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Optimal Plant Density Improves Sweet Maize Fresh Ear Yield without Compromising Grain Carbohydrate Concentration

Delian Ye [1,2,*,†], Jiajie Chen [1,†], Zexun Yu [1], Yanfang Sun [1], Wei Gao [1], Xiao Wang [1], Ran Zhang [1], Zaib-Un-Nisa [3], Da Su [1] and Muhammad Atif Muneer [2]

[1] Key Laboratory of Ministry of Education for Genetics, Breeding and Multiple Utilization of Crops, College of Agriculture, Fujian Agriculture and Forestry University, Fuzhou 350002, China; 3200130005@fafu.edu.cn (J.C.); 5220130029@fafu.edu.cn (Z.Y.); 1200102027@fafu.edu.cn (Y.S.); 12301001013@fafu.edu.cn (W.G.); 3210130062@fafu.edu.cn (X.W.); 5220130099@fafu.edu.cn (R.Z.); suda@fafu.edu.cn (D.S.)

[2] International Magnesium Institute, College of Resources and Environmental Sciences, Fujian Agriculture and Forestry University, Fuzhou 350002, China; m_atifmuneer@yahoo.com

[3] Cotton Research Institute, Multan 60000, Pakistan; zaibsci.agri@gmail.com

* Correspondence: ydl2015@fafu.edu.cn

† These authors contributed equally to this work.

Abstract: It is crucial to synergistically improve the yield and quality of sweet maize by implementing precise and strategic planting methods. However, a comprehensive understanding of how increasing plant density affects the sweet maize fresh ear yield, grain-filling rate, and grain carbohydrate concentration is not fully understood. Thus, a field experiment was performed using a split-plot design in Southeast China in 2021 and 2022, involving four sweet maize varieties (MT6855 and WT2015 were compact-type varieties, XMT10 and YZ7 were flat-type varieties) and three plant densities (D1: 4.5 plants m^{-2}; D2: 6.0 plants m^{-2}; and D3: 7.5 plants m^{-2}). The results showed that an increasing plant density markedly increased the fresh ear yield of sweet maize varieties (MT6855 and WT2015) over the two years. However, it did not influence the fresh ear yield of XMT10 and YZ7. Across all four varieties in 2021 and 2022, the increasing plant density decreased the sweet maize filled ear length, while it did not affect the grain soluble solid concentration and grain residue ratio. The sweet maize grain weight, the maximum grain-filling rate, and the mean grain-filling rate decreased significantly with the increase in planting density across all four varieties. However, plant density did not significantly affect the grain soluble sugar, sucrose, fructose, and starch concentrations across different varieties at most stages during the grain filling. The current study also found that the sweet maize fresh ear yield was dramatically positively correlated with ears ha^{-1}, grains per ear, grain-filling rate, and grain starch concentration but negatively correlated with the bare plant rate. Notably, a parabolic relationship existed between the fresh ear yield and 100-grain weight. These findings suggest that optimizing the plant density, particularly with compact-type varieties, can improve the sweet maize fresh ear yield without decreasing its quality.

Keywords: compact-type variety; grain weight; bare plant rate; grain filling; soluble sugar; grain starch

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1. Introduction

Sweet maize, characterized by its high sugar concentration, is harvested when the grains are still tender and immature. It is widely consumed as a food or vegetable and is popular for its sweet and juicy taste [1]. To meet people's needs, consistently increasing sweet maize production is necessary [2]. Considering the limited arable farmland, it is vital to continuously increase the yield of sweet corn per unit area. Increasing plant density is a vital cultivation practice to increase the maize yield by maximizing the available land and resources, leading to higher productivity [3]. Specifically, the average planting density in Southern China's sweet-waxy maize planting region is only 51,000 plants ha^{-1}, significantly lower than the optimal density of 73,000 plants ha^{-1} of sweet maize [4,5]. However, excessive planting to a density beyond the optimum level can lower the maize yield and quality [6]. Therefore, it is essential to find the right balance: increasing plant density to enhance the sweet maize yield without compromising the quality in Southeast China.

Maize yield significantly correlates with key factors such as ears per area, grains per ear, and grain weight [7]. Increasing the plant density increases the ears ha^{-1}, corresponding to the reduction in grains per ear and grain weight, when the increase in ears ha^{-1} exceeds the decrease in the grain number and weight per spike, thus increasing the yield [8]. Nevertheless, previous studies have also revealed no significant correlation between the grain yield and 100-grain weight or grains per ear [9,10]. Hence, it is crucial to investigate the relationship between the yield and grains per ear and 100-grain weight under different plant densities, specifically for sweet maize.

Grain filling, a crucial stage in maize growth, impacts both its quality and yield. It refers to when the grains develop and store essential substances, such as dry matter, sugar, starch, and nutrients [11,12]. Several studies have shown that grain filling is a key factor influencing the yield formation and grain weight and is affected by the planting density and variety characteristics [13,14]. Increasing the planting density significantly reduces the maximum and average filling rates, but it has no significant effect on the maximum grain-filling duration and the active grain-filling period [15]. Moreover, no significant correlation was observed between the grain weight and the active grain-filling period under high nitrogen rate and plant density conditions [13]. However, earlier research has demonstrated that cultivation practice increases the 100-kernel weight of maize by delaying the time to the maximum filling rate and extending the active filling period [10,16]. Therefore, it is important to consider both the planting density and variety characteristics when aiming to optimize grain filling and achieve a high yield of sweet maize.

Carbohydrates are vital in maize yield and quality, comprising soluble total sugars, sucrose, and starch [17]. In maize grain, most carbohydrates come in the form of starch, making up 60–80% of the total grain weight [7,17]. However, in sweet maize, the sugary gene inhibits the conversion of sugar into starch, leading to a higher sugar concentration and maintaining the sweet taste of sweet maize [2]. While the carbohydrate dynamic changes in grain maize are well documented, there is limited information available about sweet maize. Moreover, some studies have indicated that higher plant densities might decrease the grain carbohydrate concentration due to resource competition and limitations, while other studies have not observed significant changes [18,19]. These findings suggest inconsistent results regarding the effect of plant density on the grain maize carbohydrate concentration. However, there is a lack of understanding of the dynamic changes in grain carbohydrates of sweet maize in response to the planting density. Hence, further research is required to fully understand the effect of plant density on the dynamic characteristics of grain carbohydrates in sweet maize.

We hypothesized that densely planting sweet maize may increase its yield without compromising its quality. Notably, the grain-filling traits corresponding to carbohydrate dynamic patterns play a significant role in determining the yield components and quality, yet limited information exists for sweet maize. Therefore, our study aims to explore the effects of increasing the plant density on the fresh ear yield, ear traits, grain-filling traits, and grain carbohydrate concentration across four sweet maize varieties. We seek to establish the correlation between sweet maize fresh ear yield, ear traits, grain-filling traits, and grain carbohydrate concentration under different planting densities and varieties. These findings can assist farmers in optimizing the plant density and variety selection for increasing sweet maize productivity without sacrificing its quality in Southeast China.

2. Materials and Methods

2.1. Experimental Location

Field experiments were conducted at Yuanfeng Farm (26°14′ N, 118°75′ E) in Minqing County in Fuzhou City, Southeast China, during the autumn sweet maize growing season of 2021–2022. The climate in this region is characterized as subtropical humid monsoon, with mean temperatures of 22.6 °C and 21.6 °C and total precipitation of 175.9 mm and 230.0 mm from August to November in 2021 and 2022, respectively. The soil of the experimental site is loamy sand, with soil organic matter content, alkali hydrolyzed nitrogen, available phosphate, available potassium, and pH at 20 cm soil depth measured as 22.9 g kg^{-1}, 81.3 mg kg^{-1}, 191.8 mg kg^{-1}, 278.9 mg kg^{-1} and 5.15, respectively.

2.2. Experiment Design and Field Management

Field experiments were performed using a split-plot design. The main plots were subjected to four sweet maize varieties, including Mintian6855 (MT6855), Wantian2015 (WT2015), Xiameitian10 (XMT10), and Yongzhen7 (YZ7). MT6855 and WT2015 were compact-type varieties, but XMT10 and YZ7 were flat-type, widely planted varieties in Southeast China. Subplots tested three plant densities: 4.5 plants m^{-2} (D1), 6.0 plants m^{-2} (D2), and 7.5 plants m^{-2} (D3). The conventional planting density of local farmers was 45,000 plants ha^{-1}. Each treatment had three replicates, and each subplot was 8 m long and 3.6 m wide. The sweet maize was planted in one ridge and two rows. The ridge tillage was carried using a rotary tillage and ridging integrated operation machine (Dongfeng 504, Dongfengnongji Co. Ltd., Changzhou, China), with a ridge width of 1.2 m, ridge ditch width of 0.2 m, and ridge height of 0.15 m. The precrop of the experiment was also sweet maize using ridge tillage in the spring season and harvested in early July. The field lay fallow until mid-August, and then, autumn sweet maize was planted. Each plot received 180 kg ha^{-1} N, 45 kg ha^{-1} P_2O_5, and 180 kg ha^{-1} K_2O. Base fertilizer of 60 kg ha^{-1} N, 45 kg ha^{-1} P_2O_5, and 90 kg ha^{-1} K_2O was applied before transplanting, then 60 kg ha^{-1} N was applied at V6 (6-leaf) stage, and each plot received 60 kg ha^{-1} N as well as 90 kg ha^{-1} K_2O under V12 (12-leaf) stage. Seedling transplantation was used to ensure sweet maize's emergence and survival rate. Sweet maize seeds were sown in 105-hole seedling trays using seedling substrates, and seedlings with two leaf stages were transplanted into the field. Each plot received water in a timely manner using furrow irrigation after transplanting and subsequent irrigation with 50–100 mm once at critical growth stages if there was no rainfall.

2.3. Sampling and Measurements

2.3.1. Fresh Ear Yield, Quality, and Ear Leaf SPAD Value

During the sweet maize fresh eating stage (corresponding to grain maize milking stage, R3 stage, about 22 days after silking), the fresh ears with cob and bract were hand harvested in the center of each plot and weighed to calculate fresh ear yield. The bare plant rate was the ratio of the number of bare plants to whole plants in each plot. Subsequently, the bracts were removed from the ears to measure ear characteristics, including ear length, bare tip length, 100-grain fresh weight, and grains per ear. The filled ear length was calculated as the ear length minus the bare tip length. The soluble solid concentration in fresh grains was determined using a refractometer [20]. The residue ratio in fresh grains was measured [21]. Additionally, three sweet maize ear leaves from three representative plants of each plot were selected to measure SPAD value using SPAD-502 Chlorophyll Meter at silking and fresh eating stages.

2.3.2. Grain-Filling Rate and Grain Carbohydrate Concentration

In each plot, 30 representative sweet maize plants with consistent growth that silked on the same day were labeled. Five ears were selected at 7, 12, 17, and 22 days after silking. The bracts were removed from the ear, and intact grains of the middle ear were peeled off. The sampled sweet maize grains were divided into two parts. One part of the grain was weighed for fresh weight, then dried in an oven at 105 °C for 30 min, and subsequently at 70 °C until a constant weight was achieved, and the grain dry weight was weighed. The other part of the grains was frozen in liquid N and stored at −40 °C to measure the concentration of soluble sugar, sucrose, fructose, and starch. The soluble sugar and starch concentrations of fresh grains were measured using sulfuric acid anthrone colorimetry, while sucrose in fresh grains was measured using the resorcinol method [22].

The grain-filling process was estimated using the following logistic equation [23]:

$$W = \frac{A}{1 + Be^{-ct}} \quad (1)$$

where W is the dry weight of 100-grain after silking and t is the number of days after silking. A is the theoretical maximum dry weight of 100-grain, B is the coefficient at the initial stage, and C is the scope of the logistic curve and is related to the grain-filling rate.

The grain-filling parameters were calculated as in the previous study [23]:

The time for maximal grain-filling rate:

$$T_{max} = \frac{\ln B}{C} \quad (2)$$

Grain weight increment achieving maximum grain-filling rate:

$$W_{max} = \frac{A}{2} \quad (3)$$

The maximum grain-filling rate:

$$G_{max} = (C \times W_{max}) \times \left(\frac{1 - W_{max}}{A}\right) \quad (4)$$

The active grain-filling period (approximately 90% of total accumulation completed):

$$AGP = \frac{6}{C} \quad (5)$$

The mean grain-filling rate:

$$G_{mean} = \frac{A \times C}{6} \quad (6)$$

2.4. Statistical Analysis

We used Origin 2023 software for plotting and CurveExpert 1.4 software to simulate grain-filling characteristics. The two-way analysis of variance was carried out using the General Linear Model module of SPSS (version 22.0, SPSS, Chicago, IL, USA). Means were tested through Duncan's test at the $p < 0.05$ level, and correlation analysis was performed using the Pearson correlation analysis method.

3. Results

3.1. Sweet Maize Fresh Ear Yield and Yield Components

Increasing the plant density dramatically increased the fresh ear yield of MT6855 and WT2015 in both years. However, this increase did not affect the fresh ear yield of XMT10 and YZ7 (Figure 1). Specifically, under the D3 treatment, the average fresh ear yield of MT6855 and WT2015 was 21.5% and 31.2% higher, respectively, than those under the D1 treatment. As the plant density increased, the ears ha^{-1} substantially increased, corresponding to the reduction in 100-grain weight and grains per ear. Moreover, the fresh ear yield was significantly positively correlated with ears ha^{-1} and grains per ear, but negatively with the bare plant rate. However, a parabolic correlation existed between the fresh ear yield 100-grain weight (Figure 1 and Figure S1). In both 2021 and 2022, significant interaction effects were recorded between different planting densities and sweet maize varieties, including the fresh ear yield, ears ha^{-1}, and the rate of bare plants. In addition, increasing the plant density significantly reduced the 100-grain weight and grains per ear for XMT10 and YZ7 compared to MT6855 and WT2015. Increasing the plant density markedly increased the rate of bare plants for XMT10 and YZ7, while it did not notably affect MT6855 and WT2015.

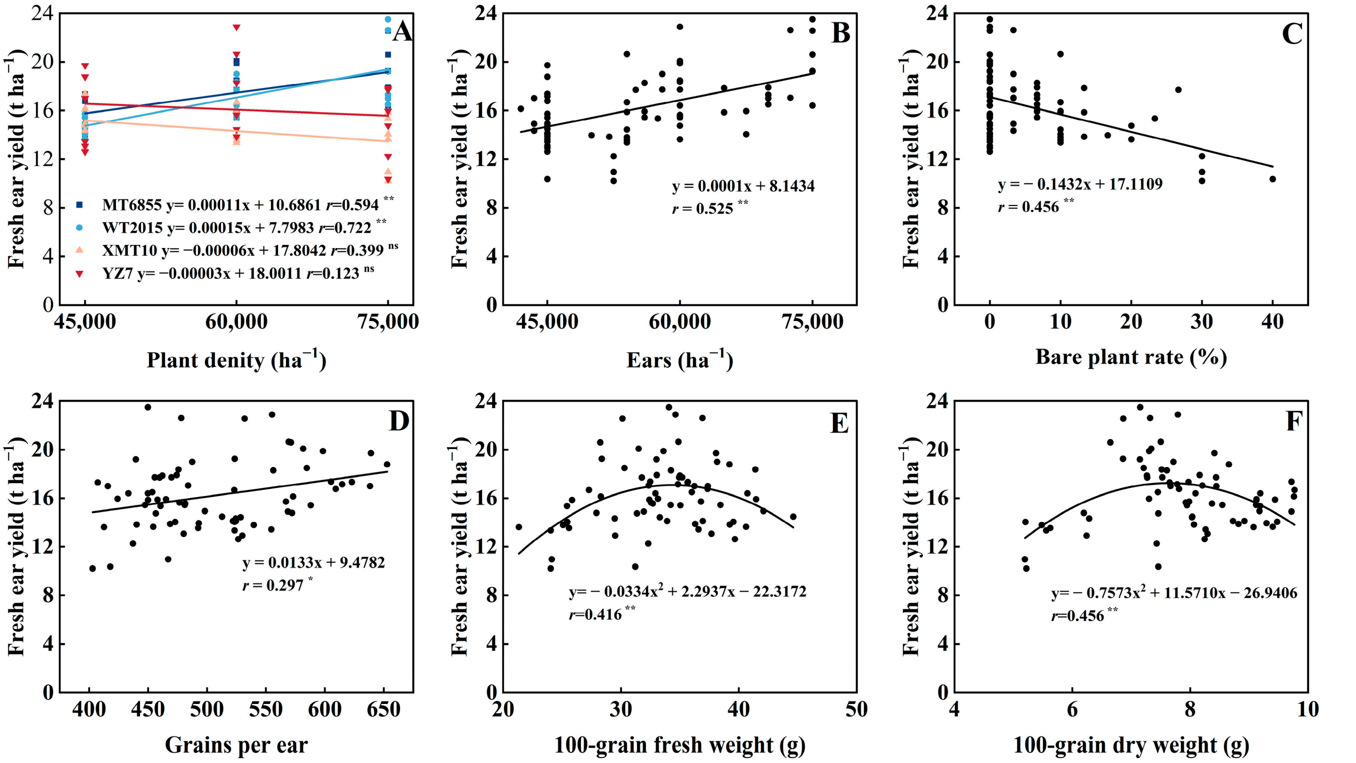

Figure 1. Correlation between fresh ear yield and plant density (**A**), ears ha^{-1} (**B**), bare plant rate (**C**), grains per ear (**D**), 100-grain fresh weight (**E**), and 100-grain dry weight (**F**). * Represents significance at $p < 0.05$, ** represents significance at $p < 0.01$, ns represents no significance.

3.2. Sweet Maize Quality

There were no significant interaction effects of the plant density and variety on sweet maize grain soluble solid concentration and grain residue ratio for both years (Figure 2). Increasing the plant density significantly decreased the sweet maize filled ear length among the four varieties in the two years. However, increasing the plant density did not affect the market ear (filled ear length $\geq$ 10 cm). High plant density had a greater reduction in the filled ear length under XMT10 and YZ7 compared to MT6855 and WT2015. In addition, there was no remarkable difference among the different planting densities in the soluble solid concentration and grain residue ratio across the four varieties (Figure 2).

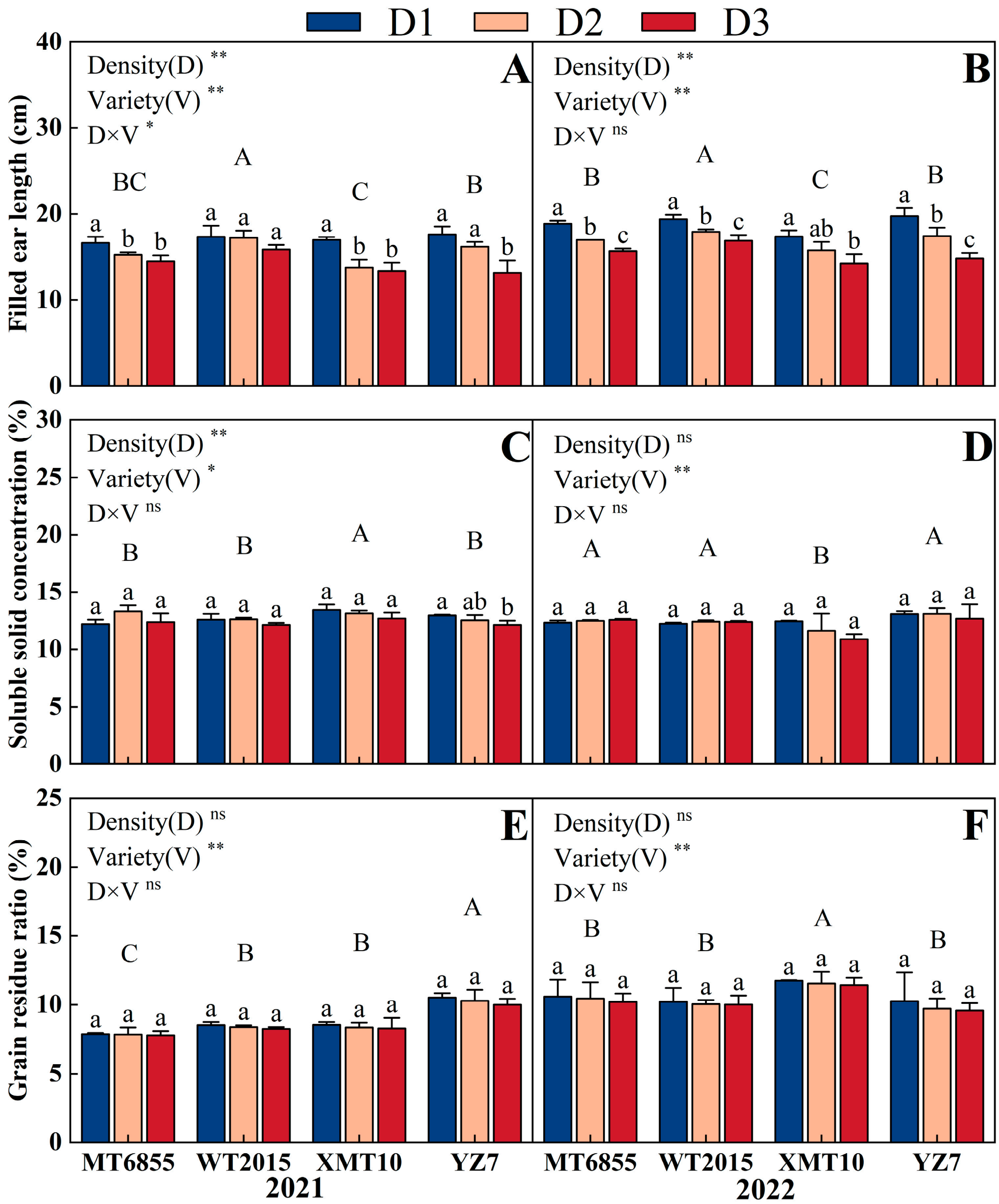

Figure 2. Filled ear length (**A**,**B**), soluble solids concentration (**C**,**D**), and grain residue rate (**E**,**F**) of sweet maize varieties MT6855, WT2015, XMT10, and YZ7 under different plant densities in 2021 and 2022. D1, D2, and D3 indicate 4.5 plants m^{-2}, 6.0 plants m^{-2}, and 7.5 plants m^{-2}, respectively. Different lowercase letters represent significant differences among different planting densities within the same variety ($p < 0.05$). Different capital letters represent significant differences among different varieties across plant densities ($p < 0.05$). * Represents significance at $p < 0.05$, ** represents significance at $p < 0.01$, ns represents no significance.

3.3. Sweet Maize Ear Leaf SPAD Value

Significant plant density × variety interactive effects were observed on the sweet maize ear leaf SPAD value at the silking and fresh eating stages in 2021 and 2022; however, there was no significant plant density × variety interaction on the ear leaf SPAD value (Figure 3). The ear leaf SPAD value at each stage was significantly decreased with the increasing plant density across four sweet maize varieties in both years. A high planting density considerably decreased the SPAD value of ear leaf, especially at the fresh eating stage, for example, the average SPAD value of MT6855, WT2015, XMT10, and YZ7 across the two years under the D3 treatment was 6.6%, 11.6%, 9.7%, and 8.0%, respectively, lower than that of the corresponding varieties under the D1 treatment (Figure 3).

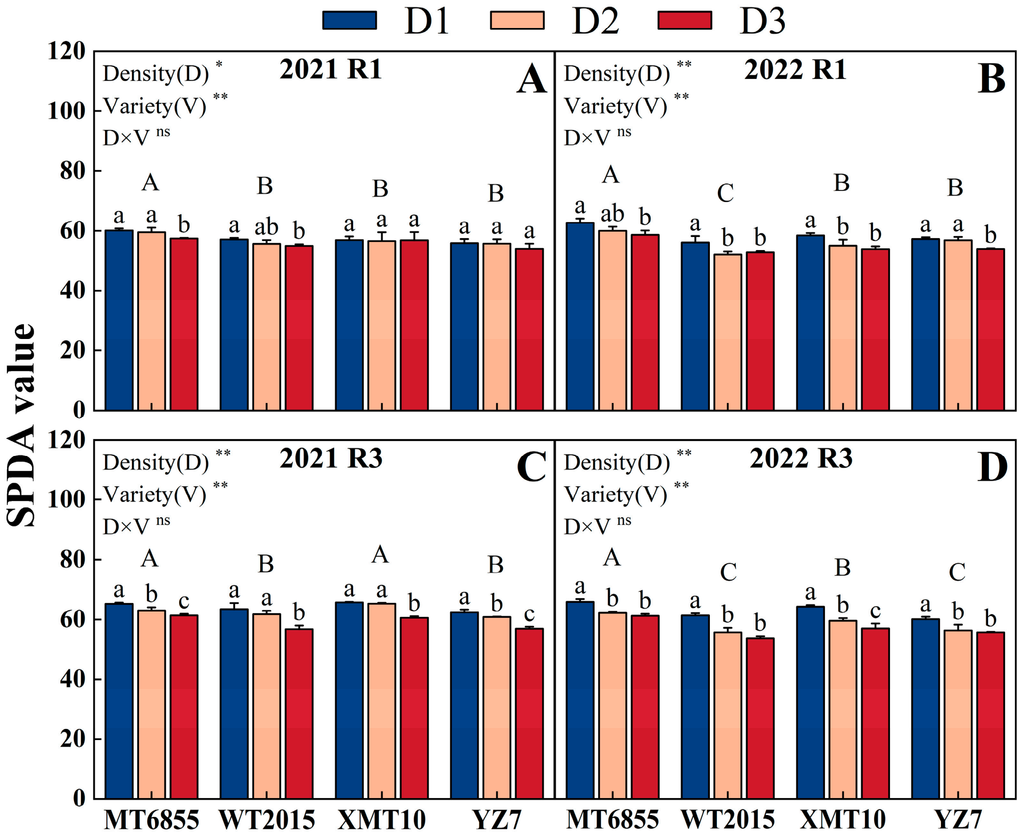

Figure 3. Ear leaf SPAD at the silking stage (R1) (**A**,**B**) and fresh eating stage (R3) (**C**,**D**) of sweet maize varieties MT6855, WT2015, XMT10, and YZ7 under different plant densities in 2021 and 2022. MT6855, Mintian6855; WT2015, Wantian2015; XMT10, Xiameitian10; YZ7, Yongzhen7. D1, D2, and D3 indicate 4.5 plants m^{-2}, 6.0 plants m^{-2}, and 7.5 plants m^{-2}, respectively. Different lowercase letters represent significant differences among different planting densities within the same variety ($p < 0.05$). Different capital letters represent significant differences among different varieties across planting densities ($p < 0.05$). * Represents significance at $p < 0.05$, ** represents significance at $p < 0.01$, ns represents no significance.

3.4. *Sweet Maize Grain Weight Dynamic and Grain-Filling Traits*

Sweet maize 100-grain fresh weight and dry weight increased with the advance of the grain filling, and they all reached the maximum value at 22 days after silking across the four varieties in 2021 and 2022 (Figures 4 and 5). The 100-grain fresh weight in the four varieties decreased with the increasing plant density during grain filling in both years and under the D3 treatment; it was significantly lower than that under the D1 treatment at 22 days after silking (Figure 4). Increasing the plant density significantly decreased the 100-grain dry weight at 7, 12, 17, and 22 days after silking across the four varieties (Figure 5). The average grain moisture was 76.3%, 78.6%, 80.1%, and 75.5% for MT6855, WT2015, XMT10, and YZ7, respectively. The plant density × variety interaction was significant for the maximum grain-filling rate and the mean grain-filling rate in both years. The maximum grain-filling rate and the mean grain-filling rate were significantly decreased with the increase in planting density across the four varieties. However, the time for the maximal grain-filling rate was not remarkedly changed, except for XMT10 in 2021. The grain weight increment achieved the maximum grain-filling rate, and the active grain-filling period decreased with increasing plant density. Meanwhile, they varied among different varieties (Table 1).

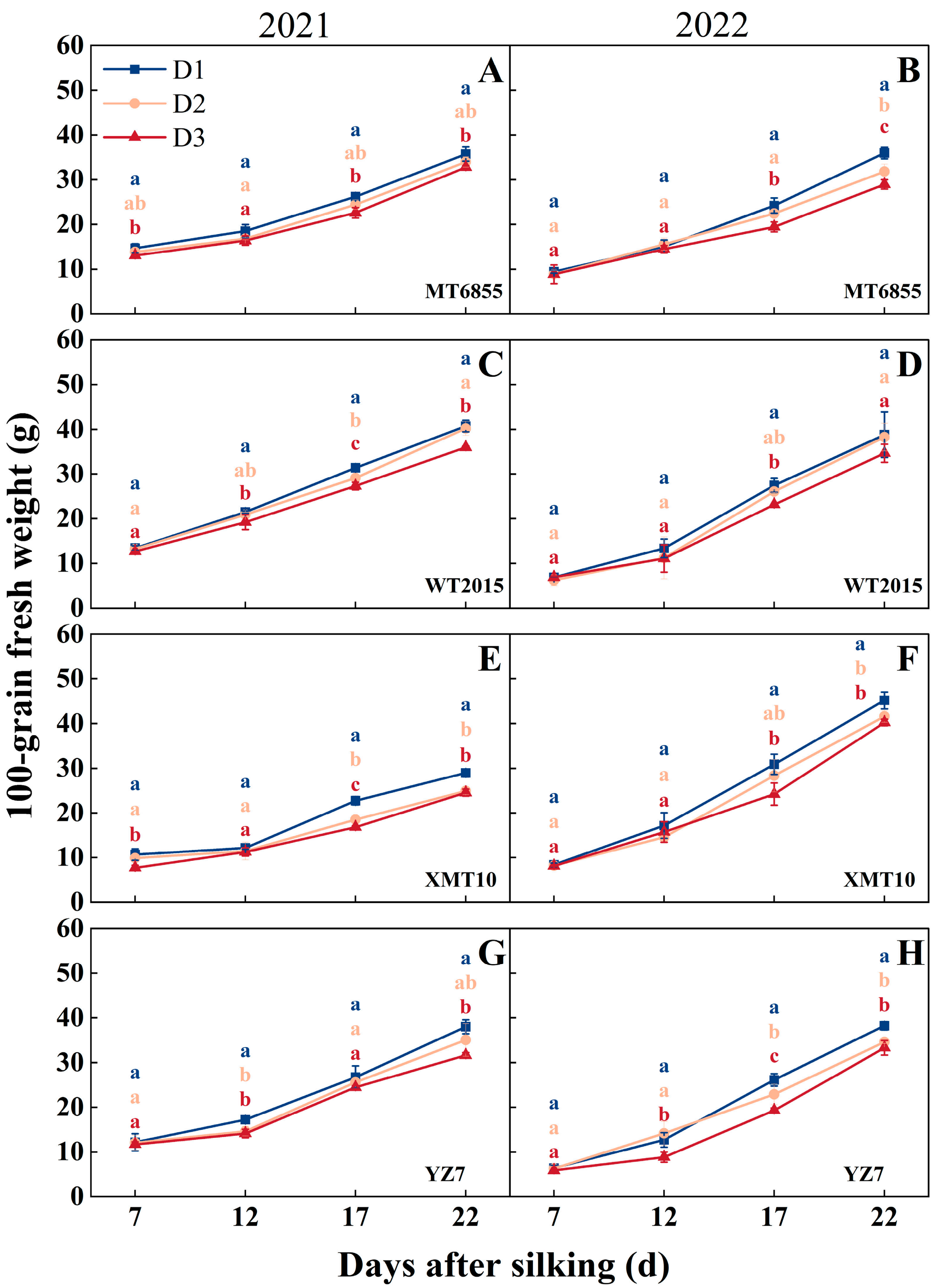

Figure 4. The 100-grain fresh weight (**A**–**H**) of MT6855, WT2015, XMT10 and YZ7 sweet maize varieties under different planting densities in 2021 and 2022. D1, D2, and D3 indicate 4.5 plants m^{-2}, 6.0 plants m^{-2}, and 7.5 plants m^{-2}, respectively. Different lowercase letters represent significant differences among different planting densities within the same day ($p < 0.05$).

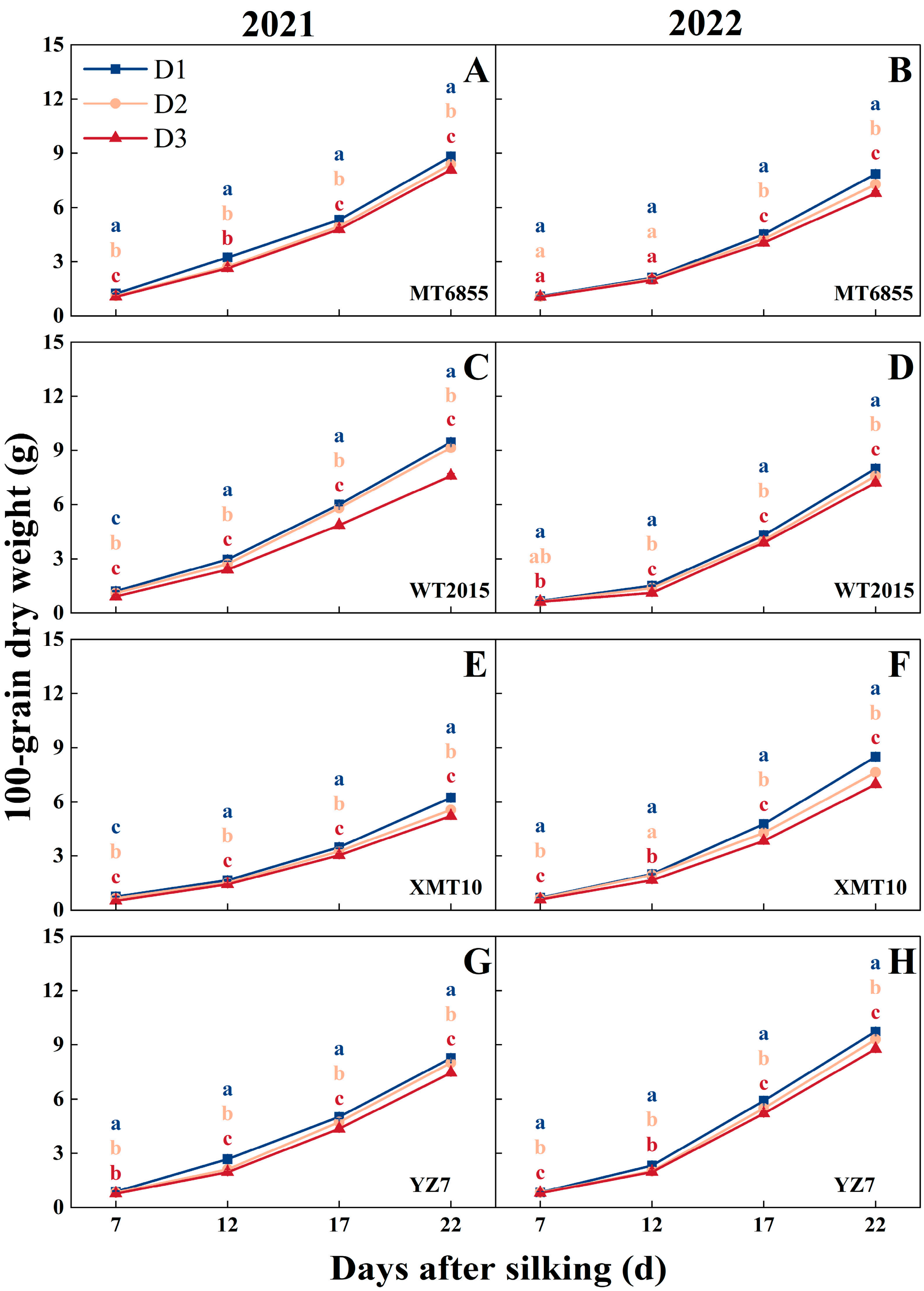

Figure 5. The 100-grain dry weight (**A**–**H**) of sweet maize varieties MT6855, WT2015, XMT10, and YZ7 under different planting densities in 2021 and 2022. D1, D2, and D3 indicate 4.5 plants m^{-2}, 6.0 plants m^{-2}, and 7.5 plants m^{-2}, respectively. Different lowercase letters represent significant differences among different planting densities within the same day ($p < 0.05$).

Table 1. Grain-filling characteristics of four sweet maize varieties in response to different plant densities.

Years	Hybrids	Density	A	B	C	R^2	T_{max} (Days)	W_{max} (g 100-Kernel^{-1})	G_{mean} (g 100-Kernel^{-1} Days^{-1})	G_{max} (g 100-Kernel^{-1} Days^{-1})	AGP (Days)
2021	MT6855	D1	17.4	33.9	0.16	0.997	21.9 a	8.7 a	0.47 ab	0.7 ab	37.2 a
		D2	16.6	42.6	0.17	0.999	21.8 a	8.3 a	0.47 a	0.71 a	34.9 a
		D3	15.7	41.6	0.17	0.999	21.7 a	7.9 a	0.45 b	0.68 b	34.9 a
	WT2015	D1	13.8	44.4	0.21	0.999	18.3 a	6.9 a	0.48 a	0.72 a	28.9 a
		D2	12.9	51.5	0.22	0.999	17.9 a	6.5 b	0.47 a	0.71 a	27.3 b
		D3	10.6	46.8	0.22	0.999	17.8 a	5.3 c	0.38 b	0.57 b	27.8 ab
	XMT10	D1	14.0	63.7	0.18	0.999	23.1 a	7.0 a	0.42 a	0.63 a	33.4 a
		D2	9.7	57.1	0.20	0.999	20.5 b	4.9 b	0.32 b	0.48 b	30.4 b
		D3	8.4	63.3	0.21	0.999	19.7 b	4.2 b	0.3 b	0.44 b	28.5 b
	YZ7	D1	12.9	46.6	0.20	0.998	19.1 a	6.4 a	0.43 a	0.65 a	29.8 a
		D2	12.4	66.1	0.22	0.999	19.3 a	6.2 a	0.45 b	0.68 b	27.6 b
		D3	11.9	65.8	0.21	0.999	19.6 a	5.9 a	0.42 a	0.64 a	28.1 ab
Source of variation											
Density (D)							**	**	**	**	**
Variety (V)							**	**	**	**	**
D × V							**	**	**	**	ns
2022	MT6855	D1	18.6	55.9	0.17	0.999	23.8 a	9.3 a	0.52 a	0.78 a	35.5 a
		D2	16.4	50.6	0.17	0.999	23.2 a	8.2 a	0.46 ab	0.69 ab	35.5 a
		D3	14.9	45.2	0.17	0.999	23.0 a	7.5 a	0.41 b	0.62 b	36.3 a
	WT2015	D1	12.4	131	0.25	0.999	19.6 ab	6.2 a	0.51 a	0.77 a	24.2 a
		D2	12.1	139.9	0.25	0.999	19.9 a	6.1 a	0.5 ab	0.75 ab	24.1 a
		D3	10.1	206.0	0.28	0.997	18.7 b	5.0 b	0.48 b	0.71 b	21.1 b
	XMT10	D1	13.3	93.4	0.23	0.999	19.5 a	6.6 a	0.51 a	0.77 a	25.8 b
		D2	12.7	77.0	0.22	0.999	20.1 a	6.3 a	0.46 b	0.68 b	27.8 a
		D3	12.0	87.1	0.22	0.999	20.5 a	6.0 a	0.44 b	0.65 b	27.5 a
	YZ7	D1	12.9	99.7	0.26	0.999	17.7 a	6.5 a	0.56 a	0.84 a	23.1 a
		D2	12.7	114.1	0.26	0.999	18.1 a	6.3 a	0.55 a	0.83 a	23 a
		D3	12.1	103.2	0.26	0.999	18.1 a	6.0 b	0.51 b	0.77 b	23.5 a
Source of variation											
Density (D)							ns	**	**	**	ns
Variety (V)							**	**	**	**	**
D × V							ns	ns	*	*	*

A–C are model parameters; T_{max}: the time for maximal grain-filling rate; W_{max}: grain weight increment achieving maximum grain-filling rate; G_{max}: the maximum grain-filling rate; G_{mean}: the mean grain-filling rate; AGP: the active grain-filling period. D1, D2, and D3 indicate 4.5 plants m^{-2}, 6.0 plants m^{-2}, and 7.5 plants m^{-2}, respectively. Different lowercase letters represent significant differences among different planting densities among within the same variety ($p < 0.05$). * Represents significance at $p < 0.05$, ** represents significance at $p < 0.01$, ns represents no significance.

3.5. Sweet Maize Grain Carbohydrate Dynamic

With the advancement of the sweet maize grain-filling process, the soluble sugar concentration in the grains first increased, then tended to stabilize or decrease (Figure 6). There was no significant difference among different planting densities for the grain soluble sugar concentration across the four sweet maize varieties at 7, 12, 17, and 22 days after silking in 2021 and 2022, except for that of MT6855 under the D3 treatment at 22 days after silking, which was lower than that under the D1 treatment. On average, the soluble sugar concentration of MT6855, WT2015, XMT10, and YZ7 was 86, 85, 84, and 85 mg g^{-1} at 22 days after silking, respectively, and no significant differences among the four varieties were observed (Figure 6).

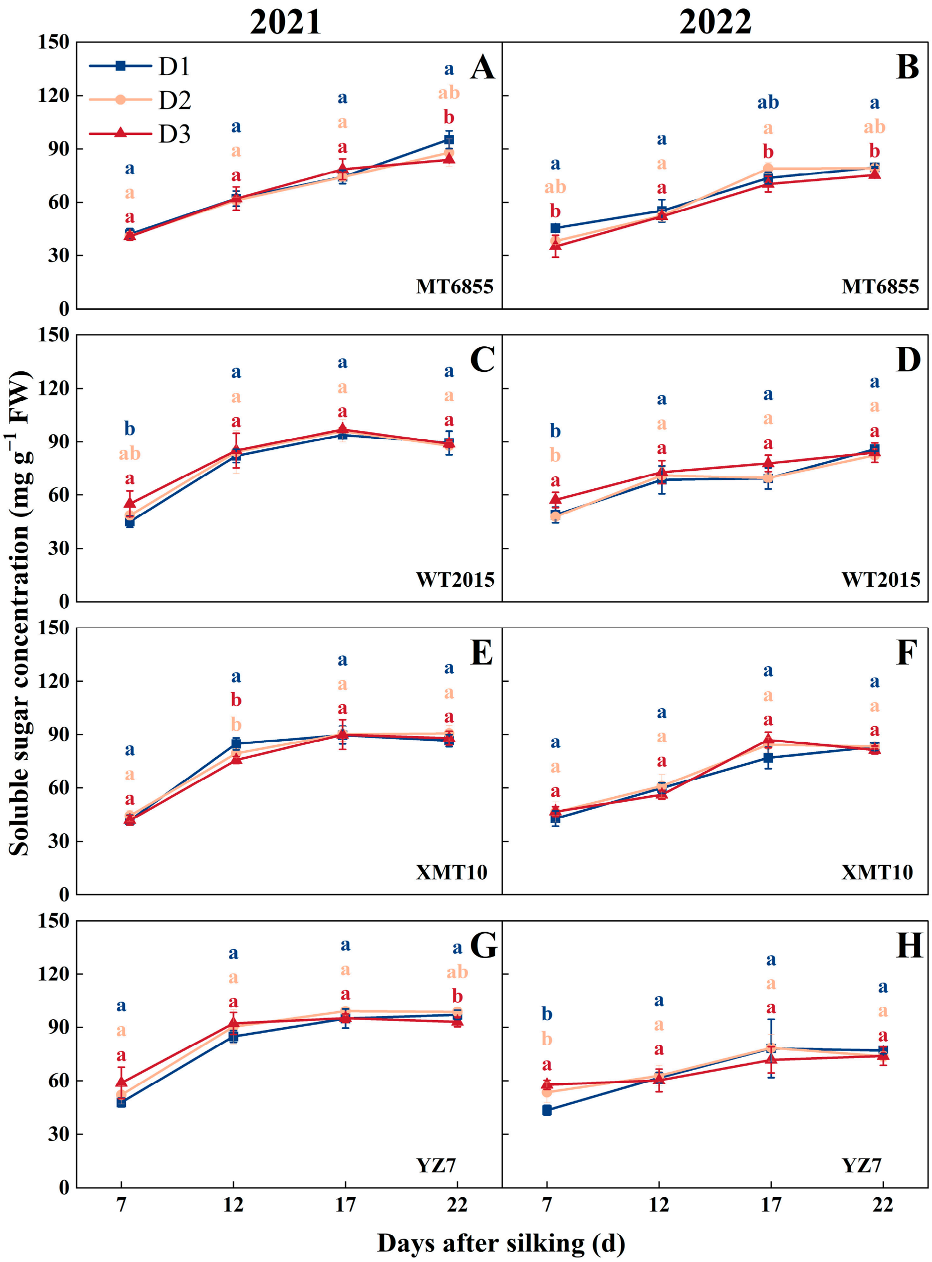

Figure 6. Soluble sugar concentration (**A**–**H**) of sweet maize varieties MT6855, WT2015, XMT10, and YZ7 under different plant densities in 2021 and 2022. D1, D2, and D3 indicate 4.5 plants m^{-2}, 6.0 plants m^{-2}, and 7.5 plants m^{-2}, respectively. Different lowercase letters represent significant differences among different planting densities within the same day ($p < 0.05$).

The sweet maize grain sucrose concentration had a similar dynamic trend to the soluble sugar concentration, and the plant density had no significant effect on the grain sucrose concentration across different varieties at most stages during grain filling in 2021 and 2022. Grain sucrose concentrations of MT6855, WT2015, XMT10, and YZ7 were 73, 68, 65, and 66 mg g^{-1} at 22 days after silking, respectively (Figure 7). The grain fructose concentration first increased before 12 days after silking, and then, it did not change markedly from 12 days to 22 days after silking. Moreover, increasing the plant density did not significantly affect the grain fructose concentration during grain filling among different varieties (Figure 8). The starch concentration in grain was increased within the grain-filling period. The largest starch concentration was achieved at 22 days after silking. Meanwhile, no significant differences among different planting densities under the four varieties were found in this study (Figure 9).

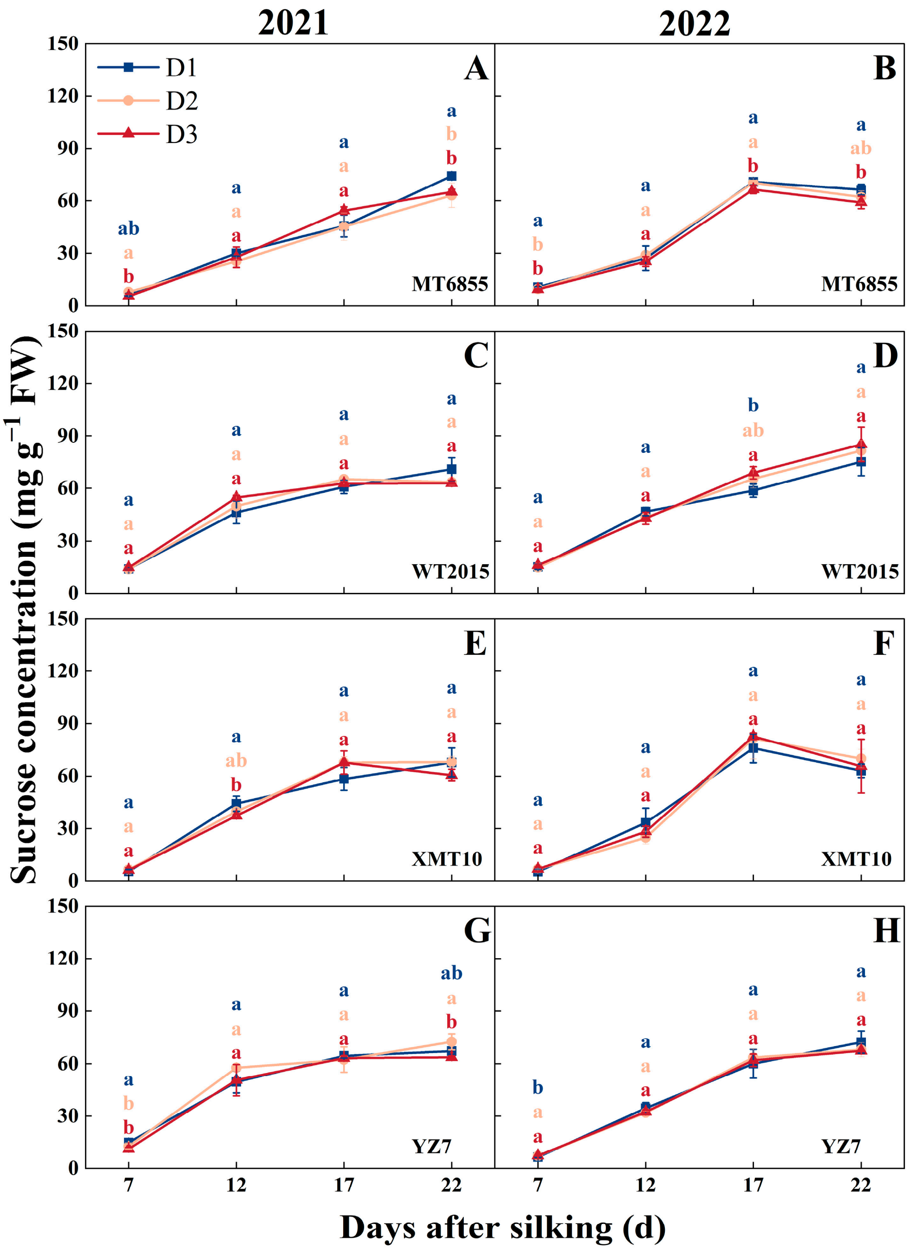

Figure 7. Sucrose concentration (**A**–**H**) of sweet maize varieties MT6855, WT2015, XMT10, and YZ7 under different plant densities in 2021 and 2022. D1, D2, and D3 indicate 4.5 plants m^{-2}, 6.0 plants m^{-2}, and 7.5 plants m^{-2}, respectively. Different lowercase letters represent significant differences among different planting densities within the same day ($p < 0.05$).

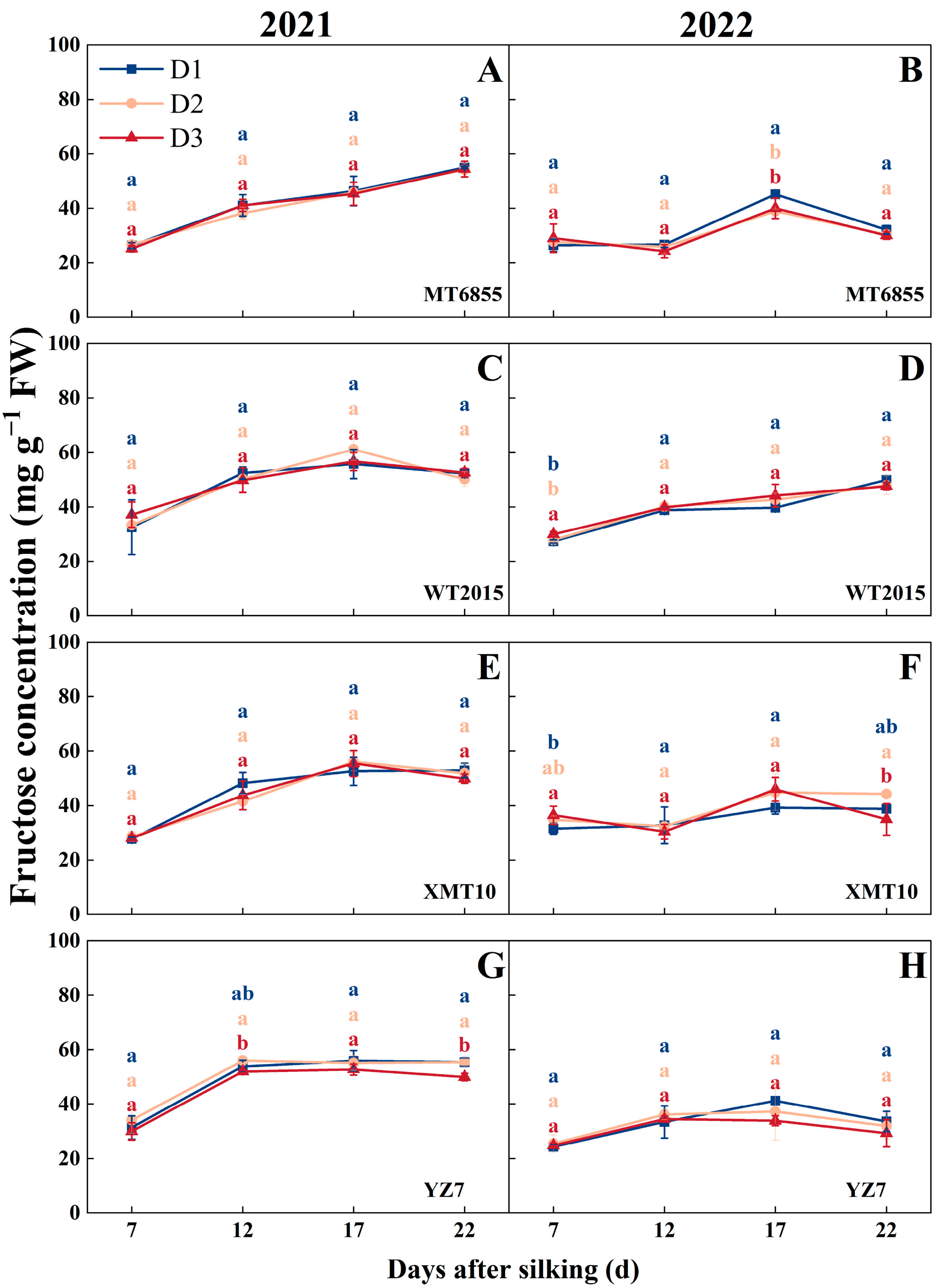

Figure 8. Fructose concentration (**A**–**H**) of sweet maize varieties MT6855, WT2015, XMT10, and YZ7 under different plant densities in 2021 and 2022. D1, D2, and D3 indicate 4.5 plants m^{-2}, 6.0 plants m^{-2}, and 7.5 plants m^{-2}, respectively. Different lowercase letters represent significant differences among different planting densities within the same day ($p < 0.05$).

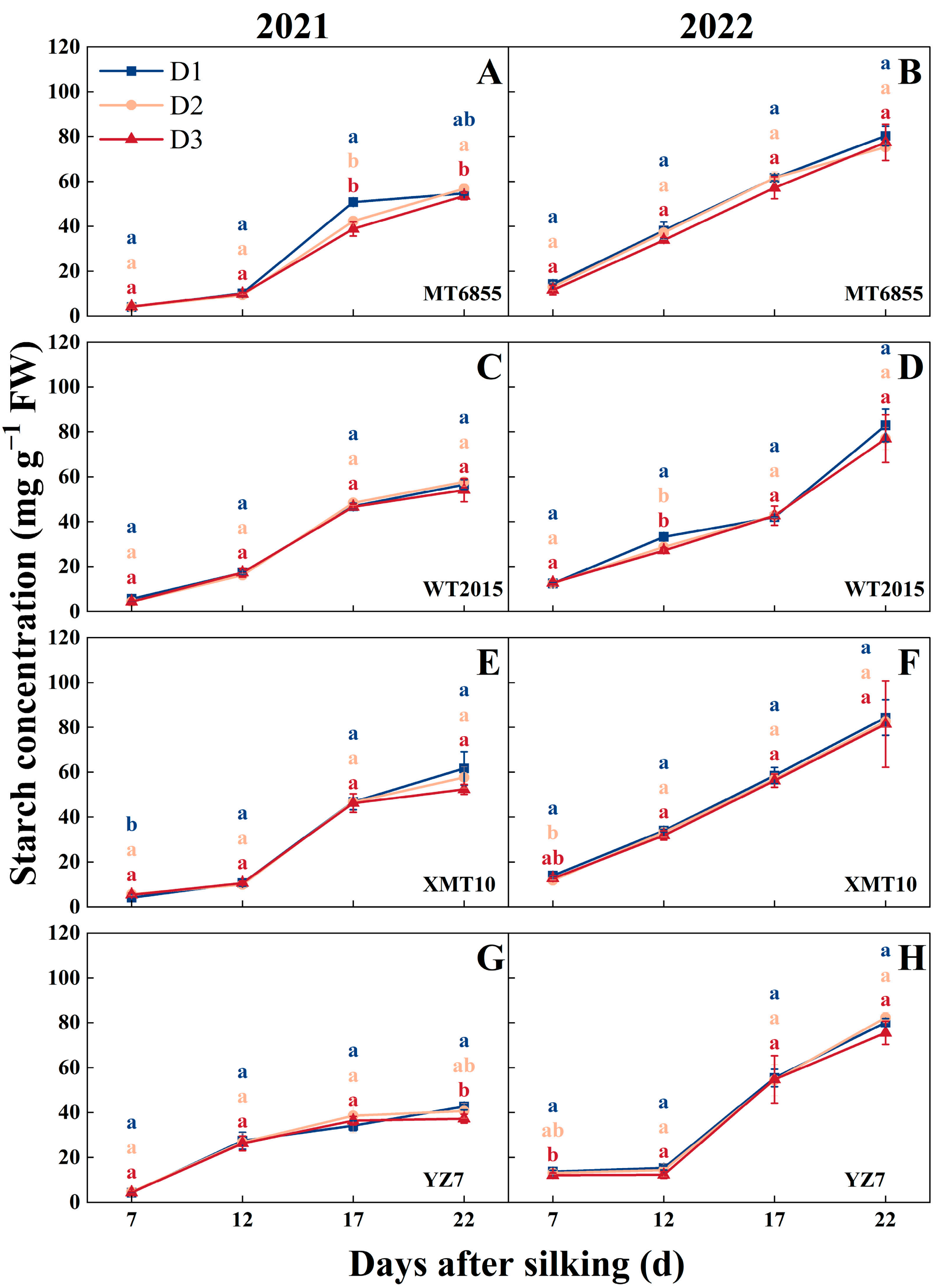

Figure 9. Starch concentration (**A**–**H**) of sweet maize varieties MT6855, WT2015, XMT10, and YZ7 under different plant densities in 2021 and 2022. D1, D2, and D3 indicate 4.5 plants m^{-2}, 6.0 plants m^{-2}, and 7.5 plants m^{-2}, respectively. Different lowercase letters represent significant differences among different planting densities within the same day ($p < 0.05$).

3.6. The Relationship between Fresh Ear Yield and Other Parameters

Sweet maize fresh ear yield was markedly positively correlated with the filled ear length, the maximum grain-filling rate (G_{max}), the average grain-filling rate (G_{mean}), and grain starch concentration but significantly negatively correlated with the SPAD value at the fresh eating stage, grain soluble sugar concentration, and grain fructose concentration (Figure 10). Moreover, grain dry weight had a considerable correlation with the grain fresh weight, filled ear length, grain residue ratio, the maximum grain-filling rate (G_{max}), the average grain-filling rate (G_{mean}), and grain weight increment achieving the maximum grain-filling rate (W_{max}) (Figure 10).

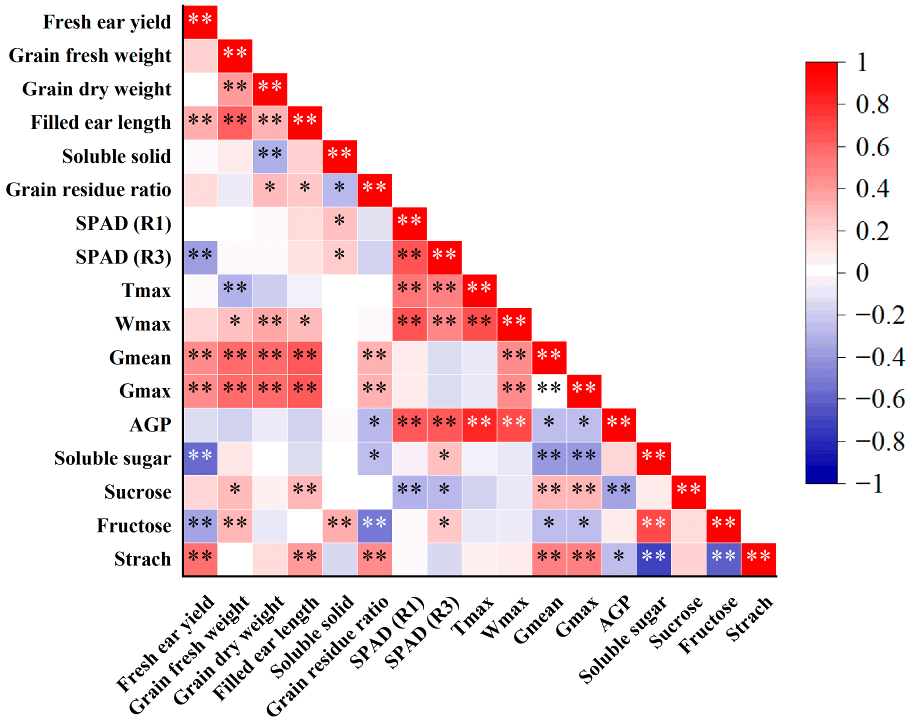

Figure 10. Correlation among fresh ear yield, grain fresh weight, grain dry weight, filled ear length, soluble solid concentration (Soluble solid), grain residue ratio, SPAD (R1), SPAD (R3), the time for maximum grain-filling rate (T_{max}), grain weight increment achieving maximum grain-filling rate (W_{max}), mean grain-filling rate (G_{mean}), maximum grain-filling rate (G_{max}), active grain-filling period (AGP), soluble sugar concentration (Soluble sugar), sucrose concentration (Sucrose), fructose concentration (Fructose), and starch concentration (Starch). * and ** indicate significance at $p < 0.05$, $p < 0.01$, respectively.

4. Discussion

4.1. Effects of Plant Density and Variety on Sweet Maize Fresh Ear Yield and Ear Traits

Maize planting at an optimal density is one of the important cultivation practices for achieving both high yield and quality of maize [24–26]. An optimal plant density can build an optimal canopy structure, improve the canopy light interception, as well as photosynthetic capacity, thereby achieving a high yield [27]. In this study, increasing the plant density significantly increased the sweet maize fresh ear yield of MT6855 and WT2015 in both years, while it did not affect the fresh ear yield of XMT10 and YZ7. This is consistent with previous research, which has stated that the optimal plant density of maize depends on the variety [28]. In addition, our results showed that sweet maize ears ha^{-1} were markedly increased, corresponding to the reduction in the 100-grain weight and grains per ear with the increasing plant density. The high bare plant rate resulting from ovary abortion, grain abortion, and lodging is the main reason maize does not enhance or decrease its yield under a high planting density [29–31]. Firstly, a high planting density may decrease the maize silk growth rate and prolong the interval between flowering and silking, resulting in ovary abortion induced by no pollination and fertilization [31,32]. Secondly, a high planting density may reduce photosynthesis and the distribution of photosynthetic products to grains, leading to a carbon–nitrogen imbalance or hormone imbalance, causing grain abortion [33,34]. Thirdly, a high planting density causes lodging occurrence, leading to a high bare plant rate by inhibiting the flow activity [30]. In the current study, the sweet maize fresh ear yield was sensibly negatively correlated with the bare plant rate but significantly positively correlated with ears ha^{-1} and grains per ear; this is agreed with previous studies [7,35]. These results indicate that maintaining higher ears ha^{-1} resulting from lower bare plant rate, with a smaller decrease in the 100-grain weight and grains per ear, is the major contribution to MT6855 and WT2015 (sweet maize compact-type variety) increased fresh ear yield with the increasing planting density. Furthermore, compact-type varieties of maize have smaller leaf angles and a greater leaf orientation value above the ear and have an ideal canopy structure, resulting in more light interception within the canopy, and they also have more dry weight accumulation and nutrient uptake, as well as having a stronger ability to distribute dry matter and nutrients to ears [27,36]. Consequently, coordinating the relationship among the ears ha^{-1}, grains per ear, and grain weight through selecting compact-type varieties is essential to enhancing the sweet maize fresh ear yield under a high plant density.

Sweet maize is mainly used as fresh eating food, and it is necessary to consider the commercial quality of the ears. A coordinated yield and quality improvement is a challenge for the dense planting of sweet maize [30,37]. The maize yield is decreased through limiting the photosynthesis and dry matter accumulation and suppressing the grain sink formation when exceeding the appropriate planting density [38]. In addition, the appearance quality of sweet maize is decreased with the increase in plant density [39,40]. Similarly, in this study, increasing the planting density significantly decreased the sweet maize filled ear length, but it did not affect the grain soluble solid concentration and grain residue ratio. Moreover, a higher plant density significantly reduced ear traits under XMT10 and YZ7 compared to MT6855 and WT2015. This coincides with some studies that have reported that maize appearance quality, including ear traits and intrinsic quality, consisting of soluble solid and sugar concentration in response to plant density, depends on varieties [4,41,42]. Notably, a parabolic curve relationship between the sweet maize fresh ear yield and grain weight was observed in our study, which may be due to the significant differences in grain weight among different varieties, indicating that the fresh ear yield may not be high for larger grain weight. Therefore, matching the optimum planting density and variety plays a vital role in achieving high yield and quality of sweet maize.

4.2. The Response of Sweet Maize Grain-Filling Rate and Grain Carbohydrate to Plant Density and Variety

Grain filling is an important physiological process that affects the formation of maize yield and quality, for example, the maize grain weight is affected by the grain-filling rate and active grain-filling period [43]. A high planting density reduces the light interception and promotes leaf senescence, reducing the active grain-filling period and grain weight [44]. However, our study confirmed that increasing the plant density decreased the grain-filling rate but did not remarkedly change the active grain-filling period in sweet maize. On the one hand, it may be that leaf senescence is not the main limiting factor influencing grain filling in sweet maize under dense planting, resulting from the ear leaf SPAD value at the fresh eating stage (R3) being higher than that at the silking stage. However, it decreases with the increase in plant density. On the other hand, the effective grain-filling period may primarily depend on different varieties, while the grain-filling rate is mainly affected by the plant density and weather conditions [9,23,45]. In addition, increasing the plant density decreases the grain weight and grain-filling rate, which may be due to the reduction in source–flow–sink activities and inhibiting key enzyme activity in photosynthesis and sugar metabolism [12]. In this study, the grain-filling rate is significantly positively correlated with the grain weight and fresh ear yield in sweet maize. This is consistent with previous correlation analyses, which have indicated that the plant density affected the grain weight mainly by influencing the grain-filling rate [7,10,23]. Therefore, increasing the grain-filling rate is conducive to improving the grain weight and fresh ear yield of sweet maize.

The carbohydrate dynamic during grain filling is closely related to the yield and quality in maize [12]. Previous studies have demonstrated that ovary abortion resulting in reduced yield and quality of maize is determined by the soluble sugar and starch concentration [35]. In grain maize, glucose and fructose concentrations in grains were significantly decreased and coincided with a steep increase in the starch concentration during grain filling [17]. In contrast, some researchers [33] have revealed that glucose and fructose concentrations initially increased and decreased within 16 days after pollination. In sweet maize, soluble sugar and sucrose concentrations firstly increased, reaching the peak at 18–22 days after pollination, then decreased; however, the starch concentration increased with the promotion of the grain-filling process [46,47], and similar results were also confirmed in our study. Furthermore, carbohydrate compositions in grains are influenced by the planting density [30]. Fresh waxy maize grain soluble sugar and starch decreased when maize plants were subjected to shading for 23 days during grain filling [18]. Nevertheless, in the current study, we found that increasing the plant density did not significantly decrease the soluble sugar, sucrose, fructose, and starch concentration across four varieties. These accord with previous results showing that increasing the plant density did not significantly decrease the sucrose and starch concentration [19,48]. It may be due to the competition for light energy and shading caused by the current density of sweet maize in this study, which has not yet affected the carbohydrate concentration [19]. Moreover, sweet maize may sacrifice grain weight to maintain its carbohydrate concentration for adapting to high densities. In addition to these possible reasons, we speculate that it may be due to the superior grains sampled in this study, with superior grains owing to strong grain carbohydrate regulation abilities. As starch in middle grains is not affected by shading, apical kernels were more sensitive to shading than middle kernels [33,49]. However, the mechanism of plant density affecting the carbohydrate concentration and the activities of sugar synthesis key enzymes in the superior and inferior grains during sweet maize grain filling needs to be investigated in the future. Additionally, some researchers have stated that increasing the density alone cannot increase maize production and needs to match nutrient management [25]. Thus, future studies should be conducted on the interaction effects of plant density and nutrient management on the sweet maize fresh ear yield and sugar metabolism.

5. Conclusions

Increasing the plant density significantly increased the ears ha^{-1} and bare plant rate but decreased the grains per ear, grain weight, filled ear length, and grain-filling rate. Meanwhile, it did not affect sweet maize's grain soluble solid concentration, residue ratio, and carbohydrate concentration. In addition, MT6855 and WT2015 (compact-type varieties) increased the fresh ear yield and quality, mainly by maintaining a low bare plant rate and a minor reduction in grains per ear, grain weight, and SPAD value under a high planting density, promoting the grain-filling rate and starch synthesis. Therefore, MT6855 and WT2015 combined with an optimal planting density of 60,000 plants ha^{-1} can improve the sweet maize fresh ear yield without sacrificing its quality in Southeast China when receiving 180 kg ha^{-1} N, 45 kg ha^{-1} P_2O_5, and 180 kg ha^{-1} K_2O and being free from water stress. These results are conducive to obtaining higher yield and quality in sweet maize production in Southeast China, assisting local farmers in increasing their production and income.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13112830/s1, Figure S1: Fresh ear yield (A,B), ears (C,D), bare plant rate (E,F), 100-grain weight (G,H), and grains per ear (I,J) of sweet maize varieties MT6855, WT2015, XMT10, and YZ7 under different plant densities in 2021 and 2022. D1, D2, and D3 indicate 4.5 plants m^{-2}, 6.0 plants m^{-2}, and 7.5 plants m^{-2}, respectively. Values with the same letters are not significantly different at $p < 0.05$, * and ** indicate significant difference at $p < 0.05$, $p < 0.01$, and ns, no significance, respectively.

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