agronomy

MDPI

Article

Silicon Spraying Enhances Wheat Stem Resistance to Lodging under Light Stress

Yonglan Chang [1,2,†], Haixing Cui [1,2,†], Yuanyuan Wang [1,2,†], Chunhui Li [1,2], Jiayu Wang [1,2], Min Jin [1,2], Yongli Luo [1,2,*], Yong Li [1,2,*] and Zhenlin Wang [1,2]

1 College of Agronomy, Shandong Agricultural University, Tai'an 271018, China; changyonglan91@163.com (Y.C.); 2017110166@sdau.edu.cn (H.C.); yuanyuanwang1424@163.com (Y.W.); chunhuili2021@163.com (C.L.); wangjiayu0817@163.com (J.W.); cobra911@163.com (M.J.); zlwang@sdau.edu.cn (Z.W.)

2 National Key Laboratory of Wheat Improvement, Shandong Agricultural University, Tai'an 271018, China

* Correspondence: luoyongli1030@sdau.edu.cn (Y.L.); xmliyong@sdau.edu.cn (Y.L.); Tel.: +86-538-8242239 (Y.L. & Y.L.)

† These authors contributed equally to this work.

Abstract: In recent years, the decrease in solar radiation has led to insufficient light, resulting in a shading effect on crops and a deterioration of stem quality, which seriously affects wheat yield. In this experiment, two different lodging-sensitive wheat varieties, SN16 (SN16) and SN23 (SN23), were selected as experimental materials, and two treatments were set up, with 50% shade (S1) and natural light as control (S0) from the jointing stage to the maturity stage. Two treatments, spraying 400 mg L^{-1} (C1) silicon fertilizer and spraying water as control (C0), were set up at the jointing stage of wheat. The effects of spraying silicon fertilizer on the yield, morphological and mechanical characteristics of the stem, and lignin content of winter wheat under low-light stress were investigated. The results showed that spraying silicon fertilizer increased the lignin content of the stem and improved stem lodging resistance mainly by improving the degree of lignification. An effective cultivation measure for wheat's resistance to lodging can be provided by spraying silicon fertilizer when future low-light stress occurs.

Keywords: wheat; low-light stress; silicon; lodging; lignin

Citation: Chang, Y.; Cui, H.; Wang, Y.; Li, C.; Wang, J.; Jin, M.; Luo, Y.; Li, Y.; Wang, Z. Silicon Spraying Enhances Wheat Stem Resistance to Lodging under Light Stress. *Agronomy* **2023**, *13*, 2565. https://doi.org/10.3390/agronomy13102565

Academic Editor: Wei Wu

Received: 7 September 2023
Revised: 27 September 2023
Accepted: 28 September 2023
Published: 6 October 2023

1. Introduction

Wheat (*Triticum aestivum* L.) is a major food crop worldwide, with more than one-third of the population depending on wheat as its primary food source and the level of wheat production directly relates to countries' livelihood [1]. Currently, frequent human activities cause severe atmospheric pollution, resulting in a decrease in effective solar radiation reaching the Earth's surface, which has become a limiting factor for agricultural development [2]. Light is critical for crop growth, and insufficient light intensity affects crop yield and yield components [3,4]. Reduced solar radiation leads to insufficient light, causing a shading effect on the population [5]. Insufficient light changes the internal structure of the stems, which reduces stem filling and stem thickness, increases plant height, and reduces the mechanical strength of the stems, easily triggering lodging [6,7]. Lodging is one of the main factors limiting wheat yield, quality, and harvesting, and studies have shown that the problem of reduced wheat yields due to failure persists in the Huanghuaihai region [8]. At the same time, light is critical for crop yield formation, and the degree and period of shade affect yield to varying degrees. The yield of the crop decreases severely with increasing shade levels. Luo et al. [9] found that shade treatment at the nodulation stage significantly reduced the tiller spike formation rate of wheat, increased shade time, and severely reduced wheat yield. It was found that shade treatment during the pre-grazing period resulted in grain abortion and a significant reduction in the number of grains in the spike, and shade treatment during the mid-to late-grazing period reduced the rate of filling, decreased the transfer of material to the grains, and reduced grain weight [10,11].

Silicon is a macronutrient that is widely found in monocotyledonous and dicotyledonous plants. Although it is not considered an essential nutrient for plants, it plays a vital role in plant growth [12,13]. Especially in monocotyledonous plants (such as wheat and rice), the absorption of Si even exceeds that of essential nutrients [14]. Studies have shown that silicon increases crops' resistance to abiotic and biotic stresses such as low light, drought, salt, heavy metals, and pests [15], thereby increasing crop productivity. As these benefits to crop production have been recognized, the global use of silicon to improve soil or foliar spray is rising.

How silicon affects crop stem resistance has been preliminarily studied. The application of silicon can improve stem strength by increasing the thickness of secondary cell walls and the number of secondary cells. Lignin biosynthetic enzyme activity and lignin accumulation increased with increasing silicon application [16]. Silicon can polymerize with lignin to form a more stable structure, significantly increasing the resistance of stems to stunting [17]. For crop yield, silicon can improve the community structure by reducing the inclination angle of the plant leaf while increasing the chlorophyll content in the leaves, enhancing the photosynthetic capacity of the leaves, increasing the accumulation of dry matter in the stems and leaves, and facilitating the transfer of dry matter to the seeds, which increases the seed yield [18]. Additionally, silicon promotes yield by increasing the number of spikes and grains, and grain weight in crops [19].

It can be seen from the above that silicon can improve crops' lodging resistance and yield. However, under low-light stress, it is unclear whether exogenous silicon can help wheat resist adversity and positively impact crops' lodging resistance and yield. Therefore, in this study, we selected two winter wheat varieties with significant differences in lodging resistance as materials and simulated low-light stress via artificial shading to clarify how the exogenous spraying of silicon fertilization affects (1) silicon accumulation in wheat stems, (2) wheat stalk lignin content, (3) the morphological characteristics and breaking resistance of wheat stems, and (4) wheat-yield formation under low-light conditions. The results may provide a theoretical basis and technical support for the regulation of wheat-lodging-resistant cultivation under the background of the reduction in solar radiation caused by extreme climate change.

2. Materials and Methods

2.1. Site Description

This experiment was conducted in 2020–2021 at the experimental station of Shandong Agricultural University, Tai'an City, Shandong Province, China (36°17′ N, 117°17′ E, 128 m above sea level). The region has a temperate continental monsoon climate, with a solar radiation of 3131.33 MJ m^{-2} and a mean temperature and precipitation of 8.92 °C and 193.06 mm, respectively, during the wheat-growing season. The experimental site comprised brown loam soil, and the previous crop was maize (*Zea mays* L.), which was harvested and returned to the field with all the straw. Before the experiment, the tillage soil (0–20 cm) contained 12.71 g kg^{-1} of organic matter, 1.01 g kg^{-1} of total nitrogen, 85.2 mg kg^{-1} of alkaline nitrogen, 30.19 mg kg^{-1} of available phosphorus, and 90.33 mg kg^{-1} of available potassium with a pH of 7.92.

2.2. Field Experiments

The experiment was conducted in a split-plot design with three replications. The main plot had two wheat varieties (i.e., the lodging-sensitive wheat variety Shannong16 (SN16) and lodging-resistant wheat variety Shannong23 (SN23)), the sub-plot had light treatment (i.e., shading treatment (S1, shading rate 50%) and normal light treatment (S0)), and the sub-sub-plot was silicon treatment [i.e., spraying $Na_2SiO_3 \cdot 9H_2O$ solution with silicon concentration of 400 mg L^{-1} (C1) and spraying NaCl solution with the same amount of Na^+ as control (C0)]. The plot size was 3×3 m^2. When the first stem internode of wheat was exposed to the ground about 1.5–2 cm, a shading shed was built, and the wheat was shaded with a black shading net with a transmittance of 50%. The roof was 1.8 m away from the ground to ensure normal ventilation of the wheat canopy. At the jointing stage, the wheat was sprayed with silicon for 3 days after 17:00 every day. In order to make silicon better attached to the leaves, the silicon solution was mixed with 0.5% (v/v) Tween-20 before spraying. The final spraying silicon solution was a $Na_2SiO_3{\cdot}9H_2O$ solution with a concentration of 400 mg L^{-1}. In each plot, 1 L solution was sprayed uniformly with a spray pot at a height of 20 cm above the plant's highest point.

2.3. Sample Collection

Samples were taken every 7 days from the second internode of the wheat base extending about 2 cm from the ground. Thirty single stems of wheat with the same growth vigor were selected each time, and fifteen single stems were taken as fresh samples, which were quickly frozen and stored in liquid nitrogen and then stored in a refrigerator at −80 °C to determine total lignin content. Another 15 single stems were used as the second internode, and the leaves were used as dry samples. They were killed at 105 °C for 30 min in the oven and then dried at 50 °C until constant weight. They were used to determine stem plumpness, lignin monomer, and silicon.

2.4. Determination Parameters and Methods

2.4.1. Morphological Characteristics of Stems and Breaking Strength

The morphological characteristics of wheat stem were measured at the flowering stage (GS65), milk stage (GS75), and wax stage (GS85). In each treatment, 20 stems of wheat with the same growth vigor were selected, and the roots were removed. The length of each node, panicle length, plant height, and center of gravity height (the distance from the base of the stem to the horizontal balance fulcrum of the single stem of wheat) were measured with a steel ruler. The basal second internode sheath was removed with YYD-1 stem strength tester (Hangzhou Tuopu Instrument Co., Ltd., Hangzhou, China) to determine the stem-breaking resistance. After removing leaf sheath, the internodes were cut in half from the middle, and the inner and outer diameters of the stem were measured via vernier caliper to calculate the stem diameter and wall thickness.

2.4.2. Lignin Content

According to the method of Zheng et al. [20] and slightly modified, fresh samples were taken in the mortar, and an appropriate amount of liquid nitrogen was added to grind them into powder. Then, 0.1 g samples were taken in a 10 mL centrifuge tube, 8 mL 95% ethanol was added, extracted for 24 h, and centrifuged at 5000 rpm for 5 min to remove the supernatant. Next, 8 mL n-hexane/anhydrous ethanol = 2:1 solution was added to the sediment, extracted for 12 h, and centrifuged at 5000 r/min for 5 min. The supernatant was removed, and the sediment was dried for later use. Additionally, 2.5 mL 25% bromoacetyl glacial acetic acid mixed solution was added to the dry matter, shaken and mixed, bathed in a water bath for 30 min at 70 °C in a water bath pan, and quickly cooled down to cold water afterward. The 0.9 mL 2 M NaOH solution was added to terminate the reaction. Then, 0.1 mL 7.5 M hydroxylamine hydrochloride and 4 mL glacial acetic acid were added, mixed well, and centrifuged at 5000 r for 5 min. The 0.1 mL supernatant was diluted in 3.9 mL glacial acetic acid, and the absorbance of the solution at 280 nm was measured using a spectrophotometer. The absorbance at 280 nm per milliliter of solution in unit mass sample was used to represent the lignin content (OD 280 mL^{-1} g^{-1} FW).

2.4.3. Silicon Content

Chen et al.'s [21] method was slightly modified. The silicon content of the sample was determined via ICP-MS (Thermo Fisher Scientific, Waltham, MA, USA). A total of 0.5 g of dried sample was weighed in a microwave digestion tube, added with 5 mL of concentrated HNO_3 solution, digested in a microwave digestion furnace (KDNX-20, Shanghai Yidian

Scientific Instrument Co., Ltd., Shanghai, China) for 120 min (until the sample was clarified), transferred to a 100 mL volumetric flask, diluted to a constant volume, filtered through a 0.22 μm filter membrane, and measured on the machine (with 50 μg L^{-1} scandium solution as an internal standard).

2.4.4. Yield and Yield Components

At maturity, 1 m^2 area of wheat with uniform growth was selected in each plot to count spike number, and then, 30 spikes were taken to count the grain number per spike, which were harvested and threshed after completion. The 1000-grain weight was investigated, and grain yield was measured at 14% moisture content.

2.5. Statistical Analysis

A two-way ANOVA was conducted using SPSS 17.0 Statistical Package (SPSS Inc., Chicago, IL, USA) on the wheat trait as the response variable and the 'light strees' and 'silicon' as fixed variables. Multiple comparisons of each indicator under different treatments were performed using the LSD method with a significant probability level of 0.05.

3. Results and Analysis

3.1. Effect of Silicon on Yield and Yield Components of Winter Wheat under Low-Light Stress

As shown in Table 1, under the same treatment, the number of spikes per acre of SN16 was higher than that of SN23, but the number of spikes and 1000-grain weight of SN16 were significantly lower than that of SN23, and the final yield of SN16 was lower than that of SN23. Shade treatments significantly reduced the yield of winter wheat and the yield components. Under low-light stress, the spike number, grain number per spike, 1000-grain weight, and the yield of SN16 were reduced by 32.94%, 18.8%, 2.44%, and 44.79%, respectively; SN23 decreased by 34.17%, 11.77%, 4.23%, and 43.37%, respectively, and exogenous spraying of silica, significantly increased the yield and yield component factors of wheat, with the spike number, grain number per spike, 1000-grain weight, and yield increasing by 9.18%, 4.44%, 2.2%, and 16.56%, respectively, in SN16; and SN23 increased by 4.30%, 5.65%, 2.02%, and 12.27%.

Table 1. Effects of silica on yield and yield composition of winter wheat under low-light stress.

Treatment			Spike Number (m^{-2})	Grain Number per Spike	1000-Grain Weight (g)	Grain Yield ($kg \cdot hm^{-2}$)
SN16	S0	C0	581.80 b	37.73 b	39.52 b	7293.01 b
		C1	608.80 a	38.48 a	40.09 a	7809.56 a
	S1	C0	400.30 d	31.57 d	37.84 d	4035.96 d
		C1	427.90 c	32.47 c	38.85 c	4481.96 c
SN23	S0	C0	434.00 b	51.45 b	43.58 b	8282.88 b
		C1	441.20 a	53.84 a	44.39 a	8811.44 a
	S1	C0	306.90 d	43.63 d	41.54 d	4713.67 d
		C1	314.70 c	47.82 c	42.81 c	5457.66 c

Note: Values followed by different lowercase letters within columns are significantly different at the 0.05 probability level.

3.2. Effect of Silicon on the Silicon Content of Winter Wheat under Low-Light Stress

It can be seen from Figure 1 that the silicon content in wheat stems increased with the advancement of the fertility period, in which the silicon content in the stems and leaves of SN23, a variety with resistance to lodging, was significantly higher than the silicon content in SN16. The low-light treatment affected silica uptake in wheat, and the accumulation of silica in wheat stems and leaves was significantly reduced after shading. Compared with the S0 treatment, the silicon content in the stems of SN16 and SN23 was reduced by 19.59% and 16.84%, and the silicon content in the leaves was reduced by 14.14% and 24.51% under the S1 treatment. Under low-light stress, exogenous silicon spraying promoted silicon uptake in wheat, and silicon content in wheat increased significantly after silicon spraying. Compared with C0, C1 treatment SN16 and SN23 increased silicon content in stems by 16.25% and 22.68% and in leaves by 15.58% and 25.25%.

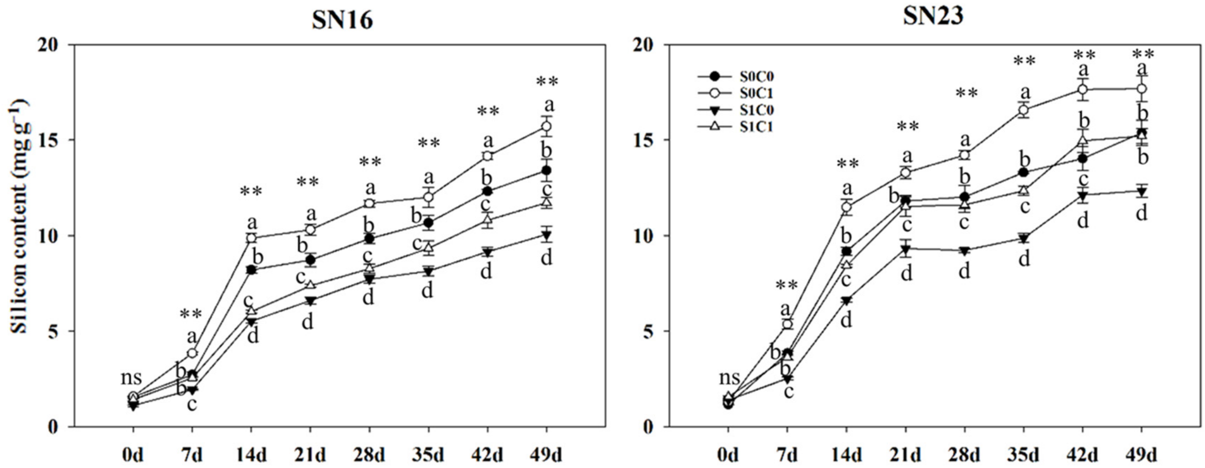

Figure 1. Effects of silica fertilization on silica content in stems of wheat in different groups. Vertical bars above mean values indicate standard deviations (n = 3). The different lowercase letters indicate significant differences ($p < 0.05$) between treatments. ns and ** indicate no significant difference and significant differences at $p < 0.01$, respectively.

3.3. *Effect of Silicon on the Resistance of Winter Wheat Stems to Lodging under Low-Light Stress*

3.3.1. Plant Height and Center of Gravity

As can be seen from Figure 2, there were significant differences in plant height among different varieties of wheat, in which SN16 plant height was 15.53% higher than that of SN23. The low-light stress led to an increase in plant height as well as the length of the basal second internode of winter wheat. Under S1 treatment, the plant height of SN16 and SN23 increased by 5.92% and 5.09%, respectively, compared with S0 treatment; the basal second internode increased by 20.45% and 16.11%, respectively. After exogenous silicon spraying, wheat plant height decreased, and the length of the basal second internode decreased. After exogenous silicon spraying, SN16 and SN23 plant heights decreased by 4.63% and 4.32%, respectively, and the length of the basal second internode decreased by 13.72% and 12.51%, respectively.

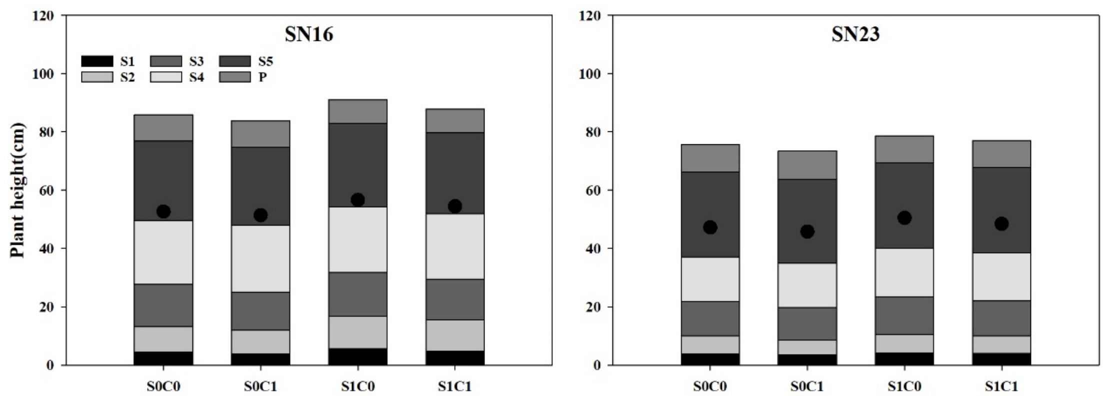

Figure 2. Effects of silica on plant height and internode configuration of winter wheat under low-light stress. The first, second, third, fourth, and fifth internode of the stem from bottom to top and spike are shown in the figure as S1, S2, S3, S4, S5, and P, respectively. The black dot represents the height of the center of gravity.

3.3.2. Thickness and Wall Thickness of the Second Internode at the Base of the Stem

According to Table 2, the basal internode stem thickness of both winter wheat varieties decreased continuously with the advancement of the growth process, and there was a difference between the stem thicknesses of different varieties of wheat. The basal second internode stem thickness of SN23 was 12.15% higher than that of SN16 at the dough stage. Under low-light stress, the two varieties of winter wheat had stunted stems and reduced stem thickness, which decreased by 8.21% and 5.19% in SN16 and SN23 under the S1 treatment, respectively, compared with the S0 treatment. Wheat stem thickness increased after exogenous silicon spraying, and under shade stress, SN16 and SN23 stem thickness increased by 5.63% and 2.8% under C1 treatment, respectively.

Table 2. Effect of silica on stem diameter of the second internode of winter wheat base under low-light stress.

Treatment			Stem Diameter (mm)		
			Anthesis Stage	Milk Stage	Dough Stage
SN16	S0	C0	4.17 b	4.14 b	4.08 b
		C1	4.28 a	4.25 a	4.16 a
	S1	C0	3.91 d	3.83 d	3.70 d
		C1	4.09 c	3.95 c	3.94 c
SN23	S0	C0	4.66 b	4.60 b	4.34 b
		C1	4.75 a	4.67 a	4.41 a
	S1	C0	4.36 d	4.32 d	4.17 d
		C1	4.47 c	4.48 c	4.30 c

Note: Values followed by different lowercase letters within columns are significantly different at the 0.05 probability level.

Table 3 shows that the wall thickness of the basal second internode of the two varieties of winter wheat gradually decreased with the advancement of fertility, and the thickness of the basal second internode of the lodging-sensitive variety SN16 was significantly lower than that of the lodging-resistant variety SN23. The low-light treatment significantly reduced the wall thickness of winter wheat, and the thickness of the stems of SN16 and SN23 decreased by 29.88% and 26.85%, respectively, under the low-light treatment. Exogenous silicon spraying increased the wall thickness of winter wheat, and the wall thickness of SN16 and SN23 increased by 13.92% and 20.32%, respectively, under the C1 treatment compared with the C0 treatment.

Table 3. Effect of silica on the wall thickness of the second internode at the base of winter wheat under low-light stress.

Treatment			Wall Thickness (mm)		
			Anthesis Stage	Milk Stage	Dough Stage
SN16	S0	C0	0.98 b	0.89 b	0.81 b
		C1	1.07 a	1.01 a	0.93 a
	S1	C0	0.73 d	0.68 d	0.62 d
		C1	0.85 c	0.79 c	0.74 c
SN23	S0	C0	1.14 b	1.08 b	0.94 b
		C1	1.29 a	1.17 a	1.09 a
	S1	C0	0.81 d	0.73 d	0.69 d
		C1	0.98 c	0.90 c	0.85 c

Note: Values followed by different lowercase letters within columns are significantly different at the 0.05 probability level.

3.3.3. Filling of the Second Internode at the Base of the Stem

In Table 4, it can be seen that the filling degree of the two varieties of winter wheat behaved differently with the advancement of the fertility process: the filling degree of SN23 gradually decreased with the development of wheat fertility, while the filling degree of SN16 gradually decreased with the advancement of the fertility process under S0 treatment, and then increased and decreased under S1 treatment. The filling degree of SN16 stems was lower than that of SN23 stems. Low-light stress significantly reduced wheat stem fullness by 30.01% and 26.96% in SN16 and SN23, respectively, under S1 treatment compared with S0. Exogenous silicon sprays increased wheat basal second internode filling under low-light stress, with SN16 and SN23 stem filling increasing by 20.49% and 13.61%, respectively, under C1 treatment.

Table 4. Effect of silica on basal second internode filling degree of winter wheat under low-light stress.

Treatment			Filling Degree (mg cm^{-1})		
			Anthesis Stage	**Milk Stage**	**Dough Stage**
SN16	S0	C0	22.28 b	19.76 b	12.71 b
		C1	23.53 a	22.10 a	16.71 a
	S1	C0	13.01 d	13.23 d	9.91 d
		C1	15.35 c	15.64 c	12.15 c
SN23	S0	C0	36.65 b	34.37 b	25.18 b
		C1	37.14 a	35.87 a	27.30 a
	S1	C0	25.15 d	18.75 d	15.65 d
		C1	26.90 c	24.73 c	17.58 c

Note: Values followed by different lowercase letters within columns are significantly different at the 0.05 probability level.

3.3.4. Breaking Strength of the Second Internode at the Base of the Stem

As can be seen from Figure 3, the effects of silicon on the breaking resistance of the two varieties of winter wheat under low-light stress were consistent. In order to advance with the fertility period, the breaking resistance of wheat stems was decreasing, which was manifested as GS65 > GS75 > GS85. The breaking resistance of the lodging-resistant variety SN23 was higher than that of the lodging-sensitive variety SN16, which was 51.52% higher than that of SN16 under low-light stress, and SN23 was 40.99% higher than that of SN16 under normal light conditions.

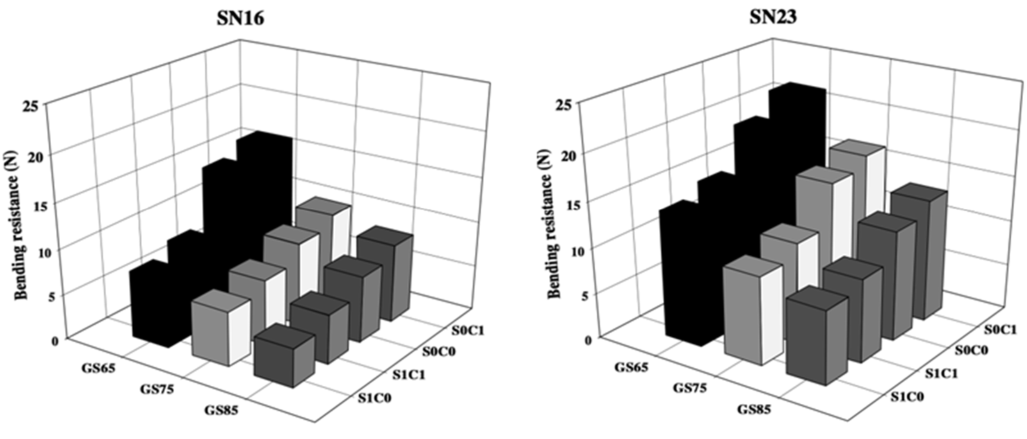

Figure 3. Effect of silica on breaking strength of the second internode of winter wheat base under low-light stress.

Low-light stress significantly reduced the stem-breaking resistance of two winter wheats. Under S1 treatment, SN16 breaking resistance was reduced by 34.62%, 49.66%, and 62.19% at anthesis, milk, and dough stages, respectively, and SN23 was reduced by 30.28%, 49.34%, and 53.32%, respectively. Exogenous silicon spraying increased the wheat-breaking strength, which increased by 10.72%, 16.42%, and 17.12% at anthesis, milk, and dough stages, respectively, in SN16, and by 8.81%, 9.88%, and 20.01%, respectively, in SN23, under C1 treatment.

3.4. Effect of Silicon on Lignin Content in Winter Wheat under Low-Light Stress

As can be seen from Figure 4, the exogenous silicon sprays showed basically the same performance on the lignin content of the two varieties of winter wheat under low-light stress. The lignin content of the two varieties of winter wheat increased continuously with the advancement of fertility. The lignin content of different varieties of wheat differed significantly, and the lignin content of the lodging-resistant type winter wheat SN23 was higher than that of the lodging-sensitive type winter wheat SN16. Low-light stress significantly reduced the lignin content of stems, and spraying silicon could effectively increase the lignin content of wheat stems under low-light stress, and different varieties of winter wheat responded differently to silicon, in which the effect of silicon was more pronounced in SN23, with the lignin accumulation higher than that in SN16. The lignin accumulation of SN23 was higher than that of SN16, and the lignin content of SN23 was 8.35%, 13.41%, and 15.14% higher than that of SN16 in the anthesis, milk, and dough stages, respectively, from the comparison of the two winter wheat varieties with different resistance to lodging. Under low-light stress, the lignin content of SN16 and SN23 decreased by 16.1% and 14.94% at the anthesis stage, respectively.

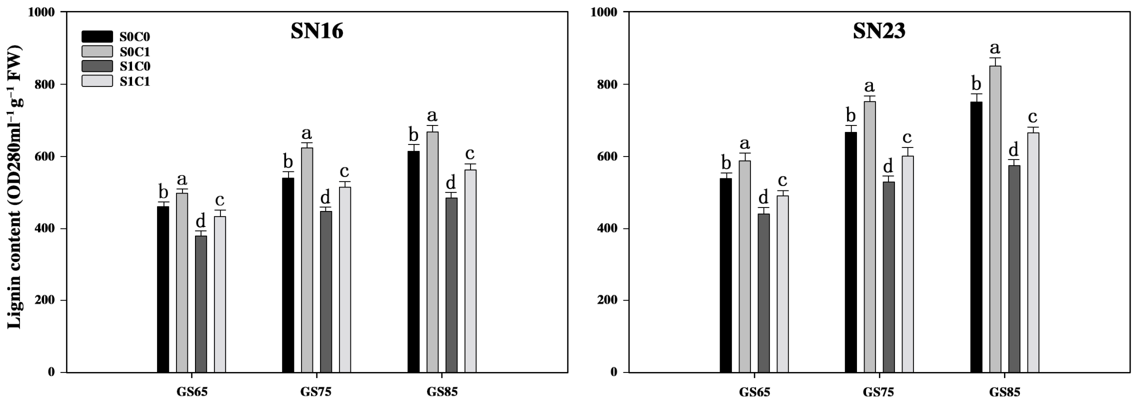

Figure 4. Effect of silica on the second internode lignin content in the base of winter wheat under low-light stress. Vertical bars above mean values indicate standard deviations (n = 3). The different lowercase letters indicate significant differences ($p < 0.05$) between treatments.

4. Discussions

Low-light stresses plants with shade avoidance responses, resulting in greater allocation of carbohydrates in the plant to stems and leaves at the expense of allocating carbon sources to yield, decreasing spike number and 1000-grain weight [22]. Shade treatment at the jointing stage was detrimental to the formation of spikes from lower tillers and significantly reduced the number of spikes in wheat [23]. Shade treatment before anthesis significantly reduced the spike number of wheat [24]. Shade treatment after anthesis with reduced dry matter accumulation as well as reduced translocation to the kernel significantly reduced the number of spikes and 1000-grain weight of wheat [25,26]. This experiment showed (Table 1) that shade treatment significantly reduced the number of spikes and grains and 1000-grain weight of wheat and reduced wheat yield. Ji et al. [27] found that silicon application could increase the number of tillers in rice, which increased with the increase of silicon application. At the same time, silicon application improved the photosynthetic characteristics of crops, increased the number of spikes, and increased crop yield [28]. Berahim et al. [29] concluded that silicon application mainly affects 1000-grain weight and the number of spikes in rice and thus contributes to the increase in yield. Under low-light stress, we found that exogenous spraying of silicon significantly increased the adequate number of spikes, as well as increased translocation to the grain, increasing the number of spikes and 1000-grain weight and improving wheat yield (Table 1).

Wheat stem morphological characteristics, including plant height, stem thickness, wall thickness, and stem filling degree, are essential indicators for evaluating the resistance of wheat stems to heading. The higher the plant height and center of gravity height, the poorer the stems' ability to resist lodging and the higher the risk of lodging [30]. In contrast, Xue et al. [31] found a decreasing trend in plant height with increasing shade level in maize shade treatments, where shade led to a decrease in dry matter synthesis, which was harmful to stem morphogenesis. Under low-light stress, photosynthetic assimilation capacity was reduced, and the accumulation of carbohydrates by stems was reduced, resulting in thin and weak stems and reduced stem wall thickness [31]. Hussain et al. [32] found that low-light stress significantly reduced the stem filling degree of soybean, which was harmful to the morphological characteristics of the stems, significantly reduced the breaking strength of the stems, and increased the risk of lodging. Under shade stress, wheat basal internodes elongated, plant height and center of gravity height improved, and basal internode stem thickness, wall thickness, and filling degree decreased, reducing stem breaking strength and increasing the risk of lodging (Figures 2 and 3; Tables 2–4). Exogenous silicon sprays can effectively improve the morphological characteristics of crops, and Ma et al. [33] and Hong et al. [34] also found that silicon can reduce internode length, decrease plant height, increase stem sheath filling degree, and enhance stem breaking strength. Fallah [35] found that silicon could increase stem thickness and wall thickness and improve stem breaking strength. The results of this experimental study are consistent with the results of previous studies after the treatment of low-light stress, exogenous spray silicon reduced the length of wheat basal internodes and plant height, and spray silicon fertilizer can increase wheat stem thickness, wall thickness, stem filling degree, and improve stem breaking strength (Figures 2 and 3; Tables 2–4).

Lignin is an essential component of the cell wall, accounting for 30% of plant organic carbon, and plays a vital role in plant rigidity and resistance to lodging, and cross-linking with other carbohydrates enhances cell wall strength [36–38]. Lignin biosynthesis was found to be significantly reduced by shade stress, and the effect on lignin synthesis became more severe with increasing shade [39,40]. Under shading stress, the expression of *PAL*, *4CL*, and *CAD* decreased, reducing lignin synthesis [41]. Shade stress significantly reduces photosynthetic rate, decreases carbohydrate formation, and harms lignin synthesis in stems. Similarly, this study found that the lignin content of both varieties of winter wheat was significantly reduced under low-light stress and differed significantly between the two varieties of winter wheat, with SN23 having significantly higher lignin content than SN16 (Figure 4). Increasing planting density decreased lignin synthesis-related enzyme activities, which was unfavorable to lignin synthesis [42,43]. Silicon can increase the expression of lignin synthesis genes and promote lignin synthesis [44,45]. Meanwhile, silicon can enhance carbon uptake and fixation, promote lignin synthesis, and improve stem strength [46]. This experiment is consistent with the results of previous studies (Figure 4) that exogenous silicon spraying can effectively promote the accumulation of lignin synthesis in wheat stems under low-light stress.

In recent years, the uncertainty of global climate change has posed a severe challenge to wheat production. There is frequent rainy weather in the critical period of wheat growth and development, which is a potential threat to stem development. It is an efficient, economical, and convenient method to improve stem quality and ensure wheat's stable yield by spraying silicon fertilizer to deal with the weather with insufficient light, such as rain and rain. However, in the future, genome, RNAseq transcriptome, proteome, and metabolome analysis should be carried out to understand the benefits of silicon on crop growth and development.

5. Conclusions

Spraying silicon promoted the silicon absorption of wheat and increased silicon accumulation in the stem, thereby significantly increasing stem diameter, wall thickness, and lignin content, thereby improving stem lodging resistance. Spraying silicon also significantly increased wheat spike number, grain number per spike, and 1000-grain weight to increase yield. The straightforward and cost-effective exogenous silicon spraying measures improved wheat's ability to withstand stress in low-light conditions, increased the financial advantages of planting, and could be utilized as an effective crop control technique to fend off low-light stress.

Author Contributions: Y.C.: Investigation, Data curation, Formal analysis, Writing—original draft. H.C.: Investigation, Data curation, Visualization, Writing—review and editing. Y.W.: Investigation, Data curation. C.L.: Investigation, Writing—original draft. J.W.: Investigation, Writing—original draft. M.J.: Supervision, Validation. Y.L. (Yongli Luo): Resources, Supervision, Validation, Writing—review and editing. Y.L. (Yong Li): Funding acquisition, Resources, Project administration, Writing—review and editing. Z.W.: Funding acquisition, Resources, Project administration. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the Key Research and Development Program of Shandong Province (LJNY202103), the Shandong Province Agricultural Major Technology Collaborative Promotion Plan Project (SDNYXTTG-2023-33), the National Natural Science Foundation of China (NO. 32172117, 32101834), the Natural Science Foundation of Shandong Province (NO. ZR2020QC106), and the Post-doctoral Science Foundation of China (2022M711968).

Data Availability Statement: All data generated or analyzed during this study are presented in this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Shumayla; Sharma, S.; Kumar, R.; Mendu, V.; Singh, K.; Upadhyay, S.K. Genomic Dissection and Expression Profiling Revealed Functional Divergence in *Triticum aestivum* Leucine Rich Repeat Receptor Like Kinases (*TaLRRKs*). *Front. Plant Sci.* **2016**, *7*, 1374. [CrossRef] [PubMed]
2. Fu, C.B.; Dan, L.; Chen, Y.L.; Tang, J.X. Trends of the sunshine duration and diffuse radiation percentage on sunny days in urban agglomerations of China during 1960–2005. *J. Environ. Sci.* **2015**, *34*, 206–211. [CrossRef] [PubMed]
3. Estrada-Campuzano, G.; Miralles, D.J.; Slafer, G.A. Yield determination in triticale as affected by radiation in different development phases. *Eur. J. Agron.* **2008**, *28*, 597–605. [CrossRef]
4. Guo, Z.J.; Yu, Z.W.; Wang, D.; Shi, Y.; Zhang, Y.L. Photosynthesis and winter wheat yield responses to supplemental irrigation based on measurement of water content in various soil layers. *Field Crop. Res.* **2014**, *166*, 102–111. [CrossRef]
5. Liu, W.G.; Ren, M.L.; Liu, T.; Du, Y.L.; Zhou, T.; Liu, X.M.; Liu, J.; Hussain, S.; Yang, W.Y. Effect of shade stress on lignin biosynthesis in soybean stems. *J. Integr. Agric.* **2018**, *17*, 1594–1604. [CrossRef]
6. Li, X.J.; Yang, Y.; Yao, J.L.; Chen, G.X.; Li, X.H.; Zhang, Q.F.; Wu, C.Y. *FLEXIBLE CULM 1* encoding a cinnamyl-alcohol dehydrogenase controls culm mechanical strength in rice. *Plant Mol. Biol.* **2009**, *69*, 685–697. [CrossRef] [PubMed]
7. Wu, L.M.; Zhang, W.J.; Ding, Y.F.; Zhang, J.W.; Cambula, E.D.; Weng, F.; Liu, Z.H.; Ding, C.Q.; 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]
8. Peng, D.L.; Chen, X.G.; Yin, Y.P.; Lu, K.L.; Yang, W.B.; Tang, Y.H.; Wang, Z.L. 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]
9. Luo, Y.L.; Chang, Y.L.; Li, C.H.; Wang, Y.Y.; Cui, H.X.; Jin, M.; Wang, Z.L.; Li, Y. Shading decreases lodging resistance of wheat under different planting densities by altering lignin monomer composition of stems. *Front. Plant Sci.* **2022**, *13*, 1056193. [CrossRef]
10. Wang, Y.; Zhang, Z.K.; Liang, Y.Y.; Han, Y.L.; Han, Y.L.; Tan, J.F. High potassium application rate increased grain Yield of shading-stressed winter wheat by improving photosynthesis and photosynthate translocation. *Front. Plant Sci.* **2020**, *11*, 134. [CrossRef]
11. Naseer, M.A.; Hussain, S.; Nengyan, Z.; Ejaz, I.; Ahmad, S.; Farooq, M.; Ren, X.L. Shading under drought stress during grain filling attenuates photosynthesis, grain yield and quality of winter wheat in the Loess Plateau of China. *J. Agron. Crop. Sci.* **2022**, *208*, 255–263. [CrossRef]
12. Ma, J.F.; Yamaji, N. Silicon uptake and accumulation in higher plants. *Trends Plant Sci.* **2006**, *11*, 392–397. [CrossRef] [PubMed]
13. Guntzer, F.; Keller, C.; Meunier, J.D. Benefits of plant silicon for crops: A review. *Agron. Sustain. Dev.* **2012**, *32*, 201–213. [CrossRef]
14. Epstein, E. The anomaly of silicon in plant biology. *Proc. Natl. Acad. Sci. USA* **1994**, *91*, 11–17. [CrossRef] [PubMed]
15. Rea, R.S.; Islam, M.R.; Rahman, M.M.; Nath, B.; Mix, K. Growth, Nutrient Accumulation, and Drought Tolerance in Crop Plants with Silicon Application: A Review. *Sustainability* **2022**, *14*, 4525. [CrossRef]
16. Zhao, D.Q.; Xu, C.; Luan, Y.T.; Shi, W.B.; Tang, Y.H.; Tao, J. Silicon enhances stem strength by promoting lignin accumulation in herbaceous peony (*Paeonia lactiflora Pall.*). *Int. J. Biol. Macromol.* **2021**, *190*, 769–779. [CrossRef]
17. Radotić, K.; Djikanović, D.; Kalauzi, A.; Tanasijević, G.; Maksimović, V.; Maksimović, J.D. Influence of silicon on polymerization process during lignin synthesis. Implications for cell wall properties. *Int. J. Biol. Macromol.* **2022**, *198*, 168–174. [CrossRef]

18. Rastogi, A.; Yadav, S.; Hussain, S.; Kataria, S.; Hajihashemi, S.; Kumari, P.; Yang, X.H.; Brestic, M. Does silicon really matter for the photosynthetic machinery in plants. . .? *Plant Physiol. Bioch.* **2021**, *169*, 40–48. [CrossRef]
19. Liu, C.G.; Lu, W.K.; Ma, Q.N.; Ma, C.C. Effect of silicon on the alleviation of boron toxicity in wheat growth, boron accumulation, photosynthesis activities, and oxidative responses. *J. Plant Nutr.* **2017**, *40*, 2458–2467. [CrossRef]
20. Zheng, M.J.; Chen, J.; Shi, Y.H.; Li, Y.X.; Yin, Y.P.; Yang, D.Q.; Luo, Y.L.; Pang, D.W.; Xu, X.; Li, W.Q.; et al. Manipulation of lignin metabolism by plant densities and its relationship with lodging resistance in wheat. *Sci. Rep.* **2017**, *7*, 41805. [CrossRef]
21. Chen, G.Y. Study on determination method of si in rice and its plant by ICP-MS. *Heilongjiang Agric. Sci.* **2008**, *4*, 105–107.
22. Carriedo, L.G.; Maloof, J.N.; Brady, S.M. Molecular control of crop shade avoidance. *Curr. Opin. Plant Biol.* **2016**, *30*, 151–158. [CrossRef] [PubMed]
23. Ji, X.; Shiran, B.; Wan, J.; Lewis, D.C.; Jenkins, C.L.; Condon, A.G.; Richards, R.A.; Dolferus, R. Importance of pre-anthesis anther sink strength for maintenance of grain number during reproductive stage water stress in wheat. *Plant Cell Environ.* **2010**, *33*, 926–942. [CrossRef] [PubMed]
24. Acreche, M.M.; Briceño-Félix, G.; Sánchez, J.A.M.; Slafer, G.A. Grain number determination in an old and a modern mediterranean wheat as affected by pre-anthesis shading. *Crop. Pasture Sci.* **2009**, *60*, 271–279. [CrossRef]
25. Suryanto, P.; Putra, E.T.S.; Kurniawan, S.; Suwignyo, B.; Sukirno, D.A.P. Maize response at three levels of shade and its improvement with intensive agro forestry regimes in Gunung Kidul, Java, Indonesia. *Procedia Environ. Sci.* **2014**, *20*, 370–376. [CrossRef]
26. Asseng, S.; Kassie, B.T.; Labra, M.H.; Amador, C.; Calderini, D.F. Simulating the impact of source-sink manipulations in wheat. *Field Crops Res.* **2017**, *202*, 47–56. [CrossRef]
27. Ji, X.H.; Liu, S.H.; Juan, H.; Bocharnikova, E.A.; Matichenkov, V.V. Effect of silicon fertilizers on cadmium in rice (*Oryza sativa*) tissue at tillering stage. *Environ. Sci. Pollut. R.* **2017**, *24*, 10740–10748. [CrossRef]
28. Hussain, S.; Iqbal, N.; Rahman, T.; Liu, T.; Brestic, M.; Safdar, M.E.; Asghar, M.A.; Farooq, M.U.; Shafiq, I.; Ali, A.; et al. Shade effect on carbohydrates dynamics and stem strength of soybean genotypes. *Environ. Exp. Bot.* **2019**, *162*, 374–382. [CrossRef]
29. Berahim, Z.; Omar, M.H.; Zakaria, N.I.; Ismail, M.R.; Rosle, R.; Roslin, N.A.; Che'Ya, N.N. Silicon improves yield performance by enhancement in physiological responses, crop imagery, and leaf and culm sheath morphology in new rice line, PadiU Putra. *BioMed Res. Int.* **2021**, *2021*, 6679787. [CrossRef]
30. Li, B.; Gao, F.; Ren, B.Z.; Dong, S.T.; Teng, P.; Zhao, B.; Zhang, J.W. Lignin metabolism regulates lodging resistance of maize hybrids under varying planting density. *J. Integr. Agr.* **2021**, *20*, 2077–2089. [CrossRef]
31. Xue, J.; Gou, L.; Zhao, Y.S.; Yao, M.N.; Yao, H.S.; Tian, J.S.; Zhang, W.F. Effects of light intensity within the canopy on maize lodging. *Field Crops Res.* **2016**, *188*, 133–141. [CrossRef]
32. Hussain, S.; Mumtaz, M.; Manzoor, S.; Li, S.X.; Ahmed, I.; Skalicky, M.; Brestic, M.; Rastogi, A.; Ulhassan, Z.; Shafiq, I.; et al. Foliar application of silicon improves growth of soybean by enhancing carbon metabolism under shading conditions. *Plant Physiol. Bioch.* **2021**, *159*, 43–52. [CrossRef]
33. Ma, J.F.; Yamaji, N.; Mitani-Ueno, N. Transport of silicon from roots to panicles in plants. *Plant Physiol. Biochem.* **2011**, *87*, 377–385. [CrossRef]
34. Hong, W.Y.; Chen, Y.J.; Huang, S.H.; Li, Y.Z.; Wang, Z.M.; Tang, X.R.; Pan, S.G.; Tian, H.; Mo, Z.W. Optimization of nitrogen–silicon (N-Si) fertilization for grain yield and lodging resistance of early-season indica fragrant rice under different planting methods. *Eur. J. Agron.* **2022**, *136*, 126508. [CrossRef]
35. Fallah, A. Silicon effect on lodging parameters of rice plants under hydroponic culture. *Int. J. Agric. Sci.* **2012**, *2*, 630–634.
36. Kevers, C.; Prat, R.; Gaspar, T. Vitrification of carnation in vitro: Changes in cell wall mechanical properties, cellulose and lignin content. *Plant Growth Regul.* **1987**, *5*, 59–66. [CrossRef]
37. Goujon, T.; Sibout, R.; Eudes, A.; MacKay, J.; Jouanin, L. Genes involved in the biosynthesis of lignin precursors in *Arabidopsis thaliana*. *Plant Physiol. Biochem.* **2003**, *41*, 677–687. [CrossRef]
38. Dauwe, R.; Morreel, K.; Goeminne, G.; Gielen, B.; Rohde, A.; Beeumen, J.V.; Ralgh, J.; Boudet, A.; Kopka, J.; Rochange, S.F.; et al. Molecular phenotyping of lignin-modified tobacco reveals associated changes in cell-wall metabolism, primary metabolism, stress metabolism and photorespiration. *Plant J.* **2007**, *52*, 263–285. [CrossRef]
39. Hu, D.; Liu, X.B.; She, H.Z.; Gao, Z.; Ruan, R.W.; Wu, D.Q.; Yi, Z.L. The lignin synthesis related genes and lodging resistance of *Fagopyrum esculentum*. *Biol. Plant.* **2017**, *61*, 138–146. [CrossRef]
40. Teng, R.M.; Wang, Y.X.; Li, H.; Lin, S.J.; Liu, H.; Zhuang, J. Effects of shading on lignin biosynthesis in the leaf of tea plant (*Camellia sinensis* (L.) *O. Kuntze*). *Mol. Genet. Genom.* **2021**, *296*, 165–177. [CrossRef]
41. Zou, J.L.; Liu, W.G.; Yuan, J.; Jiang, T.; Ye, S.Q.; Deng, Y.C.; Yang, C.Y.; Luo, L.; Yang, W.Y. Relationship between lignin synthesis and lodging resistance at seedlings stage in soybean intercropping system. *Acta Agron. Sin.* **2015**, *41*, 1098–1104. [CrossRef]
42. Wang, C.; Ruan, R.W.; Yuan, X.H.; Hu, D.; Yang, H.; Li, Y.; Ze, L.Y. Effects of nitrogen fertilizer and planting density on the lignin synthesis in the culm in relation to lodging resistance of buckwheat. *Plant Prod. Sci.* **2015**, *18*, 218–227. [CrossRef]
43. Khan, A.; Liu, H.H.; Ahmad, A.; Xiang, L.; Ali, W.; Khan, A.; Kamran, M.; Ahmad, S.; Li, J.C. Impact of nitrogen regimes and planting densities on stem physiology, lignin biosynthesis and grain yield in relation to lodging resistance in winter wheat (*Triticum aestivum* L.). *Cereal Res. Commun.* **2019**, *47*, 566–579. [CrossRef]
44. Kuai, J.; Sun, Y.Y.; Guo, C.; Zhao, L.; Zuo, Q.S.; Wu, J.S.; Zhou, G.S. Root-applied silicon in the early bud stage increases the rapeseed yield and optimizes the mechanical harvesting characteristics. *Field Crops Res.* **2017**, *200*, 88–97. [CrossRef]

45. Hu, Y.; Javed, H.H.; Asghar, M.A.; Peng, X.; Brestic, M.; Skalický, M.; Ghafoor, A.Z.; Cheema, H.N.; Zhang, F.; Wu, Y.C. Enhancement of lodging resistance and lignin content by application of organic carbon and silicon fertilization in *Brassica napus* L. *Front. Plant Sci.* **2022**, *13*, 217. [CrossRef]
46. Miao, W.; Li, F.C.; Lu, J.C.; Wang, D.L.; Chen, M.K.; Tang, L.; Xu, Z.J.; Chen, W.F. Biochar application enhanced rice biomass production and lodging resistance via promoting co-deposition of silica with hemicellulose and lignin. *Sci. Total Environ.* **2023**, *855*, 158818. [CrossRef]