

## Effects of Planting Density on Stalk Traits and Yield of Summer Maize in the Hilly Region of Central Sichuan Postprint

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### Abstract

Using maize variety ‘Zhenghong 505’ as experimental material, five planting density treatments of  $4.50 \times 10$  plants  $\cdot$  hm<sup>2</sup>,  $5.25 \times 10$  plants  $\cdot$  hm<sup>2</sup>,  $6.00 \times 10$  plants  $\cdot$  hm<sup>2</sup>,  $6.75 \times 10$  plants  $\cdot$  hm<sup>2</sup>, and  $7.50 \times 10$  plants  $\cdot$  hm<sup>2</sup> were established to investigate the effects of planting density on stalk traits and yield of summer maize in the hilly regions of central Sichuan. The results demonstrated that with increasing planting density, plant height, ear height, internode length, and length-to-diameter ratio of stem internodes progressively increased, whereas stem diameter, stem diameter coefficient, internode diameter, internode dry weight, dry matter weight per unit stem length, stalk crushing strength, and rind penetration strength progressively decreased; significant differences were observed among all traits except ear height. Specifically, when planting density increased to  $7.50 \times 10$  plants  $\cdot$  hm<sup>2</sup>, the rind penetration strength of the 1st, 3rd, and 5th stem internodes decreased by 27.10%, 22.78%, and 30.80%, respectively, compared with  $4.50 \times 10$  plants  $\cdot$  hm<sup>2</sup>. Within the experimental density range, maize yield initially increased and subsequently decreased with increasing density, reaching its maximum at  $6.00 \times 10$  plants  $\cdot$  hm<sup>2</sup>, which significantly increased yield by 12.02% compared with  $4.50 \times 10$  plants  $\cdot$  hm<sup>2</sup>. With increasing planting density, ear length, ear diameter, ear setting rate, kernel number per ear, and 1000-kernel weight significantly decreased, while effective ear number and bare tip length significantly increased. Correlation analysis revealed that stalk crushing strength was extremely significantly positively correlated with rind penetration strength ( $r=0.93^{**}$ ), and both stalk crushing strength and rind penetration strength were significantly or extremely significantly positively correlated with stem diameter, stem diameter coefficient, internode diameter, internode dry weight, and dry matter weight per unit stem length, while being negatively correlated or extremely significantly negatively correlated with plant height, internode length, and length-to-diameter ratio of stem internodes.

Among these, stalk agronomic traits exhibited stronger correlations with stalk crushing strength. Yield per plant was significantly or extremely significantly positively correlated with stem diameter, stem diameter coefficient, internode diameter, internode dry weight, dry matter weight per unit stem length, stalk crushing strength, and rind penetration strength, and significantly negatively correlated with internode length and length-to-diameter ratio of stem internodes. Stepwise regression analysis indicated that stem diameter coefficient and dry matter weight per unit stem length exerted the greatest influence on stalk crushing strength. In conclusion, planting density represents a crucial factor affecting maize stalk traits and yield; appropriately increasing planting density can significantly enhance maize population yield, while stem diameter coefficient and dry matter weight per unit stem length can serve as important agronomic indicators for evaluating maize stalk lodging resistance.

### Full Text

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## Effect of Planting Density on Stem Characteristics and Yield of Summer Maize in the Hilly Central Sichuan Basin, China

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**Abstract:** Using the maize cultivar ‘Zhenghong 505’ as experimental material, five planting density treatments were established:  $4.50 \times 10$ ,  $5.25 \times 10$ ,  $6.00 \times 10$ ,  $6.75 \times 10$ , and  $7.50 \times 10$  plants  $\cdot$  hm<sup>2</sup> to investigate the effects of planting density on stem characteristics and yield of summer maize in the Hilly Central Sichuan Basin. The results showed that with increasing planting density, plant height, ear height, internode length, and length-to-diameter ratio of internodes gradually increased, while stem diameter, stem diameter coefficient, internode dry weight, dry matter weight per unit stem length, stalk crushing strength (SCS), and rind penetration strength (RPS) gradually decreased. Except for ear height, all other traits showed significant differences among density treatments. Specifically, when planting density increased to  $7.50 \times 10$  plants  $\cdot$  hm<sup>2</sup>, the RPS of the 1st, 3rd, and 5th internodes decreased significantly by 27.10%, 22.78%, and 30.80%, respectively, compared with the  $4.50 \times 10$  plants  $\cdot$  hm<sup>2</sup> treatment. Within the density range tested, maize yield initially increased and then decreased with increasing density, reaching its maximum at  $6.00 \times 10$  plants  $\cdot$  hm<sup>2</sup>, which produced a significant yield increase of 12.02% compared with  $4.50 \times 10$

plants  $\cdot$  hm<sup>2</sup>. With increasing planting density, ear length, ear diameter, spike rate, kernels per spike, and 1000-seed weight decreased significantly, while effective panicle number and barren tip length increased significantly. Correlation analysis indicated that SCS was extremely significantly positively correlated with RPS ( $r=0.93^{**}$ ). Both SCS and RPS showed significant or extremely significant positive correlations with stem diameter, stem diameter coefficient, internode diameter, internode dry weight, and dry matter weight per unit stem length, but negative or extremely significant negative correlations with plant height, internode length, and length-to-diameter ratio. The correlations between stem agronomic traits and SCS were stronger. Grain yield per plant showed significant or extremely significant positive correlations with stem diameter, stem diameter coefficient, internode diameter, internode dry weight, dry matter weight per unit stem length, SCS, and RPS, but significant negative correlations with internode length and length-to-diameter ratio. Stepwise regression analysis revealed that stem diameter coefficient and dry matter weight per unit stem length had the greatest influence on SCS. In conclusion, planting density is a critical factor affecting maize stem characteristics and yield; appropriately increasing planting density can significantly increase population yield, while stem diameter coefficient and dry matter weight per unit stem length can serve as important agronomic indicators for evaluating maize stalk lodging resistance.

**Keywords:** Summer maize; Planting density; Stalk characteristics; Lodging resistance; Yield; Hilly Central Sichuan Basin

## Introduction

Maize (*Zea mays*) is the largest grain crop in China and one of the important food crops in the Hilly Central Sichuan Basin [1-2]. Increasing planting density has been a primary measure for exploiting maize yield potential [3-6]; however, increased density affects maize stem characteristics, such as taller plant height and ear height, thinner stem diameter, and reduced stem strength, ultimately decreasing stalk lodging resistance and increasing the risk of lodging [7-9]. Previous studies have indicated that after lodging, maize shows significantly reduced dry matter accumulation, shorter ear length, thinner ear diameter, and significantly decreased yield [10]. It is estimated that annual losses due to maize stalk lodging range from 5% to 25%, with severe lodging causing near-total crop failure [11-12]. Therefore, investigating the effects of planting density on maize stem characteristics and exploring the relationship between stem traits and yield have important theoretical and practical significance.

Previous research has demonstrated that planting density significantly affects stem agronomic traits such as plant height, ear height, and internode length, as well as mechanical traits including stalk crushing strength and rind penetration strength. Plant height, ear height, internode length, and length-to-diameter ratio show significant or extremely significant positive correlations with lodging rate, while internode dry weight, percentage of internode dry weight, dry

matter weight per unit stem length, and stem mechanical characteristics show significant or extremely significant negative correlations with lodging rate, with the best correlations observed at the basal 3rd internode. Stem diameter, dry matter weight per unit stem length, and stem mechanical traits can serve as indicators for evaluating stalk lodging resistance [11,13-20]. Currently, research on maize lodging resistance has focused primarily on northern China, investigating the effects of planting density on stem traits, relationships between stem traits and lodging rate, and screening of lodging resistance evaluation indicators [11,13-21]. However, few studies have reported on lodging resistance in Southwest China or on the relationship between maize stem traits and yield. In recent years, with the development of cropping systems and large-scale farming operations, the wheat (*Triticum aestivum*)-summer maize double-cropping system has become an important planting pattern in the hilly drylands of Southwest China. No studies have examined the effects of density on summer maize stem traits and yield under this system. This study systematically analyzed the effects of different planting densities on summer maize stem characteristics and yield in the Hilly Central Sichuan Basin and explored the relationships among planting density, stem traits, and yield, providing a theoretical basis for constructing high-yield cultivation systems for summer maize in the wheat-maize cropping system of Southwest China's hilly regions.

### 1.1 Experimental Site Overview

The experiment was conducted at the experimental field of HuiNong Grain Professional Cooperative in Jiqing Town, Zhongjiang County, Deyang City, Sichuan Province (30°35' N, 104°37' E), located in hilly dryland. The region has a subtropical humid monsoon climate with an average annual temperature of 16.7°C, annual precipitation of 883 mm, and a frost-free period of 286 days. Meteorological data for Zhongjiang in 2015 are shown in [Figure 1: see original paper]. The basic physicochemical properties of the topsoil (0-20 cm) were: soil bulk density 1.40 g · cm<sup>-3</sup>, total nitrogen 1.61 g · kg<sup>-1</sup>, organic matter 14.78 g · kg<sup>-1</sup>, alkaline hydrolysis nitrogen 42.93 mg · kg<sup>-1</sup>, available phosphorus 5.9 mg · kg<sup>-1</sup>, available potassium 104.44 mg · kg<sup>-1</sup>, and pH 7.80.

### 1.2 Experimental Design

A single-factor randomized block design was adopted using the maize cultivar 'Zhenghong 505' (provided by Zhenghong Seed Industry Co., Ltd. of Sichuan Agricultural University), a recommended cultivar by the Sichuan Provincial Department of Agriculture. Five planting densities were established: 4.50×10 plants · hm<sup>-2</sup> (spacing 27.78 cm), 5.25×10 plants · hm<sup>-2</sup> (spacing 23.81 cm), 6.00×10 plants · hm<sup>-2</sup> (spacing 20.83 cm), 6.75×10 plants · hm<sup>-2</sup> (spacing 18.52 cm), and 7.50×10 plants · hm<sup>-2</sup> (spacing 16.67 cm). A wide-narrow row planting pattern was used with wide rows of 1.2 m and narrow rows of 0.4 m. The experiment was replicated three times with 15 plots total, each plot measuring 19.2 m<sup>2</sup>. Sowing occurred on May 14, 2015, and harvest on August 25, 2015.

Before sowing, compound fertilizer with an N:P:K ratio of 25:7:8 was applied uniformly as base fertilizer at a rate of  $900 \text{ kg} \cdot \text{hm}^{-2}$ .

### 1.3 Measurement Methods

**1.3.1 Plant Height, Ear Height, Internode Length and Stem Diameter** At 7 days and 25 days after silking, 10 representative plants were selected from each plot to measure plant height, ear height, internode length (1st, 3rd, and 5th internodes), and stem diameter (1st, 3rd, and 5th internodes). The length-to-diameter ratio of internodes (internode length/internode diameter), stem diameter coefficient (stem diameter/plant height  $\times 100\%$ ), and ear height coefficient (ear height/plant height  $\times 100\%$ ) were calculated.

**1.3.2 Rind Penetration Strength (RPS)** At 7 days and 25 days after silking, three representative plants were selected from each plot. The 1st, 3rd, and 5th above-ground internodes were collected, leaf sheaths were removed, and rind penetration strength was measured using an AWOS-SL04 plant stem strength tester produced by Shijiazhuang Aiwoshi Technology Co., Ltd. A probe with a cross-sectional area of  $0.01 \text{ cm}^2$  was inserted vertically and slowly into the middle of the internode at constant speed, and the maximum value at penetration was recorded.

**1.3.3 Stalk Crushing Strength (SCS)** At 7 days and 25 days after silking, three representative plants were selected from each plot. The 1st, 3rd, and 5th above-ground internodes were collected, leaf sheaths were removed, and stalk crushing strength was measured using an AWOS-SL04 plant stem strength tester produced by Shijiazhuang Aiwoshi Technology Co., Ltd. A probe with a cross-sectional area of  $1 \text{ cm}^2$  was pressed vertically and slowly onto the middle of the internode until the stalk ruptured, and the maximum value was recorded.

**1.3.4 Internode Weight** At 7 days and 25 days after silking, three representative plants were selected from each plot. The 1st, 3rd, and 5th above-ground internodes were collected, leaf sheaths were removed, and fresh weight of each internode was measured. Samples were then killed at  $105^\circ\text{C}$  for 60 minutes and oven-dried at  $80^\circ\text{C}$  to constant weight. The percentage of stalk dry weight and dry matter weight per unit stem length were calculated, where internode dry weight percentage (%) = internode dry weight/internode fresh weight  $\times 100$ , and dry matter weight per unit stem length = internode dry weight/internode length ( $\text{g} \cdot \text{cm}^{-1}$ ).

**1.3.5 Yield and Yield Components** Maize was harvested by plot for actual yield measurement. Twenty ears were selected using the average ear weight method for indoor examination to determine ear length, ear diameter, and 1000-seed weight.

## 1.4 Data Analysis

Data were processed using Microsoft Excel 2007. Statistical analysis was performed using SPSS 19.0 software, and graphs were prepared using GraphPad Prism 5.0 software.

## 2 Results

### 2.1 Effects of Planting Density on Stem Agronomic Traits

**2.1.1 Plant Height, Ear Height, Stem Diameter, Ear Height Coefficient and Stem Diameter Coefficient** As shown in , with increasing planting density, maize plant height and ear height showed increasing trends, stem diameter and stem diameter coefficient gradually decreased, while ear height coefficient first decreased and then increased. Planting density had significant effects on plant height, stem diameter, and stem diameter coefficient ( $P < 0.05$ ). Compared with  $4.50 \times 10$  plants  $\cdot$  hm<sup>2</sup>, plant height and ear height under  $6.75 \times 10$  plants  $\cdot$  hm<sup>2</sup> increased by 9.83% and 9.86%, respectively, while stem diameter and stem diameter coefficient under  $7.50 \times 10$  plants  $\cdot$  hm<sup>2</sup> decreased by 16.11% and 21.95%, respectively. Data patterns at 25 days after silking were consistent with those at 7 days after silking.

**2.1.2 Internode Length, Internode Diameter and Length-to-Diameter Ratio** As shown in , planting density had significant effects on internode length, internode diameter, and length-to-diameter ratio ( $P < 0.05$ ). With increasing density, internode length and length-to-diameter ratio showed increasing trends, while internode diameter gradually decreased. As node position increased, internodes became longer and thinner. At 7 days after silking, when density increased to  $6.75 \times 10$  plants  $\cdot$  hm<sup>2</sup>, the 3rd internode length and length-to-diameter ratio increased significantly by 31.00% and 51.62%, respectively, compared with  $4.50 \times 10$  plants  $\cdot$  hm<sup>2</sup>. Meanwhile, the 1st, 3rd, and 5th internode diameters under  $7.50 \times 10$  plants  $\cdot$  hm<sup>2</sup> decreased significantly by 15.87%, 14.90%, and 15.26%, respectively, compared with  $4.50 \times 10$  plants  $\cdot$  hm<sup>2</sup>. Data patterns at 25 days after silking were consistent with those at 7 days after silking.

**2.1.3 Internode Dry Weight and Dry Weight Percentage** shows that with increasing planting density, both internode dry weight and dry weight percentage showed decreasing trends. At 7 days after silking, the 1st, 3rd, and 5th internode dry weights under  $7.50 \times 10$  plants  $\cdot$  hm<sup>2</sup> decreased significantly by 22.55%, 18.47%, and 23.98%, respectively, compared with  $4.50 \times 10$  plants  $\cdot$  hm<sup>2</sup>. The 1st internode dry weight percentage under  $7.50 \times 10$  plants  $\cdot$  hm<sup>2</sup> decreased significantly by 13.04% and 14.58% compared with  $4.50 \times 10$  and  $6.00 \times 10$  plants  $\cdot$  hm<sup>2</sup>, respectively. Data patterns at 25 days after silking were consistent with those at 7 days after silking, although differences in internode dry weight percentage among treatments were not significant at 25 days after

silking.

From 7 days to 25 days after silking, except for basal internodes, dry weights of all internodes decreased to varying degrees, with more pronounced decreases at higher node positions, likely related to the proximal transport and distribution of dry matter. Internode dry weight percentage increased with rising node position and advancing growth stage, possibly due to drought conditions during the experimental year, resulting in lower plant water content and higher dry weight percentage.

**2.1.4 Dry Matter Weight per Unit Stem Length** As shown in [Figure 2: see original paper], planting density had substantial effects on dry matter weight per unit stem length, generally following the pattern of low density > high density, and 1st internode > 3rd internode > 5th internode. At 7 days after silking, the dry matter weight per unit stem length of the 1st, 3rd, and 5th internodes under  $6.75 \times 10$  plants  $\cdot$  hm<sup>2</sup> decreased significantly by 24.84%, 22.21%, and 25.24%, respectively, compared with  $4.50 \times 10$  plants  $\cdot$  hm<sup>2</sup>. Data patterns at 25 days after silking were consistent with those at 7 days after silking. From 7 days to 25 days after silking, due to the translocation of stem dry matter to the ear, internode dry weights (except basal internodes) decreased to varying degrees, while internode length remained essentially unchanged or increased slightly, resulting in decreased dry matter weight per unit stem length across all density treatments.

## 2.2 Effects of Planting Density on Stem Mechanical Traits

**2.2.1 Stalk Crushing Strength** As shown in [Figure 3: see original paper], stalk crushing strength showed a decreasing trend with increasing planting density and advancing internode position. At 7 days after silking, when density increased to  $6.75 \times 10$  plants  $\cdot$  hm<sup>2</sup>, the crushing strength of the 3rd and 5th internodes decreased significantly by 14.15% and 27.71%, respectively, compared with  $4.50 \times 10$  plants  $\cdot$  hm<sup>2</sup>. Data patterns at 25 days after silking were consistent with those at 7 days after silking. From 7 days to 25 days after silking, crushing strength of all internodes decreased to varying degrees.

**2.2.2 Rind Penetration Strength** As shown in [Figure 4: see original paper], rind penetration strength showed a decreasing trend with increasing planting density and advancing internode position. At 25 days after silking, when density increased to  $7.50 \times 10$  plants  $\cdot$  hm<sup>2</sup>, the rind penetration strength of the 1st, 3rd, and 5th internodes decreased significantly by 27.10%, 22.78%, and 30.80%, respectively, compared with  $4.50 \times 10$  plants  $\cdot$  hm<sup>2</sup>. Data patterns at 7 days after silking were consistent with those at 25 days after silking.

## 2.3 Effects of Planting Density on Yield and Yield Components

shows that planting density had significant effects on maize yield. Population yield increased initially and then decreased with increasing density, reaching

its maximum at  $6.00 \times 10$  plants  $\cdot$  hm<sup>2</sup>, while grain yield per plant decreased significantly. Compared with  $4.50 \times 10$  plants  $\cdot$  hm<sup>2</sup>, the  $6.00 \times 10$  plants  $\cdot$  hm<sup>2</sup> treatment significantly increased yield by 12.02% but decreased grain yield per plant by 16.35%. Additionally, planting density significantly affected ear length, ear diameter, barren tip length, effective panicle number, spike rate, kernels per spike, and 1000-seed weight ( $P < 0.05$ ). When planting density increased to  $7.50 \times 10$  plants  $\cdot$  hm<sup>2</sup>, ear length, ear diameter, spike rate, kernels per spike, and 1000-seed weight decreased significantly by 7.56%, 3.88%, 14.69%, 22.90%, and 8.30%, respectively, compared with  $4.50 \times 10$  plants  $\cdot$  hm<sup>2</sup>, while barren tip length and effective panicle number increased significantly by 42.18% and 20.15%, respectively. These results indicate that increasing planting density damages ear characteristics and reduces grain yield per plant. However, the significant yield increase at higher densities demonstrates that population productivity compensated for individual plant productivity deficiencies, thereby increasing population yield—one reason why increasing planting density can achieve high yields. When planting density exceeded the optimal level, the advantage of effective panicle number no longer existed, resulting in decreased population yield.

## 2.4 Correlation and Regression Analysis

**2.4.1 Correlation Analysis** shows that correlations between planting density and various indicators such as plant height and stem diameter reached significant ( $P < 0.05$ ) or extremely significant levels ( $P < 0.01$ ). Planting density was positively correlated with plant height, internode length, and length-to-diameter ratio, but negatively correlated with stem diameter, stem diameter coefficient, internode diameter, internode dry weight, dry matter weight per unit stem length, rind penetration strength, stalk crushing strength, and grain yield per plant. Correlations between stem agronomic traits and mechanical traits revealed that stem diameter, stem diameter coefficient, internode diameter, internode dry weight, and dry matter weight per unit stem length showed significant or extremely significant positive correlations with both rind penetration strength and stalk crushing strength, while plant height, internode length, and length-to-diameter ratio showed negative or extremely significant negative correlations with both mechanical traits. The correlation coefficients between stem agronomic traits and stalk crushing strength were greater than those with rind penetration strength (except for internode dry weight), indicating better correlations between stalk crushing strength and stem agronomic traits. Additionally, rind penetration strength and stalk crushing strength were extremely significantly correlated ( $r = 0.93^{**}$ ).

Correlations between stem traits and grain yield per plant showed that grain yield per plant was negatively correlated with plant height, internode length, and length-to-diameter ratio, but positively correlated with stem diameter, stem diameter coefficient, internode diameter, internode dry weight, dry matter weight per unit stem length, stalk crushing strength, and rind penetration strength.

Except for plant height, all other indicators showed significant correlations with grain yield per plant.

**2.4.2 Multiple Regression Analysis** Using the agronomic trait indicators from correlation analysis as independent variables ( $X$ ) and stalk crushing strength as the dependent variable ( $Y$ ), stepwise regression analysis was performed to eliminate non-significant variables and obtain the optimal regression equation:

$$Y = -103.065 + 549.971X + 222.068X \quad (P < 0.05)$$

The equation shows that stem diameter coefficient ( $X$ ) and dry matter weight per unit stem length ( $X$ ) had the greatest influence on stalk crushing strength, with their positive effects on stalk crushing strength reaching significant levels, indicating they can serve as important agronomic indicators for evaluating maize stalk lodging resistance.

### 3 Discussion

#### 3.1 Effects of Planting Density on Maize Stem Traits

Planting density significantly affects maize stem traits. Previous studies have shown that with increasing planting density, plant height and ear height increase [8,22], ear height coefficient [1,23] and internode length [11,22] increase, while stem diameter, stem diameter coefficient [1,19], internode dry weight [11,19], internode dry weight percentage [11], dry matter weight per unit stem length [11,24], stalk crushing strength, and rind penetration strength [11,23-24] decrease. Our results are consistent with these previous findings. With increasing planting density, competition among individual plants intensifies, leading to nutrient deficiency, decreased individual plant dry weight, reduced stem strength, and ultimately decreased lodging resistance. This study also examined the length-to-diameter ratio of internodes, finding a significant positive correlation between length-to-diameter ratio and density ( $r=0.90^*$ ), consistent with Wang et al. [16]. Li et al. [25] also found that maize plants with smaller length-to-diameter ratios and larger stem diameter coefficients had stronger lodging resistance. This indicates that as planting density increases, the length-to-diameter ratio increases and lodging resistance decreases.

#### 3.2 Effects of Planting Density on Maize Yield and Components

Maize yield is determined by effective panicle number per unit area, kernels per spike, and 1000-seed weight. Increasing planting density is a major measure for increasing maize yield. To achieve high yield, a reasonable population structure must be established to coordinate the contradictions among these three yield components and maximize their product [3]. Previous studies have shown that planting density significantly affects maize yield components: as density increases, ear length shortens, barren tip length increases, ear diameter decreases,

and row kernel number, kernels per spike, and 1000-seed weight decrease, resulting in reduced grain yield per plant [26-27]. Our results are consistent with these findings: as planting density increased, grain yield per plant decreased while population yield initially increased then decreased. The optimal planting density for summer maize in the Hilly Central Sichuan Basin should comprehensively consider yield, stem traits, lodging rate, and even pest damage. Based on our results, yield reached its maximum at  $6.00 \times 10^4$  plants  $\cdot$  hm<sup>2</sup>. However, considering yield, lodging resistance, and practical production factors, the appropriate density for summer maize should be within the range of  $5.25$ - $6.75 \times 10^4$  plants  $\cdot$  hm<sup>2</sup>. Subsequent experiments could further refine planting density to explore the optimal density for summer maize in the Hilly Central Sichuan Basin.

### 3.3 Relationships Between Stem Agronomic Traits and Lodging Resistance Mechanical Traits

Gou et al. [11] reported that stalk crushing strength and rind penetration strength showed extremely significant positive correlations with internode dry weight percentage and dry matter weight per unit stem length, and extremely significant negative correlations with internode length, while stalk crushing strength and rind penetration strength were also extremely significantly correlated. Li et al. [21] found that maize rind penetration strength showed significant or extremely significant positive correlations with plant height, ear height, and internode length. Gao et al. [24] reported that dry weight per unit length (i.e., dry matter weight per unit stem length) was extremely significantly correlated with stem mechanical characteristics. Our results are generally consistent with these previous studies. Except for internode dry weight, the correlation coefficients between stem agronomic traits and stalk crushing strength were greater than those with rind penetration strength, which may explain why stalk crushing strength decreased more than rind penetration strength with advancing growth stage. Stepwise regression analysis further demonstrated that stem diameter coefficient and dry matter weight per unit stem length had the greatest positive effects on stalk crushing strength and can serve as important indicators for evaluating maize stalk lodging resistance. These findings indicate close relationships among maize stem traits, and breeding programs should coordinate these relationships to develop comprehensive, lodging-resistant maize varieties.

### 3.4 Relationships Between Stem Traits and Yield

Stem trait quality affects final maize harvest yield. Li et al. [21] reported that stem diameter was extremely significantly positively correlated with grain yield, while plant height and internode length were significantly or extremely significantly negatively correlated with yield, but grain yield showed positive correlations with ear height and negative correlations with rind penetration strength, though neither was significant. Huang et al. [28] found that rice internode diameter and dry weight per unit internode were negatively correlated with effective

panicles per plant and total grains per panicle. Our results showed that grain yield per plant was positively correlated with stem diameter, stem diameter coefficient, internode diameter, internode dry weight, dry matter weight per unit stem length, stalk crushing strength, and rind penetration strength, but negatively correlated with plant height, internode length, and length-to-diameter ratio. Except for plant height, all other indicators showed significant correlations with grain yield per plant. These results demonstrate close relationships between maize stem traits and grain yield per plant, with stem diameter, internode dry weight, dry matter weight per unit stem length, stalk crushing strength, and rind penetration strength being important indicators affecting maize yield. Therefore, when constructing high-yield cultivation systems for summer maize in the Hilly Central Sichuan Basin, the relationship between grain yield per plant and stem traits should be fully understood to coordinate contradictions and achieve both high yield and lodging resistance.

#### 4 Conclusion

Planting density significantly affects maize stem traits and yield. When planting density increased to  $6.00 \times 10$  plants  $\cdot$  hm<sup>2</sup>, population yield reached its maximum, significantly increasing by 12.02% compared with  $4.50 \times 10$  plants  $\cdot$  hm<sup>2</sup>. With increasing planting density, maize plant height, ear height, internode length, and length-to-diameter ratio increased significantly, while stem diameter, stem diameter coefficient, internode dry weight, dry matter weight per unit stem length, stalk crushing strength, and rind penetration strength decreased significantly. Stem agronomic traits and mechanical traits were closely related: stem diameter, stem diameter coefficient, internode diameter, internode dry weight, and dry matter weight per unit stem length showed significant or extremely significant positive correlations with both rind penetration strength and stalk crushing strength, while plant height, internode length, and length-to-diameter ratio showed negative or extremely significant negative correlations with both mechanical traits. Stalk crushing strength showed better correlations with stem agronomic traits, and stem diameter coefficient and dry matter weight per unit stem length had the greatest influence on stalk crushing strength. Correlations between stem traits and grain yield per plant reached significant or extremely significant levels: yield showed significant negative correlations with internode length and length-to-diameter ratio, but significant or extremely significant positive correlations with stem diameter, stem diameter coefficient, internode diameter, internode dry weight, dry matter weight per unit stem length, stalk crushing strength, and rind penetration strength. In summary, planting density is an important factor affecting maize stem traits and yield; appropriately increasing planting density can significantly increase maize population yield, while stem diameter coefficient and dry matter weight per unit stem length can serve as important agronomic indicators for evaluating maize stalk lodging resistance.

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