agronomy

Article

Silicon Fertilizer Addition Can Improve Rice Yield and Lodging Traits under Reduced Nitrogen and Increased Density Conditions

Liqiang Dong , Tiexin Yang, Liang Ma, Rui Li, Yingying Feng and Yuedong Li *

Liaoning Rice Research Institute, Shenyang 110101, China; liqiang_dong@163.com (L.D.); lnasytx@126.com (T.Y.); malhd@163.com (L.M.); lir2010@126.com (R.L.); fengyingying7576@163.com (Y.F.)
* Correspondence: daozuosuo@126.com

Abstract: Reducing nitrogen fertilizer application, selecting a reasonable planting density, and adding silicon fertilizer can be used together to decrease excessive nitrogen fertilizer inputs in rice fields, reduce production costs, and ensure stable rice yield. However, the dynamics of the stem and internodes, as well as the changes in the physical and physiological characteristics of rice under a combination of these three strategies, are still unclear. In this study, we aimed to clarify these effects to improve the efficiency of rice production in northeastern China. A 2-year field experiment was conducted using five treatments: a conventional densification treatment (DM), a densification combined with reduced N input (−20%) treatment (DLM), and three densifications combined with reduced N input (−20%) and basal silicon fertilizer treatments (low fertilizer: DLMS1; medium fertilizer: DLMS2; and high fertilizer: DLMS3). This study revealed that the addition of silicon fertilizer improved rice yield compared to that under reduced nitrogen or increased density treatments alone, prevented excessive ineffective tillering after a density increase, and increased the number of productive panicles. Among the treatments, the DLMS3 treatment had the highest yields of 10.53 t/ha and 10.73 t/ha over the 2 years. Reducing nitrogen and increasing density reduced the weight and length of single panicles, while the addition of silicon fertilizer was beneficial for improving stem toughness, improving the physical and physiological characteristics of the plants and panicles, and enhancing plant bending resistance. Among the treatments, DLMS3 had the highest bending resistance, which increased by 440.1 g and 503.8 g compared to the lowest values in the DM treatment in 2020 and 2021, respectively. Nitrogen reduction resulted in the lowest lodging index values, with DLMS3 having the lowest values in both years, which decreased by 19.6% and 22.5% compared to the highest values in DM (2020) and DLM (2021), respectively. This study indicates that the application of 150.0 kg/ha silicon fertilizer in combination with reduced nitrogen and increased density (DLMS3) reduces the lodging index while ensuring rice yield, preventing a tradeoff between yield reduction and lodging due to a density increase or due to nitrogen reduction combined with a density increase and allowing for a reduction in nitrogen fertilizer input, which could ensure a uniform yield and an increase in lodging resistance. These results provide a scientific basis for rice cultivation measures that lead to high yield and lodging resistance while protecting the environment.

Keywords: rice; silicon fertilizer; yield components; stem lodging

Citation: Dong, L.; Yang, T.; Ma, L.; Li, R.; Feng, Y.; Li, Y. Silicon Fertilizer Addition Can Improve Rice Yield and Lodging Traits under Reduced Nitrogen and Increased Density Conditions. *Agronomy* **2024**, *14*, 464. https://doi.org/10.3390/agronomy14030464

Academic Editor: Wenxu Dong

Received: 25 January 2024
Revised: 23 February 2024
Accepted: 23 February 2024
Published: 26 February 2024

1. Introduction

Rice is an important food crop [1], with an area of 165.04 million hectares and an annual production of 776.5 million tons worldwide in 2022 [2]. As the largest rice producer, China cultivated 29.69 million hectares and produced 210.07 million tons in 2022 [3]. More than half of the Chinese population relies on rice as their primary food source [4,5] and the production of japonica rice in Northeast China is closely related to food security in China. In recent years, many producers have blindly pursued high rice yields by increasing nitrogen (N) fertilizer application, resulting in an increasing amount of fertilizer application each year [6,7]. At present, China's N fertilizer application accounts for 30% of global N fertilizer usage, making China the world's largest consumer of N fertilizer. However, the average utilization rate of N fertilizer is only 30–35%, far below the world average level, causing problems such as high economic cost, eutrophication of water bodies, and scarcity of resources [6,8].

In order to improve N utilization efficiency and stabilize rice yield, the combined cultivation of densification and N reduction has been widely concerned by researchers. However, this method still faces the problems of increasing competition among individuals within the population and in rising the lodging index of rice, which limits mechanized rice harvesting processes and results in yield loss [9,10]. Furthermore, the traditional method of rice cultivation can readily lead to nonpoint source pollution in farmland due to excessive nitrogen fertilizer application, while densification-only treatment can reduce individual morphological indicators and increase the rice lodging index.

Silicon (Si) is a macronutrient that is widely found in monocotyledonous plants [11]. Si concentrations range from 0.1 to 10% of the dry biomass in a plant [12]. It can promote rice growth and nutrient absorption, participate in various physiological and biochemical processes in plants, and play an important role in promoting plant growth, development, and metabolism [13]. Si exists in soil, and silicon dioxide comprises around 50–70% of soil mass [14,15]. It can improve crop yield and quality and enhance crop resistance [16]. After silicon fertilizer is applied to the soil, it releases its available silicon, some of which can be absorbed by plant roots; the remaining parts can be absorbed and utilized by the next crop in the soil or undergo ineffective reactions [17,18]. Si deficiency occurs in approximately 13.3 million hectares of rice fields in China. How to increase soil silicon content, improve soil silicon morphology, and increase rice yield is a major scientific problem currently faced in high-yield rice cultivation [16,19]. Researchers have conducted extensive research on the effects of the application of N fertilizer, planting density, and Si fertilization in rice [20,21]. The results indicate that N fertilizer affects yield by changing yield components, planting density affects yield by altering tradeoffs between individuals and populations, and Si fertilizer affects the yield and harvest of rice by affecting rice biomass accumulation and morphology. In addition, an increase in planting density, a reduction in nitrogen fertilizer input, and the application of silicon fertilizer change the population structure and individual morphology of rice plants during the reproductive period and cause changes in rice yield and lodging. Studies have shown that lodging is most likely to occur in the fourth segment from the top of rice 40 days after the full heading stage [22,23]. The deposition of substances such as cellulose, lignin, polysaccharides, starch, and potassium in rice epidermal tissue affects stem base width and stem wall thickness and affects rice yield and lodging traits. Therefore, increasing the planting density and applying appropriate amounts of silicon fertilizer at a reduced N fertilizer application rate can ensure rice yield and improve lodging resistance. However, there are few reports on the effects of the combination of the three management techniques mentioned above. In recent years, with increases in nitrogen fertilizer dosing and resultant increases in yield, lodging problems have become increasingly serious [24], having many adverse effects and seriously limiting rice production. On the one hand, lodging reduces yield and is also an important factor limiting mechanical rice harvesting, which leads to an approximately 10% to 30% rice yield reduction in China every year. On the other hand, lodging can affect the quality of rice [25] and increase farmers' production costs. Therefore, silicon application can be used as an important measure to increase rice yield. However, it remains unclear whether it can affect rice production under nitrogen reduction and densification conditions.

A 2-year field experiment was conducted using five treatments with Liaojing 401 as the rice cultivar. The yield components, lodging, dynamics of rice stems, and physical and physiological characteristics of stems and internodes were measured to investigate the changes in yield and lodging characteristics resulting from combined N fertilizer reduction, planting density increase, and silicon fertilizer application. The study aimed to explore the changes in rice yield, related factors, and lodging characteristics; reduce excessive N fertilizer input to rice fields; reduce production costs; and avoid damage to the agricultural environment; thereby providing a basis for high-yield, environmentally friendly, and anti-lodging cultivation measures for rice. This study provides a reference for ensuring the sustainability of regional rice production.

2. Materials and Methods

2.1. Experimental Design

The variety of rice used in the experiments was Liaojing 401, which was provided by the Liaoning Rice Research Institute (LRRI). The variety has a growth period of approximately 158 days and is a mid- to late-maturing variety in Liaoning Province. The plant height is 105.2 cm, the panicle length is 17.3 cm, the number of grains per panicle is 126.9, and the thousand grain weight is 25.5 g.

The field experiment was conducted in Bayi Town, Sujiatun District, Shenyang City, Liaoning Province, from 2020 to 2021 (E: 123.18°, N: 41.49°) in the experimental field of the LRRI. The region has a temperate humid continental climate and has been a long-term single season and single-cropping area for rice. It is a medium- and high-yield field production area in the region, and the soil type is loam. The sunshine, rainfall, and temperature data for the test area are shown in Figure 1. Each treatment was repeated three times, totaling 18 plots, with a test plot of width 6 m and length 10 m, a plot area of 60 m^2, and randomly arranged, mechanized transplanting. The initial pH of the soil was 6.2, and the contents of alkali-hydrolyzable N, available phosphorus, and available potassium were 94.6 mg/kg, 54.7 mg/kg, and 91.4 mg/kg, respectively. The silicon content was 27.8% (silicon-deficient land). Meteorological data of the experimental area are shown in Figure 1. Local farming modes (FMs) were used as a control, and a conventional densification treatment (DM), a densification with reduced N (−20%) treatment (DLM), and three densifications with reduced N (−20%) and base silicon fertilizer treatments (low fertilizer: DLMS1, medium fertilizer: DLMS2, high fertilizer: DLMS3) were set up (Table 1). In the reduced N treatments, the total N fertilizer application amount was reduced by 20% during the base fertilizer period, and the silicon fertilizer was bio-organic silicon (27% granular silicon fertilizer with an algal source extract of reproductive organs and tender tissues. This bio-organic silicon can break down and release silicon ions into the soil water solution, and be absorbed by the rice roots; Anhui Nongwang Agricultural Technology Co., Ltd., Hefei, China).

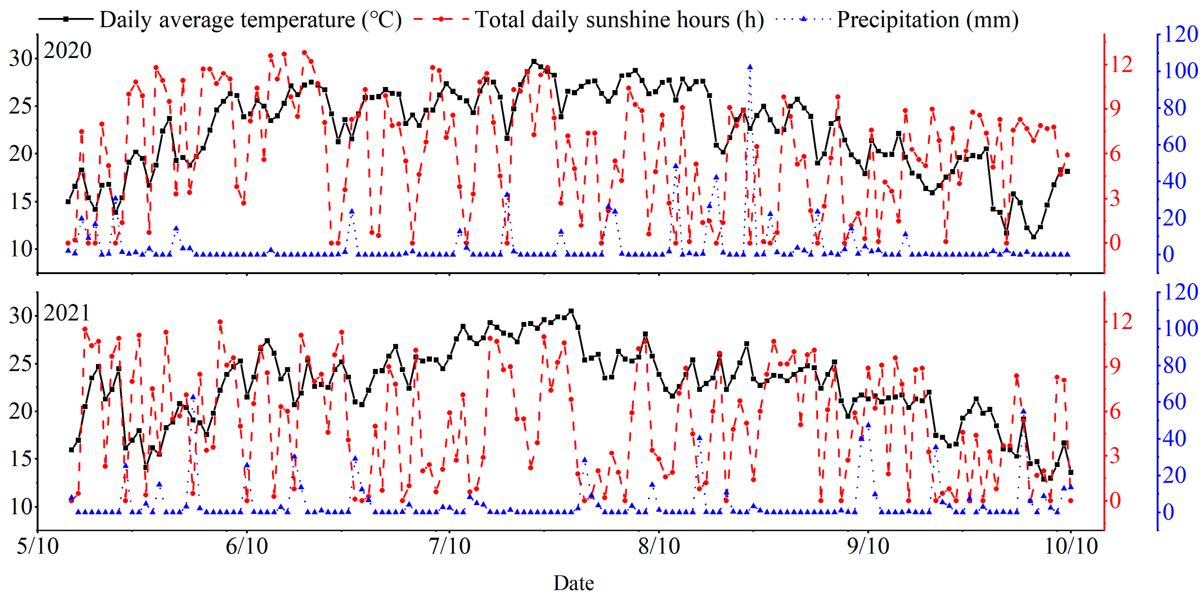

Figure 1. Meteorological data of the experimental area.

Table 1. Experimental design.

Treatments	Row Distance (cm)	Hill Distance (cm)	N Application Rate (kg/ha)	Si Application Rate (kg/ha)	Hill Number (/m^2)
FM (Farming mode)	30.0	20.0	600	0	16.7
DM (Increased density mode)	30.0	13.2	600	0	25.3
DLM (Increased density with decreased N mode)	30.0	13.2	480	0	25.3
DLMS1 (Increased density with decreased N and Si application mode 1)	30.0	13.2	480	75	25.3
DLMS2 (Increased density with decreased N and Si application mode 2)	30.0	13.2	480	150	25.3
DLMS3 (Increased density with decreased N and Si application mode 3)	30.0	13.2	480	225	25.3

Fertilization was performed according to the local high-yield cultivation practices. Urea fertilizer (having 46% N, North Huajin Industries Co., Ltd., Panjin, China) was divided into base fertilizer, tillering fertilizer, and panicle fertilizer at a ratio of 6:3:1. The application rate of phosphate fertilizer (P_2O_5, calcium superphosphate) was 150.0 kg/ha, which was applied as base fertilizer. The application rate of potassium fertilizer (K_2O, potassium sulfate) was 125.0 kg/ha, with equal amounts applied as base fertilizer and panicle fertilizer.

During the critical growth period of rice, well water irrigation was maintained in a shallow water layer. In other periods, a "shallow wet–dry" water layer irrigation management method was used, and other cultivation management techniques were carried out according to high-yield field management measures [26].

2.2. Measured Parameters

Yield components, lodging, dynamics of rice stems, and the physical and physiological characteristics of stems and internodes changed with the combination of reduced N fertilizer application, increased planting density, and silicon fertilizer application, and the following parameters were measured:

2.2.1. Stem Number in the Growth Stage

Stem number were measured in transplanting stage (TS), jointing stage (JS), heading stage (HS), full heading stage (FHS), and maturity stage (MS).

2.2.2. Yield and Composition Factors

Productive panicle number (PPN), number of primary branches (NPB), number of secondary branches (NSB), full grain number (FGN), seed setting rate (SSR), thousand grain weight (TGW), and actual yield (AY) were measured after harvest.

2.2.3. Biochemical Indicators

40 days after heading, the main stem was taken, and the test sample was dried, weighed, crushed, and sieved through a 100 mesh sieve to determine the soluble sugar content (SSC) and starch content (SC) with anthrone colorimetry by an ultraviolet spectrophotometer, referring to Liu [27]; the cellulose content (CC) and lignin content (LC), referring to the operation manual of the FibertecTMM$_6$ 1020/1021 cellulose analyzer from FOSS (Hilleroed, Denmark); and total K (TK) with sodium hydroxide melting process by an atomic absorption spectrophotometer (AA7000, Shimadzu, Kyoto, Japan), referring to Bao [28].

2.2.4. Traits Related to Lodging

40 days after the full heading stage were measured with Vernier calipers and a ruler (accuracy 0.1 cm), according to Xiao [10], and included the following: plant height (PH),

plant center of gravity (PCG), panicle weight (PW), plant length (PL), internode length (IL), distance to the top of the plant (DTP), internode weight (IW), and weight to the top of the plant (WTP).

The stem wall thickness (SWT), stem diameter (SD), and oblate rate (OR) were determined according to Wang [20].

The stem diameter (SD) = [(longest diameter + shortest diameter)/2]; flattening rate (FR) = [(1-minimum axis width/maximum axis width) × 100].

After measuring stem and panicle traits, a YYD-1 stem strength instrument (Zhejiang Top Instrument Co., Ltd., Hangzhou, China) was then used to evaluate the breaking resistance (BR), bending moment (BM), and lodging index (LI) for each internode and calculated according to the method of Xiao [10].

The BM between basal nodes (g/cm) = SL × FW represents the magnitude of the force applied between nodes. In the formula, SL is the shear length, defined as the distance from the base of each internode to the top of the panicle (cm), and FW is the fresh weight, defined as the fresh weight from the base of each elongated internode to the top of the panicle (g).

BR (g/cm) = F × L/4 represents the magnitude of the bending resistance. In the formula, F is the added weight (g) corresponding to the breaking of internodes, and L is the distance between the two support points.

LI (%) = BM/BR × 100 represents the degree of lodging that is prone to occur.

2.3. Statistical Analyses

Excel (2020, Microsoft, Redmond, WA, USA) was used for data organization, SPSS (22.0; SPSS Inc., Chicago, IL, USA) was used for data difference analysis, and Origin (OriginLab, Hampton, MA, USA) was used for data plotting.

3. Results

3.1. Effect of Silicon Fertilizer on Rice Yield and Its Components under Reduced N and Increased Density Conditions

To elucidate the influence of silicon fertilizer addition on rice cultivation in this study, we first aimed to determine the effect of silicon fertilizer on rice yield and its components under reduced N and increased density conditions by measuring relevant parameters during the 2-year field experiment. The planting density and the application amounts of N and silicon fertilizers affect the yield and its components during the mature stage of rice. Analysis of rice panicles (Table 2) showed that the variation patterns of each treatment tended to be consistent between years. The yield was the highest in the DLMS3 treatment, with values of 10.53 t/ha and 10.73 t/ha. The DLM treatment had the lowest yield, with values of 9.54 t/ha and 9.69 t/ha. The productive panicle number was the highest in DM and the lowest in FM, and it tended to increase with increasing silicon fertilizer application rate in the silicon fertilizer combination treatments. The number of primary and secondary branches and grains per panicle in the FM treatment were significantly higher than those in the other treatments, reaching 13.6 and 13.6, 43.9 and 44.1, and 133.2 and 130.2 grains, respectively, among which those in the DLM treatment were the lowest. The difference in the seed setting rate among the different treatments during each year was not significant, ranging from 83.0% to 86.6%. The difference in thousand grain weight among different treatments in 2020 was not significant, ranging from 23.4 to 24.5 g. In 2021, the thousand grain weights of the DLMS2 and DLMS3 treatments were significantly higher than those of the DM and DLM treatments. The combination of reduced N and increased density with silicon fertilizer application can improve rice yield compared to reduced nitrogen or increased density alone.

Table 2. Rice yield and its components.

Year	Treatments	Productive Panicle Number (10^4/ha)	Primary Branch Number	Secondary Branch Number	Full Grain Number	Seed Set Rate (%)	Thousand Grain Weight (g)	Actual Yield (t/ha)
2020	FM	341.8 c	13.6 a	43.9 a	133.2 a	86.4 a	24.1 a	10.50 a
	DM	381.7 a	12.4 b	36.7 b	125.1 b	83.0 a	23.4 a	10.51 a
	DLM	345.8 c	12.5 b	34.0 c	116.9 c	85.6 a	23.9 a	9.54 b
	DLMS1	358.6 bc	12.7 b	33.3 c	115.8 c	85.7 a	24.1 a	9.88 b
	DLMS2	371.5 ab	12.9 ab	33.7 c	119.7 bc	86.4 a	24.5 a	10.53 a
	DLMS3	374.4 ab	12.7 b	35.2 bc	119.7 bc	86.4 a	24.5 a	10.53 a
2021	FM	350.1 c	13.6 a	44.1 a	130.2 a	86.6 a	25.0 ab	10.65 a
	DM	385.7 a	12.3 b	35.9 b	120.5 b	83.3 a	24.1 b	10.72 a
	DLM	351.0 c	12.4 b	32.5 c	114.9 b	85.9 a	24.2 b	9.69 b
	DLMS1	360.4 bc	12.5 b	33.0 c	117.7 b	86.0 a	25.2 ab	10.40 a
	DLMS2	372.9 ab	12.5 b	33.1 c	118.1 b	86.4 a	25.6 a	10.73 a
	DLMS3	378.9 ab	12.6 b	34.5 bc	118.2 b	86.5 a	25.5 a	10.73 a

Note: Data in the table are means with three replicates. Different letters indicate significant difference at a $p = 0.05$ probability level within the same column in the same year.

3.2. Effect of Silicon Fertilizer on the Dynamics of Rice Stems under Reduced N and Increased Density Conditions

The number of stems and tillers was affected by transplanting density, and the rice yield was regulated by fertility and other factors in each growth stage. Due to the influence of planting density and N and silicon fertilizer application rates, the dynamics of rice stems at different growth stages changed. Survey and analysis of rice stems at key growth stages (Figure 2) showed that the changes in each treatment were consistent throughout the year, with stem parameters showing a trend of first increasing, then decreasing, and finally stabilizing, reaching a peak at the full heading stage. Due to the increased planting density, the basic seedling number in the FM treatment in the transplanting period was the lowest, at 731,000/ha and 720,000/ha in the 2 years. The increased density treatment had values between 996,000/ha and 1,067,000/ha, and there was no significant difference between the 2 years. At each growth stage, the FM treatment had the lowest stem number, while the DM treatment had the highest stem tiller number. During the 2 years, the peak stem tiller numbers of the DM treatment were 705,000/ha and 686,000/ha higher than those of the FM treatment. In addition to affecting the seedlings during the transplanting period, in the reduced N and increased density treatments during the same growth period, the number of stems increased with increasing silicon fertilizer application. This trend persisted until the maturation stage, when the productive number of tillers was calculated, and the number of tillers reached 80.1% and 80.4% in the DLMS3 treatment in the 2 years. This indicates that increased silicon fertilizer application is beneficial for tillering and ear formation and can avoid the phenomenon of excessive ineffective tillering caused by increased planting density.

3.3. Effect of Silicon Fertilizer on the Physical Characteristics of Rice Plants and Panicles under Reduced N and Increased Density Conditions

The physical characteristics of rice plants and panicles changed 40 days after the full heading stage due to the influence of planting density and nitrogen and silicon fertilizer application rates. The results showed that the patterns of each treatment were consistent between years (Table 3). Plant height among the different treatments within the same year ranged from 101.0 to 104.0 cm. The difference in the plant center of gravity among the different treatments within the same year was not significant, ranging from 57.2 to 60.7 cm. The fresh panicle weight of the FM treatment was the highest (6.9 g in 2 years), and the fresh panicle weight of the FM treatment was significantly higher than that of other treatments except the DLMS3 treatment in 2020. The panicle length in FM was the highest, with values of 18.5 cm and 17.7 cm for the 2 years, which were significantly higher than those of the other treatments. There was no significant difference between the densification treatments. The trends in the panicle center of gravity and panicle fresh weight were the same, with FM having the highest panicle center of gravity values, 11.2 cm and 11.1 cm, in the 2 years. Except for the DLMS3 treatment in 2020, the panicle center of gravity of FM was significantly higher than that of the other treatments, indicating that reducing N and increasing density will reduce the single panicle weight and panicle length.

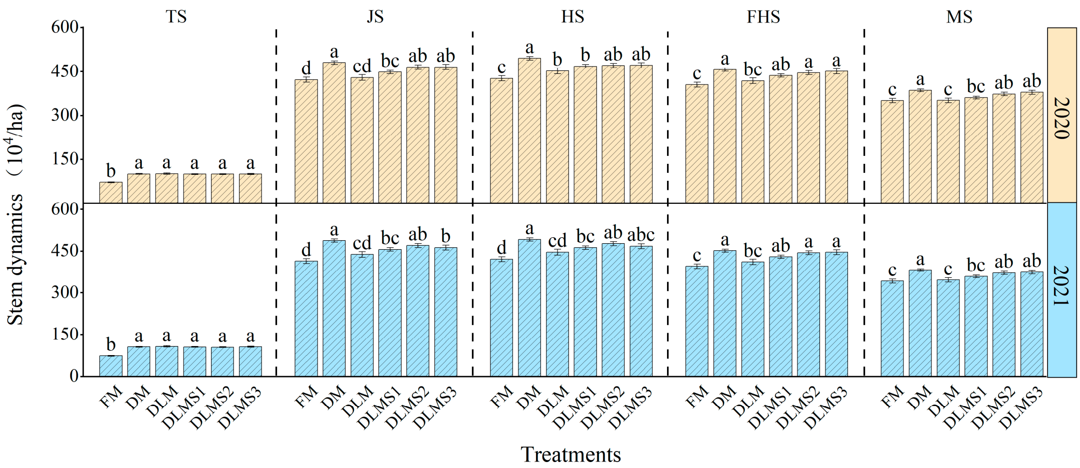

Figure 2. Dynamics of rice stems. Different letters of the same growth stage indicated significant differences in the same year ($p < 0.05$).

Table 3. Physical characteristics of rice plants and panicles.

Year	Treatments	Plant Height (cm)	Plant Center of Gravity (cm)	Panicle Weight (g)	Plant Length (cm)	Panicle Center of Gravity (cm)
2020	FM	102.1 a	59.7 a	6.9 a	18.5 a	11.2 a
	DM	104.0 a	57.2 a	6.5 b	17.0 b	9.8 c
	DLM	103.5 a	57.6 a	6.5 b	16.8 b	9.8 c
	DLMS1	101.9 a	58.0 a	6.4 b	16.9 b	9.7 c
	DLMS2	101.0 a	57.8 a	6.5 b	16.9 b	10.5 b
	DLMS3	101.6 a	58.5 a	6.6 ab	16.8 b	10.7 ab
2021	FM	102.2 a	60.7 a	6.9 a	17.7 a	11.1 a
	DM	103.8 a	57.5 a	6.3 b	16.3 b	10.2 b
	DLM	103.8 a	57.9 a	6.2 b	16.2 b	10.0 b
	DLMS1	101.7 a	57.5 a	6.2 b	16.2 b	10.0 b
	DLMS2	101.2 a	58.1 a	6.3 b	16.4 b	10.1 b
	DLMS3	101.2 a	59.1 a	6.5 b	16.3 b	10.2 b

Note: Data in the table are means with three replicates. Different letters indicate significant difference at a $p = 0.05$ probability level within the same column in the same year.

3.4. Effect of Silicon Fertilizer on the Physical Properties of the Fourth Internode (N4) of Rice under Reduced N Reduction and Increased Density Conditions

The fourth internode (N4) of rice is located at the base of the plant, which is the most likely location for rice stem lodging. Physical properties were measured and analyzed 40 days after the heading stage (Table 4), and the changes in different treatments were consistent throughout the year. The internode lengths of FM and DM were significantly higher than those of the other treatments, ranging from 12.5 to 12.8 cm, indicating that weight loss can reduce the length of the fourth internode. The difference in distance from the top among the different treatments was not significant between years, ranging from 89.4 to 92.3 cm. The internode weights of FM, DLMS2, and DLMS3 were relatively high, ranging from 4.2 to 4.4 cm, significantly higher than those of the other treatments, indicating that the application of silicon fertilizer can increase the accumulation of substances in the fourth internode and thereby increase internode weight. There was no significant difference in the distance from the top weight between different treatments in 2020, ranging from 16.7 to 17.4 g. In 2021, FM had the highest value at 17.5 g, which was significantly higher than the 16.5 g for DLMS2 and DLMS1. The stem wall thickness was the highest in DLMS3 for the 2 years, with a value of 0.76 mm. In 2020, DLM had the lowest value at 0.71 mm, and in 2021, both DM and DLM had the lowest value at 0.72 mm. During the 2 years, FM and DLMS3 had the highest stem thickness, ranging from 5.45 to 5.51 mm, which was significantly higher than those of DM and DLM. The flattening rate of the DLM was the highest, reaching 16.80% and 16.10% in the 2 years. DLMS1, DLMS2, and DLMS3 showed a gradual decrease in the flattening rate as the amount of silicon fertilizer increased, indicating that silicon fertilizer is beneficial for the thickening of the fourth internode stem while reducing the flattening rate.

Table 4. Physical properties of the fourth internode (N4) in rice.

Year	Treatments	Internode Length (cm)	Distance to the Top of the Plant (cm)	Internode Weight (g)	Weight to the Top of the Plant (g)	Stem Wall Thickness (mm)	Stem Diameter (mm)	Flattening Rate (%)
2020	FM	12.5 a	89.6 a	4.3 a	17.4 a	0.74 ab	5.46 a	13.13 c
	DM	12.8 a	91.2 a	3.6 bc	17.1 a	0.72 ab	5.06 b	15.22 b
	DLM	11.4 b	92.1 a	3.4 c	16.9 a	0.71 b	5.05 b	16.80 a
	DLMS1	11.8 b	90.1 a	3.8 b	16.8 a	0.74 ab	5.24 ab	11.45 d
	DLMS2	11.2 b	89.8 a	4.2 a	16.8 a	0.75 ab	5.48 a	11.22 d
	DLMS3	11.3 b	90.3 a	4.3 a	17.0 a	0.76 a	5.49 a	11.01 d
2021	FM	12.8 a	89.4 a	4.4 a	17.5 a	0.74 a	5.51 a	13.90 b
	DM	12.8 a	91.0 a	3.6 c	17.0 ab	0.72 a	5.10 b	15.50 a
	DLM	11.4 b	92.3 a	3.4 c	16.7 ab	0.72 a	5.11 b	16.10 a
	DLMS1	11.9 b	89.7 a	3.8 b	16.5 b	0.75 a	5.32 ab	11.50 c
	DLMS2	11.4 b	89.8 a	4.3 a	16.5 b	0.75 a	5.39 ab	11.02 c
	DLMS3	11.4 b	89.8 a	4.4 a	16.7 ab	0.76 a	5.45 a	10.90 c

Note: Data in the table are means with three replicates. Different letters indicate significant difference at a $p = 0.05$ probability level within the same column in the same year.

3.5. Effect of Silicon Fertilizer on the Physiological Characteristics of the Fourth Internode (N4) of Rice under Reduced N and Increased Density Conditions

The change in agronomic traits between rice plants and changes in the fourth node led to alterations in the physiological indexes. Physiological characteristics can be used as a physiological basis for evaluating the strength of plant stems. The physiological characteristics of the fourth internode of rice 40 days after the heading stage were measured and analyzed (Table 5), and the changes in different treatments were consistent throughout the year. The FM treatment had the highest soluble sugar and starch contents, with values of 7.6% and 7.5% in 2020 and 18.7% and 19.7% in 2021, respectively. Both indicators were significantly ($p < 0.05$) higher than those in the other treatments in 2020, and the starch content was significantly higher than that in the DM treatment in 2021. The cellulose content in DLMS3 was the highest, reaching 50.6% and 52.2% in the 2 years, followed by DLMS2, which had contents of 49.7% and 51.1% in the 2 years. The values of the DLMS3 and DLMS2 treatments were significantly ($p < 0.05$) higher than those of the DM and DLM treatments. The DM and DLM treatments had relatively low lignin contents, ranging from 6.7% to 6.8% for the 2 years, which were significantly ($p < 0.05$) lower than those of the other treatments. The DLMS2 and DLMS3 treatments had the highest lignin levels in both years. The DLMS3 treatment had the highest total K content, with values of 19.5 mg/g and 19.7 mg/g for the 2 years. The DLM treatment had the lowest total K content, with 17.0 mg/g for both years. The combination of reducing N and increasing density with silicon fertilizer application is beneficial for improving stem toughness.

Table 5. Physiological characteristics of the fourth internode (N4) in rice.

Year	Treatments	Soluble Sugar Content (%)	Starch Content (%)	Cellulose Content (%)	Lignin Content (%)	Total K (mg/g)
2020	FM	7.6 a	18.7 a	45.1 bc	7.1 bc	18.5 b
	DM	7.2 b	16.6 b	42.3 d	6.8 c	17.2 c
	DLM	7.2 b	16.2 b	43.3 cd	6.8 c	17.0 c
	DLMS1	7.2 b	16.3 b	46.1 b	7.2 ab	19.0 ab
	DLMS2	7.1 b	16.5 b	49.7 a	7.5 a	19.2 ab
	DLMS3	7.0 b	16.6 b	50.6 a	7.5 a	19.5 a
2021	FM	7.5 a	19.7 a	45.0 bc	7.3 a	18.4 b
	DM	7.4 a	18.3 b	43.7 c	6.8 b	17.1 c
	DLM	7.2 a	18.7 ab	43.7 c	6.7 b	17.0 c
	DLMS1	7.2 a	19.0 ab	47.3 b	7.5 a	19.2 ab
	DLMS2	7.3 a	19.0 ab	51.1 a	7.7 a	19.6 a
	DLMS3	7.4 a	19.1 ab	52.2 a	7.7 a	19.7 a

Note: Data in the table are means with three replicates. Different letters indicate significant difference at a $p = 0.05$ probability level within the same column in the same year.

3.6. Effect of Silicon Fertilizer on the Lodging Characteristics of Rice Stems in the Fourth Internode (N4) under Reduced N and Increased Density Conditions

The mechanical strength and growth structure of plants were affected by agronomic traits and the fourth internode physical traits and physiological characteristics, and the lodging traits of the plants also changed. The lodging traits of the fourth internode in rice are a comprehensive expression of both the physical and physiological characteristics of the plants. The lodging traits of the fourth internode in rice were measured and analyzed 40 days after the heading stage (Figure 3), and the changes in lodging traits were consistent among the different treatments throughout the year. The bending moment of the FM treatment was the highest, which was related to the formation of strong stems and relatively large panicles with low planting density. With a reduction in N fertilizer application and an increase in planting density, individual stems became thinner, leading to a sharp decrease in breaking resistance. After the application of silicon fertilizer, stem breaking resistance significantly ($p < 0.05$) increased with increasing application rate. The DM and DLM treatments had the lowest bending resistance, while the DLMS3 treatment had the highest bending resistance, which increased by 440.1 g and 503.8 g, respectively, compared to the lowest values in the DM treatment over the 2 years.

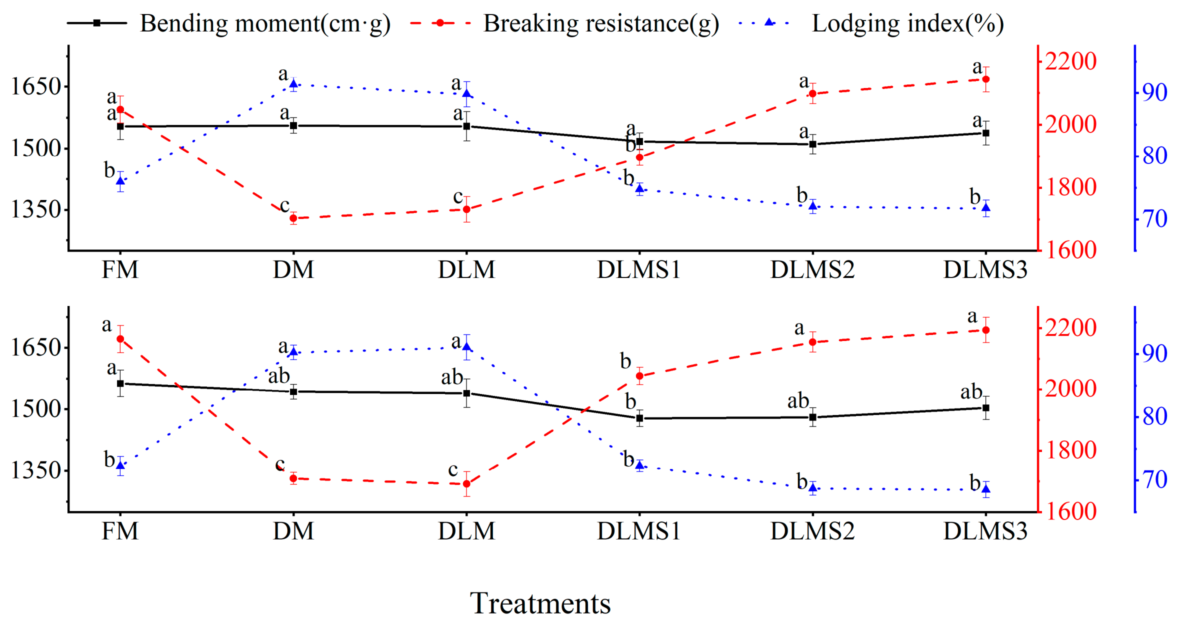

Figure 3. Stem lodging traits in the fourth internode (N4) of rice. Different letters of the same Parameters indicated significant differences in the same year ($p < 0.05$).

The lodging index is affected by both the bending moment and bending resistance. Due to the relatively stable bending moment, the lodging index and breaking resistance showed opposite trends. The lodging index of rice was low, with DLMS3 having the lowest value, which decreased by 19.6% and 22.5% compared to the highest values in DM (2020) and DLM (2021), respectively. Increased density alone and reduced N with increased density will increase the risk of lodging, and the application of silicon fertilizer can reduce the lodging index under the above conditions.

3.7. Correlation Analysis of Rice Stem Lodging Traits with Physiological Characteristics and Morphological Indicators

The correlation between the rice lodging index and various indices of the stem is shown in Figure 4. Statistical analysis of the correlation between the lodging characteristics of rice stems and yield components (Figure 4a,c) showed that the bending moment was positively correlated with the number of secondary branches and grains per panicle but negatively correlated with thousand grain weight. The bending resistance was positively correlated with the setting rate, thousand grain weight, and actual yield, and the 2-year correlation coefficients were 0.78 and 0.72, 0.90 and 0.95, and 0.57 and 0.60, respectively. This indicates that an increase in stem strength is beneficial for the single spike yield. The trend in the lodging coefficient was the opposite of the trend in the bending resistance, and as the lodging coefficient increased, both the yield and its constituent factors decreased.

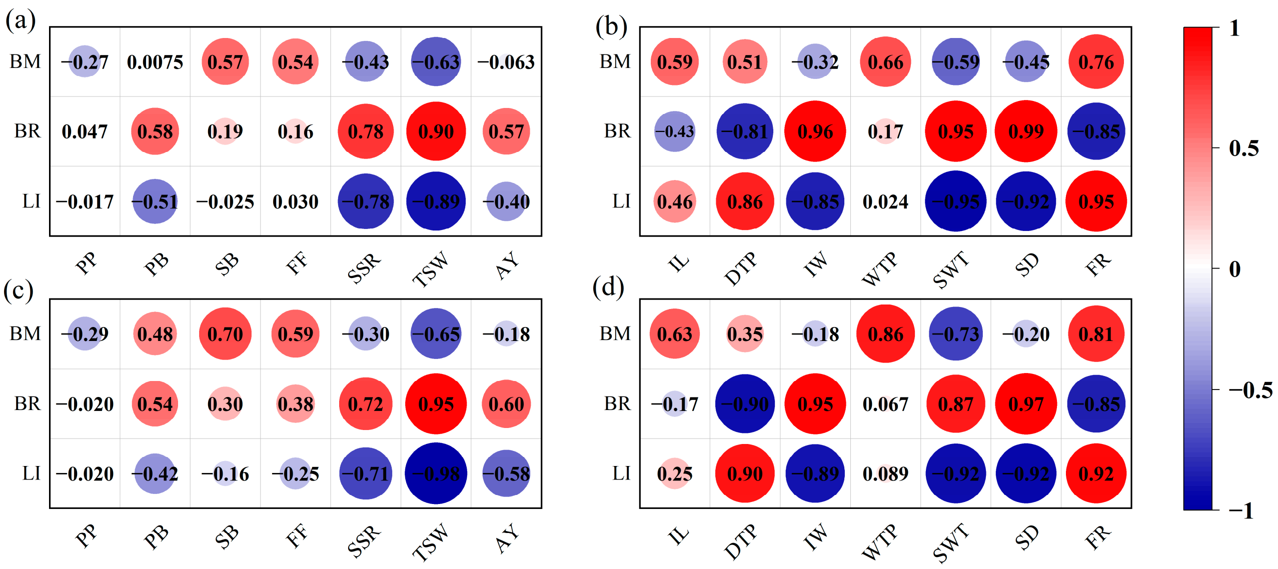

Figure 4. Correlation analysis between the lodging traits of rice stems and yield, its constituent factors, and internode morphology. (**a**) correlation between the lodging traits of rice stems and yield, its constituent factors in 2020, (**b**) correlation between the lodging traits of rice stems and internode morphology in 2020, (**c**) correlation between the lodging traits of rice stems and yield, its constituent factors in 2021 (**d**) correlation between the lodging traits of rice stems and internode morphology in 2021.

The statistical analysis of the correlation between the lodging characteristics of rice stems and internode morphology (Figure 4b,d) showed that the variation in the correlation coefficient of the bending moment was relatively small. The bending resistance was negatively correlated with the height from the top and the flattening rate, and the 2-year correlation coefficients were −0.81 and −0.85 (2020) and −0.90 and −0.85 (2021), respectively. Bending resistance was positively correlated with internode weight, internode stem wall thickness, and internode diameter, and the 2-year correlation coefficients were 0.96, 0.95, and 0.99 (2020) and 0.95 and 0.87, and 0.97 (2021), respectively. The trend in the lodging coefficient was opposite to the trend in bending resistance, negatively correlated with internode weight, internode stem wall thickness, and internode diameter, and positively correlated with the height from the top and the flattening rate. The results indicated that the lodging coefficient of stems decreased and the folding resistance increased with increasing stalk internode weight, thicker stalk wall thickness, longer internode diameter, lower height from the top, and a lower flatness rate, which enhanced the lodging resistance of the plants.

Statistical analysis of the correlation between rice stem lodging traits and population structure (Figure 5a,d) showed that the correlation between the number of tillers during critical growth periods and the rice lodging coefficient was relatively small. Bending resistance was negatively correlated with the number of stems and tillers at the basic seedling stage, jointing stage, and heading stage. The bending moment was negatively correlated with the number of stems and tillers at each stage, indicating that increasing the number of stems and tillers can lead to a decrease in the biomass of a single plant stem.

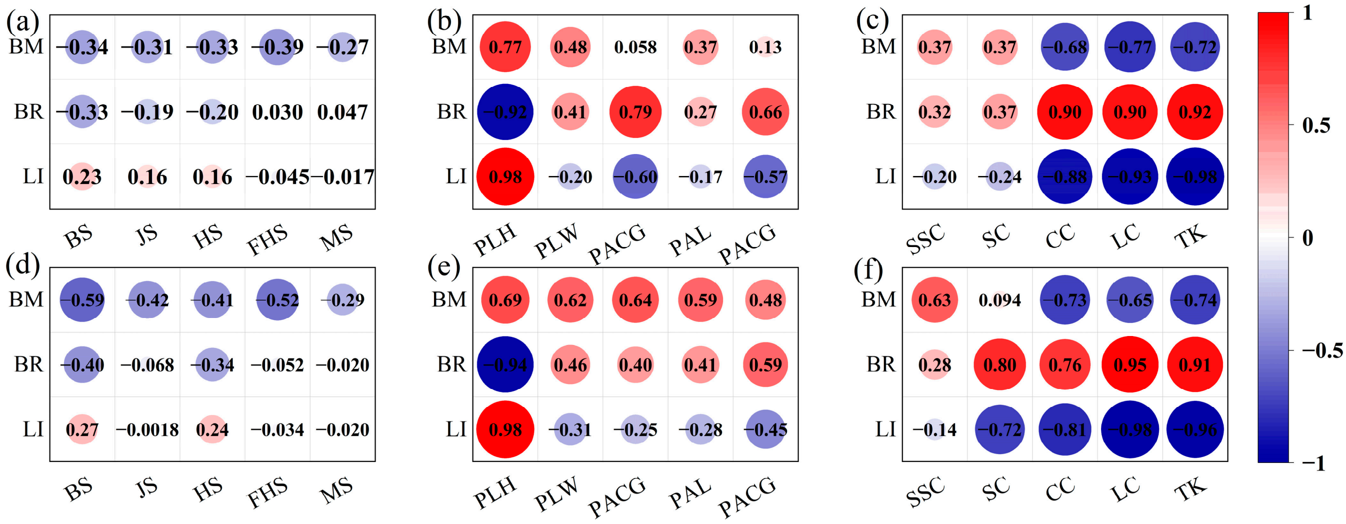

Figure 5. Correlation between the lodging traits of rice stems and population structure, panicle morphology, and stem physiological characteristics. (**a**) correlation between the lodging traits of rice stems and population structure in 2020, (**b**) correlation between the lodging traits of rice stems and panicle morphology in 2020, (**c**) correlation between the lodging traits of rice stems and stem physiological characteristics in 2020, (**d**) correlation between the lodging traits of rice stems and population structure in 2021, (**e**) correlation between the lodging traits of rice stems and panicle morphology in 2021, (**f**) correlation between the lodging traits of rice stems and stem physiological characteristics in 2021.

Statistical analysis of the correlation between rice stem lodging traits and panicle morphology and stem physiological characteristics (Figure 5b,e) showed that the correlation between the plant height and stem lodging traits was the most significant, with a negative correlation with the bending resistance and a positive correlation with the bending moment and lodging coefficient. The bending moment and bending resistance were positively correlated with the plant fresh weight, plant center of gravity, panicle length, and panicle center of gravity, while the lodging index was negatively correlated with them.

Statistical analysis of the correlation between the lodging traits and physiological characteristics of rice stems (Figure 5c,f) showed that soluble sugar content and starch content were positively correlated with the bending moment and bending resistance but negatively correlated with the lodging coefficient. The bending resistance was positively correlated with the cellulose content, lignin content, and total potassium content, and the 2-year correlation coefficients were 0.90, 0.90, and 0.92 (2020) and 0.76, 0.95, and 0.91 (2021), respectively. The bending moment and lodging index were negatively correlated with the cellulose content, lignin content, and total potassium content.

4. Discussion

In this paper, the combined effects of nitrogen fertilizer reduction, transplanting density increase, and silicon fertilizer addition on the dynamics of rice stalk, stem, and internode physical and physiological characteristics and yield were studied. Jointly increasing density, reducing N, and applying silicon fertilizer can promote the changes in stem dynamics, plant morphology, and physiological characteristics in the critical period of rice growth, thereby affecting rice yield and lodging traits. It was further verified that the DLMS3 treatment could reduce the lodging index to ensure stable rice yield, providing a reference for rice cultivation measures that achieve high yield and lodging resistance while protecting the environment.

Differences in planting density cause changes in the number of tillers during critical growth stages, affecting the morphological characteristics of stems, lignin, and cellulose composition, and lodging resistance, ultimately altering rice yield [9,29]. The combined application of silicon fertilizer is beneficial for normal physiological metabolism in rice and significantly promotes the growth of rice [9,30]. In this study, jointly increasing density, reducing N, and applying silicon fertilizer could promote changes in stem dynamics, plant morphology, and physiological characteristics during key growth stages, thereby affecting rice yield and lodging traits.

4.1. Effects of Increasing Density, Reducing Nitrogen, and Applying Silicon Fertilizer on the Yield and Morphological Characteristics of Rice

Planting density and nitrogen application, as two important cultivation and regulation techniques for rice production, have a decisive impact on rice population development and yield formation [31,32]. Yin et al. [33] believed that a reasonable nitrogen fertilizer application scheme and planting density can increase dry matter and nitrogen accumulation throughout the entire growth period of rice and increase the proportion of accumulation after heading, thereby increasing rice yield. Research conducted by Jiang et al. [34] in the high-temperature and humid rice area of southeastern Sichuan showed that increasing density by 27% and reducing nitrogen application by 15% to 30% can achieve a synergistic increase in hybrid rice yield and nitrogen fertilizer utilization efficiency. In this study, the densification with lower nitrogen treatment reduced the productive panicles number and total grains number, causing a rice yield decrease of 9.21% and 9.59%, respectively. The results showed that an emphasis on reducing N fertilizer application and increasing planting density may lead to a decrease in rice yield due to an insufficient number of productive panicles, reduced grain yield per panicle, and susceptibility to lodging. Therefore, consider adding silicon fertilizer to improve yields.

Silicon application can increase the number of productive panicles, grains per panicle, seed setting rate, and thousand grain weight of rice while reducing the number of unfertilized grains, thereby increasing rice yield [35]. Studies have shown that the nutrient content, effective panicle number, and yield of rice plants under the combined application of nitrogen and silicon fertilizer are higher than those under the application of nitrogen fertilizer or silicon fertilizer alone [16]. In this study, an increase in silicon fertilizer addition was beneficial to the formation of tillers, prevented the formation of a large number of ineffective tillers due to density increase, promoted the growth and development of rice, and resulted in increased production. Qiu et al. [36] (2022) studied the application of silicon fertilizer under intermittent irrigation conditions, indicating that silicon fertilizer has a promoting effect on the leaf area, number of grains per panicle, seed setting rate, yield, and irrigation utilization efficiency of functional leaves in rice. In this study, the application of silicon fertilizer increased the number of productive panicles and the number of grains per panicle during the mature stage. Su et al. [37] conducted a study on the silicon application rate for rice in arid areas, indicating that as the silicon fertilizer application rate increases, the yield first increases and then decreases. The optimal silicon application rate for high-yield and efficient cultivation is 30.00–47.68 kg/ha. In this study, DLMS2 and DLMS3 significantly increased the number of productive panicles and grains per panicle compared to DLMS1, significantly increasing rice yield. However, there was no significant difference between the application levels of DLMS2 and DLMS3. Thus, 150.0 kg/ha can be selected as the regional silicon fertilizer application rate based on comprehensive input factors.

4.2. Effects of Increasing Density, Reducing Nitrogen, and Applying Silicon Fertilizer on Internode Morphology, Physiological Changes, and Lodging Traits in Rice

The bending resistance of a stem can reflect its strength. The higher the strength of the stem, the less likely it is to be broken [9,25]. Wang et al. [20] believed that reasonable fertilizer and water management is conducive to improving stem morphological characteristics, reducing the plant height and center of gravity height of rice, increasing internode stem wall thickness and short axis coarseness, enhancing internode plumpness and physical strength, and reducing the lodging index. Guo et al. [16] studied the effects of shading on the morphological characteristics, lignin monomer composition, and lodging resistance of wheat stems under different planting densities. They found that shading during the jointing stage increased the length of basal internodes and plant height and proved that the center of gravity moving upward is the reason causing an increase in lodging. Similar results were obtained in our research. Compared with the FM treatment, the DM and DLM treatments decreased the fresh weight of the fourth node, but the lodging index increased with the decrease in the stem wall thickness, indicating that just densification and N reduction did weaken the lodging resistance of rice.

Silicon cannot only regulate the steady-state ion concentration in rice plants but also significantly enhance their ability to resist lodging and pests. Reasonable application of silicon fertilizer in combination with other measures is beneficial for the accumulation of lignin in rice stems, thereby improving the development of the stem xylem and enhancing the lodging resistance of rice. Lignin is a phenolic polymer that mainly increases in hardness, thickness, and compressive strength during the lignification process of plant cell walls [18,38]. In this study, both the 150.0 kg/ha and 225.0 kg/ha application levels increased the fresh weight, increased the stem wall thickness, decreased the flattening rate, and increased the cellulose content, lignin content, and total K content in the fourth internode, significantly improving the bending resistance and reducing the lodging index. The application of silicon fertilizer can shorten and thicken the internodes at the base of the stem, effectively enhancing the lodging resistance of crops. The results indicated that the combined application of silicon fertilizer was beneficial for improving stem toughness. Lou et al. [35] studied the application of silicon fertilizer to rice under nighttime warming, indicating that silicon application can increase the number of tillers, reduce plant height, increase stem wall thickness, and enhance lodging resistance. In this study, DLMS2 and DLMS3 reduced the lodging index of rice, enhanced the lodging resistance ability of rice, and improved rice yield. Topdressing with silicon fertilizer can improve the bending resistance of rice stems and reduce the lodging index, and the difference between the two application levels is not significant. Considering the cost factors of comprehensive application, 150.0 kg/ha is a reasonable regional silicon fertilizer application rate to promote lodging resistance. By investigating the effect of nitrogen reduction and densification combined with silicon fertilizer addition on lodging resistance, this study, on the one hand, filled a gap in the study on lodging resistance in response to nitrogen reduction and densification combined with silicon application and, on the other hand, showed that nitrogen reduction and densification combined with silicon application can effectively enhance lodging resistance in rice varieties, which has important practical significance for reducing lodging.

5. Conclusions

The application of Si improved rice grain yields compared to non-Si treatment under reduced nitrogen and increased density conditions. The higher grain yield of the Si treatment was complemented by the summation of effective panicle number, full grain number, and thousand grain weight. Additionally, the Si treatments effectively increased fourth internode cellulose, lignin, total K concentration, and stem strength compared to improved density mode and increased density with decreased N mode. Among the various treatment combinations, 150.0 kg/ha silicon fertilizer in combination with reduced N and increased density can reduce the lodging index while ensuring rice yield, thereby avoiding the imbalanced situation of yield reduction and lodging due to a density increase alone or to nitrogen reduction with a density increase. This achieves the goal of reducing N fertilizer input and achieving a uniform yield and lodging resistance.

Our results highlight the substantial potential of silicon fertilizer application in influencing rice yield and lodging resistance. The results provide a reference for the systematic application of silicon fertilizer and the selection of cultivation management practices to achieve a stable yield, high quality, and high efficiency in rice production.

Author Contributions: L.D., conceived and designed the experiments, performed the experiments, analyzed the data, Wrote the first and final draft; T.Y., analyzed the data, authored or reviewed drafts of the paper; L.M., analyzed the data; R.L., performed the experiments, analyzed the data; Y.F., performed the experiments, analyzed the data; Y.L., conceived and designed the experiments, contributed reagents/materials/analysis tools, reviewed the first drafts, confirmed the final manuscript, Decided on paper submission. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Key R&D Program of China (2017YFD0300700).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

References

1. Mohidem, N.A.; Hashim, N.; Shamsudin, R.; Che Man, H. Rice for Food Security: Revisiting Its Production, Diversity, Rice Milling Process and Nutrient Content. *Agriculture* **2022**, *12*, 741. [CrossRef]
2. FAOSTAT. Production/Yield Quantities of Rice, Paddy in World + (Total). Food and Agriculture Organization of the United Nations. 2022. Available online: https://www.fao.org/faostat/en/#data/QCL/visualize (accessed on 17 February 2024).
3. FAOSTAT. Production/Yield Quantities of Rice, Paddy in China. Food and Agriculture Organization of the United Nations. 2022. Available online: https://www.fao.org/faostat/en/#data/QCL/visualize (accessed on 17 February 2024).
4. Fu, W.; Zhao, Y.; Zha, X.; Ullah, J.; Ye, M.; Shah, F.; Yuan, Q.; Wang, P.; Tao, Y.; Wu, W. The Potential Role of Zinc and Silicon in Improving Grain Yield and Lodging Resistance of Rice (*Oryza sativa* L.). *Agronomy* **2023**, *14*, 91. [CrossRef]
5. Xu, C.C.; Ji, L.; Chen, Z.D.; Fang, F.P. Analysis of China's Rice Industry in 2022 and the Outlook for 2023. *China Rice* **2023**, *29*, 1–4. [CrossRef]
6. Li, H.; Li, X.; Wang, L.; LI, Y.; Wang, J. Development measures of the fertilizer industry under the carbon peaking and carbon neutrality goals: Analysis of carbon emission reduction and existing problems from 2011 to 2020. *Chin. J. Eco-Agric.* **2023**, *31*, 206–213. [CrossRef]
7. Ke, J.; Sun, J.; Chen, T.; Tao, S.; Zhu, T.; Yin, C.; He, H.; You, C.; Wu, L.; Guo, S. Effects of mixed fertilizers formed by the compounding of two targeted controlled-release nitrogen fertilizers on yield, nitrogen use efficiency, and ammonia volatilization in double-cropping rice. *Crop J.* **2023**, *11*, 628–637. [CrossRef]
8. Yang, S.Q. Thought of Pollution Comprehensive Prevention and Control System of Non-Point Sources Based on National Food Security. *Sci. Agric. Sin.* **2022**, *55*, 3380–3394.
9. Chen, Y.; Liu, Y.; Dong, S.; Liu, J.; Wang, Y.; Hussain, S.; Wei, H.; Huo, Z.; Xu, K.; Dai, Q. Response of Rice Yield and Grain Quality to Combined Nitrogen Application Rate and Planting Density in Saline Area. *Agriculture* **2022**, *12*, 1788. [CrossRef]
10. Xiao, N.; Dong, L.Q.; Cong, L.; Sun, X.S.; Zhou, C.C.; Wang, Y.Z.; Jia, B.Y.; Huang, Y.C.; Wang, S. Effect of Nitrogen Application on Lodging Resistance and Yields of Japonica Rice under Drill Seeding. *J. Shenyang Agric. Univ.* **2017**, *48*, 647–653.
11. 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. [CrossRef]
12. Ma, J.F.; Yamaji, N. A cooperative system of silicon transport in plants. *Trends Plant Sci.* **2015**, *20*, 435–442. [CrossRef]
13. Liu, G.; Ouyang, X.; Li, Z.; Fu, Y.; Shen, H. Seaweed Oligosaccharide Synergistic Silicate Improves the Resistance of Rice Plants to Lodging Stress under High Nitrogen Level. *Agronomy* **2022**, *12*, 1750. [CrossRef]
14. Ahsan, M.; Valipour, M.; Nawaz, F.; Raheel, M.; Abbas, H.T.; Sajid, M.; Manan, A.; Kanwal, S.; Mahmoud, E.A.; Casini, R.; et al. Evaluation of Silicon Supplementation for Drought Stress under Water-Deficit Conditions: An Application of Sustainable Agriculture. *Agronomy* **2023**, *13*, 599. [CrossRef]
15. Wang, M.; Wang, R.; Mur, L.A.J.; Ruan, J.; Shen, Q.; Guo, S. Functions of silicon in plant drought stress responses. *Hortic. Res.* **2021**, *8*, 254. [CrossRef] [PubMed]

16. Guo, B.; Luo, Y.S.; Liang, Y.C.; Zhang, J.; Hua, H.X.; Xi, Y.L. Effects of nitrogen and silicon applications on the growth and yield of rice and soil fertility. *Chin. J. Ecol.* **2004**, *23*, 33–36.
17. Pati, S.; Pal, B.; Badole, S.; Hazra, G.C.; Mandal, B. Effect of Silicon Fertilization on Growth, Yield, and Nutrient Uptake of Rice. *Commun. Soil Sci. Plant Anal.* **2016**, *47*, 284–290. [CrossRef]
18. Rangaraj, S.; Gopalu, K.; Rathinam, Y.; Periasamy, P.; Venkatachalam, R.; Narayanasamy, K. Effect of silica nanoparticles on microbial biomass and silica availability in maize rhizosphere. *Biotechnol. Appl. Biochem.* **2014**, *61*, 668–675. [CrossRef] [PubMed]
19. Zhao, X.; Hu, Y.; Liang, B.; Chen, G.; Feng, L.; Pu, T.; Sun, X.; Yong, T.; Liu, W.; Liu, J.; et al. Coordination of Density and Nitrogen Fertilization Improves Stalk Lodging Resistance of Strip-Intercropped Maize with Soybeans by Affecting Stalk Quality Traits. *Agriculture* **2023**, *13*, 9. [CrossRef]
20. Wang, Z.; Cheng, X.; Xie, Y.; Hong, C.; Hu, M.; Gao, Y.; You, J.; He, Y.; Liu, J.; Xiao, B. Effects of different water and fertilizer use patterns on the lodging resistances of indica and japonica rice. *Trans. Chin. Soc. Agric. Eng.* **2022**, *38*, 108–118.
21. Guo, D.; Chen, F.; Inoue, K.; Blount, J.W.; Dixon, R.A. Down regulation of caffeic acid 3-O-methyltransferase and caffeoyl CoA 3 methyltransferase in transgenic alfalfa impacts on lignin structure and implications for the biosynthesis of G and S lignin. *Plant Cell* **2001**, *13*, 73–88. [CrossRef]
22. Liang, Y.; Nikolic, M.; Bélanger, R.; Gong, H.; Song, A. Effect of Silicon on Crop Growth, Yield and Quality. In *Silicon in Agriculture*; Springer: Berlin/Heidelberg, Germany, 2015; pp. 209–223.
23. Inanaga, S.; Higuchi, Y.; Chishaki, N. Effect of silicon application on reproductive growth of rice plant. *Soil Sci. Plant Nutr.* **2002**, *48*, 341–345. [CrossRef]
24. Yang, H.; Yang, R.; Li, Y.; Jiang, Z.; Zheng, J. Relationship between culm traits and lodging resistance of rice cultivars. *Fujian J. Agric. Sci.* **2000**, *15*, 1–7.
25. Xu, Q.; Guo, L.; Liu, Y.; Gao, Y. Effects of potassium and silicon fertilization on lignin metabolism and lodging resistance of oil flax stem. *Chin. J. Eco-Agric.* **2022**, *30*, 1451–1463. [CrossRef]
26. Dong, L.Q.; Gao, H.; Li, Y.D.; Li, R.; Shan, W.Q.; Yao, J.P.; Ma, L.; Sui, G.M. Effects of Row and Hill Spacing on Rice Canopy Structure and Yield. *J. Shenyang Agric. Univ.* **2021**, *52*, 265–271.
27. Liu, K.; Huang, J.; Zhou, S.Q.; Zhang, W.Y.; Zhang, H.; Gu, J.F.; Liu, L.J.; Yang, J.C. Effects of panicle nitrogen fertilizer rates on grain yield in super rice varieties with different panicle sizes and their mechanism. *Acta Agron. Sin.* **2022**, *48*, 2028–2040. [CrossRef]
28. Bao, S. *Soil and Agricultural Chemistry Analysis*; Agriculture Press: Beijing, China, 2000; pp. 57–83.
29. Luo, Y.; Chang, Y.; Li, C.; Wang, Y.; Cui, H.; Jin, M.; Wang, Z.; 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] [PubMed]
30. Han, Y.Q.; Wei, C.G.; Hou, M.L. Role of silicon in regulating plant resistance to insect herbivores. *Acta Ecol. Sin.* **2012**, *32*, 974–983. [CrossRef]
31. Zhai, J.; Zhang, Y.M.; Zhang, G.Q.; Tian, M.; Xie, R.Z.; Ming, B.; Hou, P.; Wang, K.R.; Xue, J.; Li, S.K. Effects of Nitrogen Fertilizer Management on Stalk Lodging Resistance Traits in Summer Maize. *Agriculture* **2022**, *12*, 162. [CrossRef]
32. Shi, N.; Wen, S.Y.; Gao, Q.W.; Gao, Z.Q.; Yang, H.B. Printed sowing of high-density mechanical transplanted hybrid rice can reduce the amount of fertilizer needed. *Agronomy* **2022**, *12*, 2002. [CrossRef]
33. Yin, C.X.; Liu, Z.Q.; Kong, L.L.; Li, Q.; Zhang, L.; Hou, Y.P.; Hao, C.H. Reducing nitrogen and increasing rice transplanting density in a cold region of China can improve rice yield, nitrogen absorption, and nitrogen utilization. *J. Agric. Resour. Environ.* **2022**, *39*, 1124–1132.
34. Jiang, P.; Xu, F.; Zhang, L.; Zhou, X.; Zhu, Y.; Guo, X.; Liu, M.; Chen, L.; Zhang, R.; Xiong, H. Effect of increased plant density with reduced nitrogen on yield formation and nitrogen use efficiency of hybrid rice under high temperature and high humidity conditions. *Chin. J. Eco-Agric.* **2021**, *29*, 1679–1691. [CrossRef]
35. Lou, Y.S.; Yu, Y.J.; Liu, Y.; Yang, H.L.; Zhou, D.X. Effects of silicate application on rice growth, yield and quality under nighttime warming in southern China. *Chin. J. Appl. Ecol.* **2023**, *34*, 985–992.
36. Qiu, J.H.; Xue, Z.; Sun, S.H.; Peng, J.Z.; Zhang, P.F.; Dong, J.S.; Yi, R.C. Effects of water-soluble silicon fertilizer application at different growth stages on rice yield and quality under intermittent irrigation. *J. Northeast Agric. Univ.* **2022**, *53*, 50–57.
37. Su, Q.W.; Cang, B.F.; Bai, C.Y.; Li, Y.Z.; Song, Z.; Li, J.C.; Wu, M.K.; Wei, X.S.; Cui, J.J.; Wu, Z.H. Effect of Silicon Application Rate on Yield and Dry Matter Accumulation of Rice Under Dry Cultivation. *Chin. J. Rice Sci.* **2022**, *36*, 87–95.
38. Raes, J.; Rohde, A.; Christensen, J.H.; Van de Peer, Y.; Boerjan, W. Genome-Wide Characterization of the Lignification Toolbox in Arabidopsis. *Plant Physiol.* **2003**, *133*, 1051–1071. [CrossRef] [PubMed]