

*Original Research*

# Optimizing Maize Plant Density to Enhance Growth, Yield, and Lodging Resistance for Climate-Resilient Crop Development

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## Abstract

Maize is a vital cereal crop enhancing food security. Optimizing plant density is a common practice to increase crop yield. This study investigates the impacts of high plant density on the biochemical composition, dry matter accumulation (DMA), photosynthesis-active radiation (PAR), radiation use efficiency (RUE), grain production, and stalk lodging in maize cultivation. Five plant densities (4.5, 6, 7.5, 9, and 15 plants m<sup>-2</sup>) referred to as PD4.5, PD6, PD7.5, PD9, and PD15, respectively, were tested on three maize hybrids, Zhengdan 958 (ZD958), Longping 206 (LP206), and Jinqiu 119 (JQ119), at the Mengcheng Research Station during 2016 and 2017. High plant densities increased PAR, RUE, DMA, and grain yield and led to a higher incidence of stalk lodging. The highest grain yields were achieved at PD6 (9.44%) and PD7.5 (2.98%), while yields decreased at PD15 (12.5%) due to a 60% increase in lodging. Under high plant density, internodes experienced rapid accumulation of carbohydrates but ceased elongating, expanding, and developing structural carbohydrates. Stem bending resistance positively correlated with cellulose, hemicellulose, and lignin content (0.9293\*\*, 0.8572\*\*, 0.8976\*\*), as did stem crushing resistance with the same components (0.9096\*\*, 0.8372\*\*, 0.8738\*\*). The present study's outcome will help determine the optimum plant density to improve food security and enhance maize yield under different climatic conditions.

**Keywords:** corn physiology, radiation use efficiency, biomass accumulation, biochemical composition, grain yield

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## Introduction

Food and energy crises are major global challenges today, and increasing maize production and grain yield can play a significant role in addressing these issues [1-3]. China, the second-largest maize producer [4], has four to six main maize production zones [5, 6]. In 2014, approximately 37 million hectares in China were dedicated to maize, making it the most widely cultivated cereal crop in the country [National Bureau of Statistics of China, 2015]. Maize growth and yield are generally influenced by the genotype and environmental factors, as well as their interactions. Under optimal conditions, crop yield response to plant density follows a parabolic pattern, and increasing plant population is a key agronomic practice for boosting maize production [7-10]. However, high plant density restricts root growth and nutrient uptake [11-13], causing competitive shading that limits radiation interception by lower leaves, accelerates leaf senescence, and reduces photosynthesis in individual plants [14, 6, 15, 16].

In recent decades, maize yield potential per plant has remained relatively stable, with overall yield increases achieved primarily through increased plant density and the development of high-yielding cultivars worldwide [17-20]. This trend encourages maize growers to increase plant density to maximize yields [21]. However, there is a contrary opinion that high plant density can also intensify competition among plants, leading to crowding stress, reduced grain yield [22, 23], and a higher risk of lodging [8, 24]. Final grain production in maize depends on the number of seeds per unit area at maturity. A high plant population is a common agronomic practice to achieve increased maize yield [25], although kernel numbers per plant tend to decrease as plant population increases [25, 26]. In addition, kernel weight may decrease by 5-30% [27, 19], though in some cases this effect is minimal [28]. RUE (Radiation Use Efficiency) is a crucial metric for measuring biomass production and is closely linked to yield-related traits [29].

Proximity planting increases competition for essential resources, such as light, water, heat, and nutrients, reducing the storage capacity of carbohydrates in maize leaves and affecting the growth of basal internodes. Previous research has shown that basal internode width significantly increases with plant population [30]. However, contrasting evidence suggests that the basal internode dimensions, dry weight per unit length (DWUL), and rind penetration strength (RPS) of basal internodes decrease as maize densities increase [31]. Previous studies have focused on examining the impact of plant density on fully developed basal internodes, while this study examines its effects on morphological growth, biochemical composition, and their relationship to lodging resistance in maize. Maize plant density differs in China based on weather conditions, particularly solar radiation, rainfall, and wind speed, though finding optimal plant density for different regions remains uncertain. Therefore, it is important to determine the

optimum plant population for different cultivars to minimize yield losses from lodging across diverse climatic conditions. The objectives of this study are (i) to investigate the effects of plant density on ear development, ear characteristics, kernel abortion, and grain yield among different cultivars; (ii) to evaluate the impact of plant density on biomass, PAR, and RUE; and (iii) to understand how carbohydrate development affects internode length, diameter, and stalk lodging traits.

## Materials and Methods

### Soil and Analysis

Field trials were conducted in 2016 and 2017 at the Mengchen Research Station in the North China Huaibei Plain (Latitude is 33°09'N, Longitude 116°32'56"E). Before sowing, soil tests were performed to determine nutrient requirements. Soil samples were collected from each subplot at depths of 10 cm, 15 cm, and 20 cm, and the average values were calculated. Table 1 includes the physicochemical features of the soil. The closest conventional local weather station provided the daily meteorological data, including the highest temperature, lowest temperature, average temperature, and amount of precipitation, with average temperature and precipitation shown in Fig. 1. Nutrient management included synthetic fertilizers for N, P<sub>2</sub>O<sub>5</sub>, K<sub>2</sub>O, and ZnSO<sub>4</sub>·7H<sub>2</sub>O, administered at rates of 60 kg ha<sup>-1</sup>, 140 kg ha<sup>-1</sup>, 125 kg ha<sup>-1</sup>, and 15 kg ha<sup>-1</sup>. An initial irrigation of 900 cm<sup>3</sup> ha<sup>-1</sup> was applied before crop sowing.

### Experimental Design and Crop Husbandry

A previous publication [9] discussed crop husbandry and experimental treatments. In brief, 3 maize hybrids, Zhengdan 958 [ZD958], Longping 206 [LP206], and Jinqiu 119 [JQ119], were grown at 5 plant densities (4.5, 6, 7.5, 9, and 15 plants m<sup>-2</sup>) referred to as PD4.5, PD6, PD7.5, PD9, and PD15 m<sup>-2</sup>, respectively, in both 2016 and 2017. The maize cultivars were assigned to the main plots, and the plant densities were assigned to the subplots in a randomized split-plot experimental design. Using a sowing drill, the hybrid maize seeds were manually sown on June 12, 2016, and June 7, 2017. The crop was harvested on October 5, 2016, and September 27, 2017.

### Sample Collection

#### *Growth Parameters*

In 2016, leaf area was measured every 3 days starting at the fourth leaf stage, and sampling continued until the silking stage [8]. Leaf area was measured at the jointing, flowering, and anthesis stages, and then the average was calculated in 2017. Five plants were selected from

Table 1. Soli physical propertiees.

	10 cm	15 cm	20 cm	Mean
Soil Ph	7.7	8.9	7.6	8.07
Organic mattet g/kg	11.34	12.45	11.4	11.73
Total nitrogen mg/kg	134.5	135.67	133.3	134.9
Available P K (mg·kg <sup>-1</sup> )	16.6	15.8	16.2	16.2
Available K (mg·kg <sup>-1</sup> )	106.7	105.7	105.8	106.067

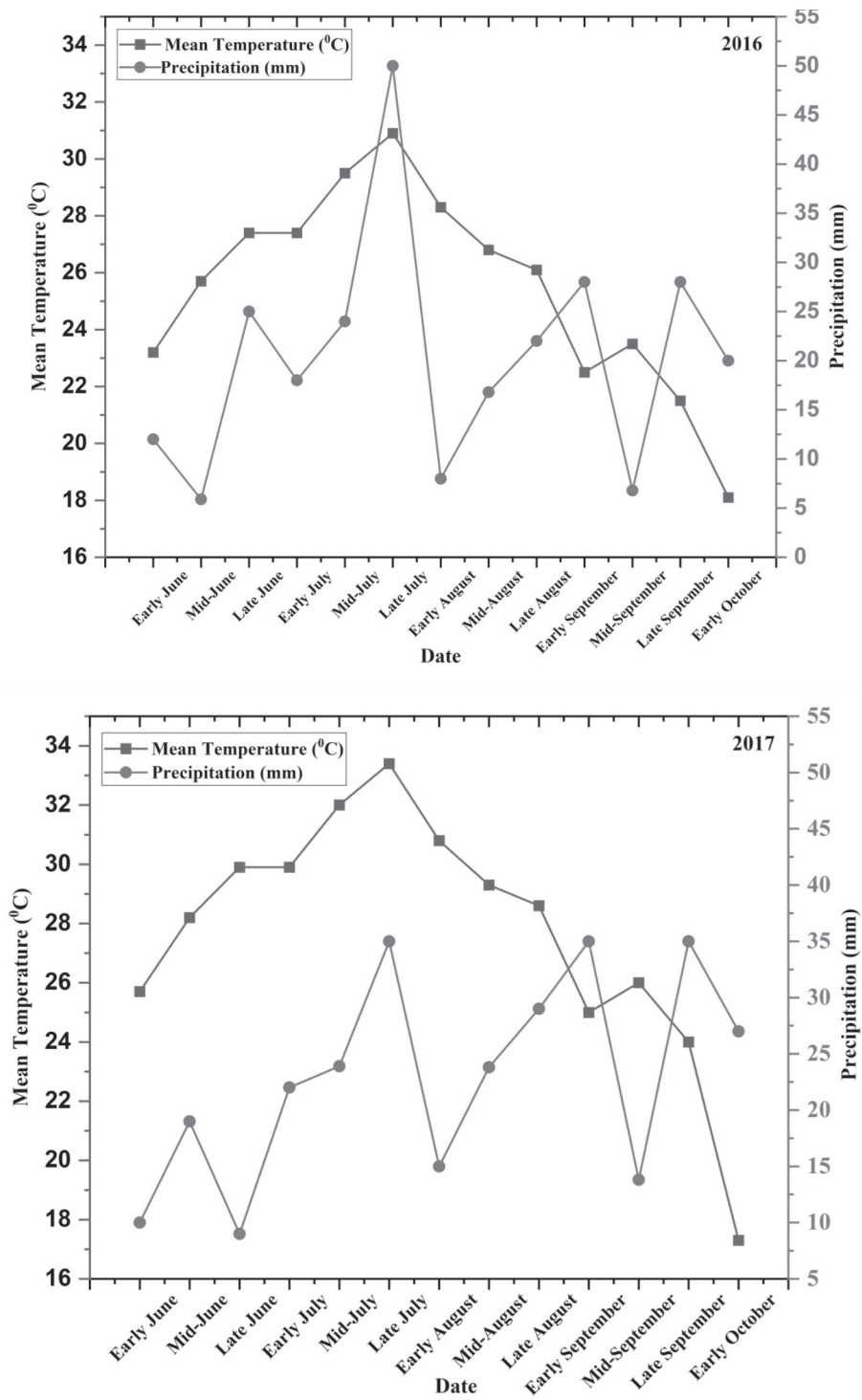


Fig. 1. Meteorological data of mean temperature (°C) and precipitation (mm) during 2016 and 2017.

each plot to calculate the leaf area, and the average value was computed. Leaf length (L) and width (W) were measured using a ruler, and the leaf area was calculated using the following formula [32].

$$S = 0.75 \times L \times W$$

Plant height was measured at physiological maturity with a meter rod.

#### Yield and Yield Component-Related Parameters

When the ears reached physiological maturity, 20 cobs were taken from the central rows of every plot. Twenty randomly chosen ears were used to measure ear diameter, tip-back length, and barren portion. Additionally, the number of kernel rows [NKR] and kernels per row [NKPR] were counted for 20 of these randomly chosen ears. Five ears were selected and split into 3 sections: the bottom, middle, and top portions. The number of grains was then manually counted. The weight was determined using an electronic balance. The grain moisture content was determined with a portable moisture meter (PM8188, Kett Electric Laboratory, Tokyo, Japan). The grain yield and 1000-kernel weight (TKW) were adjusted to 14% moisture content.

#### Light Interception Measurements

The line quantum sensor (SUNSCAN, Delta, UK) was used for light interception measurement. At least

five readings of physiological photon flux density (PPFD) were taken in each plot during flowering, and the measurements were taken between 13:00 and 15:00 (solar noon). To assess canopy height, the plants were divided into 6 sections, designated as P1 through P6: P1, positioned above the senescent leaves; P2, halfway between the soil level and the cob; P3, at cob height; P4, halfway between the cob and canopy; P5, 20 cm above the canopy; and P6, at the top canopy level.

#### Biochemical Composition Measurements

Plant samples were collected from every treatment at flowering, silking, and the mid-grain filling stage, and were then separated into sheaths, stems, and leaves. The separated samples were ground into powder in liquid nitrogen. Cellulose, lignin, and hemicellulose contents were determined [33].

#### Statistical Analysis

Statistical analysis of leaf area was performed at a significance level of  $p = 0.05$ ; individual comparisons were carried out using a t-test (MS Excel, Microsoft Inc., Seattle, WA, United States). The impacts of plant density, variety, and year on measured parameters (yield-related traits, lodging metrics, and biochemical parameters) were analyzed by analysis of variance (ANOVA) using Statistix 8.1 (Tallahassee, FL: Analytical Software, 2013). Differences among means were compared using the least significant difference test (LSD) at a 0.05 probability level.

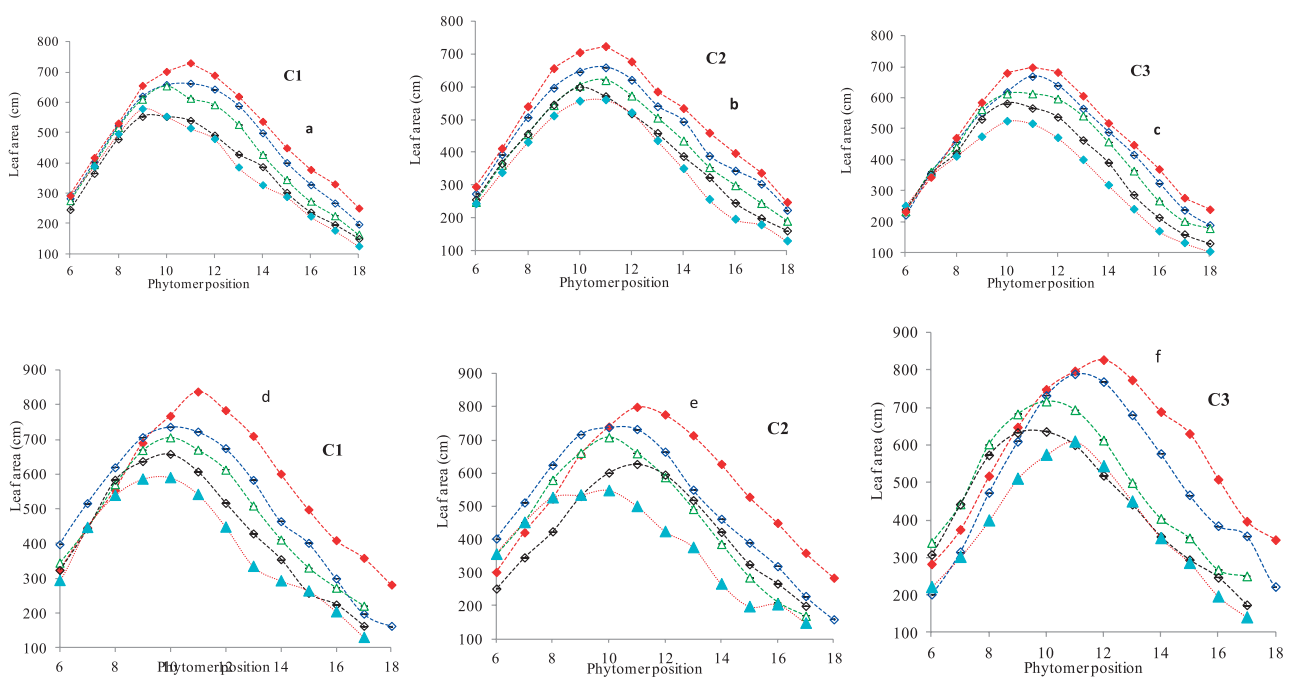


Fig. 2. Leaf area (a-c) during 2016 and (d-f) during 2017 under different plant densities [PD4.5 (red dashed line), PD6 (blue dashed line), PD7.5 (green dashed line), PD9 (black dashed line), and PD15  $m^{-2}$  (pink dashed line)] and cultivars (C1: Zhengdan 958, C2: Longping 206, and C3: Jinjiu 119).

**Results**

**Effect of Planting Density on Leaf Area of Maize Cultivars**

The effect of plant density on maize leaf area is depicted in Fig. 2. At PD4.5, leaf area for all cultivars increased for lower ranks and decreased for higher ranks. Overall, leaf area decreased with increasing plant density. ZD958 exhibited longer and broader leaves than the other cultivars, resulting in a larger leaf area.

**Effect of Planting Density on Plant Height in Maize Cultivars**

Fig. 3 demonstrates the effects of plant density on the plant height of different maize cultivars. Plant height increased by 8.6% from PD4.5 to PD6, followed by a 9.2% increase from PD6 to PD7.5, a 3.4% increase from PD7.5 to PD9, and a 6.4% increase from PD9 to PD15. This trend is attributed to increased competition among plants, causing the internodes to become slimmer and their length to increase. No significant differences in plant height were observed among the cultivars.

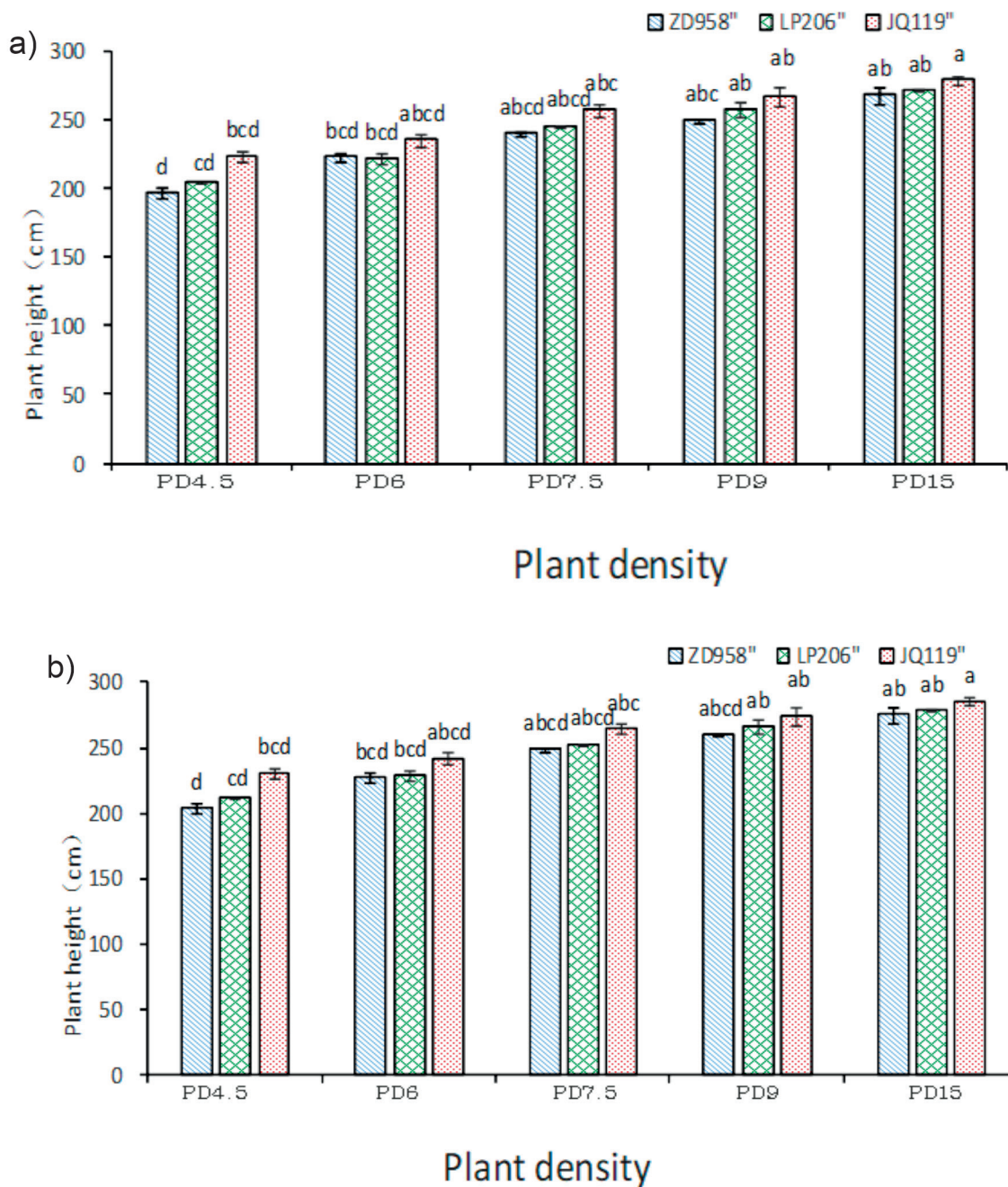


Fig. 3. Plant height a) during 2016 and b) during 2017 under different plant densities (PD4.5, PD6, PD7.5, PD9, and PD15 plants m<sup>2</sup>) and cultivars, i.e., Zhengdan 958 (ZD958), Longping 206 (LP206), and Jinqiu 119 (JQ119). Vertical bars indicate standard error.

### Effect of Planting Density on Yield and Yield Components of Maize Cultivars

The effect of planting density on the yield and yield components of maize cultivars is presented in Table 2. Overall plant density had a significant effect on yield and yield components. While cultivar significantly affected yield and 1000-kernel weight, its effect on kernel number and ear number was not significant. The maximum grain yield was recorded at PD7.5, which was similar to PD4.5, PD6, and PD9, and the minimum grain yield was recorded at PD15. As planting density increased, grain yield (GY) increased by 9.44% from PD4.5 to PD6, and by 2.98% from PD6 to PD7.5. However, GY decreased by 6.60% from PD7.5 to PD9, and by 12.54% from PD9 to PD15. Among the cultivars, ZD958 had a higher yield compared with LP206, but it was at par with JQ119. The results also showed an increase in ear number, but a decrease in 1000-kernel weight (TKW) and kernel number per ear. Across years and plant densities, the order of decrease for kernel number per ear and TKW was PD15 < PD9 < PD7.5 < PD6 < PD4.5.

### Effect of Planting Density on Different Positions of the Ear of Maize Cultivars

Table 3 shows the planting density effect on the various positions of cultivars' ears. Based on length, the ear was divided into 3 sections: the top, middle, and bottom. Planting density and year had a considerable impact on the ear positions. For the top, middle, and bottom, the highest number of grains and grain weight were recorded at PD4.5, while the lowest values were recorded at PD15. Grain weight in the middle and bottom parts of the cultivars showed a substantial variation, although there was no discernible change in the number of grains for the top, middle, and bottom parts.

### Effect of Planting Density on Ear Characteristics of Maize Cultivars

Planting density had a significant impact on ear characteristics, and the results are presented in Table 4. Our findings showed that ear length declined with increasing planting density and that the maximum ear

Table 2. Yield and yield components of maize in response to different plant densities and cultivars.

Treatments	Yield (kg ha <sup>-1</sup> )	TKW(g)	kernels (No. ear <sup>-1</sup> )	Ear No. ha <sup>-1</sup>
YEAR				
2017	8212.7b	304.86b	524.52a	82824a
2016	9360.2a	314.91a	526.77a	82799b
Plant Density (PDm <sup>2</sup> )				
PD4.5	8457.6ab	333.74a	569.73a	74560b
PD6	9255.6a	318.02ab	572.82a	76788b
PD7.5	9531.2a	300.95bc	521.43b	79843b
PD9	8902.2a	299.09c	499.64bc	84335.3b
PD15	7785.9b	297.64c	470.62c	92334.0a
Cultivar				
ZD958	9174.7a	299.79b	511.90a	66352a
LP206	8469.3 b	313.47a	531.34a	65923a
JQ119	8715.4ab	316.40a	533.70a	63251a
S.O.V				
YEAR	*	*	NS	NS
Plant density	**	**	**	**
Cultivar (C)	*	*	NS	NS
PD*C	**	NS	NS	NS
Y*PD	*	NS	NS	NS
Y*C	*	NS	NS	NS
Y*PD*C	NS	NS	NS	NS

PD is an abbreviation for plant densities. Different letters among treatments indicate significant differences; \* and \*\* indicate significance at P0.05 and P0.01, respectively, according to the least significant difference (LSD). NS indicates that treatment effects were not significant. Among cultivars, ZD 958 is (Zhengdan 958), LP 206 is (Longping206), and JQ119 is (Jiniqu 119), respectively.

Table 3. Plant density effect on different cob parts (top, mid, bottom) of maize crop for different hybrids.

Treatments	No. of grains	Weight (g)	No. of grains	Weight (g)	No. of grains	Weight (g)
	top part	top part	mid part	mid part	bottom part	bottom part
YEAR						
2017	148.57a	45.117a	196.10a	59.237a	176.64a	55.621a
2016	141.57b	38.117b	189.1b	52.237b	169.64b	48.621b
Plant Density (PDm <sup>-2</sup> )						
PD4.5	161.32a	52.806a	213.68a	63.558a	185.52a	58.479a
PD6	158.3a	44.091ab	197.01a	59.757ab	182.50ab	56.799a
PD7.5	144.9a	43.057ab	195.11a	55.602bc	175.07ab	50.83b
PD9	144.18a	38.419ab	194.37a	54.833c	170.32b	50.827b
PD15	116.63b	29.714b	162.83b	44.932d	152.29c	43.671c
Cultivar						
ZD958	146.45a	37.813a	185.75a	58.601a	168.18a	49.314b
LP206	153.43a	41.237a	191.21a	57.001a	171.42a	52.095ab
JQ119	135.32a	45.802a	200.84a	51.608b	179.83a	54.955a
S.O.V						
YEAR	*	*	*	*	*	*
Plant density	**	*	**	**	**	**
Cultivar (C)	NS	NS	NS	*	NS	*
PD*C	**	NS	*	*	**	*
Y*PD	NS	NS	NS	NS	NS	NS
Y*C	NS	NS	NS	NS	NS	NS
Y*PD*C	NS	NS	NS	NS	NS	NS

PD is an abbreviation for plant densities. Different letters among treatments indicate significant differences; \* and \*\* indicate significance at P0.05 and P0.01, respectively, according to the least significant difference (LSD). NS indicates that treatment effects were not significant. Among cultivars, ZD 958 is (Zhengdan 958), LP206 is (Longping 206), and JQ119 is (Jinjiu 119), respectively.

length (19.36) was recorded at PD4.5. At PD15, the smallest ear length (15.47) was recorded. Ear length reduced from PD4.5 to PD6 to PD7.5 to PD9 to PD15 by 5.4%, 6%, 1.6%, and 8.7%, respectively, as planting density increased. In terms of ear length, no significant variations were recorded across cultivars. The barren area was significantly affected by both planting density and cultivar, and their interaction was significant.

The barren area increased with planting density; the largest value was measured at PD15 (0.9372), and the lowest value was measured at PD4.5 (0.3722). Among the cultivars, JQ119 showed greater barrenness than ZD958 and LP206. Ear diameter was significantly affected by both cultivar and plant density, and a significant correlation was recorded between them. Ear diameter declined with increasing plant density; the highest ear diameter (49.09) was measured at PD4.5, and the minimum (44.529) was measured at PD15. Ear diameter decreased by 0.33%, 3.18%, 1.66%, and 4.43%, respectively, as plant density increased, with

the sequence PD4.5 > PD6 > PD7.5 > PD9 > PD15. Among the cultivars, JQ119 had a larger ear diameter than LP206 and ZD958.

Plant population was found to have a substantial (P<0.01) influence on the number of kernel rows per ear (NKPR). The greatest NKR (15.764) was recorded in treatment with the lowest population (PD4.5), while the lowest NKR (14.885) was recorded in the treatment with the greatest density (PD15). The number of kernel rows reduced as the plant population increased, and the sequence was PD4.5 > PD6 > PD7.5 > PD9 > PD15. Cultivars differed significantly from one another; JQ119 produced the most kernel rows in contrast to LP206 and ZD958. Plant density had a substantial impact on the NKPR; at PD4.5, the highest values of NKPR (36.973) were recorded, whereas at PD15, lower NKPR values (30.8532) were recorded. PD7.5 and PD9 showed similar numbers of kernels per row. There was no significant difference in the number of kernels per row among cultivars.

Table 4. Cob characteristics response to different plant densities and cultivars.

Treatments	Length	BP	Diameter	NKR	NKPR
YEAR					
2017	17.830a	0.6953a	48.417a	15.511a	34.448a
2016	17.104b	0.5776a	46.193b	15.517a	33.885a
Plant Density (PDm <sup>2</sup> )					
PD4.5	19.369a	0.3722c	49.096a	15.764a	36.973a
PD6	18.32b	0.5016bc	48.932a	15.846a	36.114a
PD7.5	17.223c	0.61ab	47.377b	15.622a	33.497b
PD9	16.948c	0.6511abc	46.592b	15.454a	33.397b
PD15	15.47d	0.9372a	44.529c	14.885b	30.8532c
Cultivar					
ZD958	17.347a	0.402b	46.175b	14.680c	34.529a
LP206	17.486a	0.3387b	48.197a	15.623b	34.304a
JQ119	17.567a	1.1687a	47.544a	16.240a	33.667a
S.O.V					
YEAR	*	NS	*	NS	NS
Plant density	**	**	**	**	**
Cultivar (C)	NS	*	*	**	NS
PD*C	**	**	**	**	**
Y*PD	NS	NS	*	NS	NS
Y*C	NS	NS	NS	NS	NS
Y*PD*C	NS	NS	NS	NS	NS

PD is an abbreviation for plant densities. Cob length (cm), BP barren cob part (cm), cob diameter (mm), number of kernel rows (NKR), number of kernels per row (NKPR). Data are the means of 20 cobs per plot. Different letters among treatments indicate significant differences; \* and \*\* indicate significance at P0.05 and P0.01, respectively, according to the least significant difference (LSD). NS indicates that treatment effects were not significant. Among cultivars, ZD 958 is (Zhengdan 958), LP206 is (Longping 206), and JQ 119 is (Jinjiu 119), respectively.

#### Effect of Planting Density on Dry Matter (DM) Accumulation of Maize Cultivars

Biomass production is a vital parameter for determining grain yield and crop development. Biomass production at the pre-silking stage increased significantly as plant density increased in ZD958 from PD4.5 to PD15, and the interaction between plant density and cultivar was significant (Table 5). The trend for total above-ground dry matter was recorded as grain yield < LP206 < ZD958. For all cultivars, post-silking dry matter was higher than pre-silking dry matter, while the ratio of pre-silking dry matter to post-silking dry matter for ZD958 averaged 0.73, which was higher than for LP206 and JQ119.

#### Effect of Planting Density on PAR Interception of Maize Cultivars

Table 6 shows how plant density affects the PAR of different varieties of maize. Results showed that PAR decreased in the canopy as plant density increased. The highest PAR value was recorded at P5, and the variations were less noticeable at P6. Plant densities differed significantly in intercepted PAR values, with the greatest values recorded at PD4.5 and the minimum values recorded at PD15. In comparison with other cultivars, ZD958 has a greater PAR value.

#### Effect of Planting Density on Radiation Use Efficiency (RUE) of Maize Cultivars

As planting density increased, RI and RUE values also increased. The reason for this increase may be that, as plant density increased, the amount of radiation

Table 5. Dry matter (DM) production under different plant densities and cultivars.

Treatments	Pre silk (kg ha <sup>-1</sup> )	Post silk (kg ha <sup>-1</sup> )	the ratio of pre /post silk (kg ha <sup>-1</sup> )	Total DM (kg ha <sup>-1</sup> )
YEAR				
2017	7784.7a	13027a	0.7135a	20245a
2016	7741.6a	13213a	0.7141a	20512a
Plant Density (PDm <sup>2</sup> )				
PD4.5	6237.4d	7407a	0.871a	13644c
PD6	6889.6c	9304b	0.9479a	16194c
PD7.5	8451.6b	11873bc	0.7323ab	20324b
PD9	8892.5b	13828cd	0.5377b	20990b
PD15	9482.7a	22006d	0.4551b	31489b
Cultivar				
ZD958	7927.6a	13215 a	0.7332a	20587a
LP206	7634.3b	13107a	0.6771a	20741a
JQ119	7372.0c	12329a	0.7031a	20256a
S.O.V				
YEAR	NS	NS	NS	NS
Plant density	**	**	**	**
Cultivar (C)	*	NS	NS	NS
PD*C	**	NS	NS	NS
Y*PD	NS	NS	NS	NS
Y*C	NS	NS	NS	NS
Y*PD*C	NS	NS	NS	NS

PD is an abbreviation for plant densities. Different letters among treatments indicate significant differences; \*, \*\* indicate significance at P0.05 and P0.01, according to the least significant difference (LSD), respectively, NS indicates that treatment effects were not significant. Among cultivars, ZD 958 is (Zhengdan 958), LP206 is (Longping 206), and JQ 119 is (Jinjiu 119), respectively.

intercepted by the plant canopy increased, which enhanced the capacity of plants to intercept more solar radiation. In this study, RUE increased from -31.30% to -11.51% for ZD958, 28.45% to 10.43% for LP206, and 26.34% to 9.89% for JQ119. RIacc increased from -12.42% to -3.48% for ZD958, -11.23% to -3.51% for LP206, and -11.78% to 3.40% for JQ119. There is a strong positive correlation between plant densities and RUE (a) and plant densities and RI (b), as shown in Fig. 4.

#### Effect of Planting Density on Biochemical Composition of Maize Cultivars

To comprehend the effects of plant density on the strength of carbohydrate content in response to various cultivars, measurements of the lignin, cellulose, and hemicellulose contents of the basal third internode are represented in Table 7. During internode development, the cellulose and lignin contents increased at the flowering, silking, and grain-filling stages. Furthermore,

as plant density increased, the cellulose and lignin concentrations of the basal third internode decreased. In contrast to the fluctuation of lignin and cellulose levels throughout internode growth, the hemicellulose concentration of cultivars peaked during the silking stage and decreased during the grain filling stage. ZD958 had more lignin, cellulose, and hemicellulose content compared with LP206 and JQ119. As a result, ZD958 was more resistant to lodging than the other cultivars

#### Discussion

##### Plant Density Effect on Growth Parameters

When plant population increases, particularly at the tillering stage in Gramineae species, leaf area per plant decreases [34]. In wheat, leaf area was larger at low plant densities for lower leaf ranks, but it declined for upper leaf ranks as plant density increased [35].

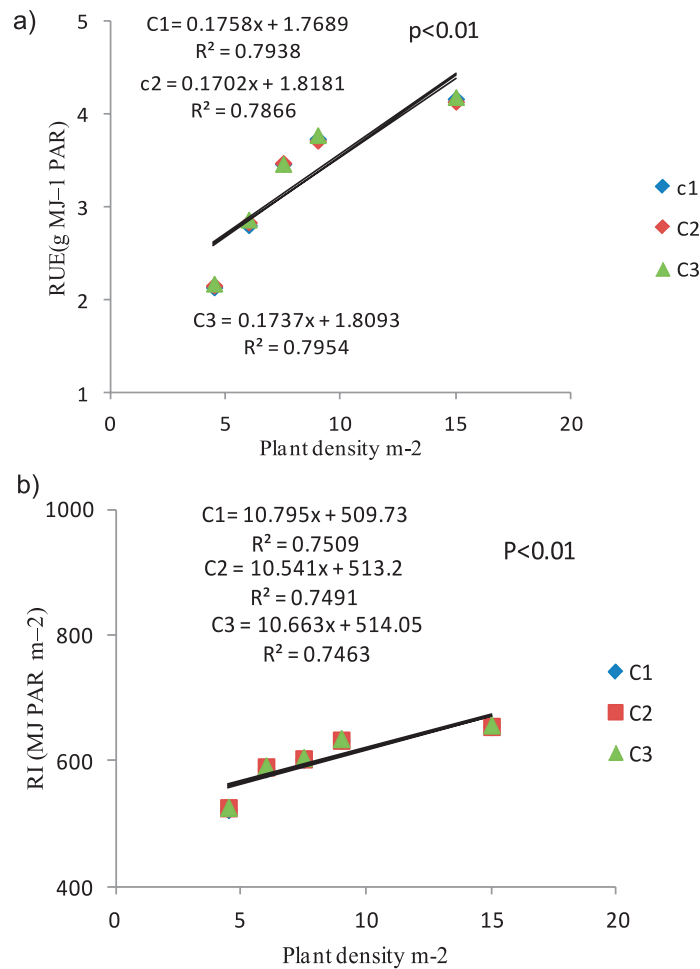


Fig. 4. Correlation between plant density and a) RUE (g MJ<sup>-1</sup> PAR) and b) RI (MJ PAR m<sup>-2</sup>) effect PD4.5, PD6, PD7.5, PD9, and PD15 m<sup>-2</sup> and different cultivars, i.e., C1: Zhengdan 958 (ZD958), C2: Longping 206 (LP206), and C3: Jinqiu 119 (JQ119). R<sup>2</sup> is significant at P<0.01.

This reduction in leaf area at high plant population can be attributed to increased competition for resources. Closer planting leads to decreased leaf area, which in turn reduces the net assimilation rate of individual plants, promotes earlier leaf senescence, and causes increased shading among leaves. These findings are consistent with previous studies, which reported the highest leaf area at the lowest plant density and the lowest leaf area at the highest plant population [36-38].

An increase in plant density also intensifies competition between plants, leading to an elongation of internodes and a reduction in their diameter, resulting in taller, thinner stems [7, 8]. As a result, plant height increases significantly. For instance, plant height increased from 209 cm to 221 cm as density increased [39]. High plant populations tend to produce taller plants with thinner stems. An increase in plant height due to high plant density can be attributed to enhanced interplant competition for light and the disruption of growth regulators that influence crop growth [40]. According to meteorological data presented in the supplementary material (Fig. 1), more precipitation was recorded at the anthesis stage, leading to over 60%

lodging [8], which ultimately reduced grain yield. Fig. 5(a-b) show a positive correlation between plant height and lodging percentage, and a negative correlation between yield and lodging percentage.

#### Plant Density Effect on Yield and Yield-related Components

In modern crop production, high plant density is often regarded as a key agronomic practice for enhancing yield [41-44]. However, it is crucial to note that increased plant density does not always correspond to higher yields [45, 46]. In this study, grain yield significantly increased at a plant density of PD7.5, which aligns with findings from other research [45, 46]. Although higher plant densities generally boosted dry matter and grain yield, yields at PD9 and PD15 declined due to lodging in cultivars LP206 and JQ119, as previously reported [8]. In contrast, ZD958 maintained stability under these conditions. Similar studies have documented yield losses of 5% to 40% from stalk lodging under high-density planting [47-49]. The main reason for lodging in LP206 and JQ119 was the reduction in stem diameter

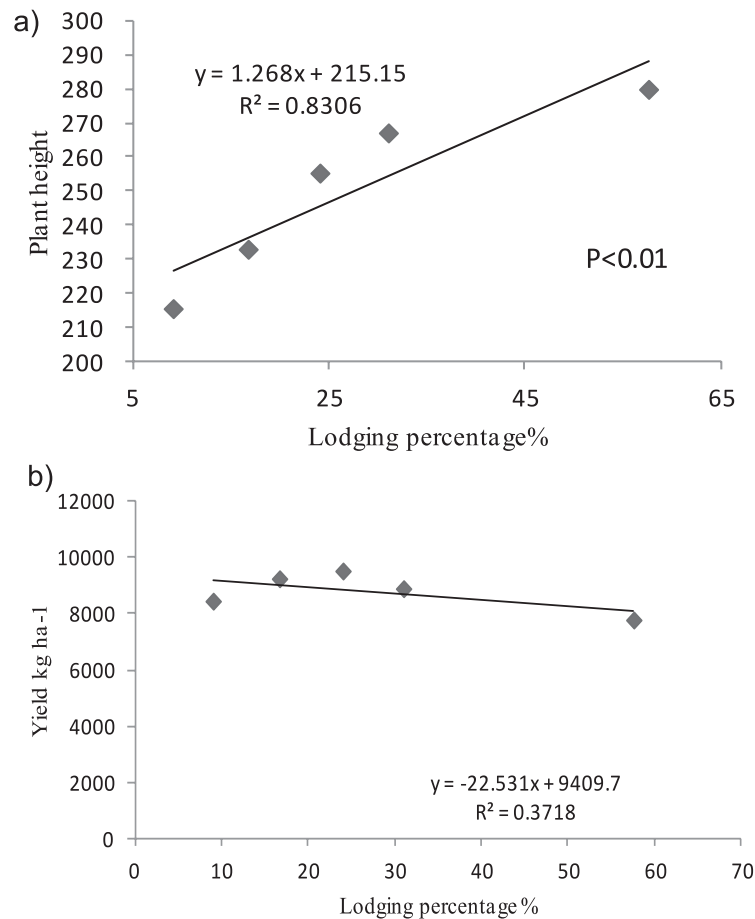


Fig. 5. Correlation between a) plant height and lodging percentage and b) between yield and lodging percentage.

and length due to high competition at high plant density (8).

1000 kernel weight (TKW) was highest at PD4.5 and decreased as plant density increased, with discernible differences among hybrids, as presented in Table 1. These findings align with previous research that also demonstrated a significant decrease in TKW as plant density increased [50, 51]. Other studies have shown a linear reduction in TKW with increasing plant population. Our results are consistent with the findings of [22, 27, 52, 53], who reported that there is a slight correlation between plant population and TKW. Additionally, increased plant density led to a reduction in ear length, likely due to competition for essential resources such as space, water, and nutrients [54, 9]. This competition adversely affected ear length, ear weight, and ear diameter, which collectively reduced yield per plant [55]. Previous studies similarly observed that the highest ear length occurs at lower plant densities, with the lowest recorded at high plant densities [56, 57].

The number of kernel rows (NKR) is another important trait that affects yield. In our study, NKR decreased as plant population increased, with the maximum NKR observed at PD4.5 and the minimum at PD15. This reduction in NKR at higher densities likely results from efficient resource utilization at lower densities, where plants face less competition for critical

resources such as space, water, nutrients, and light [58-60]. Similarly, as plant density increased, NKPR significantly decreased. This reduction in NKPR at high plant populations is likely due to competition among plants for nutrients, limiting kernel growth and development [57-61]. Table 8 represents a robust positive correlation between cob diameter, cob length, NKR, NKPR, and TKW. Additionally, cob characteristics, such as cob diameter, number of kernel rows, and number of kernels per ear, showed significant correlations and cultivar-specific interactions. High plant density led to a reduction in cob length (-10.8%), ear weight (-6%), and the NKPR (-10%) [62-64].

#### Plant Density Effect on Biomass Accumulation, PAR, and RUE

Biomass production is a vital parameter for determining grain yield and crop development. In our study, we observed a positive correlation between biomass production and grain yield, consistent with previous studies indicating that high biomass production is associated with high yield [28]. Specifically, our results demonstrated that biomass production was enhanced with plant density, increasing from PD4.5 to PD15 plants m<sup>-2</sup>. This aligns with the previous findings demonstrating that dry matter increased with increasing

plant population [65-67]. The enhancement in dry biomass yield is attributed to a greater number of plants per unit area, enhancing overall productivity.

PAR and RUE are important physiological traits in agronomy, as they help intercept light to support the C:N ratio and improve the metabolic pathways of crops. Our results showed that as plant density increased, RI and RUE also increased due to increased leaf area and lamina length, driven by higher interplant competition. High plant density enhanced both the amount and quantity of radiation captured by the plant canopy, enabling plants to intercept more solar radiation (51). Fig. 4 illustrates strong positive correlations between plant density and both RUE (a) and RI (b), underscoring the importance of RUE and RI in determining dry matter accumulation in crops.

#### Plant Density Effect on Cellulose, Lignin, and Hemicellulose Content of Maize Cultivars

Lodging resistance is a critical trait in crop cultivation, and morphological characteristics significantly impact lodging resistance. Studies have been conducted to examine the morphological, histological, and anatomical differences in response to different plant populations to breed lodging-resistant cultivars. Table 6 represents the effects of plant density on cellulose, lignin, and hemicellulose content in maize. Previous research indicates that a higher plant population extends

the period of rapid internode elongation [33]. Close planting reduces light intensity within the maize canopy, inhibiting the photodestruction of auxin and increasing internode length [28]. However, rapid thickening of internodes terminates earlier, and the duration of fast internode thickness and internode elongation is reduced as carbohydrates are predominantly used for internode elongation, causing a decrease in diameter. As a result, high-density plantings produce taller plants with reduced internode diameter, leading to less light penetration and reduced photosynthetic capacity in lower canopy layers [68]. Our study found that high plant density leads to a shorter period of rapid dry matter accumulation in the basal third internode. As a result, the rate of RPS (rind penetration strength) generation declined with higher plant density. Dense planting has significant effects on the basal third internode. This effect on the basal internode involves accelerated elongation but a reduced growth period for internode diameter. Previous research indicates that dense planting inhibits carbohydrate production in the basal internode, which in turn slows the accumulation of cellulose and lignin, as well as cortical development. Morphogenesis primarily occurs during stalk development, with the diameter of the basal internode increasing along with its length. The decrease in structural carbohydrates necessary for RPS development in maize internodes has been observed. Nonstructural carbohydrates produced in the leaves are transported to the internodes, where they are converted

Table 6. Plant density effect on PAR in different corn cultivars.

Treatments	P1	P2	P3	P4	P5	P6
Plant density m <sup>-2</sup>						
PD4.5	417.82a	540a	669a	892.56a	1422a	1598a
PD6	411.67b	532b	656b	860.5b	1402.9b	1572.32b
PD7.5	405.98c	521.68c	642.6c	848.69c	1387.6c	1556c
PD9	401.34cd	509d	630d	839.6cd	1375.1d	1540d
PD15	397d	505.22de	622.3e	815e	1351.3e	1518e
Cultivar						
ZD958	417.78a	526.28a	648.34a	849.93a	1392.2a	1560a
LP206	402.93b	520ab	642.56b	845.34ab	1388.3a	1558a
JQ119	395.18c	512.8b	640.38b	830.23c	1380.3b	1550b
S.O.V						
Plant density	**	**	**	**	**	**
Cultivar	*	*	*	*	*	*
P*C	NS	NS	NS	NS	NS	NS

PD is an abbreviation for plant densities. Photosynthetically active radiation (PAR) in different canopy layers is affected by plant density at the flowering stage. Abbreviations for canopy height: P1, above the senescent leaves; P2, halfway between the soil surface and the cob; P3, cob height; P4, halfway between the cob and the canopy top; P5, 20 cm above the canopy; P6, at the top canopy level. Different letters among treatments indicate significant differences; \* and \*\* indicate significance at P0.05 and P0.01, respectively, according to the least significant difference (LSD). NS indicates that treatment effects were not significant. Among cultivars, ZD 958 is Zhengdan 958, LP206 is Longping 206, and JQ119 is Jinqiu 119, respectively.

Table 7. Plant density effect on biochemical parameters of maize cultivars.

Treatments	Cellulose			Lignin			Hemicellulose		
	Flowering	Silking	Blister	Flowering	Silking	Blister	Flowering	Silking	Blister
YEAR									
2017	152.17a	203.54a	243.73a	32.433a	50.411a	63.033a	130.52a	143.01a	135.57a
2016	146.47b	197.64b	237.93b	25.133b	43.111b	55.733b	124.62b	137.11b	129.67b
Plant Density (PDm <sup>-2</sup> )									
PD4.5	192.85a	293.62a	404.57a	42.094a	77.761a	90.781a	165.62a	184.62a	171.28a
PD6	171.52b	247.51b	270.57b	32.65b	64.317b	73.123b	143.73b	154.62b	144.62b
PD7.5	157.18c	193.95c	217.9c	27.317c	43.206c	60.986c	125.39c	131.84c	127.95c
PD9	132.18d	153.95d	175.9d	22.983d	27.539d	40.213d	109.28cd	119.62d	117.28d
PD15	92.85e	113.95e	135.23e	18.872e	20.983e	29.983e	93.84d	109.62e	101.95e
Cultivar									
ZD958	159.45a	209.35a	250.5a	34.183a	53.317a	67.05a	140.75a	148.35a	140.82a
LP206	147.45b	198.35b	238.1b	27.317b	46.65ab	57.05b	128.42b	138.48b	130.88b
JQ119	141.05c	194.08c	233.9c	24.85c	40.317b	54.05c	113.55c	133.35b	126.15c
S.O.V									
YEAR	*	*	*	*	*	*	*	*	*
Plant density	**	**	**	**	**	**	**	**	**
Cultivar (C)	**	**	*	**	**	*	**	**	*
PD*C	NS	NS	NS	NS	NS	NS	NS	NS	NS
Y*PD	NS	NS	NS	NS	NS	NS	NS	NS	NS
Y*C	NS	NS	NS	NS	NS	NS	NS	NS	NS
Y*PD*C	NS	NS	NS	NS	NS	NS	NS	NS	NS

PD is an abbreviation for plant densities. Different letters within a year, density, or cultivars indicate significant differences; \*, \*\* at P0.05 and P0.01, according to the least significant difference (LSD), respectively. NS indicates that treatment effects were not significant. Among cultivars, ZD 958 is (Zhengdan 958), LP206 is (Longping206), JQ119 is (Jinqiu 119), respectively.

Table 8. Correlation between cob characteristics.

	Length	BP	Diameter	NKR	NPKR
BP	-0.2919**				
Diameter	0.6338**	0.0733ns			
NKR	0.4964 **	0.2334*	0.5129**		
NPKR	0.8851**	-0.4616**	0.4386**	0.3856**	
1000 G	0.3441**	0.0125NS	0.3304*	0.2051*	0.2051*

\*, \*\* indicate significance at P<0.05 and 0.01, respectively; NS indicates that the correlation was not significant. BP is barren part, NKR is the number of kernel rows, NPKR is the number of kernels per row.

into structural carbohydrates. The rapid build-up of total carbs precedes the quick synthesis of structural carbohydrates. ZD958 outperforms LP206 and JQ119 in terms of biochemical metrics. Our results (Fig. 6) showed that there is a strong positive correlation between stem crushing resistance, stem bending resistance, and

cellulose, hemicellulose, and lignin content. In brief, our findings demonstrate the impact of plant density on the basal third internode of maize plants, with implications for carbohydrate production, structural development, and biochemical metrics.

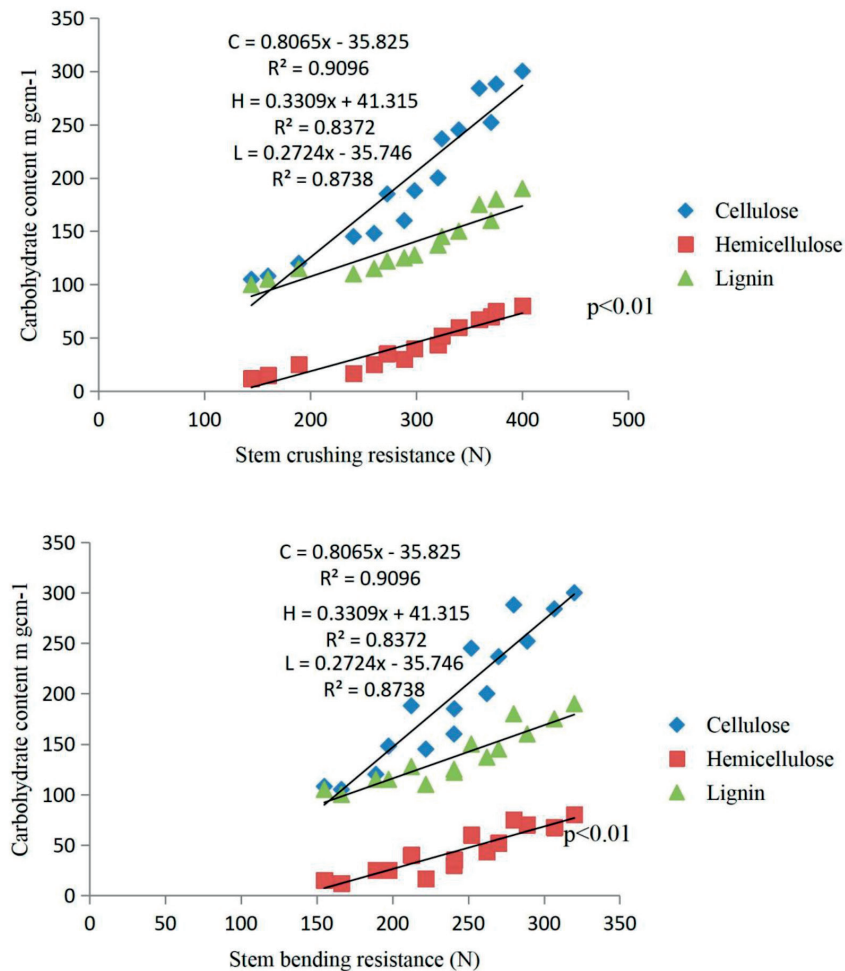


Fig. 6. Correlation between carbohydrate content (cellulose, hemicellulose, and lignin) and stem bending resistance (N) and stem crushing resistance (N).

## Conclusions

In summary, higher plant densities enhance radiation interception, resulting in higher DMA, RUE, and grain production, along with significant changes in ear traits. Optimal grain production was achieved at planting densities of PD6 and PD7.5, while densities of PD9 and PD15 reduced yield due to increased lodging in JQ119 and LP206. Planting density had a substantial impact on ear traits, showing a strong correlation between cob length and kernel count per row. Cultivars JQ119 and LP206 performed well at PD6 and PD7.5, whereas the lodging-resistant ZD958 achieved higher yields at greater densities. In general, we recommend that the ideal plant densities for maize production to achieve high yield are PD6 and PD7.5. Furthermore, to enhance photosynthesis and dry matter accumulation, we suggest the application of plant growth regulators such as ethephon and optimized fertilizer strategies to boost internode thickness, rind strength, and lodging resistance.

## Conflict of Interest

All authors declare no conflict of interest.

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## References

1. CASSMAN K.G., DOBERMANN A., WALTERS D.T., YANG H. Meeting cereal demand while protecting natural resources and improving environmental quality. *Annual Review of Environment and Resources*. **28** (1), 315, 2003.

2. CASSMAN K.G., LISKA A.J. Food and fuel for all: Realistic or foolish? *Biofuels, Bioproducts and Biorefining*. **1** (1), 18, **2007**.
3. GRASSINI P., THORBURN J., BURR C., CASSMAN K.G. High-yield irrigated maize in the Western U.S. Corn Belt: I. On-farm yield, yield potential, and impact of agronomic practices. *Field Crops Research*. **120** (2), 142, **2011**.
4. CI X., LI M., XU J., LU Z., BAI P., RU G., DONG S. Trends of grain yield and plant traits in Chinese maize cultivars from 1950 to 2000. *Euphytica*. **185** (1), 395, **2012**.
5. QIU J.J., TANG H.J., FROLKING S., BOLES S., LI C., XIAO X., QIN X.G. Mapping single-, double-, and triple-crop agriculture in China at  $0.5 \times 0.5^\circ$  by combining county-scale census data with a remote sensing-derived land cover map. *Geocarto International*. **18** (1), 3, **2003**.
6. LI S.K., WANG C.T. Potential and ways to high yield in maize. In *Maize Production Handbook*, Science Press: Beijing, China, pp. 154, **2010**.
7. LUO N., MENG Q., FENG P., QU Z., YU Y., LIU D.L., MÜLLER C., WANG P. China can be self-sufficient in maize production by 2030 with optimal crop management. *Nature Communications*. **14** (1), 2637, **2023**.
8. SHER A., HE L., ZHANG S., LI J.C., SONG Y. Analysis and characterization of interplant competition on maize canopy morphology for modeling. *Proceedings of the IEEE International Conference on Functional-Structural Plant Growth Modeling, Simulation, Visualization and Applications*. **1** (1), 189, **2016**.
9. SHER A., KHAN A., ASHRAF U., LIU H.H., LI J.C. Characterization of the effect of increased plant density on canopy morphology and stalk lodging risk. *Frontiers in Plant Science*. **9** (1), 1047, **2018**.
10. SHER A., ZHANG L.G., NOOR M.A., NADEEM M., ASHRAF U., BALOCH S.K., GUO P.Y. Nitrogen use efficiency in cereals under high plant density: manufacturing, management strategies and future prospects. *Applied Ecology and Environmental Research*. **17** (4), 10139, **2019**.
11. SHAO H., XIA T., WU D., CHEN F., MI G. Root growth and root system architecture of field-grown maize in response to high planting density. *Plant and Soil*. **430** (1), 395, **2018**.
12. SHAO H., SHI D., SHI W., BAN X., CHEN Y., REN W., CHEN F., MI G. Genotypic difference in the plasticity of root system architecture of field-grown maize in response to plant density. *Plant and Soil*. **439** (1), 201, **2019**.
13. ZHANG L., LIU G., YANG Y., GUO X., JIN S., XIE R., MING B., XUE J., WANG K., LI S. Root characteristics for maize with the highest grain yield potential of 22.5 Mg ha<sup>-1</sup> in China. *Agriculture*. **13** (4), 765, **2023**.
14. CHRISTOPHER R.B., JUDITH B.S., TOLLENAAR M., TONY J.V. Maize morphophysiological responses to intense crowding and low nitrogen availability: An analysis and review. *Agronomy Journal*. **101** (6), 1426, **2009**.
15. MADDONNI G.A., OTEGUI M.E., CIRILO A.G. Plant population density, row spacing, and hybrid effects on maize canopy architecture and light attenuation. *Field Crops Research*. **71** (3), 183, **2001**.
16. ANTONIETTA M., FANELLO D.D., ACCIARESI H.A., GUIAMET J.J. Senescence and yield responses to plant density in stay green and earlier-senescing maize hybrids from Argentina. *Field Crops Research*. **155** (1), 111, **2014**.
17. CARLONE M.R., RUSSELL W.A. Response to plant densities and nitrogen levels for four maize cultivars from different eras of breeding. *Crop Science*. **27** (3), 465, **1987**.
18. ASSEFA Y., CARTER P., HINDS M., BHALLA G., SCHON R., JESCHKE M., PASZKIEWICZ S., SMITH S., CIAMPITTI I.A. Analysis of long-term study indicates both agronomic optimal plant density and increased maize yield per plant contributed to yield gain. *Scientific Reports*. **8** (1), 4937, **2018**.
19. National Bureau of Statistics of China. *China Statistical Yearbook*. Available online: <https://data.stats.gov.cn/easyquery.htm?cn> (accessed on 1 January 2023).
20. SANGIO L., GRACIETTI M.A., RAMPAZZO C., BIANCHETTI P. Response of Brazilian maize hybrids from different eras to changes in plant density. *Field Crops Research*. **79** (2-3), 39, **2002**.
21. TOKATLIDIS I.S., KOUTROUBAS S.D. A review of maize hybrids' dependence on high plant populations and its implications for crop yield stability. *Field Crops Research*. **88** (2-3), 103, **2004**.
22. TOLLENAAR M., WU J. Yield improvement in temperate maize is attributable to greater stress tolerance. *Crop Science*. **39** (6), 1597, **1999**.
23. TOLLENAAR M., LEE E.A. Yield potential, yield stability and stress tolerance in maize. *Field Crops Research*. **75** (2-3), 161, **2002**.
24. SHER A., IQBAL J., NAZEER W., MAQBOOL M.M., NADEEM M., FAIZ S., KHAN S. A review on overcoming dual challenges for maize cropping under high plant density: Stalk lodging and kernel abortion. *Journal of Bioresource Management*. **9** (1), 1, **2022**.
25. TOKATLIDIS I.S., HAS V., MELIDIS V., HAS I., MYLONAS I. Maize hybrids less dependent on high plant densities improve resource-use efficiency in rainfed and irrigated conditions. *Field Crops Research*. **120** (3), 345, **2011**.
26. MADDONNI G.A., OTEGUI M.E. Intra-specific competition in maize: Early establishment of hierarchies among plants affects final kernel set. *Field Crops Research*. **85** (1), 1, **2004**.
27. EDMEADES G.O., DAYNARD T.B. The relationship between final yield and photosynthesis at flowering in individual maize plants. *Canadian Journal of Plant Science*. **59** (4), 585, **1979**.
28. TETIO-KAGHO F., GARDNER F.P. Response of maize to plant population density: II. Reproductive developments, yield. *Euphytica*. **185** (1), 395, **1988**.
29. TRIPATHI A.M., POHANKOVÁ I.D.E., FISCHER M., ORSÁG M., TRNKA M., KLEM K., MAREK M.V. The evaluation of radiation use efficiency and leaf area index development for the estimation of biomass accumulation in short rotation poplar and annual field crops. *Forests*. **9** (4), 168, **2018**.
30. GOU L., HUANG J.J., ZHANG B., ZHAO M. Effects of population density on stalk lodging resistant mechanism and agronomic characteristics of maize. *Acta Agronomica Sinica*. **33** (1), 1688, **2007**.
31. NOVACEK M.J., MASON S.C., GALUSHA T.D., YASEEN M. Twin rows minimally impact irrigated maize yield, morphology, and lodging. *Agronomy Journal*. **105** (1), 268, **2013**.
32. MONTGOMERY E.G. Correlation studies in corn. *Nebraska Agricultural Experimental Station Annual Report*. **24** (1), 108, **1911**.
33. XUE J., ZHAO Y., GOU L., SHI Z., YAO M., ZHANG W. How high plant density of maize affects basal internode development and strength formation. *Crop Science*. **56** (1), 3295, **2016**.

34. HAY R.K.M., WALKER A.J. Introduction to the physiology of crop yield. In *Crop Physiology*; Longman Group UK: Harlow, UK, pp. 154, **1989**.
35. BOS H.J., VOS J. Morphological analysis of plant density effects in wheat. *Field Crops Research*. **67** (1), 49, **2000**.
36. WELDU M.A. Effect of nitrogen fertilizer rates and plant densities on yield and yield related traits of maize (*Zea mays L.*) under irrigation in Southern Tigray, Ethiopia. PhD Thesis, Addis Ababa University, pp. 154, **2015**.
37. SANGAKKARA U.R., LIEDGENS M., SOLDATI A., STAMP P. Root and shoot growth of maize (*Zea mays*) as affected by incorporation of *Crotalaria juncea* and *Tithonia diversifolia* as green manures. *Journal of Agronomy and Crop Science*. **190** (5), 339, **2004**.
38. IMRAN S., ARIF M., KHAN A., SHAH W., ABDUL L., ALI KHAN M. Effect of nitrogen levels and plant population on yield and yield components of maize. *Advanced Crop Science Technology*. **3** (1), 170, **2015**.
39. ZAMIR M.S.I., AHMAD A.H., JAVEED H.M.R., LATIF T. Growth and yield behavior of two maize hybrids towards different plant spacing. *Cercetări Agronomice în Moldova*. **44** (2), 33, **2011**.
40. SEYYED G.M., MOHAMAD J.S., ALI M. Effect of planting date and plant density on morphological traits, LAI and forage corn (Sc. 370) yield in second cultivation. *International Research Journal of Applied and Basic Sciences*. **3** (1), 57, **2012**.
41. BEGNA S.H., HAMILTON R.I., DWYER L.M., STEWART D.W., SMITH D.L. Effects of population density and planting pattern on the yield and yield components of leafy reduced-stature maize in a short-season area. *Journal of Agronomy and Crop Science*. **179** (1), 9, **1997**.
42. DUVRICK D.N., CASSMAN K.G. Post-green revolution trends in yield potential of temperate maize in north-central United States. *Crop Science*. **39** (6), 1622, **1999**.
43. CHEN G.P., GAO J.L., ZHAO M., DONG S.T., LI S.K., YANG Q.F. Distribution, yield structure, and key cultural techniques of maize super high yield plots in recent years. *Acta Agronomica Sinica*. **1** (1), 80, **2012**.
44. ITTERSUM M.K., CASSMAN K.G. Yield gap analysis—rationale, methods and applications—introduction to the special issue. *Field Crops Research*. **143** (1), 1, **2013**.
45. XU W., LIU C., WANG K., XIE R., MING B., WANG Y., HOU P. Adjusting maize plant density to different climatic conditions across a large longitudinal distance in China. *Field Crops Research*. **212** (1), 126, **2017**.
46. BAVEC F., BAVEC M. Effects of plant population on leaf area index, cob characteristics and grain yield of early maturing maize cultivars (FAO 100-400). *European Journal of Agronomy*. **16** (2), 151, **2002**.
47. NIELSEN B. Stalk lodging in corn: Guidelines for preventive management. In *Corn Production Handbook*; Purdue University Press: West Lafayette, IN, USA, pp. 154, **2006**.
48. LI S.Y., MA W., PENG J.Y., CHEN Z.M. Study on yield loss of summer maize due to lodging at the big flare stage and grain filling stage. *Scientia Agricultura Sinica*. **19** (1), 3952, **2015**.
49. VAN DYK J. Corn lodging sets. In *Integrated Crop Management: Plant Diseases*; Iowa State University Press: Ames, IA, USA, pp. 154, **2001**.
50. IJAZ M., SAMMAR R.M.A., SAJID A., KAMRAN G., TAUQEER A.Y., MUHAMMAD S., MUHAMMAD N. Differential planting density influences growth and yield of hybrid maize. *Journal of Environmental and Agricultural Sciences*. **2** (3), 1, **2015**.
51. AMIN F., MEYSAM M. Effect of plant density on yield and yield components of maize cultivars. *Bioenhancement, Environment, Protection and Life Sciences*. **3** (1), 123, **2014**.
52. ABUZAR M.R., SADOZAI G.U., BALOCH M.S., BALOCH A.A., SHAH I.H., JAVAID T., HUSSAIN N. Effect of plant population densities on yield of maize. *Journal of Animal and Plant Sciences*. **21** (4), 692, **2011**.
53. ANDRADE F.H., RIZZALLI R., DELLAMAGGIORA A., CASSANOVAS M. Kernel number prediction in maize under nitrogen or water stress. *Crop Science*. **42** (5), 1173, **2002**.
54. TOLLENAAR M., DEEN W., ECHARTE L., LIU W. Effect of crowding stress on dry matter accumulation and harvest index in maize. *Agronomy Journal*. **98** (4), 930, **2006**.
55. ADENIYAN O.N. Effect of different population densities and fertilizer rates on the performance of different maize varieties in two rain forest agro ecosystems of South West Nigeria. *African Journal of Plant Science*. **8** (8), 410, **2014**.
56. DONATUS F.U., CYNTHIA C.O. Effects of poultry manure and plant population on soil properties and agronomic performance of sweet maize. *International Journal of Applied Science and Technology*. **4** (4), 190, **2014**.
57. GOBEZE L., CERONIO M.G., DANIEL V.R. Effect of row spacing and plant density on yield and yield components of maize (*Zea mays L.*) under irrigation. *Journal of Agricultural Science and Technology*. **2** (1), 263, **2012**.
58. SABERI A., FEIZBAKHS M.T., MOKHTARPOUR H., MOSAVAT A., ASKAR M. Effect of plant density and planting pattern on grain yield and yield components in grain maize. *Journal of Agronomy and Seed Plant*. **2** (26), 136, **2010**.
59. ABENDROTH L.J., ELMORE R.W., BOYER M.J., MARLAY S.K. Corn growth and development. In *Corn Production Systems*; Iowa State University Extension: Ames, IA, USA, pp. 154, **2011**.
60. MEHDI S., BAHRAM M. Crop yield and weed biomass as affected by seeding rate and nitrogenous fertilizer case study: sc640; a new released cultivar. *Indian Journal of Fundamental and Applied Life Sciences*. **4** (4), 74, **2014**.
61. NIK M.M., MAHDI B., ABOLFAZL T., AHMAD A. Effect of plant density on yield and yield components of corn hybrids (*Zea mays L.*). *Science Research Essays*. **6** (22), 4821, **2012**.
62. TRIFUNOVIC B.V. Proucavanje zavisnosti i odnosa prinosa zrna i nekih morfoloskih osobina hibrida kukuruza. *Arhiv za poljoprivredne nauke*. **49** (1), 69, **1988** [In Serbian].
63. REMISION S.U., LUCAS E.O. Effects of planting density on leaf area and productivity of two maize cultivars. *Experimental Agriculture*. **18** (2), 203, **1982**.
64. TESTA G., REYNERI A., BLANDINO M. Maize grain yield enhancement through high plant density cultivation with different inter-row and intra-row spacings. *European Journal of Agronomy*. **72** (1), 28, **2016**.
65. XU C., HUANG S., TIAN B., REN J., MENG Q., WANG P. Manipulating planting density and nitrogen fertilizer application to improve yield and reduce environmental impact in Chinese maize production. *Frontiers in Plant Science*. **8** (1), 1234, **2017**.
66. RAHMATI H. Effect of plant density and nitrogen rates on morphological characteristics grain maize.

- Journal of Basic and Applied Scientific Research. **2** (5), 4680, **2012**.
67. AYMAN H.A., SAMIER K.A. Maize productivity as affected by plant density and nitrogen fertilizer. International Journal of Current Microbiology and Applied Sciences. **4** (6), 870, **2015**.
68. LI T., LIU L.N., JIANG C.D., LIU Y.J., SHI L. Effects of mutual shading on the regulation of photosynthesis in field-grown sorghum. Journal of Photochemistry and Photobiology B: Biology, **137** (1), 31, **2014**.