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Full Length Article

Effect of Planting Density on Grain-Filling and Mechanized Harvest Grain Characteristics of Summer Maize Varieties in Huang-Huai-Hai Plain

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Abstract

Three maize varieties were planted as the main corn varieties in the Huang-huai-hai Plain as materials with five planting densities. Differences in grain filling and mechanised harvest grain characteristics to planting density amongst summer maize cultivars were examined. As plant density increased, the 100-grain dry weights of the three varieties gradually decreased. In the filling period, the 100-grain fresh weights increased initially and then decreased, and the 100-grain fresh weights decreased as plant density increased. At different densities, the grain-filling rates of the three varieties showed single-peak curves, and the highest peak of the grain-filling rate was achieved 30 days after pollination. In the whole grain-filling period, the different densities of the three maize varieties exhibited a decline in the percentage of grain water (PGW). The grain-filling processes of maize varieties with different plant densities were analysed with a logistic model, and the total filling period was divided into gradual increase stage, rapid increase stage and slow growth stage. The yield factors of the three varieties were also analysed. With the increased density, the number of lines per ear (NE), the number of grains per line (NL) and 1000-grain weight (GW) decreased. The grain yield initially increased and then decreased. The maximum yields of Zhengdan958 and Liyu16 were achieved at a density of 75,000 plants ha^{-1}, and the yield of Hengdan6272 was obtained at 90,000 plants ha^{-1}. These results indicated that the negative effects of dense planting on grain filling and mechanised harvest grain functions in Hengdan6272 were lower than those in Zhengdan958 and Liyu16 and suggested that the yielding potential of the former variety was higher than that of the latter two.

Keywords: Planting density; Grain-filling; Maize; Yield; Logistic equation; Correlation

Introduction

Maize (*Zea mays* L.) is a highly important grain crop in China that plays a substantial role in ensuring food security (Qin *et al*., 2016). It is widely used to provide food, forage and industrial raw materials (Alvarez and Grigera, 2005; Akmal *et al*., 2015; Li *et al*., 2015). The Huang-Huai-Hai Plain is the main producing area of summer maize in China. The sowing area accounts for about 28% of the total sowing area of maize in China, and the yield constitutes about 30% of that of the whole country (Wang *et al.*, 2008). Heterosis utilisation and adaptation to high-density planting stress are often associated with yield improvement in maize (Liu and Tollenaar, 2009; Mbah and Nneji, 2010). Within a certain range, rising planting density and improving utilisation ratios of light and heat resources are the key measures to obtain a high maize yield (Sangoi *et al*., 2002; Mbah and Nneji, 2010). Maize grain yield is significantly affected by planting density. Thus, the number of spikes per plant and the grain weight per plant should be maintained when the number of harvested ears per unit area increases, and the yield per unit area should be enhanced by relying on high-population advantages (Bukhsh *et al.*, 2011; Tanveer *et al*., 2014). At present, in the Huang-huai-hai Plain, various maize genotypes that can adapt to high planting densities are widely grown. Such adaptability is derived from the higher partitioning of assimilates to the shoot than to the root that also results in diminished root/shoot ratio (Zhou *et al*., 2008). Therefore, an appropriate crop density may help effectively maximise all renewable and non-renewable resources to achieve a high crop yield (Amanullah *et al*., 2010). At a low density, the crop grain yield per plant is high, but the population yield is low. When the planting densities of maize varieties exceeds a certain limit, the yield per plant decreases, but the grain yield per unit area increases (Gözübenli, 2010). The material production capacity between maize individuals and populations plays a key role in the high yield potential of close planting

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(Sarlangue *et al.*, 2007). Numerous studies have shown that maize yield is significantly positively correlated with dry matter accumulation (Frey, 1981; Paponov *et al*., 2005; Tollenaar *et al.*, 2006; Kosgey *et al*., 2013). The grain-filling period is critical for maize yield and grain quality, and the grain yield is closely related to the grain-filling characteristics (Sadras and Egli, 2008; Borrus *et al*., 2009). The grain-filling rate and uration determine the final grain yield and directly affect the whole-grain physiological water content of maize. Studying grain filling characteristics not only helps enhance the understanding of the grain weight formation process but also contributes to the development of effective control measures for the key grouting process to achieve high yield and good quality (Rajcan and Tollenaar, 1999).

The low-level mechanised harvest of maize, especially low-level mechanised grain harvest, is the main bottleneck to corn industrialisation in China (Qiao *et al.*, 2015). At present, most of the corn attained from mechanised harvest is mainly gathered using spikes, but grain harvest is the future development trend of corn harvest machinery. The high water content of summer maize at physiological grain maturity limits corn grain harvesting and causes problems, such as high corn grain damage rates and loss rates (Huang *et al*., 2015). Corn grain harvesting can directly reduce labour cost, solve rural labour shortage and improve harvest quality. Thus, corn harvesting process should be developed. Different studies have focused on the yield of different maize varieties and the physiological characteristics of the source sink and the growth period (Wang, 2012; Wang *et al*., 2012; Gasura and Setimela, 2013). Studies have also systematically investigated and compared the different responses to dry matter accumulation. The grain-filling rate and mechanised grain harvest of maize varieties are low.

In this study, three maize varieties widely grown in the Huang-huai-hai Plain were used to investigate the dry matter accumulation, grain filling and yield formation of maize at different planting densities. This work aimed to provide a theoretical reference and technical support for the development of a high-yield cultivation technology for summer maize in the Huang-huai-hai Plain and for breeding density-tolerant varieties.

Materials and Methods

Experimental Details and Treatments

Site description: The experiments were performed from June to October of 2016-2017 at the dry farming experimental station of the Dry Farming Institute of the Hebei Academy of Agricultural and Forestry Sciences (37°53′N, 115°42′ E) located in Shenzhou County, Hebei Province. The test site was situated in the north-central region of the Huang-huai-hai Plain and coincided with the continental monsoon climate zone, where summers are hot and dry and winters are warm and wet. The soil type was clay loam composed of 15.4 g kg^{-1} organic matter, 81 mg kg^{-1} available nitrogen, 20.7 mg kg^{-1} available phosphorus and 179.7 mg kg^{-1} available potassium at pH 8.3.

Experimental material: The experimental materials were three locally popularised maize varieties, namely, Hengdan6272, Zhengdan958 and Liyu16.

Treatments: The experiment adopted a randomised complete block design with a split-plot arrangement of three replications. Factorial experimental treatments of the maize varieties (Hengdan6272, Zhengdan958 and Liyu16) were allotted to the main plots, whereas experiments on the planting densities (45,000, 60,000, 75,000, 90,000 and 105,000 plants ha^{-1}) were assigned to the subplots. A total of 15 plots were assembled in each replication. The size of each plot was 10.0 m × 30.0 m. Each plot consisted of 10 rows that were 50 m long with a row-to-row distance of 60 cm.

The sowing dates were June 16 and 15, and the harvesting dates were October 10 and 8, in 2016 and 2017, respectively. The same type of reaping machine was used for mechanised harvest for 2 years. The land was not planted with any crop in the final season. Before sowing, the plots were finely cultivated and irrigated, and basal fertiliser was applied as described by Anhui Liuguo. Compound fertiliser (containing 22% N, 12% P_2O_5 and 14% K_2O; 460 kg ha^{-1}) and additional nitrogen fertiliser (180 kg N ha^{-1}) were added at the 12^{th} leaf stage (V12). Irrigation was conducted twice during the maize growing season of each year depending on rainfall. The other field management steps were similar to those used in conventional production fields.

Weather Conditions during the Experimental Period

Fig. 1 shows the weather conditions of the study site during the maize growth period in 2016 and 2017. The daily mean temperature, average sunshine hours and rainfall were recorded by the Chinese Meteorological Administration. The daily average temperature and average sunshine hours showed the same trend in 2016 and 2017. The daily average temperature was the highest in July and lowest in October, whereas the average sunshine hours were the highest in June and lowest in August. The rainfall trends varied throughout the 2 years. Rainfall concentrated in the early period of 2016 and in the middle and late periods of 2017.

Determination Items and Methods

Determination of grain-filling process: Before the maize silking stage, plants with simultaneous silking and strong uniform growth were selected for bagging and unified artificial pollination. Sampling was performed from day 7 after silking, and pollination was conducted once every 10 days until the seeds matured. In each plot, 100 grains were obtained from the middle grain parts of three ears until the seeds matured. The dry weight and fresh weight of 100 grains were measured.

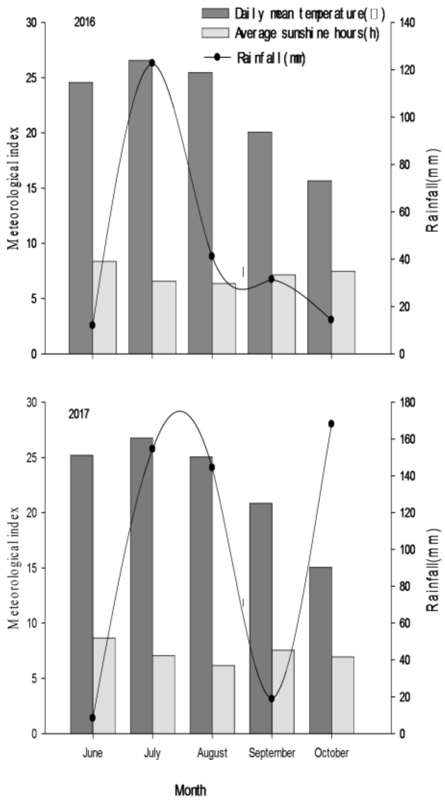

Fig. 1: Meteorological index of temperature, sunshine and rainfall during maize growth period in 2016 and 2017

Dry weight determination method: The sample was placed in the oven at 105°C for 30 min and then dried at 80°C to constant weight. The final weight was recorded for analysis.

Then, the water content and grain-filling rate were calculated as follows:

Percentage of grain water (PGW, %) = (water amount/fresh weight) × 100%

Grain-filling rate (g/d) = [dry weight of 100 grains in later time (g)−dry weight of 100 grains in former time (g)]/sampling interval between the two times (d).

The steps of the analysis method of population grain filling characteristics were as follows:

The grain-filling process of the population was simulated by logistic curve, and the equation is $W = A/(1+Be^{-kt})$. In the formula, W is the dry weight of the grain per unit area, A is the maximum grain weight of theoretical unit area, B and K are the parameters to be determined, and t is the days after silking. For the first derivative of logistic equation, the equation of the grain-filling rate G, i.e. $G=AKBe^{-kt}/(1+Be^{-kt})^2$, can be obtained. When applied, the following secondary parameters can also be derived for describing the grain-filling characteristics:

(1) Maximum grain-filling rate (G_{max}) and the maximum filling time (T_{max}), where (T_{max}) = ln B/K. The (T_{max}) is inputted into the filling rate equation G_{max}, and the initial accumulation potential R_0 = K.

(2) Average grain-filling rate (G_{mean}) and active grain filling period (D) (G = AK/6, D = A/G).

(3) Grain-filling process divided into three periods (Qiao *et al.*, 2015). The three periods include the early, middle and late stages. In the early grain filling stage (grain weight increasing stage), $T_1 = t_1$. In the middle filling stage (grain weight quickening stage), $T_2 = t_2 - t_1$. In the late filling stage (grain weight slowing stage), $T_3 = t_3 - t_2$. The average filling rates p_1, p_2 and p_3 of the population grains in the early, middle and late filling stages can be calculated through the following formulas: $p_1 = W_1/T_1$, $p_2 = (W_2-W_1)/T_2$ and $p_3 = (W_3-W_2)/T_3$. The dry weights of t_1, t_2 and t_3 corresponded to W_1, W_2 and W_3, respectively.

Yield and yield components: In the mature stage, two rows (not sampled) were harvested in each plot and dried naturally after harvest. After threshing, the yield was measured (in accordance with the standard water content of 14%). After harvest, 10 ears were randomly selected from each plot, and the row number, grain number per row and 1000-grain weight were measured.

Determination of Grain Mechanical Harvest Characteristics

In the harvest section, random selection was applied to three samples. Each sample point was 8 m long, and a cutting width (three lines) was adopted. The samples were measured for the gleaning and grain weights, and the yield loss rate (YLR) was calculated as follows:

YLR (%) = (field samples in field grain weight + gleaning grain weight)/sample yield × 100.

In the harvest of the cabin, 500 g grain samples were randomly selected, and the grain breakage particles and impurities were manually sorted. The samples were then weighed to calculate for the damage rate and impurity rate as shown below:

Grain crashing rate (%) = Damaged grain weight per sample/sample grain total weight × 100;

Grain impurity rate (%) = Weight of the sample impurity/total weight of the sample grain × 100.

Statistical Analysis

Microsoft Excel (version 2007) software (Microsoft Corporation, Redmond, WA, USA, 2007) and SPSS (version 17.0) software (SPSS Inc., Chicago, IL, USA, 2008) were used for data processing and statistical analysis, respectively. The CurveExpert (version 1.4) software was adopted to simulate the grain-filling process after flowering. Significant testing was carried out by the LSD method, and the significant level was set at 0.05. Sigmaplot (version 12.0) software (Sigmaplot Inc., San Jose, CA, USA, 2006) was utilised for mapping.

Results

Changes in the 100-Grain Dry Weight and 100-Grain Fresh Weight of Different Varieties

The 100-grain dry weights of the three maize varieties showed a slow–fast–slow ‘S’ change as the grain-filling process progressed (Fig. 2). The grain dry weight increased relatively slowly within 15 days. Then, the 100-grain dry weights of the three varieties rose rapidly within 15–55 days after pollination. This period is an important stage for dry matter accumulation in grains. After pollination, a slow increase in dry weight accumulation was noted within 55–65 days in the three varieties. The results of 2 years’ testing showed that the dry weight accumulation processes of the same varieties at different densities were consistent, and the low-density grain accumulation potential was higher than that of high-density grain accumulation potential.

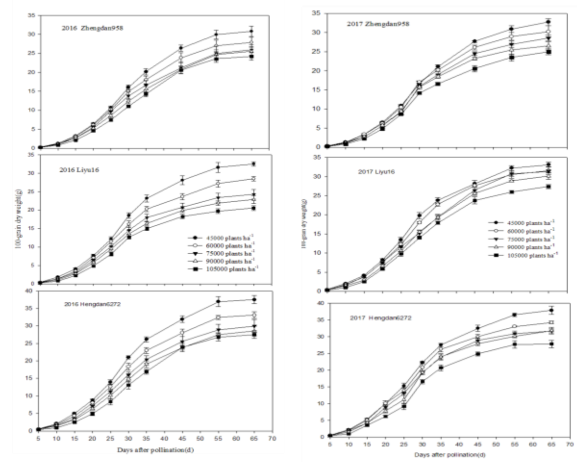

Fig. 2: Effects of planting density on the 100-grain dry weight in maize hybrids

Changes in the 100-Grain Fresh Weights of Maize Varieties under Different Planting Densities

The dynamics of fresh weight accumulation for different planting densities in 2016 and 2017 are shown in Fig. 3. The ‘days’ are expressed as days after pollination to directly examine the difference in grain fresh weight amongst the planting densities at different grain-filling stages. During the grain-filling stage, the fresh weight for different planting densities showed the same trend, that is, ‘rapid growth–slow decline’. The rapid growth concentrated within 5–45 days after pollination. The maximum grain fresh weight of each variety was achieved 45 days after pollination, but the value differs significantly amongst the three varieties. The maximum grain fresh weights of Hengdan6272 and Zhengdan958 were significantly higher than that of Liyu16 ($P < 0.05$), and no significant difference was observed between Hengdan6272 and Zhengdan958 ($P > 0.05$) in 2016 and 2017. The grain fresh weights of the same variety at different densities were dissimilar. The grain fresh weight of the planting density of 45,000 plants ha^{-1} was significantly higher than those for the other planting densities in 2016 and 2017.

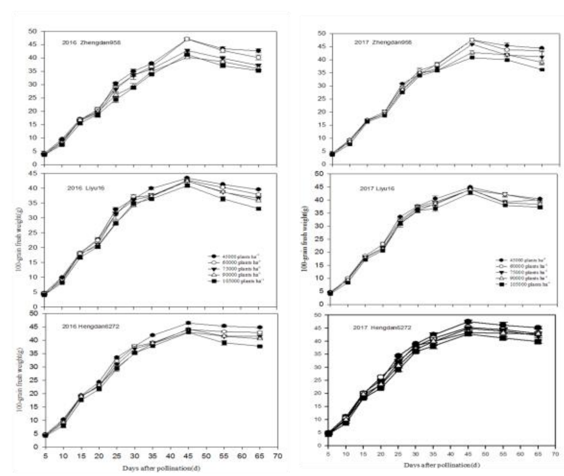

Fig. 3: Effects of planting density on the 100-grain fresh weight in maize hybrids

Changes in Grain-filling Rate of the Maize Varieties under Different Planting Densities

The grain-filling rates of the three varieties under five planting densities all showed a changing trend of single-peak type in the whole-grain filling stage (Fig. 4). The maximum filling rates of the three varieties were all attained at about 30 days after pollination and exhibited the order of Hengdan6272 > Liyu16 >Zhengdan958. During the grain-filling stage, the grain-filling rates at different planting densities were similar.

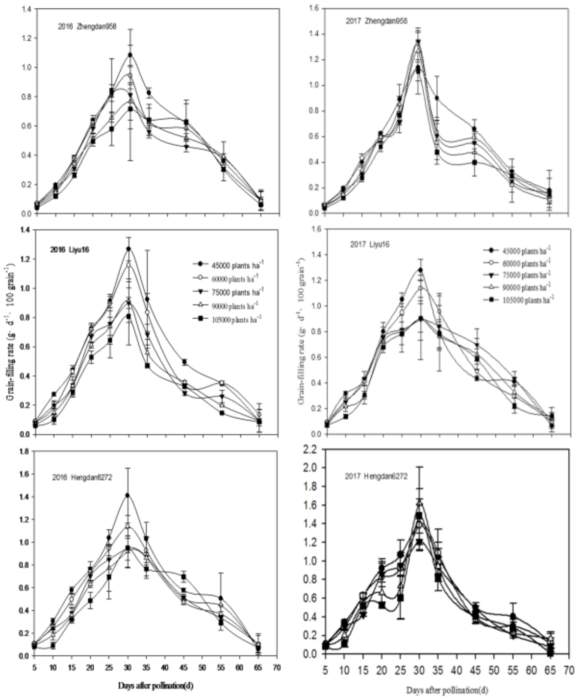

Fig. 4: Effects of planting density on the grain-filling rate in maize hybrids

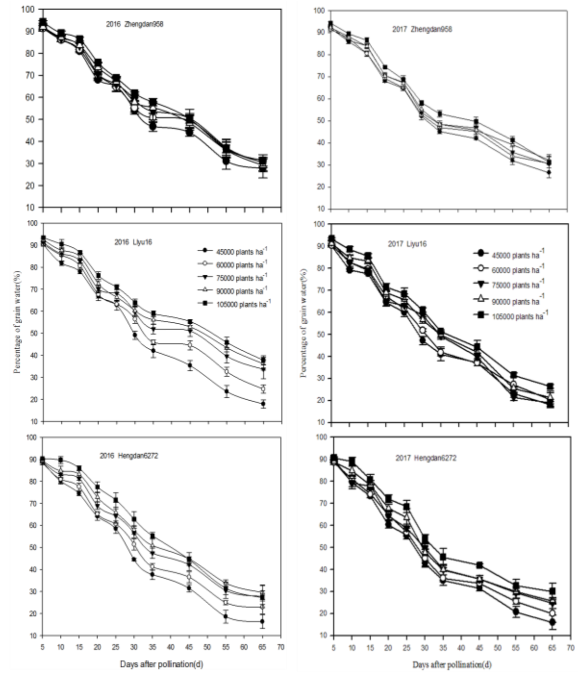

Fig. 5: Effects of planting density on water content in maize hybrids

Moreover, the grain-filling rates at low density were higher than those at high density. This observation was true, except for Hengdan6272 in 2017, when the grain-filling rate at low density was lower than that at high density. However, no significant difference was noted between the five planting densities.

Changes in Water Content of Maize Varieties under Different Planting Densities

Grain water content is an important aspect in the study of grain development in the grain-filling stage (Sala *et al.*, 2007). The PGWs of the three maize varieties diminished continuously with the growth process (Fig. 5). This observation was consistent with the continuous accumulation of dry matter in the grain. The water contents of the three varieties under the same density were analysed. The PGW of Hengdan6272 was significantly lower than those of Liyu16 and Zhengdan958.

Simulation of Grain Filling

With the number of days after pollination (t) as independent variable and the grain weight (Y) as dependent variable, the filling progress of grains was simulated with the logistic equation $Y = A/(1+Be^{-kt})$ (where A, B and k are parameters, and A is the final growth quantity). The logistic equation fitted well the filling progress of maize grains (Table 1), and the determination coefficient was >0.99.

Among the grain-filling characteristics of the three varieties (Table 1), initial grain-filling potential (R_0) of Liyu16 was the highest in 2016, Hengdan6272 was the highest in 2017 and Zhengdan958 was the lowest in 2016-2017. The time reaching the maximum grain-filling rate (T_{max}) and the active grain-filling period (D) showed that Zhengdan958 > Hengdan6272 > Liyu16. The maximum grain-filling rate (G_{max}) and mean grain-filling rate (G_{mean}) followed the order of Hengdan6272 > Liyu16 > Zhengdan958. For the analyses of the varying densities of the same maize variety, only a small difference was noted in R_0, and the G_{max} and G_{mean} showed a gradual decline with increasing density. Moreover, no obvious rule involving the T_{max} and D was noted amongst the different densities.

On the basis of the two turning points of the logistic equation, the grain-filling process was divided into three stages: the grain weight increase period (T_1), rapid increase stage (T_2) and grain weight slow growth stage (T_3). By analysing the parameter changes (Table 2), we noted that the grain weight increase period (T_1), rapid increase stage (T_2), grain weight slow growth stage (T_3), the completion time of the rapid increase stage (t_2) and the completion time of the slow growth stage (t_3) of Zhengdan958 were the greatest, followed by Liyu16 and Hengdan6272. The increased grain weight of the gradual increase stage (W_1), increased grain weight of the rapid increase stage (W_2), increased grain weight of the slow growth stage (W_3), mean grain-filling rate of the gradual increase stage (P_1), mean grain-filling rate of the rapid increase stage (P_2) and the mean grain-filling rate of the slow growth stage (P_3) of Hengdan6272 were the greatest.

Table 1: Grain-filling parameters of three maize varieties under different planting density

Year	Varieties	Density (plants ha^{-1})	A	B	K	R^2	R_0	T_{max} (d)	G_{max} (g/d)	G_{mean} (g/d)	D(d)
2016	Zhengdan958	45000	30.66	58.69	0.14	0.9982	0.14	29.91	1.04	0.70	44.07
		60000	27.73	51.34	0.13	0.9971	0.13	29.64	0.92	0.61	45.15
		75000	25.60	45.80	0.13	0.9945	0.13	29.73	0.82	0.55	46.64
		90000	25.63	46.31	0.12	0.9968	0.12	31.22	0.79	0.52	48.84
		105000	24.51	62.92	0.13	0.9984	0.13	31.90	0.80	0.53	46.21
	Liyu16	45000	32.04	56.80	0.14	0.9979	0.14	28.30	1.14	0.76	42.03
		60000	27.64	49.79	0.14	0.9947	0.14	27.87	0.97	0.65	42.80
		75000	23.61	53.78	0.15	0.9961	0.15	27.13	0.87	0.58	40.84
		90000	22.28	56.26	0.15	0.9970	0.15	27.46	0.82	0.55	40.88
		105000	20.02	77.71	0.16	0.9972	0.16	27.41	0.79	0.53	37.79
	Hengdan6272	45000	37.31	49.53	0.14	0.9971	0.14	28.77	1.27	0.84	44.23
		60000	32.85	46.68	0.13	0.9970	0.13	28.70	1.10	0.73	44.81
		75000	29.66	48.04	0.13	0.9980	0.13	29.03	0.99	0.66	44.98
		90000	28.28	50.73	0.13	0.9974	0.13	29.67	0.94	0.62	45.33
		105000	27.68	75.25	0.14	0.9992	0.14	31.26	0.96	0.64	43.41
2017	Zhengdan958	45000	32.21	61.16	0.14	0.9981	0.14	30.16	1.10	0.73	43.99
		60000	29.68	66.41	0.14	0.9968	0.14	29.10	1.07	0.71	41.61
		75000	27.80	75.55	0.15	0.9962	0.15	29.26	1.03	0.68	40.59
		90000	25.88	78.47	0.15	0.9966	0.15	28.34	1.00	0.66	38.98
		105000	23.96	73.71	0.15	0.9931	0.15	28.96	0.89	0.59	40.41
	Liyu16	45000	32.40	51.67	0.14	0.9959	0.14	27.60	1.16	0.77	41.98
		60000	31.08	58.56	0.14	0.9984	0.14	28.08	1.13	0.75	41.39
		75000	31.90	39.07	0.12	0.9967	0.12	30.73	0.95	0.63	50.31
		90000	29.91	53.06	0.13	0.9978	0.13	30.01	0.99	0.66	45.33
		105000	27.01	62.38	0.14	0.9977	0.14	29.72	0.94	0.63	43.15
	Hengdan6272	45000	37.11	47.14	0.14	0.9970	0.14	27.53	1.30	0.87	42.86
		60000	33.51	55.10	0.15	0.9973	0.15	26.89	1.25	0.83	40.25
		75000	31.41	58.96	0.15	0.9991	0.15	27.13	1.18	0.79	39.93
		90000	30.88	77.38	0.16	0.9961	0.16	27.52	1.22	0.81	37.97
		105000	27.68	90.15	0.16	0.9963	0.16	28.29	1.10	0.73	37.70

Note: A, B and K: the grouting coefficients; R_0: initial grain-filling potential; T_{max}: the time reaching the maximum grain-filling rate; G_{max}: maximum grain-filling rate; G_{mean}: mean grain-filling rate; D: active grain-filling period

Table 2: The parameters characteristics of the three grain-filling phases in maize hybrids under different planting density

Year	Varieties	Density (plants ha^{-1})	t_1 (d)	T_1 (d)	W_1 (g·100-kernel^{-1})	P_1 (g/d)	t_2 (d)	T_2 (d)	W_2 (g·100-kernel^{-1})	P_2 (g/d)	t_3 (d)	T_3 (d)	W_3 (g·100-kernel^{-1})	P_3 (g/d)
2016	Zhengdan958	45000	15.15	15.15	3.62	0.24	34.49	19.35	19.96	0.84	63.66	29.17	30.36	0.36
		60000	14.51	14.51	3.28	0.23	34.33	19.82	18.05	0.75	64.21	29.88	27.45	0.31
		75000	14.10	14.10	3.02	0.21	34.58	20.47	16.66	0.67	65.45	30.87	25.34	0.28
		90000	14.86	14.86	3.03	0.20	36.30	21.44	16.69	0.64	68.63	32.33	25.37	0.27
		105000	16.42	16.42	2.90	0.18	36.70	20.28	15.96	0.64	67.29	30.59	24.27	0.27
	Liyu16	45000	14.22	14.22	3.78	0.27	32.67	18.45	20.86	0.93	60.49	27.82	31.72	0.39
		60000	13.54	13.54	3.27	0.24	32.32	18.79	18.00	0.78	60.65	28.33	27.37	0.33
		75000	13.44	13.44	2.79	0.21	31.37	17.93	15.37	0.70	58.40	27.03	23.37	0.30
		90000	13.76	13.76	2.63	0.19	31.71	17.95	14.51	0.66	58.77	27.06	22.06	0.28
		105000	14.76	14.76	2.37	0.16	31.34	16.59	13.03	0.64	56.35	25.01	19.82	0.27
	Hengdan6272	45000	13.95	13.95	4.41	0.32	33.37	19.41	24.29	1.02	62.64	29.28	36.93	0.43
		60000	13.69	13.69	3.88	0.28	33.36	19.67	21.38	0.89	63.02	29.66	32.52	0.38
		75000	13.96	13.96	3.50	0.25	33.70	19.74	19.31	0.80	63.47	29.77	29.37	0.34
		90000	14.48	14.48	3.34	0.23	34.38	19.90	18.41	0.76	64.38	30.01	28.00	0.32
		105000	16.72	16.72	3.27	0.20	35.78	19.06	18.02	0.77	64.51	28.74	27.40	0.33
2017	Zhengdan958	45000	15.42	15.42	3.81	0.25	34.73	19.31	20.97	0.89	63.84	29.11	31.89	0.38
		60000	15.16	15.16	3.51	0.23	33.42	18.26	19.32	0.87	60.96	27.54	29.38	0.37
		75000	15.66	15.66	3.28	0.21	33.47	17.82	18.10	0.83	60.34	26.87	27.52	0.35
		90000	15.29	15.29	3.06	0.20	32.40	17.11	16.85	0.81	58.20	25.80	25.62	0.34
		105000	15.42	15.42	2.83	0.18	33.16	17.74	15.60	0.72	59.90	26.75	23.72	0.30
	Liyu16	45000	13.54	13.54	3.83	0.28	31.96	18.43	21.09	0.94	59.75	27.79	32.08	0.40
		60000	14.21	14.21	3.67	0.26	32.38	18.17	20.24	0.91	59.78	27.40	30.77	0.38
		75000	13.88	13.88	3.77	0.27	35.96	22.08	20.77	0.77	69.26	33.30	31.58	0.32
		90000	14.82	14.82	3.53	0.24	34.72	19.90	19.48	0.80	64.73	30.01	29.61	0.34
		105000	15.27	15.27	3.19	0.21	34.21	18.94	17.58	0.76	62.77	28.56	26.74	0.32
	Hengdan6272	45000	13.17	13.17	4.38	0.33	31.98	18.81	24.16	1.05	60.35	28.37	36.74	0.44
		60000	13.41	13.41	3.96	0.30	31.08	17.67	21.82	1.01	57.72	26.64	33.18	0.43
		75000	13.75	13.75	3.71	0.27	31.28	17.53	20.45	0.96	57.71	26.43	31.10	0.40
		90000	14.80	14.80	3.65	0.25	31.47	16.67	20.11	0.99	56.61	25.14	30.57	0.42
		105000	15.66	15.66	3.27	0.21	32.21	16.55	18.02	0.89	57.16	24.96	27.40	0.38

Note: t_1: the stop time of gradual increase stage; t_2: the stop time of rapid increase stage;t_3: the stop time of slow growth stage;T_1:grain-filling duration of gradual increase stage;T_2: grain-filling duration of rapid increase stage;T_3: grain-filling duration of slow growth period; W_1:increased grain weight of gradual increase stage;W_2: increased grain weight of rapid increase stage; W_3: increased grain weight of slow growth stage; P_1: mean grain-filling rate of gradual increase stage; P_2: mean grain-filling rate of rapid increase stage; P_3: mean grain-filling rate of slow growth stage

The parameters for Liyu16 and Zhengdan958 exhibited small differences. During the analysis of the same variety under different densities, small differences in T_1, T_2, T_3, t_2 and t_3 were noted amongst the densities. The performance trend was consistent with that of P_1, P_2 and P_3, and all the parameters gradually decreased with increasing planting density.

Yields and Yield Components of the Three Varieties under Different Planting Densities

As shown in Table 3, the number of lines per ear (NE), number of grains per line (NL), 1000-grain weight (GW) and yield of Hengdan6272 were the greatest, whereas Liyu16 and Zhengdan958 showed small differences in 2016-2017 under the same planting density. Under the same variety but different density, the yield increased initially and then decreased with increasing planting density. The minimum yield for Zhengdan958 was achieved at 45,000 plants ha^{-1}, and maximum was at 75,000 plants ha^{-1}. By contrast, the lowest yields for Liyu16 and Hengdan627 were attained at the planting density of 105,000 plants ha^{-1}, whereas the highest yields were achieved at 75,000 and 90,000 plants ha^{-1}, respectively. The yield differences between densities were significant.

Comparison between Grain Water and Grain Mechanical Harvesting Characteristics of the Three Varieties under Different Planting Densities

Planting density considerably influences the grain water content and mechanical characteristics (Table 4). Under the same density, the PGW, grain crashing rate (GCR), grain impurity rate (GIR) and YLR of Hengdan6272 were significantly lower than those of the other two cultivars in 2016-2017. By contrast, the lodging rate (LR) did not follow this relation. The GCR and YLR of Liyu16 were higher than those of Zhengdan958, and the GIR of Liyu16 was greater than that of Zhengdan958, except under the 105,000 plants ha^{-1} density.

The LR values were the same between Liyu16 and Zhengdan958 under low planting density (45,000 and 60,000 plants ha^{-1}), whereas the LR of Liyu16 was lower than that of Zhengdan958 under the other densities. The PGW values were lower in Liyu16 than in Zhengdan 958 under low density (45,000 and 60,000 plants ha^{-1}), whereas the opposite trend was noted at high density in 2016.Under the same density, the PGW of Liyu 16 was lower, whereas the GIR and YLR were higher, than those of Zhengdan958.

Amongst the different densities of the same variety, the PGWs, LRs, GCRs and YLRs all increased with rising density. The highest density (105,000 plants ha^{-1}) reached a significant level of difference to the performance under the lowest density (45,000 plants ha^{-1}), except for the PGW changes of Zhengdan958 in 2016.

Relationships

To identify the association of maize yield with related characteristic indices, we conducted a correlation analyses amongst the grain-filling factors, yield components, mechanical harvest index and yield (Table 5).

As shown in Table 5, the yield was strongly significantly correlated with the G_{max}, G_{mean}, W_1, W_2, P_2, W_3, P_3 and NL ($P < 0.01$), but strongly significantly negatively correlated with the LR ($P < 0.01$). Moreover, the yield was significantly correlated with the P_1 and GW, but showed no significant correlation with the remaining factors.

Discussion

Grain quantity is closely related to the late grain-filling period and that differences exist between varieties (Khan *et al*., 1998; Otegui and Bonhomme, 1998; Paponov *et al*., 2005; Qinwu *et al*., 2016). High-yield maize can only increase its yield potential under a suitable planting density. In particular, the photosynthetic physiological activity of leaf sources during grain filling is especially important for grain yield formation. Plant density substantially affects the dry matter accumulation of individuals and groups. The dry matter weight per plant decreases significantly as plant density increases. The results of our 2-year experiment showed that the yield components of the three maize varieties rose significantly with augmenting planting density. The NE, NL and GW elevations with rising density showed a downward trend, and the values at high plant density (105,000 plants ha^{-1}) were significantly lower than those under low density (45,000 plants ha^{-1}). The yields of the three varieties increased initially and then diminished with increasing planting density. The yields of Zhengdan958 and Liyu16 were the highest at the 75,000 plants ha^{-1} plant density, whereas the highest Hengdan6272 yield was attained at the 90,000 plants ha^{-1} plant density. Hengdan6272 exhibited a better tolerance to high planting density and better adaptability to high-density stress than those of Zhengdan958 and Liyu16.

This study also found that under different planting densities, the grain-filling rates of the three maize varieties followed an ‘S’ curve, which is consistent with the results of previous studies (Poneleit and Egli, 1979; Wang *et al*., 2012; Zhang *et al*., 2015). With elevating density, the maize grain weight declined significantly. The grain-filling rate showed a single-peak curve, and the maximum grain-filling rate decreased with increasing planting density. Dry matter accumulation depends on the grain-filling period and speed. The actual filling period of corn and the length of effective grain filling is significantly related to grain yield (Johnson and Tanner, 1972; Tollenaar and Aguilera, 1992). The present study revealed that the grain-filling process can be fitted by the logistic model, and derivation was achieved. The biologically important characteristic parameters can thoroughly explain the grain-filling process.

Table 3: Yield and yield components of three maize varieties under different planting density

Year	Varieties	Density (plants ha^{-1})	Number of lines per ear (line)	Number of grains per line	1000-grain weight (g)	Yield (kg ha^{-1})
2016	Zhengdan958	45000	16.75±1.04a	40.38±1.85a	339.88±3.44a	7537.54±349.66c
		60000	16.25±1.28a	38.75±1.91b	335.75±2.05b	8005.92±356.81c
		75000	16.00±1.07ab	35.00±1.60c	333.13±1.73b	9993.90±75.32a
		90000	16.00±1.06ab	34.13±1.13c	329.88±2.30c	9178.67±315.49b
		105000	15.00±1.07b	32.38±1.30d	322.00±3.74d	7889.48±407.34c
	Liyu16	45000	17.00±1.07a	40.88±1.36a	341.13±6.10a	7504.86±565.65d
		60000	16.75±1.04a	38.37±2.00b	336.63±3.50a	8352.12±497.67c
		75000	16.75±1.04a	35.01±1.31c	330.88±2.53b	10429.62±239.45a
		90000	16.50±0.93a	34.04±1.07c	326.63±4.66b	9580.47±322.74b
		105000	14.75±1.04b	32.25±1.49d	320.38±5.01c	7212.06±244.00d
	Hengdan6272	45000	17.25±1.04a	41.13±1.25a	345.25±3.37a	8485.35±574.85bc
		60000	17.25±1.04a	39.50±1.85b	342.13±2.90b	8686.07±450.52b
		75000	17.00±1.07a	38.25±1.28b	339.50±2.14bc	10975.31±371.38a
		90000	16.25±1.28ab	35.38±1.41c	337.63±2.92c	11098.71±181.71a
		105000	15.25±1.04b	33.13±1.81d	332.61±2.39d	7926.05±268.16c
2017	Zhengdan958	45000	17.25±1.04a	41.63±1.60a	342.13±4.36a	7799.82±266.22c
		60000	16.75±1.04a	39.88±1.13b	337.38±1.51b	8050.03±395.07c
		75000	16.25±0.71bc	37.13c±1.36c	333.63±3.81c	10164.20±266.22a
		90000	16.00±1.07bc	35.00±1.20d	330.50±3.30c	9424.91±309.60b
		105000	15.50±0.93c	33.25±1.28e	324.13±4.12d	7932.03±196.02c
	Liyu16	45000	17.50±0.93a	41.88±0.99a	343.25±2.66a	7857.41±240.54d
		60000	17.00±1.51ab	39.50±2.20b	338.13±3.36b	8306.98±192.22c
		75000	16.75±1.04a	37.25±1.58c	333.38±4.27c	10665.44±222.26a
		90000	16.25±0.71bc	36.00±1.93c	327.13±4.22d	9842.13±240.54b
		105000	15.25±1.04c	33.50±1.20c	320.38±3.96e	7686.13±263.86d
	Hengdan6272	45000	17.50±0.93a	42.63±0.92a	348.38±3.70a	8623.20±293.49b
		60000	17.25±1.04ab	40.50±1.93b	344.38±3.74b	8871.74±275.68b
		75000	17.25±1.04ab	39.38±1.06b	342.25±4.23b	11855.15±275.68a
		90000	16.50±0.93b	37.13±1.13c	338.38±2.67c	12966.53±272.66a
		105000	15.50±0.93c	33.25±1.49d	334.38±2.33d	8603.74±317.30b

Note: The data in the table indicate mean ± standard deviation, values followed by a different letter significant different at $P < 0.05$, the same below

Table 4: Analysis of the percentage of grain water and mechanical harvesting quality indexes of three maize varieties under different planting density

Year	Varieties	Density (plants ha^{-1})	Percentage of grain water (%)	Lodging rate (%)	Grain crashing rate (%)	Grain impurity rate (%)	Yield loss rate (%)
2016	Zhengdan958	45000	27.76±4.41a	0.00±0.00d	3.83±0.25e	2.00±0.20d	1.43±0.15e
		60000	30.47±2.29a	0.00±0.00d	4.50±0.30d	2.43±0.21cd	1.90±0.20d
		75000	30.35±3.58a	4.67±0.58c	5.43±0.35c	2.63±0.15c	2.33±0.06c
		90000	29.15±2.91a	8.33±0.58b	8.13±0.31b	3.93±0.31b	3.13±0.21b
		105000	31.36±2.61a	11.33±1.15a	9.87±0.31a	5.20±0.40a	4.50±0.26a
	Liyu16	45000	17.85±1.84c	0.00±0.00d	3.93±0.23e	2.47±0.25d	1.77±0.21e
		60000	24.62±1.88b	0.00±0.00d	4.60±0.40d	3.10±0.30c	2.37±0.15d
		75000	33.62±4.30a	3.33±0.58c	5.77±0.25c	4.03±0.25b	2.83±0.15c
		90000	36.14±2.85a	6.33±1.15b	8.43±0.40b	4.20±0.20ab	3.40±0.20b
		105000	37.78±2.07a	9.67±1.15a	10.23±0.25a	4.47±0.06a	4.67±0.25a
	Hengdan6272	45000	16.29±3.12c	0.00±0.00d	3.03±0.15e	1.67±0.12e	1.37±0.15d
		60000	22.84±2.92b	0.00±0.00d	3.80±0.20d	2.03±0.21d	1.83±0.15c
		75000	27.80±5.19ab	2.33±0.58c	4.47±0.31c	2.47±0.12c	1.97±0.12c
		90000	29.57±3.14a	3.67±1.15b	7.47±0.31b	3.07±0.25b	2.47±0.06b
		105000	27.21±3.12ab	6.67±0.58a	8.73±0.21a	3.80±0.20a	3.83±0.21a
2017	Zhengdan958	45000	26.44±2.29b	0.00±0.00d	4.19±0.27d	2.07±0.31d	1.50±0.19d
		60000	30.58±4.10ab	0.67±0.58d	4.48±0.30d	2.53±0.25c	2.11±0.32c
		75000	30.51±0.24ab	3.33±0.58c	5.70±0.50c	2.80±0.20c	2.55±0.37c
		90000	32.11±1.78a	6.67±1.15b	8.61±0.50b	4.03±0.12b	3.53±0.21b
		105000	31.19±2.53a	9.67±0.58a	10.16±0.55a	5.27±0.31a	5.14±0.29a
	Liyu16	45000	21.07±1.44b	0.00±0.00d	4.18±0.23d	2.40±0.20e	1.73±0.20d
		60000	24.35±3.11b	0.33±0.58d	4.73±0.43d	3.20±0.26d	2.75±0.69c
		75000	25.01±1.52b	2.67±0.58c	6.05±0.41c	4.13±0.12c	3.46±0.38bc
		90000	26.36±2.80b	6.33±0.58b	8.48±0.25b	4.50±0.10b	3.78±0.17b
		105000	29.31±0.80a	10.33±0.58a	11.02±0.34a	5.50±0.20a	5.33±0.32a
	Hengdan6272	45000	16.02±3.28c	0.00±0.00d	3.02±0.16e	1.67±0.06e	1.44±0.22d
		60000	20.07±4.12bc	0.00±0.00d	3.78±0.18d	2.17±0.25d	1.82±0.21cd
		75000	24.24±2.52ab	1.67±0.58c	4.69±0.31c	2.63±0.12c	2.15±0.29c
		90000	25.76±1.11ab	4.33±0.58b	8.05±0.27b	3.33±0.31b	2.78±0.16b
		105000	29.02±3.76a	5.67±0.58a	9.03±0.41a	4.20±0.30a	4.38±0.17a

Table 5: Correlation of yield and different character factors in maize hybrids

	R_0	T_{max}	G_{max}	G_{mean}	D	T_1	W_1	P_1	t_2	T_2	W_2	P_2	t_3	T_3	W_3	P_3	Number of lines per ear	Number of grains per line	1000-g rain weight	Percentage of grain water	Lodging rate	Grain crashing rate	Grain impure rate	Yield loss rate
Yield	0.87	-0.58	1.00**	1.00**	-0.83	-0.43	1.00**	0.96*	-0.6	-0.83	1.00**	1.00**	-0.7	-0.83	1.00**	1.00**	0.91	1.00**	0.97*	-0.77	-0.99**	-0.95	-0.82	-0.81

Note: *' ** indicate significance at $P < 0.05$ and $P < 0.01$ levels, respectively

This study also revealed that planting density does not significantly affect the D and emergence time of the T_{max}. By contrast, the G_{max}, G_{mean}, W_1, W_2, W_3, P_1, P_2 and P_3 decreased with increasing planting density. The grain-filling period is a crucial period for maize yield formation; the grain-filling conditions directly affect the final yield. In grain filling, the grain-filling rate and filling time to the corn grain weight plays an important role. The final weight of a corn grain is mainly determined by the grain-filling rate than the grain-filling duration (Zhang *et al*., 2007). Our work discovered that the G_{mean} and G_{max} of Hengdan6272 were higher than those of Zhengdan958 and Liyu16 under the same planting density. The grain yield of Hengdan6272 was also higher than those of Zhengdan958 and Liyu16 because of the augmented filling rate in the former variety. In the analysis of the mechanical harvesting index under the same density, the PGWs, LRs, GCRs, GIRs and YLRs were lower in Hengdan6272 than in the other two varieties. The mechanical harvesting indices of the three varieties declined with increasing planting density.

Conclusion

The light resources in the northern Huang-Huai-Hai Plain are relatively short-lived, and this area experiences a winter wheat–summer corn planting pattern in a year and two seasons. Given the photothermal deficiency, corn is harvested early in the maize growth stage. Hence, late-maturing maize varieties cannot be normally matured and are seriously reduced in number. Earlier spikelet flowering leads to greater mean and maximum grain-filling rates. By contrast, shorter active grain-filling period and time to reach the maximum grain-filling rate result in greater grain weight. We believe that the mid-early maturing maize varieties in the northern area of the Huang-huai-hai Plain hold a greater market prospect than that of the late-maturing maize cultivars.

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