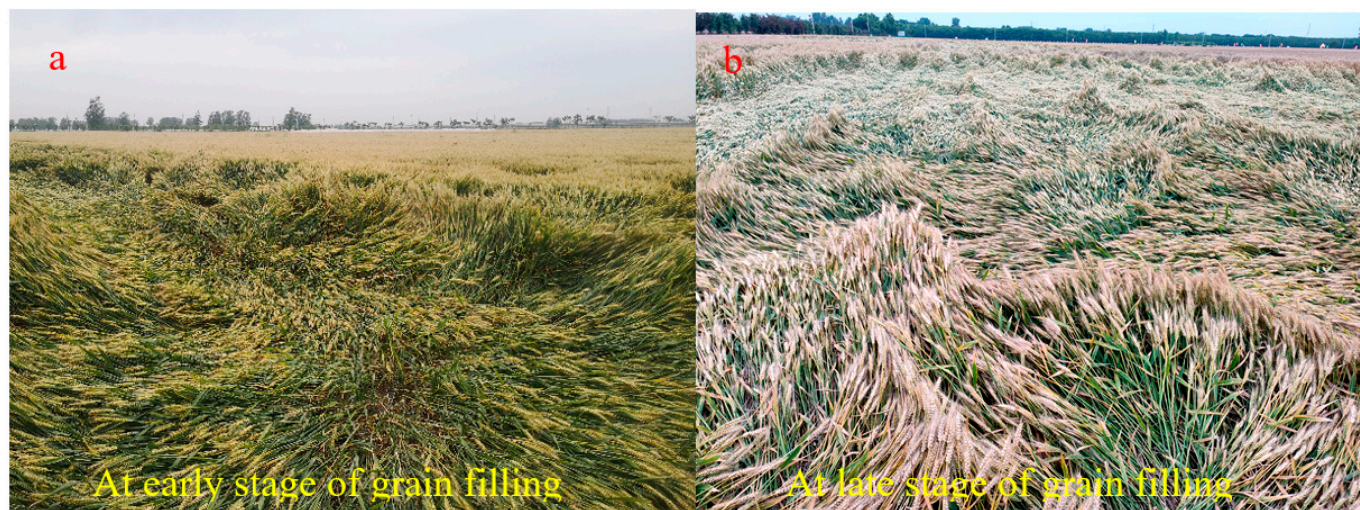


Figure 1. Lodging phenomena and stem lodging types of wheat under border irrigation in different regions of the North China Plain: (a) Northern Henan and (b) Southern Henan.

According to most studies, the characteristics of the second internode are considered pivotal factors influencing stem lodging in wheat [3,9,10]. The length, diameter, wall thickness, density, and component content of the second internode significantly affect stem strength [11–13]. The selection of a larger stem diameter and wall thickness can improve lodging resistance in wheat by increasing stem strength [8]. Increasing the secondary wall thickness of wheat could also increase the unit dry weight, laying a foundation for grain filling and reducing lodging risk in later growth periods [7]. In addition, stem strength increased with an increase in stem wall density. Li et al. [14] showed that stem density was related to the content of soluble substances in stems. Therefore, soluble assimilates in the stems of wheat play an important role in enhancing the physical strength of the stems [15,16].

The grain formation of wheat is closely related to the redistribution of assimilates in nutrient organs [17]. Fang et al. [18] and Zhang et al. [19] believed that soluble carbohydrates stored in stems during anthesis and post-anthesis photosynthates were the total material sources for grain filling. Redistribution of storage assimilates in stems also results in a decrease in stem strength [10]. Therefore, it is of great significance to coordinate the transport of stem materials through management measures to maintain yield and reduce lodging risk.

Optimized crop management systems play an important role in stabilizing and increasing crop yield, especially as high-yielding varieties have stronger demands for water and fertilizer [20,21]. Future genetic gains in grain yield may rely on increasing total crop biomass, which in turn may require more water and nutrients [22], thus also increasing lodging risk. Irrigation has a great influence on lodging, and excessive irrigation increases plant height and upper plant weight, thus increasing the possibility of stem lodging and grain yield loss [11,15]. Excessive irrigation can also reduce water use efficiency (WUE), resulting in a serious waste of water resources [18,23]. Ma et al. [24] showed that appropriate drought stress in the early growth period of wheat could enhance stem lodging resistance in the later growing stage by perfecting basal internode characteristics.

Global rainfall is unevenly distributed, and winter wheat needs multiple SI during the growth period to achieve high yields [25,26]. However, over irrigation causes the

depletion of groundwater resources and decreases water utilization efficiency, which seriously threatens the sustainable development of agriculture [27]. Although spray-irrigation, drip-irrigation, and micro-spray-irrigation under controlled deficit irrigation, measured soil moisture, and demand irrigation are beneficial for improving WUE, the land in the Huang-Huai region of China is dispersed, and most farmers still use border irrigation. At present, there are many studies on the effects of irrigation periods and irrigation frequency on wheat yield and WUE, but the results are not uniform [27–29] and ignore the effects of supplementary irrigation (SI) periods and times on lodging performance. Therefore, it is necessary to conduct in-depth research on the effects of different SI times on the stem characteristics of wheat to improve WUE without sacrificing yield and to reduce the risk of stem lodging.

The objective of this study was to determine the effects of SI at different growing stages on the basal internode characteristics of wheat and the relationship between stem strength and grain filling, stem vigor, and assimilate redistribution. At the same time, combined with yield and WUE, the reasonable SI frequency for improving stem lodging resistance, yield, and water efficiency of wheat could ultimately be determined.

2. Materials and Methods

2.1. Experimental Design

This study was conducted from 2018 to 2020 at the Langgongmiao research field ($35^{\circ}17' \text{ N}$, $113^{\circ}90' \text{ E}$), Henan Province, China. The research field was alluvial soil. Maize (*Zea mays* L.) was the previous crop. The organic matter, total nitrogen, hydrolyzable nitrogen, available phosphorous, and available potassium in the 0–20 cm soil layer of the experimental field before sowing were 16.58 g kg^{-1} , 1.19 g kg^{-1} , 93.62 mg kg^{-1} , 32.30 mg kg^{-1} , and $129.63 \text{ mg kg}^{-1}$ in 2018–2019 and 14.63 g kg^{-1} , 1.11 g kg^{-1} , 88.59 mg kg^{-1} , 28.29 mg kg^{-1} , and $118.27 \text{ mg kg}^{-1}$ in 2019–2020, respectively. The soil bulk density of the 20 cm soil layer was 1.40 g cm^{-3} in 2018–2019 and 1.37 g cm^{-3} in 2019–2020. Meteorological data were collected for both growing seasons (2018/19 and 2019/20) from the weather station in the experimental plot. The temperature in Figure 2 was shown every 10 days as the average maximum and minimum air temperatures. The rainfall throughout the wheat growth period was 94.5 mm and 130.7 mm, and the monthly precipitation was calculated. The temperature and precipitation of the test site at each growing stage are shown in Figure 2.

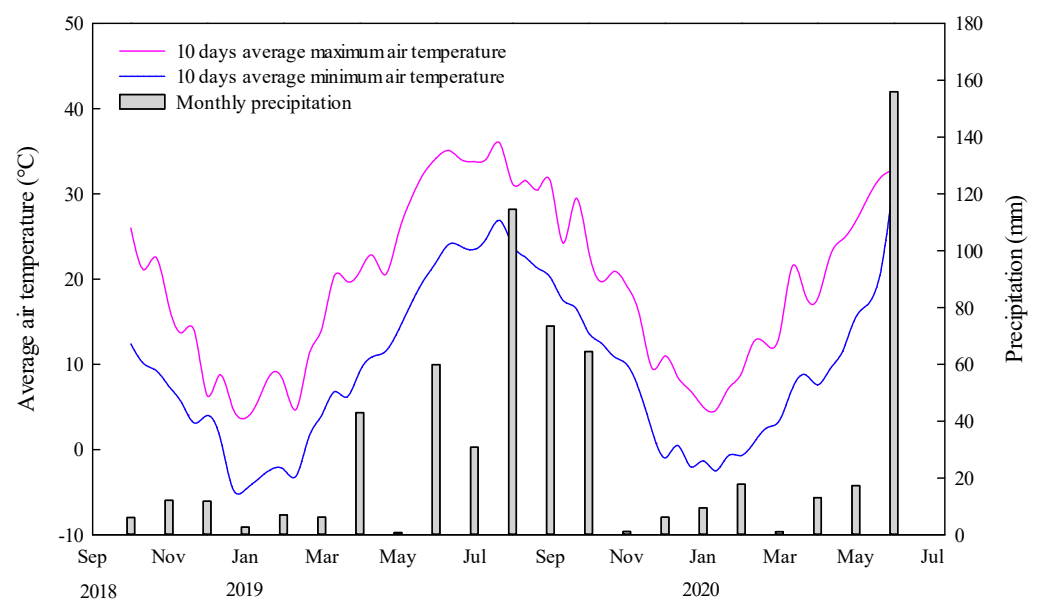


Figure 2. Weather data during the 2018–2019 and 2019–2020 growing seasons. The figure shows 10 days' average maximum and minimum air temperatures (°C) and monthly precipitation (mm).

A split-plot design with three replicates was used in the experiment. The plot size was $15\text{ m} \times 2.8\text{ m} = 42\text{ m}^2$. Two wheat varieties with large planting areas in the Huang-Huai region of China were the main plots: ‘Bainong4199’ (‘BN4199’) is a dwarf variety, and ‘Zhoumai18’ (‘ZM18’) is a middle-height variety; and the subplots were treated with four SI treatments. Based on the same water measures before seedling emergence, four SI treatments were designed using a border irrigation method during the regreening, jointing, and anthesis periods: rain-fed (T0), SI at jointing (T1), SI at jointing + anthesis (T2), and SI at regreening + jointing + anthesis (T3). An isolation belt was set between adjacent plots to block lateral water seepage. During border irrigation, it is 90% for the water cutoff ratio, and we recorded the SI water amount using a water meter. The SI amounts of T1, T2, and T3 during the whole growing period were 104.4 mm, 224.7 mm, and 329.2 mm in 2018–2019 and 121.6 mm, 248.2 mm, and 370.4 mm in 2019–2020, respectively.

Nitrogen, phosphorus (P_2O_5), and potassium (K_2O) were applied before sowing as basal fertilizers at 90, 90, and 90 kg hm^{-2} , respectively. Pure N of 90 kg hm^{-2} was applied at jointing before SI. A compound fertilizer with a ratio of N, P_2O_5 , and K_2O of 15:15:15 was used as the base fertilizer, and urea containing 46% pure N was used as the top fertilizer. The basic seedlings of 180×10^4 plants/ hm^2 were sown using a machine on 10 October 2018, and 8 October 2019, respectively, and harvested on 8 June 2019, and 2 June 2020. Wheat diseases and pests were controlled during the growing period.

2.2. Determination Index and Experimental Method

2.2.1. Stem Morphology and Structure

Mechanical stem strength: the stem strength was measured using the pressure method that was reported by Niu et al. [30]. A portable electronic measuring instrument (HP-50, Yueqing Edbao Instrument Co., Ltd., Wenzhou, China) for anti-lodging was used to place the second internode in the groove of the support frame with an interval of 5 cm. The V-shaped probe of the self-made crop stem anti-toppling strength measuring instrument was chosen to press down hard, and the mechanical strength of the stem segments was the maximum force used for stem breaking, and 20 stems per treatment were selected.

Stem morphological characteristics: plant height, gravity height, and internode length were measured with a ruler. The stem wall thickness was measured with vernier calipers, and thirty consecutive plants per treatment were cut as a replication.

Stem vigor: An improved TTC (triphenyl tetrazolium chloride) method was used to measure stem vigor. At 0, 10, 20, and 30 days after anthesis (DAA), 20 representative single stems of wheat were selected on the same day as anthesis, and the second internode of the stem base was cut into stem segments with a length of 0.2–0.3 cm. A sample of 0.5 g was weighed, added to 5 mL of phosphoric acid buffer solution and 5 mL of 0.4% TTC solution, and placed in the dark at $37\text{ }^\circ\text{C}$ for 3 h. Added two milliliters of $1\text{ mol L}^{-1}\text{ H}_2\text{SO}_4$ to terminate the reaction. Furthermore, stem segments were extracted with 10 mL of methanol for 2 h. The reduction amount of TTC can represent dehydrogenase activity, and its color depth is positively correlated with stem vigor, with the highest absorption peak at a wavelength of 485 nm. Therefore, stem vigor is expressed by its ability to reduce TTC [31].

2.2.2. Lodging Index

At 0, 10, 20, and 30 DAA, 20 representative single stems were selected on the same day as anthesis, and the fresh weight (G) in grams of the aboveground part, the height of the center of gravity (H) in centimeters, and the mechanical strength of the basal second internode (S) in grams were measured. The relative strength of lodging resistance was measured by referring to the lodging index (LI) proposed by Wang et al. [32]. The smaller the lodging index of the variety, the stronger its lodging resistance; thus, the higher the lodging index, the more likely it is to lodge. The lodging index was calculated as follows:

$$\text{LI} = \frac{G * H}{S}. \quad (1)$$

2.2.3. Dry Matter Transport

Thirty consecutive plants were taken manually at ground level from each plot at the anthesis and maturity stages. Plants at the maturity stage were sampled according to vegetative organs and grains and dried at 70 °C for 30 min after sterilizing at 105 °C. The dry weight was recorded to calculate the input grain amount of post-anthesis storage compounds of vegetative organs (DMA, kg hm⁻²) and the contribution rate to grains (CDMA, %). The DMA and CDMA were calculated as follows in our previous study [33]:

$$\text{DMA (kg hm}^{-2}\text{)} = \text{dry matter at maturity (kg hm}^{-2}\text{)} - \text{dry matter at anthesis (kg hm}^{-2}\text{)} \quad (2)$$

$$\text{CDMA (\%)} = \text{DMA/GY} \times 100\% \quad (3)$$

where GY (kg hm⁻²) is the grain yield per hectare.

2.2.4. Grain Filling Rate

Each variety is marked with 200 single stems that flower on the same day, grow consistently, and are without pest or disease hazards during wheat anthesis. Samples were taken at 7 DAA and every 7 days thereafter until maturity. Ten ears from each variety were collected each time, taken back to the laboratory, and quickly peeled off the seeds. The green part was killed in the oven at 105 °C for 30 min and then dried to a constant weight at 80 °C. The dry weight of seeds was determined and converted to a 1000-grain weight. The grain filling rate was calculated using its 1000-grain dry weight.

$$\text{Filling rate (g/d)} = (C_{n+7} - C_n)/7 \quad (4)$$

In the formula, C represents the 1000-grain dry weight during sampling, and n represents the DAA, which are 0, 7, 14, 21, 28, and 35 d.

2.2.5. Yield and WUE

The valid spike number and grain number per ear were surveyed in the maturation period. The grain yield and 1000-grain weight were calculated after harvest, and the grain yield per hectare (GY, kg hm⁻²) was calculated according to a water content of 12.5%.

The calculation of water use efficiency (WUE, kg hm⁻² mm⁻¹) was referring to the method in Wang et al. [34].

2.3. Data Analysis

Microsoft Excel 2013 was used to calculate and organize the test data, and the data shown are averages. SigmaPlot 12.5 (Systat Software Inc., San Jose, CA, USA) was used for plotting. Statistical analysis was performed using SPSS 13.0 (SPSS Inc., Chicago, IL, USA) statistical analysis software. The mutual relationships between stem vigor of the second internode, CDMA, stem strength, and grain filling were analyzed by linear correlation analysis. The least significant difference (LSD) method was used to appraise if significant differences existed between treatments in their mean stem characteristics, stem vigor, lodging index, grain filling, WUE, yield, etc. at a probability level of $p \leq 0.05$.

3. Results

3.1. Stem Length and Stem Diameter at the Anthesis Stage

Irrigation significantly affected stem length, stem diameter, and stem flexion strength at the second internode of wheat (Figure 3). Stem length grew with the increase in irrigation times ($T3 > T1/T2 > T0$), and the changing trend of the two varieties was consistent. The stem length of the two varieties was lower than that of the same treatments in 2018–2019 compared with 2019–2020. In 2019–2020, the second stem length of ‘BN 4199’ under the T0 and T3 treatments was significantly higher than that of ‘ZM 18’, which was in contrast to the results of 2018–2019. The stem diameter of the SI treatments was higher than that of the

T0 treatment after anthesis. The stem diameter of ‘BN 4199’ was significantly higher than that of ‘ZM 18’ under T3 treatment. The stem fracture resistance of the T1/T2 treatment was higher than that of the T0 and T3 treatments, and the two varieties behaved the same in both years.

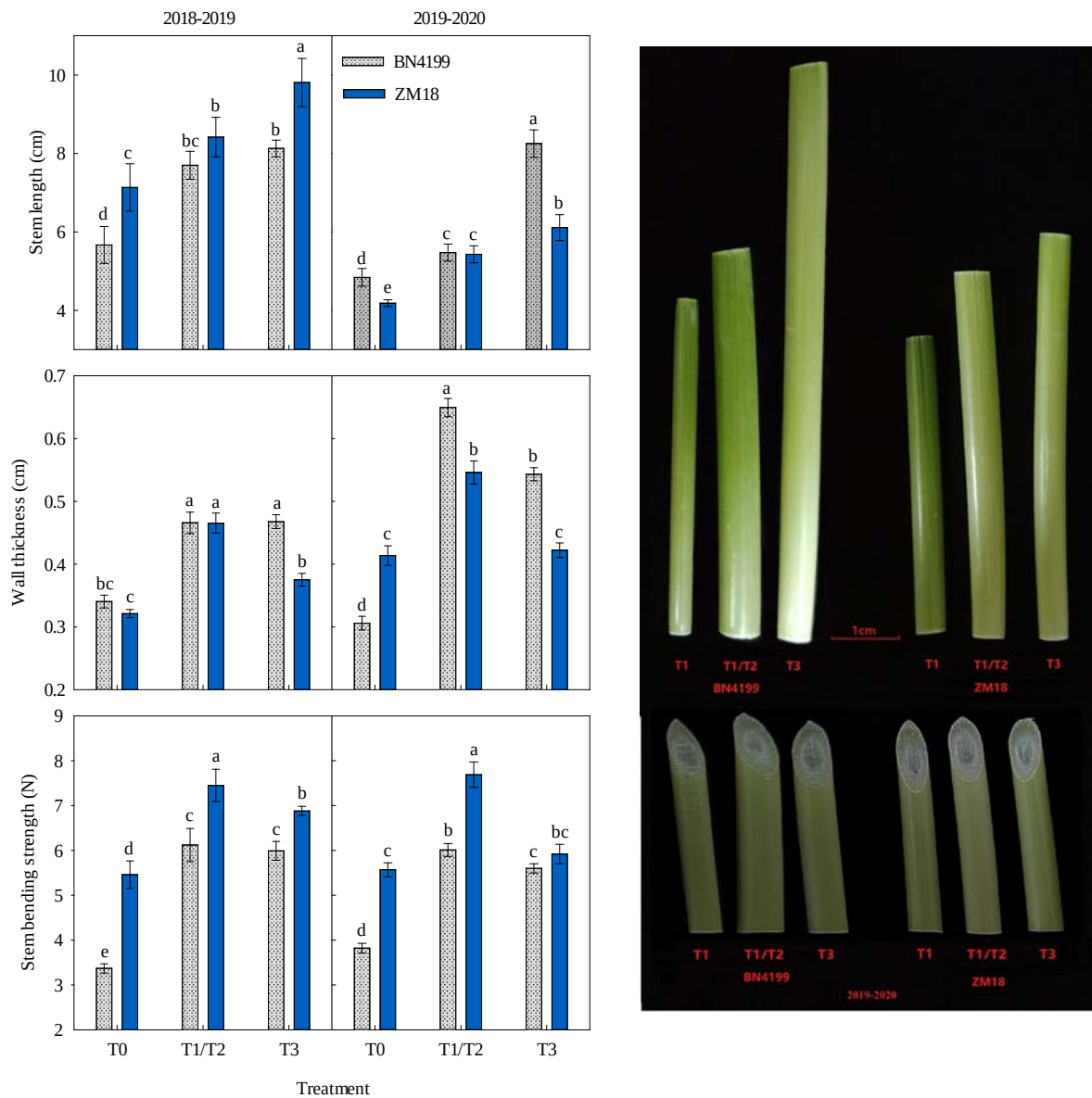


Figure 3. Stem length, wall thickness, and stem bending strength of the second internode at anthesis under four supplemental irrigation treatments: no-irrigation after emergence (T0), supplemental irrigation at jointing (T1), supplemental irrigation at jointing and anthesis (T2), and supplemental irrigation at regreening, jointing, and anthesis (T3) in 2019–2020. Vertical bars indicate the standard deviation, and different letters on the error bars indicate significant differences between treatments in same year at $p < 0.05$ based on the LSD test.

3.2. Stem Vigor

As shown in Figure 4, after anthesis, stem vigor decreased with the progress of filling and increased with SI treatments. The stem vigor of the T0 treatment was higher at the anthesis stage, decreased rapidly after anthesis, and was significantly lower than that of each SI treatment at 20 DAA. At 10–30 DAA, the stem vigor of the two cultivars was $T3 > T2 > T1$ from high to low, and the change was consistent between the two years. In 2019–2020, the average stem vigor of ‘BN 4199’ was significantly higher than that of ‘ZM 18’.

The average post-anthesis stem vigor of each treatment in 2018–2019 was significantly lower than that in 2019–2020. In 2018–2019, the stem vigor of the T2 treatment was significantly lower than that of the T3 treatment at 20–30 DAA but significantly higher than that of the T0 and T1 treatments. In 2019–2020, the changing trend of ‘BN 4199’ was consistent with that of 2018–2019, but there was no significant difference in stem vigor between T3 and T2 treatments of ‘ZM18’ at 10–30 DAA.

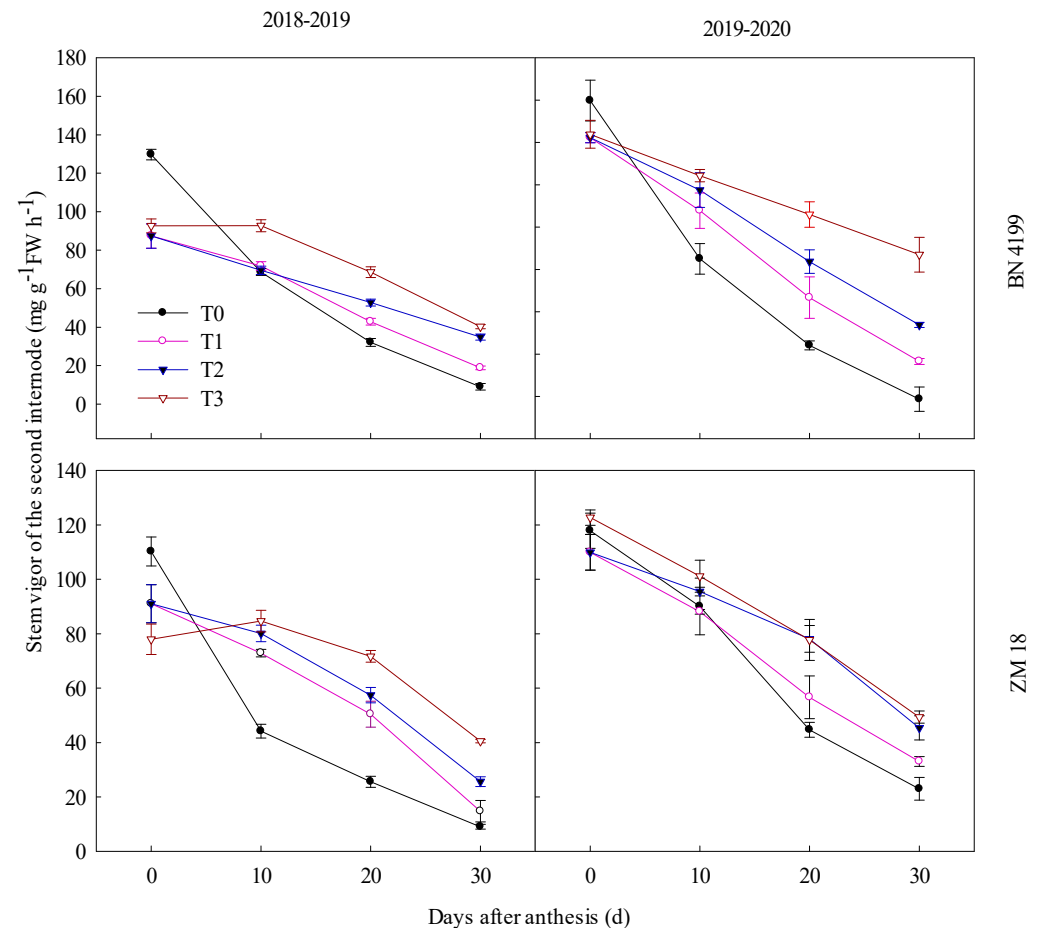


Figure 4. Stem vigor of the second internode of winter wheat after anthesis in four treatments: no-irrigation after emergence (T0), supplemental irrigation at jointing (T1), supplemental irrigation at jointing and anthesis (T2), and supplemental irrigation at regreening, jointing, and anthesis (T3) in 2018–2020. The vertical bars indicate the standard deviation.

3.3. Lodging Index

As shown in Figure 5, the stem lodging index of wheat treated with SI at the growth stage rose with the filling process and was significantly higher than that treated with T0. The lodging index increased with the number of SI treatments. At 20–30 DAA, the lodging index was significantly higher in the T2 treatment than in the T1 and T0 treatments but significantly lower than in the T3 treatment, and the two varieties showed the same trend in both years. The lodging index of ‘BN 4199’ in the T1 and T2 treatments showed a downward trend at 30 DAA, while the lodging index of the T3 and T0 treatments showed an upward trend. At 10–30 DAA, the lodging index of ‘ZM 18’ showed an increasing trend, except in the T0 treatment. In comparison with T3, the average stem lodging index of T2 was reduced by 21.92% for ‘BN4199’ and 36.63% for ‘ZM18’, and the average value of each treatment in 2019–2020 was significantly higher than that in 2018–2019.

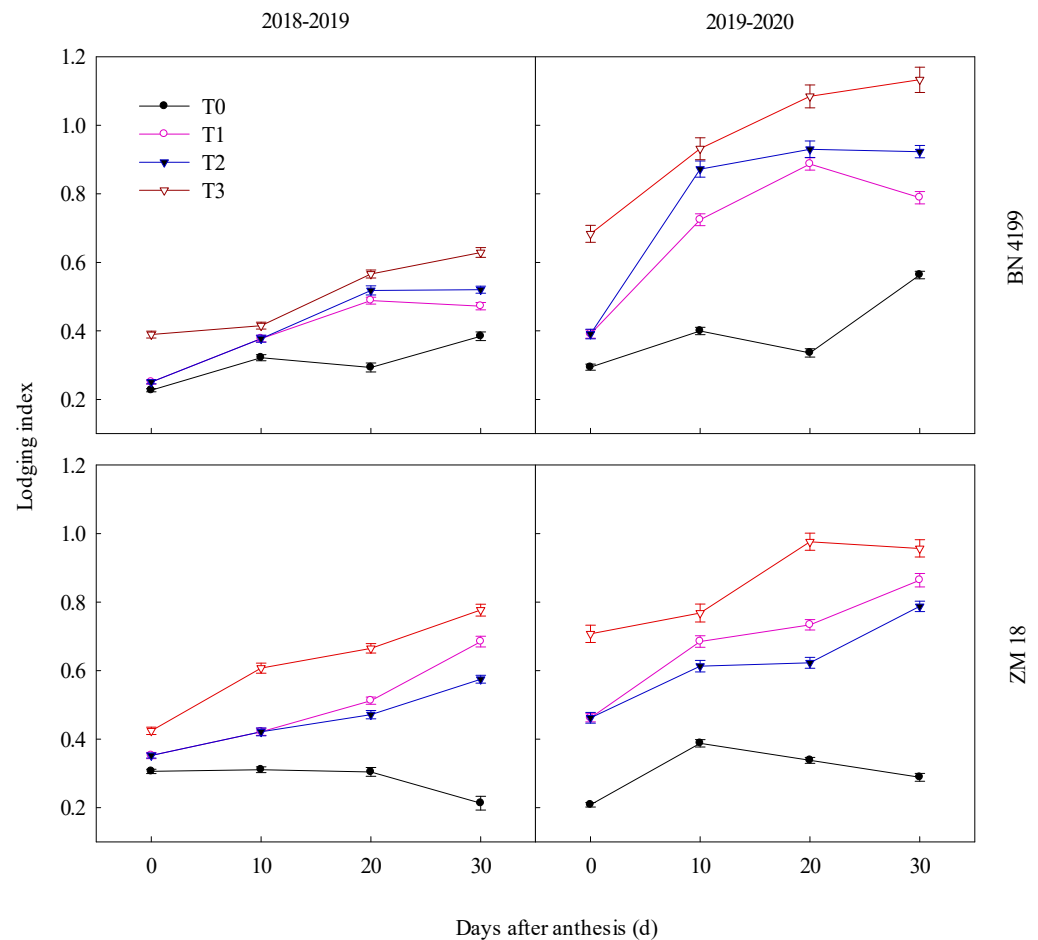


Figure 5. Lodging index of winter wheat after anthesis in four treatments: no irrigation after emergence (T0), supplemental irrigation at jointing (T1), supplemental irrigation at jointing and anthesis (T2), and supplemental irrigation at regreening, jointing, and anthesis (T3) in 2018–2020. The vertical bars indicate the standard deviation.

3.4. Grain Filling

As shown in Figure 6, at 0–14 DAA, the filling rate of T3 and T2 was significantly lower than that of T1 and T0 but significantly higher than that of T1 and T0 at 21–35 DAA. At 35 DAA, the grain filling rate of T3 was non-significantly higher than that of T2, but it was significantly higher than that of T1 and T0. There were great differences in grain filling rates among different varieties. Under the T0 and T1 treatments, ‘BN 4199’ reached a filling peak at 14 DAA. For the T2 and T3 treatments, the filling peak was reached at 21 DAA. The filling rate reached its peak at 21 DAA for each SI treatment in ‘ZM 18’. In 2018–2019, the average filling rate of ‘BN 4199’ in T3 and T2 was not significantly different, but it was significantly higher than that of T1 and T0. The average filling rates of ‘ZM 18’ in T1 and T2 were not significantly different, but both were lower than in T3. In 2019–2020, the two wheat varieties were not significantly different in average filling rate under T2 and T3 treatments but were significantly higher than those of T1 and T0.

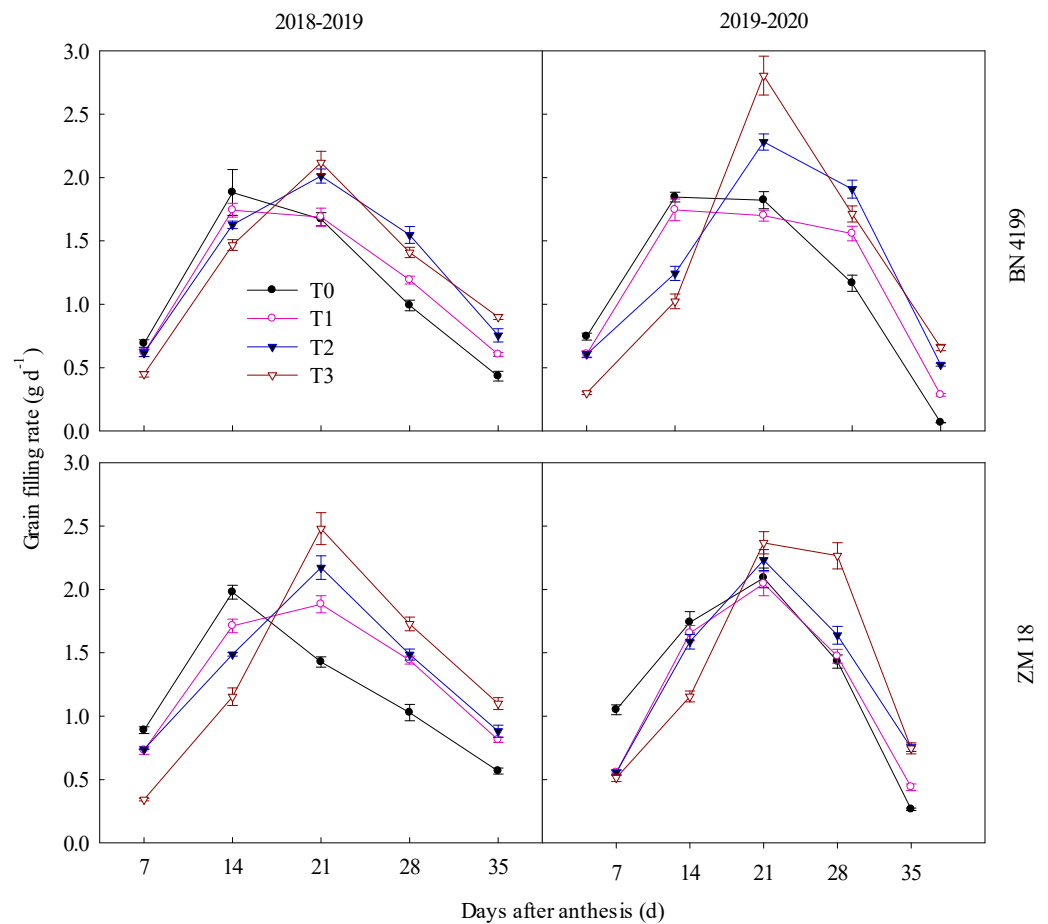


Figure 6. Grain filling of winter wheat after anthesis in four treatments: no irrigation after emergence (T0), supplemental irrigation at jointing (T1), supplemental irrigation at jointing and anthesis (T2), and supplemental irrigation at regreening, jointing, and anthesis (T3) in 2018–2020. The vertical bars indicate the standard deviation.

3.5. Yield and WUE

As shown in Figure 7, SI had a great effect on yield and WUE during the growing stage. Winter wheat yield increased with the increase in SI times, and SI at the growing stage was significantly higher than that of the T0. The grain yield of 2018–2019 was higher than that of 2019–2020, and the grain yield of ‘BN 4199’ was higher than that of ‘ZM 18’ under the same treatment. The results of the two varieties showed consistent changes over the two years. In 2018–2019, the grain yield of T3 was not significantly different compared with T2, but significantly higher than that of T1 and T0. The average grain yield of ‘BN 4199’ was higher than that of ‘ZM 18’ by 28.27% and 23.87% at two test years, and the WUE increased by 29.76% and 14.92%, respectively. The WUE of T2 was significantly higher than that of the other treatments in 2018–2019, and the changing trend of the two varieties in the two years is consistent. From 2019 to 2020, T1 treatment had the highest WUE, followed by T2 treatment.

3.6. Correlation Analysis

Based on the data from two years, a correlation between stem vigor and material transport and between basal stem strength and grain filling was observed. The CDMA after anthesis was significantly positively correlated with the stem vigor of the second basal node at 10 and 20 d (Figure 8), especially with the stem vigor at 10 DAA; the correlation coefficient reached 0.7807. There was a very significant positive correlation between stem strength at 30 DAA and stem vigor at the second basal internode at 20 d and 30 d (Figure 9), and the correlation coefficients were 0.7679 and 0.7080, respectively. According to the

correlation analysis between the grain filling rate and stem strength and vigor (Figure 10), the grain filling rate at 21 and 28 DAA was significantly positively correlated with stem strength at 30 DAA and with stem vigor at 20 and 30 DAA, while it was not significantly correlated with stem strength and vigor at the anthesis stage.

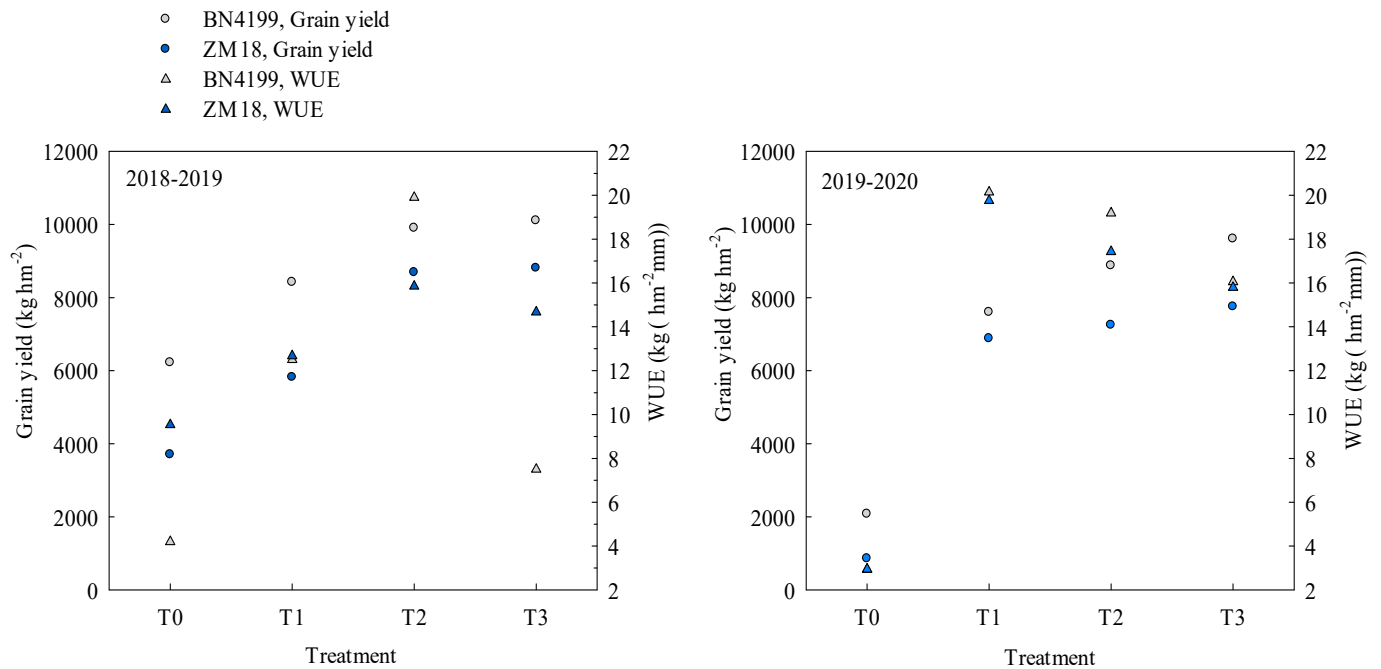


Figure 7. Effect of variety and water interaction on grain yield and water use efficiency (WUE) of winter wheat in four treatments: no-irrigation after emergence (T0), supplemental irrigation at jointing (T1), supplemental irrigation at jointing and anthesis (T2), and supplemental irrigation at returning-green, jointing, and anthesis (T3) in 2018–2020.

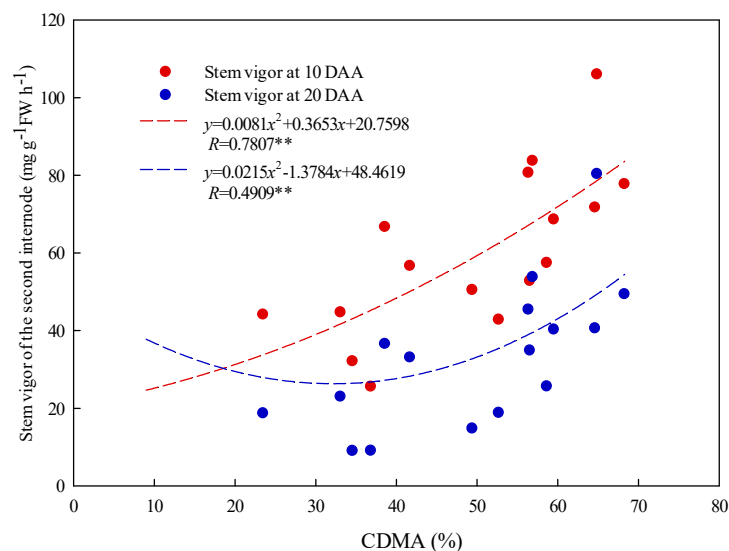


Figure 8. Relationship between stem vigor of the second internode at 10 and 20 DAA and contribution to dry matter accumulation in the grain post-anthesis (CDMA). **: Significance of the relationship at the 0.01 level, respectively.

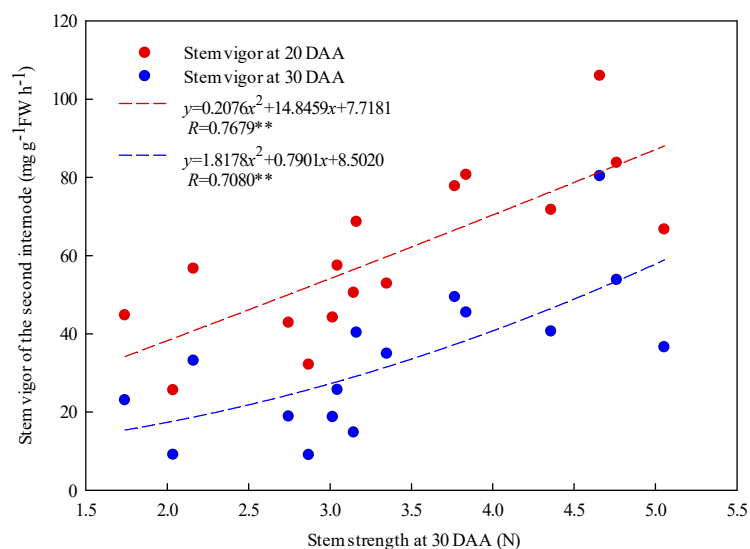


Figure 9. Relationship between stem vigor of the second internode at 20 and 30 DAA and stem strength at 30 DAA. **: Significance of the relationship at the 0.01 level, respectively.

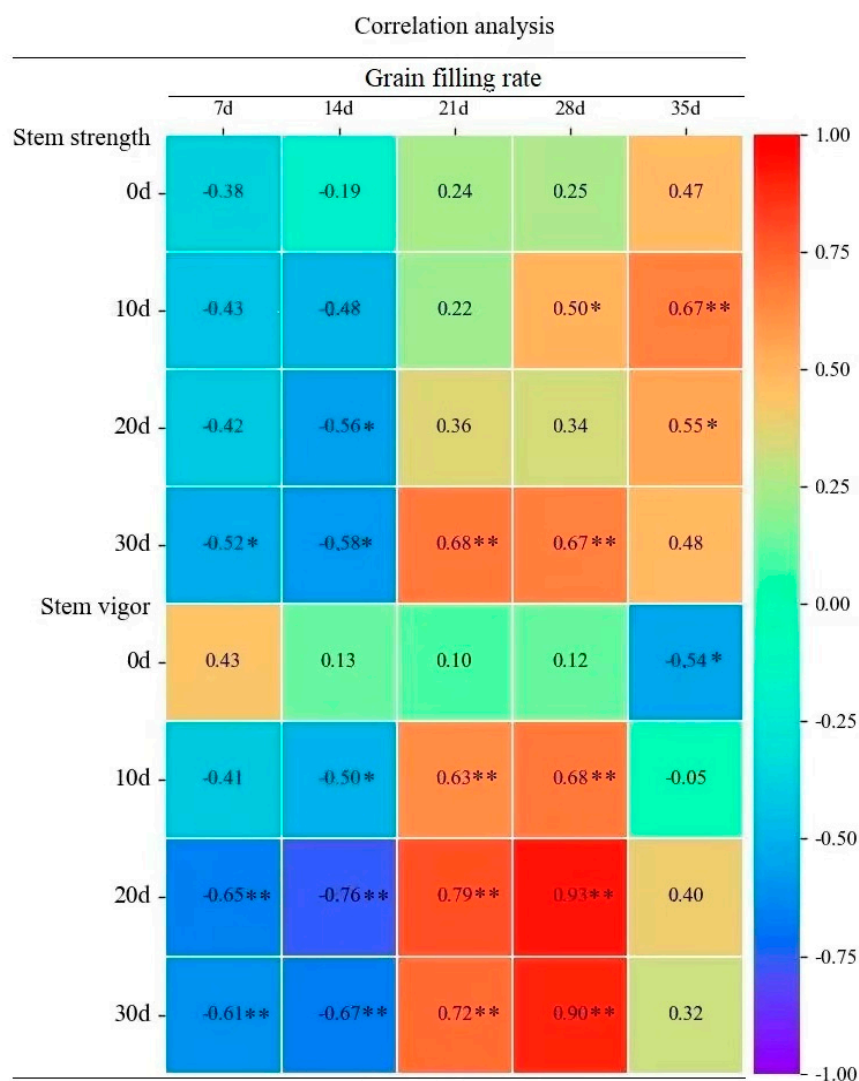


Figure 10. Correlation analysis between grain filling rate (GFR) after anthesis and stem strength and vigor. * $p < 0.05$, ** $p < 0.01$.

4. Discussion

4.1. Effects of SI on Stem Structural Characteristics

It was concluded that stem length, stem wall thickness, number of vascular bundles, and stem strength at the base of the second internode are key indicators for the study of stem characteristics [8,10,13,14]. SI could improve the internode characteristics of the stem base, promote material accumulation and transport, and enhance lodging resistance. The wall thickness and stem strength in the second internode at the wheat stem base decreased with an increase in SI times [10]. This research found that without SI during the growth period, although the second internode at the wheat stem base was shorter and the plant height was significantly lower, the lodging risk was relatively small. Grain yield was also significantly lower due to the thinner stem and smaller population and grains per spike (Figures 3, 5 and 7). Among the stem characteristics of wheat, stem strength is the most direct reflection of the lodging index [35]. In current high-yielding varieties, increasing stem strength to improve crop lodging resistance rather than simply relying on stem dwarfing is the main feature of today's high-yielding varieties [7,13]. Stem thickness is a key indicator of the stem-breaking strength of wheat [36]. This experiment showed that the stem length and thickness of basal stem segments after irrigation were significantly higher than those without irrigation. SI at jointing and anthesis resulted in shorter, thicker, and stronger stems than those of SI at regreening, jointing, and anthesis (Figures 3 and 5). Wheat lodging resistance is influenced by various factors, and different wheat varieties represent significant differences in different rainfall intensity years. Varieties with strong lodging resistance are generally chosen in production, but there are few methods for evaluating the comprehensive lodging resistance of wheat varieties, especially the dynamic evaluation methods during the wheat growing period, that need further exploration.

The lodging index is a comprehensive index used to evaluate the stem lodging resistance ability of wheat, and the lodging index is closely related to stem strength. However, the stem strength is greatly affected by SI frequency and SI amount during the growth period, and the stem strength varies greatly among different varieties [10].

Researchers generally thought that increasing the SI frequency reduced stem lodging resistance [37]. In this experiment, the stem strength and vigor of wheat decreased after anthesis, and SI at the growing period increased stem strength and maintained the stem vigor at the later growing stage (Figures 3 and 4), promoting the accumulation of post-anthesis assimilates and providing a material basis for later grain filling (Figure 4). SI before jointing is beneficial for increasing spring tillering, delaying the polarization stage, reducing the effective ears, and increasing fearless consumption of nutrients, which is not conducive to stem material accumulation [33]. However, the role of assimilate distribution in strong stem formation and young ear development needs further exploration.

Only SI at jointing will contribute to the formation of stem strength, which is conducive to improving the ability of the stem to cope with lodging. More SI applications or no irrigation during the growing period were not conducive to strong stems (Figure 3). In 2019–2020, less precipitation during the wheat growing period and no SI at the seedling stage resulted in a decrease in the population of the two varieties. In particular, the population of 'ZM 18' was more affected by water stress, and drought stress inhibited population development, while the smaller population promoted individual development. Therefore, the stem resistance of 'ZM 18' was stronger than that of 'BN 4199'. However, the plant height was significantly higher than that of 'BN 4199', and compared with 'ZM 18', 'BN 4199' had short basal stem internodes, high breaking resistance, and low lodging risk in the later period under SI during the 2018–2019 sowing period (Figures 3 and 5).

4.2. Relationship between Stem Internode Characteristic Parameters and Yield and Lodging Resistance in Wheat

As a bridge connecting the ear and root, the stem is key for wheat to achieve high yield and lodging resistance [13], and lodging is an important factor to limit the sustainable growth of wheat yield [38]. Therefore, it is of great importance to coordinate the relationship between yield and lodging. Foulkes et al. [38] found that the lodging risk was increased under high-yield conditions, and lodging decreased wheat yield and quality. The stem lodging resistance is related to the characteristics of the basal stem internodes of plants [3,7]. Our previous study found that basal stem strength was closely related to the lodging resistance of wheat stems [7]. SI at regreening was beneficial to maintaining stem vigor in the later growing stage of grain filling, promoting the accumulation of post-anthesis assimilates, and increasing the contribution rate of post-anthesis assimilates to grain. Therefore, the stem strength in the later growth period was maintained by reducing the transfer volume of storage assimilates (Figures 3 and 8). However, SI at regreening during the growth period resulted in population enlargement, inhibited ontogeny, caused a longer basal internode, and reduced stem strength, which increased the stem lodging risk (Figures 3 and 5). Pre-jointing water stress followed by rewatering at the jointing stage can reduce ineffective tillering, promote the development of tillers, and improve individual stem thickness and strength (Figure 3), thus coordinating the population and individual growth of wheat. It has been suggested that SI at anthesis, based on watering during jointing, could help optimize the distribution of assimilates in the stem and spike [31]. In this experiment, only SI at jointing was used, and the state of water stress occurred in the anthesis stage. The stem vigor decreased rapidly in the later stage of grain filling, the transfer volume of storage compounds in the stem before anthesis increased, and the decrease in mechanical strength increased the lodging index and lodging risk. Rewatering at the anthesis stage was beneficial to maintain strong stem vigor at the later filling stage, promote the grain filling rate, prolong grain filling time, and ultimately increase grain weight (Figures 4, 6 and 7). These results are consistent with those of Xu et al. [39]. Therefore, SI at jointing and anthesis during the wheat growth stage can simultaneously improve post-anthesis stem strength and vigor and increase the contribution rate of post-anthesis assimilation to the grain while maintaining stem strength and promoting grain filling and post-anthesis stem lodging resistance (Figures 9 and 10). With the further improvement of wheat yield, promoting the translocation of assimilates from nutrient organs to grains and improving harvest index are key issues that need to be addressed in cultivation and breeding. However, further research is needed to coordinate the relationship between dry matter translocation in stems, grain formation, and stem strength.

4.3. Effects of SI on the Yield and WUE of Wheat

Rational SI during the wheat growing stage is beneficial for increasing yield and WUE while improving the characteristics of basal stem nodes [40–42]. Precipitation during the wheat growth period in the NCP is low, which is not enough to meet water requirements throughout the wheat growth period [43]. Therefore, SI throughout the wheat growth period is an important way to improve a high yield. No SI was given throughout the wheat growth period after emergence, and all key growth stages were under drought stress, which seriously affected the growth of the wheat population and individuals (Figures 3 and 7). Previous studies have shown that the period and frequency of SI have different effects on wheat growth [44–46]. Our results indicated that grain yield increased with the increase in SI frequency, but WUE decreased, and the lodging index significantly increased. Based on SI at sowing, the effect of regreening water on the wheat yield increase was not obvious, while without SI at sowing, the effect of regreening water on the wheat yield increase was obvious, but the WUE and stem lodging resistance decreased (Figures 3 and 7). The low precipitation after seedling emergence in 2019–2020 resulted in drought throughout the wheat growth period, and the grain yield of every treatment was significantly lower than in 2018–2019. Moreover, ‘ZM 18’ is sensitive to soil water, and drought stress during the

growing period significantly affects yield formation. The yield and WUE of ‘ZM 18’ were significantly lower than ‘BN 4199’, and no supplementary irrigation treatment was given during the growth period. The grain yield was only 856.39 kg hm⁻².

Rewatering at the jointing stage can promote the transport of dry matter to seeds after anthesis and ultimately improve grain yield and WUE by coordinating the source-sink relationship [39]. The WUE of SI at jointing and anthesis was better than that of no SI and full irrigation, and the lodging risk of stems also decreased comparatively. This indicates that a moderate water deficit can optimize the water use of wheat, giving it a higher WUE than full irrigation while maintaining higher stem strength (Figures 3 and 7). However, severe water stress could not offset the loss of grain yield even though the dry matter in vegetative organs was transported to grains [47,48]. Therefore, based on ensuring seedling emergence, it was watered twice during the growth stage and can improve WUE and stem lodging resistance while not reducing yield.

This experiment selected two wheat varieties with different plant heights, and further research is needed on the effects of SI amount, method, and water and fertilizer synchronization on the stem lodging resistance of wheat, simultaneously setting up many years of multi-ecological area experiments to verify the universality of the research results.

5. Conclusions

Rational SI is an important method to coordinate the growth of wheat populations and individuals and ensure the high yield, high efficiency, and safe production of wheat. Different irrigation treatments not only affected yield and WUE but also affected stem lodging resistance, and different wheat varieties showed notable disparities. Based on the same water management before seedling emergence, SI at jointing and anthesis was beneficial for forming strong stems, improving the mechanical strength of culms, and maintaining strong stem vigor at the later growth stage. At the same time, it promoted the transport of post-anthesis assimilates to grain, increased the grain filling rate, significantly increased WUE, and reduced the stem lodging risk without reducing grain yield. Therefore, according to the results of this study and the comprehensive consideration of irrigation water resources, it is recommended that SI be applied at jointing and anthesis based on sufficient water before sowing to reduce lodging risk and ensure a high yield and high WUE. In addition, the selection of suitable wheat varieties is highly conducive to coordinating high yield, efficient water use, and lodging resistance.

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References

1. Li, C.; Chang, Y.; Luo, Y.; Li, W.; Jin, M.; Wang, Y.; Cui, H.; Sun, S.; Li, Y.; Wang, Z. Nitrogen regulates stem lodging resistance by breaking the balance of photosynthetic carbon allocation in wheat. *Field Crop. Res.* **2023**, *296*, 108908. [\[CrossRef\]](#)
2. Berry, P.M.; Spink, J. Predicting yield losses caused by lodging in wheat. *Field Crop. Res.* **2012**, *196*, 268–275. [\[CrossRef\]](#)
3. Peng, D.; Chen, X.; Yin, Y.; Lu, K.; Yang, W.; Tang, Y.; Wang, Z. Lodging resistance of winter wheat (*Triticum aestivum* L.): Lignin accumulation and its related enzymes activities due to the application of paclobutrazol or gibberellin acid. *Field Crop. Res.* **2014**, *157*, 1–7. [\[CrossRef\]](#)
4. Wu, W.; Ma, B.; Fan, J.; Sun, M.; Yi, Y.; Guo, W. Management of nitrogen fertilization to balance reducing lodging risk and increasing yield and protein content in spring wheat. *Field Crop. Res.* **2019**, *241*, 107584. [\[CrossRef\]](#)

5. Chen, X.; Wang, J.; Wang, Z.; Li, W.; Wang, C.; Yan, S.; Li, H.; Zhang, A.; Tang, Z.; Wei, M. Optimized nitrogen fertilizer application mode increased culms lignin accumulation and lodging resistance in culms of winter wheat. *Field Crop. Res.* **2018**, *228*, 31–38. [\[CrossRef\]](#)
6. Tripathi, S.C.; Sayre, K.D.; Kaul, J.N.; Narang, R.S. Growth and morphology of spring wheat (*Triticum aestivum* L.) culms and their association with lodging: Effects of genotypes, N levels and ethephon. *Field Crop. Res.* **2004**, *84*, 207–220. [\[CrossRef\]](#)
7. Feng, S.; Ru, Z.; Ding, W.; Hu, T.; Li, G. Study of the relationship between field lodging and stem quality traits of winter wheat in the north China plain. *Crop Pasture Sci.* **2019**, *70*, 772–780. [\[CrossRef\]](#)
8. Piñera-Chávez, F.J.; Berry, P.M.; Foulkes, M.J.; Molero, G.; Reynolds, M.P. Avoiding lodging in irrigated spring wheat. II. Genetic variation of stem and root structural properties. *Field Crop. Res.* **2016**, *196*, 64–74. [\[CrossRef\]](#)
9. Zhang, R.; Jia, Z.; Ma, X.; Ma, H.; Zhao, Y. Characterising the morphological characters and carbohydrate metabolism of oat culms and their association with lodging resistance. *Plant Biol.* **2019**, *22*, 267–276. [\[CrossRef\]](#)
10. Wang, Y.; Jin, M.; Luo, Y.; Chang, Y.; Zhu, J.; Li, Y.; Wang, Z. Effects of irrigation on stem lignin and breaking strength of winter wheat with different planting densities. *Field Crop. Res.* **2022**, *282*, 108518. [\[CrossRef\]](#)
11. Islam, M.; Peng, S.; Visperas, R.; Ereful, N.; Bhuiya, M.; Julfikar, A. Lodging-related morphological traits of hybrid rice in a tropical irrigated ecosystem. *Field Crop. Res.* **2007**, *101*, 240–248. [\[CrossRef\]](#)
12. Zheng, M.; Chen, J.; Shi, Y.; Li, Y.; Yin, Y.; Yang, D.; Luo, Y.; Pang, D.; Xu, X.; Li, W.; et al. Manipulation of lignin metabolism by plant densities and its relationship with lodging resistance in wheat. *Sci. Rep.* **2017**, *7*, srep41805. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Niu, Y.; Chen, T.; Zhao, C.; Zhou, M. Lodging prevention in cereals: Morphological, biochemical, anatomical traits and their molecular mechanisms, management and breeding strategies. *Field Crop. Res.* **2022**, *289*, 108733. [\[CrossRef\]](#)
14. Li, W.; Han, M.; Pang, D.; Chen, J.; Wang, Y.; Dong, H.; Chang, Y.; Jin, M.; Luo, Y.; Li, Y.; et al. Characteristics of lodging resistance of high-yield winter wheat as affected by nitrogen rate and irrigation managements. *J. Int. Agric.* **2022**, *21*, 1290–1309. [\[CrossRef\]](#)
15. Zhang, J.; Li, G.; Song, Y.; Liu, Z.; Yang, C.; Tang, S.; Zheng, C.; Wang, S.; Ding, Y. Lodging resistance characteristics of high-yielding rice populations. *Field Crop. Res.* **2014**, *161*, 64–74. [\[CrossRef\]](#)
16. Deng, Y.; Liu, W.; Yuan, X.; Yuan, J.; Zou, J.; Du, J.; Yang, W. Relationship between cellulose synthesis metabolism and lodging resistance in intercropping soybean at seedling stage. *Chin. J. Appl. Ecol.* **2016**, *27*, 469–476. (In Chinese with an English Abstract) [\[CrossRef\]](#)
17. Zhang, Y.; Xu, W.; Wang, H.; Dong, H.; Qi, X.; Zhao, M.; Fang, Y.; Gao, C.; Hu, L. Progress in genetic improvement of grain yield and related physiological traits of Chinese wheat in Henan Province. *Field Crop. Res.* **2016**, *199*, 117–128. [\[CrossRef\]](#)
18. Fang, Q.; Chen, Y.; Li, Q.; Yu, S.; Yu, S.; Dong, Q.; Luo, Y.; Yu, Q.; Ou-Yang, Z. Effects of irrigation on photosynthate supply and conversion and related enzymes activity during grain filling period. *Acta Agron Sin.* **2004**, *30*, 1113–1118.
19. Zhang, H.; Han, K.; Gu, S.; Wang, D. Effects of supplemental irrigation on the accumulation, distribution and transportation of ¹³C-photosynthate, yield and water use efficiency of winter wheat. *Agric. Water Manag.* **2019**, *214*, 1–8. [\[CrossRef\]](#)
20. Fathian, M.; Bazrafshan, O.; Jamshidi, S.; Jafari, L. Impacts of climate change on water footprint components of rainfed and irrigated wheat in a semi-arid environment. *Environ. Monit. Assess.* **2023**, *195*, 324. [\[CrossRef\]](#)
21. Jamshidi, S.; Zand-Parsa, S.; Kamgar-Haghighi, A.; Shahsavar, A.; Niyogi, D. Evapotranspiration, crop coefficients, and physiological responses of citrus trees in semi-arid climatic conditions. *Agric. Water Manag.* **2020**, *227*, 105838. [\[CrossRef\]](#)
22. Reynolds, M.; Foulkes, M.J.; Slafer, G.A.; Berry, P.; Parry, M.A.J.; Snape, J.W.; Angus, W.J. Raising yield potential in wheat. *J. Exp. Bot.* **2009**, *60*, 1899–1918. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Wang, C.; Zhao, J.; Feng, Y.; Shang, M.; Bo, X.; Gao, Z.; Chen, F.; Chu, Q. Optimizing tillage method and irrigation schedule for greenhouse gas mitigation, yield improvement, and water conservation in wheat–maize cropping systems. *Agric. Water Manag.* **2021**, *248*, 106762. [\[CrossRef\]](#)
24. Ma, S.; Duan, A.; Ma, S.; Yang, S. Effect of early-stage regulated deficit irrigation on stem lodging resistance, leaf photosynthesis, root respiration and yield stability of winter wheat under post-anthesis water stress conditions. *Irrig. Drain.* **2016**, *65*, 673–681. [\[CrossRef\]](#)
25. Naghdizadegan, J.; Zand-Parsa, S.; Razzaghi, F.; Jamshidi, S.; Didari, S.; Doosthosseini, A.; Pourghasemi, H. Developing machine learning models for wheat yield prediction using ground-based data, satellite-based actual evapotranspiration and vegetation indices. *Eur. J. Agric.* **2023**, *146*, 126820. [\[CrossRef\]](#)
26. Bazrafshan, O.; Ehteram, M.; Moshizi, Z.; Jamshidi, S. Evaluation and uncertainty assessment of wheat yield prediction by multilayer perceptron model with bayesian and copula bayesian approaches. *Agric. Water Manag.* **2022**, *273*, 107881. [\[CrossRef\]](#)
27. Li, Q.; Bian, C.; Liu, X.; Ma, C.; Liu, Q. Winter wheat grain yield and water use efficiency in wide-precision planting pattern under deficit irrigation in North China Plain. *Agric. Water Manag.* **2015**, *153*, 71–76. [\[CrossRef\]](#)
28. Zhang, Y.; Zhang, Y.; Wang, Z.; Wang, Z. Characteristics of canopy structure and contributions of non-leaf organs to yield in winter wheat under different irrigated conditions. *Field Crop. Res.* **2011**, *123*, 187–195. [\[CrossRef\]](#)
29. You, Y.; Song, P.; Yang, X.; Zheng, Y.; Dong, L.; Chen, J. Optimizing irrigation for winter wheat to maximize yield and maintain high-efficient water use in a semi-arid environment. *Agric. Water Manag.* **2022**, *273*, 107901. [\[CrossRef\]](#)
30. Niu, L.; Feng, S.; Ru, Z.; Li, G.; Zhang, Z.; Wang, Z. Rapid determination of single-stalk and population lodging resistance strengths and an assessment of the stem lodging wind speeds for winter wheat. *Field Crop. Res.* **2012**, *139*, 1–8. [\[CrossRef\]](#)
31. Feng, S.; Ding, W.; Shi, C.; Zhu, X.; Hu, T.; Ru, Z. Optimizing the spatial distribution of roots by supplemental irrigation to improve grain yield and water use efficiency of wheat in the North China Plain. *Agric. Water Manag.* **2023**, *275*, 107989. [\[CrossRef\]](#)

32. Wang, Y.; Li, Q. Evaluation method of stem lodging resistance in wheat. *Acta Agric. Boreali-Sin.* **1995**, *10*, 84–88. (In Chinese with an English Abstract)
33. Feng, S.; Gu, S.; Zhang, H.; Wang, D. Root vertical distribution is important to improve water use efficiency and grain yield of wheat. *Field Crop. Res.* **2017**, *214*, 131–141. [[CrossRef](#)]
34. Wang, T.; Wei, L.; Wang, H.; Ma, S.; Ma, B. Responses of rainwater conservation, precipitation-use efficiency and grain yield of summer maize to a furrow-planting and straw-mulching system in northern China. *Field Crop. Res.* **2011**, *124*, 223–230. [[CrossRef](#)]
35. Wu, L.; Zhang, W.; Ding, Y.; Zhang, J.; Cambula, E.D.; Weng, F.; Liu, Z.; Ding, C.; Tang, S.; Chen, L.; et al. Shading contributes to the reduction of stem mechanical strength by decreasing cell wall synthesis in japonica rice (*Oryza sativa* L.). *Front. Plant Sci.* **2017**, *8*, 881. [[CrossRef](#)]
36. Okuno, A.; Hirano, K.; Asano, K.; Takase, W.; Matsuoka, R.; Morinaka, Y.; Ueguchi-Tanaka, M.; Kitano, H.; Matsuoka, M. New approach to increasing rice lodging resistance and biomass yield through the use of high gibberellin producing varieties. *PLoS ONE*. **2014**, *9*, e86870. [[CrossRef](#)]
37. Gao, Z.; Zhao, L.; Guo, L.; Huang, B.; Li, Y.; Niu, J. Effects of irrigation and nitrogen fertilizer rates on oil seed flax stem lodging resistance and yield. *Chin. J. Eco-Agric.* **2015**, *23*, 544–553. (In Chinese with an English Abstract)
38. Foulkes, M.J.; Slafer, G.A.; Davies, W.J.; Berry, P.M.; Sylvester-Bradley, R.; Martre, P.; Calderini, D.F.; Griffiths, S.; Reynolds, M.P. Raising yield potential of wheat. III. Optimizing partitioning to grain while maintaining lodging resistance. *J. Exp. Bot.* **2011**, *62*, 469–486. [[CrossRef](#)]
39. Xu, X.; Zhang, M.; Li, J.; Liu, Z.; Zhao, Z.; Zhang, Y.; Zhou, S.; Wang, Z. Improving water use efficiency and grain yield of winter wheat by optimizing irrigations in the North China Plain. *Field Crop. Res.* **2018**, *221*, 219–227. [[CrossRef](#)]
40. Li, C.; Wen, X.; Wan, X.; Liu, Y.; Han, J.; Liao, Y.; Wu, W. Towards the highly effective use of precipitation by ridge-furrow with plastic film mulching instead of relying on irrigation resources in a dry semi-humid area. *Field Crop. Res.* **2016**, *188*, 62–73. [[CrossRef](#)]
41. Zhang, Y.; Xu, W.; Wang, H.; Fang, Y.; Dong, H.; Qi, X. Progress in improving stem lodging resistance of Chinese wheat cultivars. *Euphytica* **2016**, *212*, 275–286. [[CrossRef](#)]
42. Rathore, V.S.; Nathawat, N.S.; Bhardwaj, S.; Sasidharan, R.P.; Yadav, B.M.; Kumar, M.; Santra, P.; Yadava, N.D.; Yadav, O.P. Yield, water and nitrogen use efficiencies of sprinkler irrigated wheat grown under different irrigation and nitrogen levels in an arid region. *Agric. Water Manag.* **2017**, *187*, 232–245. [[CrossRef](#)]
43. Li, D.; Zhang, D.; Wang, H.; Li, H.; Fang, Q.; Li, H.; Li, R. Optimized Planting Density Maintains High Wheat Yield Under Limiting Irrigation in North China Plain. *Int. J. Plant Prod.* **2019**, *14*, 107–117. [[CrossRef](#)]
44. Ma, S.; Wang, T.; Guan, X.; Zhang, X. Effect of sowing time and seeding rate on yield components and water use efficiency of winter wheat by regulating the growth redundancy and physiological traits of root and shoot. *Field Crop. Res.* **2018**, *221*, 166–174. [[CrossRef](#)]
45. Xu, C.; Tao, H.; Tian, B.; Gao, Y.; Ren, J.; Wang, P. Limited-irrigation improves water use efficiency and soil reservoir capacity through regulating root and canopy growth of winter wheat. *Field Crop. Res.* **2016**, *196*, 268–275. [[CrossRef](#)]
46. Xu, X.; Zhang, Y.; Li, J.; Zhang, M.; Zhou, X.; Zhou, S.; Wang, Z. Optimizing single irrigation scheme to improve water use efficiency by manipulating winter wheat sink-source relationships in northern china plain. *PLoS ONE* **2018**, *13*, e0193895. [[CrossRef](#)] [[PubMed](#)]
47. Shang, Y.; Wang, S.; Lin, X.; Gu, S.; Wang, D. Supplemental irrigation at jointing improves spike formation of wheat tillers by regulating sugar distribution in ear and stem. *Agric. Water Manag.* **2023**, *279*, 108160. [[CrossRef](#)]
48. Ma, J.; Huang, G.; Yang, D.; Chai, Q. Dry matter remobilization and compensatory effects in various internodes of spring wheat under water stress. *Crop Sci.* **2014**, *54*, 331–339. [[CrossRef](#)]

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