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Comparative Yield and Photosynthetic Characteristics of Two Corn (*Zea mays* L.) Hybrids Differing in Maturity under Different Irrigation Treatments

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Abstract: Effective irrigation strategies are of great significance for improving crop yields. There is an increasing concern that short-season corn hybrids are gradually being encouraged to plant in the North China Plain (NCP) with the development of mechanized grain harvesting, but the photosynthetic characteristics and productivity of short-season hybrids are not well documented. The objective of the study was to investigate the effects of different irrigation treatments on photosynthetic characteristics, dry matter accumulation (DMA) and photo-assimilate translocation (PAT/PT), grain yield (GY) and water productivity (WP) of two corn hybrids differing in maturity. In the experiment plots under the rainout shelter facility, short-season hybrid Denghai518 (DH518) and medium- and full-season hybrid Denghai605 (DH605) were grown under three irrigation levels (severe water stress, T1; mild water stress, T2; and non-stress, T3) by two irrigation methods (flood irrigation, FI; surface drip irrigation, SDI) in 2020 and 2021. The results indicated that non-stomatal limitation (NSL) was the main factor leading to the reduction in photosynthesis during the reproductive stage. Severe water stress significantly decreased net photosynthetic rate (P_n) and chlorophyll soil-plant analysis development (SPAD) value, resulting in lower DMA and GY. The contribution rate of vegetative organ photosynthate before flowering (CRP) decreased with the irrigation levels increasing. DMA, GY and WP of SDI increased by 16.23%, 21.49% and 51.31%, respectively, compared to FI. The yields of DH518 were 7.22% lower than those of DH605. The WP penalty for DH605 was attributed to a relatively larger ET. It suggested that applying the optimum irrigation level (T3) under SDI could increase DMA, GY and WP of summer corn in the NCP.

Keywords: corn; hybrid maturity; irrigation; yield; photosynthetic characteristics

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1. Introduction

Increasing crop productivity is an urgent requirement to meet food demand for the predicted increase of 2.3 billion people by the mid-21st century [1,2]. Genetic improvements, advanced mechanization and the availability of irrigation and fertilizer are helpful in increasing crop yields worldwide with the development of the Green Revolution [3,4]. Irrigation has immensely contributed to higher grain production, and approximately four-fifths of crops are produced in irrigation districts [5]. Corn is a leading cereal crop cultivated as the staple food in the world [6]. China is one of the most important cereal-producing countries and about 30% of the cereal production refers to corn [7]. The NCP belongs to the major corn growing regions in China, accounting for 40% of corn-producing areas [8]. As the climate becomes drier and wetter, extreme climate events (e.g., droughts and dry spells) are becoming common in this area [9], and many farmlands still suffer from a lack of sufficient available water for crop production. Furthermore, FAO [10] demonstrated that a future increase in grain production was dependent on higher plant density and yields owing to the limitation of available land for agricultural use. It is anticipated that the magnitude of agricultural water consumption will grow gradually with population pressure and the increasing need for food security in the future. Therefore, one of the greatest challenges to increasing crop production is obtaining a higher yield and an effective utilization of water resources.

Indeed, farmers are planting longer season hybrids to increase GY in the NCP. However, full-season hybrids generally obtain higher grain moisture content at harvest, which could cause larger harvest losses and increase the relatively high cost of drying and storage [11]. The use of short-season hybrids has become more widespread because hybrids with earlier harvest dates would likely lead to sufficient in-field grain dry-down and high-quality mechanical harvesting [12]. Previous studies examining irrigation management factors influencing corn production responses to hybrid maturity have been inconsistent [13–15], and optimal irrigation management for corn hybrids of different maturities is still a problem to be solved. Additional research is necessary to understand the mechanism of what influences the hybrid maturity response to various irrigation treatments.

Flood irrigation is a traditional irrigation technique that exhibits WP [16]. Numerous water-saving cultivation techniques (e.g., supplemental irrigation and drip irrigation) have been developed and applied to maintain high GY and WP over the past several decades. Supplemental irrigation is an irrigation method that uses an adequate amount of water when applied during crop growth stages [17]. In Turkey, Dogan [18] reported that proper supplemental irrigation levels increased the number of branches and pods per plant on vetch. A similar result was also reported by Mbagwu and Osuigwe [19], who found that the growth of corn was best when irrigation with water was equivalent to 75% field capacity at daily intervals. Drip irrigation plays an important role in increasing crop productivity by applying water precisely [20], which also has obvious advantages in reducing production costs and crop evapotranspiration [21]. At present, China is the country with the largest micro irrigation area in the world, and there is a growing interest in applying drip irrigation to cereal crops such as corn [22]. For instance, the use of drip irrigation techniques significantly decreased the cost of corn field management and improved water use efficiency in Northeast China [23]. As such, optimizing supplemental irrigation and drip irrigation could be highly efficient irrigation treatments with great potential for increasing crop productivity.

Photosynthesis is an important physiological process for crops to accumulate organic matter. Irrigation is a key factor affecting corn photosynthetic characteristics. Severe water stress significantly decreased relative chlorophyll content, net photosynthesis and delayed corn growth, resulting in significant yield loss [24]. Within a certain range of irrigation amounts, photosynthetic rate and SPAD value increase with the irrigation [25]. Moreover, it is stomatal limitations (SL) and non-stomatal limitations (NSL) that become the major factor in reducing plant photosynthesis under different irrigation levels [26]. Song et al. [27] reported that the reduction in photosynthesis under mild water stress was mainly caused by SL, while with the opening of plant stomata significantly decreased under severe water stress, causing the decreases in the activity of Rubisco and chloroplasts, NSL became the main factor leading to the reduction in photosynthesis capacity. Moreover, crop yield depends on the rate of biomass accumulation and proportion of carbohydrate partition to ears. The contribution of biomass after anthesis to the grain is correlated with GY [23]. The proportion of remobilization of dry matter from vegetative organs to the grain is associated with climatic conditions, soil nutrients, water availability, crop cultivars and all of which are critical for determining grain yield [28–30]. Therefore, one of the main purposes in this study is to investigate the photosynthetic characteristics, DMA and PAT/PT under different irrigation treatments throughout the corn-growing season.

The field experiment under the rainout shelter was conducted by using two corn hybrids differing in maturity, three irrigation levels and two irrigation methods. Accordingly, the experiment reported here was undertaken to test the effects of different irrigation treatments on (i) leaf SPAD value and photosynthetic characteristics; (ii) DMA and PAT/PT; and (iii) GY and WP of two corn hybrids differing in maturity in NCP.

2. Materials and Methods

2.1. The Experimental Site

The study was performed during two summer corn growing seasons in 2020 and 2021 at Liangzhuang research field (35°97′ N; 117°26′ E; 130 m a.s.l.) and at the State Key Laboratory of Crop Biology, which were both located in Taian, Shandong Province, China. The experimental region had a temperate continental monsoon climate and the soil of the experimental field is silty clay loam in the US system of soil taxonomy [31]. The mean monthly air temperature during the experiment periods from June to October was 27.42, 26.44, 28.51, 23.39 and 13.58 °C in 2020 and from June to October was 28.14, 28.48, 27.19, 22.63 and 14.54°C in 2021, respectively, by the Taian meteorological station of China Meteorological Administration. The average available N, P, K and soil organic matter content in 0–20 cm soil depth was 102.1 mg/kg, 39.4 mg/kg, 88.4 mg/kg and 11.6 g/kg, respectively. The pH, soil bulk density and field capacity of the soil in the 0–100 cm soil layers were shown in Table 1.

Table 1. The soil bulk density, field capacity and pH of the soil in the 0–100 cm soil layer in the experimental plots.

Soil Layer (cm)	0–20	20–40	40–60	60–80	80–100
Bulk density (g/cm^3)	1.49	1.54	1.52	1.56	1.53
Field capacity (%)	21.01	20.45	18.19	19.64	20.98
pH	6.58	6.55	6.51	6.54	6.59

2.2. Experimental Design

Two corn hybrids, Denghai518 (short-season DH518) and Denghai605 (medium- and full-season DH605), were seeded on 15 June in 2020 and 12 June in 2021 in the experimental plots with a row spacing of 60 cm and a plant density of 67,500 plants/ha. Both hybrids are widely planted in Shandong Province, China. The hybrid maturity is classified as 113 d for DH605 and 103 d for DH518. The growing season duration (from planting to physiology maturity) for two hybrids under different irrigation treatments was shown in Table 2.

Table 2. Corn phenology (from sowing date to physiology maturity, SD-R6) for two corn hybrids differing in maturity under different irrigation treatments (d).

Year	Hybrid	Treatment	SD-V6	V6-VT	VT-R3	R3-R6	SD-R6
2020	DH605	FIT1	25	22	28	34	109
		FIT2	25	23	27	34	109
		FIT3	25	23	27	34	109
		SDIT1	25	22	28	36	111
		SDIT2	25	22	28	36	111
		SDIT3	25	22	28	36	111
	DH518	FIT1	24	22	22	34	102
		FIT2	24	21	24	34	103
		FIT3	24	21	24	34	103
		SDIT1	24	22	23	35	104
		SDIT2	24	22	24	34	104
		SDIT3	24	22	24	34	104
2021	DH605	FIT1	25	27	24	34	110
		FIT2	25	26	26	34	111
		FIT3	25	26	26	34	111
		SDIT1	25	26	27	35	113
		SDIT2	25	26	27	35	113
		SDIT3	25	26	27	35	113
	DH518	FIT1	23	23	23	34	103
		FIT2	23	22	24	34	103
		FIT3	23	22	24	34	103
		SDIT1	23	22	24	35	104
		SDIT2	23	23	24	35	105
		SDIT3	23	23	24	35	105

The field experiment used a split-plot design of twelve treatments with three replications in 2020 and 2021. The corn hybrid maturity was the whole-plot factor, and factorial combinations of three irrigation levels (T1, T2 and T3) and two irrigation methods (surface drip irrigation, SDI; flood irrigation, FI) were randomly assigned to the subplots.

Each experimental plot was 4 m × 4 m and separated by concrete walls of 0.5 m-thick water barriers. Each wall was built 2.5 m below the surface and the remaining 0.3 m was above ground. The experimental plots were equipped with the moveable waterproof shed to prevent rainfall onto experimental plots. Irrigation was conducted to maintain field capacity of upper 60 cm soil layer before planting in each plot.

The irrigation levels were determined according to the design by maintaining the soil relative water content (SRWC) of the tested soil layer (0–60 cm) at 45% ± 5% (severe water stress) of field capacity for FIT1 and SDIT1; at 60% ± 5% (mild water stress) of field capacity for FIT2 and SDIT2; and at 75% ± 5% (non-stress) of field capacity for FIT3 and SDIT3. Field capacity refers to the water moisture of the upper 60 cm soil layer following saturation with water when free drainage is negligible [17]. The SRWC in T1, T2 and T3 treatments were maintained from planting to harvesting. The amounts of irrigation were calculated based on pre-irrigation soil water content (SWC) described in Sidika et al. [32] as follows:

$$\mathrm{IA} = 10 \times \gamma_{bd} \times \mathrm{H} \times (\theta_i - \theta_j)$$

where IA (mm) refers to the amount of irrigation, γ_{bd} is the soil bulk density, H refers to the depth of the soil layer (in this paper it is 60 cm), θ_i refers to the target SWC on a weight basis after irrigating and θ_j refers to SWC on a weight basis before irrigating. The value for θ_i was calculated as follows:

$$\theta_i = \theta_{max} \times \theta_{tr}$$

where θ_{max} (%) refers to the field capacity and θ_{tr} (%) refers to the SRWC for each tested soil layer.

Irrigation was applied with designed irrigation levels when the predicted SRWC was less than the designed SRWC limit. The average duration of each irrigation interval was 10–12 days in 2020 and 12–15 days in 2021. The soil water content was measured by oven-drying method [33] one day prior to each irrigation period at each experimental plot. For SDI, the main pipes were set vertical to the row direction in front of each experiment plot. The capillary pipes were laid among each row on 15 June 2020 and 12 June 2021. The drip irrigation belt was maintained at an emitter spacing of 300 mm and the emitter discharge rate was 2.8 L/h at 0.1 MPa operating pressure. The volume of irrigation water applied to each plot was measured by flow meters installed on the water pipes used for irrigation. The water application levels were shown in Table 3.

The fertilizer rates of N, P_2O_5 and K_2O were 210 kg/ha, 52.5 kg/ha and 67.5 kg/ha, respectively. All N, P and K fertilizer were applied one-off to prepare soil for sowing as basal dressing before planting. Disease, pests and weeds were well controlled in each treatment.

2.3. Sample Collection and Measurements

2.3.1. Corn Phenology

Corn phenology is usually divided into vegetative (V) and reproductive (R) [34,35]. The following corn phenological stages in each experiment plot were recorded and calculated for two hybrids throughout two growing seasons: the sowing date (SD), the sixth leaf stage (V6), the twelfth leaf stage (V12), tasseling stage (VT), silking stage (R1), milking stage (R3) and physiological maturity stage (R6). The interval among these growth stages of each hybrid was also carefully calculated.

Table 3. Irrigation amounts of two corn hybrids differing in maturity under different irrigation treatments (mm).

Year	Hybrid	Treatment	SD-V6	V6-VT	VT-R3	R3-R6	SD-R6
2020	DH605	FIT1	38.54	85.67	42.70	44.05	210.96
		FIT2	27.38	170.84	79.12	71.56	348.91
		FIT3	20.02	196.40	129.57	113.28	459.26
		SDIT1	20.56	57.31	24.02	20.04	121.92
		SDIT2	27.97	97.96	69.04	55.71	250.68
		SDIT3	12.86	146.04	92.20	80.86	331.95
	DH518	FIT1	33.98	78.06	38.23	42.95	193.22
		FIT2	28.61	131.99	84.79	88.89	334.29
		FIT3	22.55	140.41	144.08	120.19	427.23
		SDIT1	15.42	40.78	29.37	25.23	110.80
		SDIT2	12.89	94.76	65.75	49.92	223.32
		SDIT3	26.52	110.48	96.36	67.99	301.34
2021	DH605	FIT1	37.18	90.43	61.75	22.33	211.70
		FIT2	52.51	146.83	118.51	54.24	372.10
		FIT3	61.04	189.71	163.00	62.74	476.49
		SDIT1	26.90	78.33	42.24	29.08	176.55
		SDIT2	20.58	84.70	58.04	57.16	220.48
		SDIT3	44.61	135.39	123.59	44.53	348.12
	DH518	FIT1	27.95	68.04	43.98	18.42	158.38
		FIT2	40.09	123.52	103.80	48.06	315.47
		FIT3	50.68	179.02	156.64	55.94	442.28
		SDIT1	9.72	41.20	39.00	11.85	101.77
		SDIT2	18.40	74.38	66.06	16.12	174.96
		SDIT3	30.16	114.66	102.85	28.02	275.68

2.3.2. Chlorophyll Soil Plant Analysis Development (SPAD) Value

The chlorophyll SPAD value was measured at V6, V12, VT, R3 and R6 stages on ten randomly selected plants in each plot by using the portable chlorophyll meter (SPAD-502, Soil Plant Analysis Development Section; Minolta Camera Co., Osaka, Japan).

2.3.3. Leaf Gas Exchange Parameters

The net photosynthetic rates (P_n), stomatal conductance (G_s) and intercellular CO_2 concentration (C_i) of three ear leaves representational in each treatment were measured at VT, VT + 20, VT + 30, beginning dent, VT + 40, VT + 50 stages by using a portable infrared gas analysis system (CIRAS II, PP System; Hansatech, King's Lynn, UK) equipped with a clamp-on leaf cuvette that exposed 1.7 cm^2 of the leaf area (PLC version, PP System). The CO_2 concentration (C_a) in the leaf chamber was consistent with that of the outside world, the flow rate was set to 400 μmol/s. The stomatal limitation value (L_s) was calculated by the formula:

$$L_s = 1 - C_i/C_a$$

where C_i refers to intercellular CO_2 concentration; C_a refers to the CO_2 concentration in the air.

2.3.4. Dry Matter Accumulation and Translocation

Three representative plants were collected for each treatment at V6, V12, VT, R3 and R6 stages in the experimental plots. Aboveground plant parts were collected and separated into leaves and stems at V6, V12 and VT and into stems, leaves, cobs and grains at the R3 and R6 stage. The samples were then dried at 80 °C in a forced-air oven (DHG-9420A; Shanghai Bilon Instruments Co., Ltd., Shanghai, China) to constant weight and weighed separately. In order to estimate PAT/PT, all of the dry matter lost from the vegetative parts were supposed to translocate to the grain except considering the loss of dry matter due to respiration.

The following parameters were calculated as follows [36,37]:

Translocation amount of vegetative organ photosynthate before flowering (TAP, g/plant) = dry matter of vegetative organs at flowering stage (DMF)—dry matter of vegetative organs at maturity;

Translocation rate of vegetative organ photosynthate before flowering (TRP) = TAP/DMF × 100%;

Contribution rate of vegetative organ photosynthate before flowering to grain (CRP) = TAP/Grain dry weight at maturity × 100%;

Translocation amount of vegetative organ photosynthate after pollination (TAA, g/plant) = Grain dry weight at maturity—TAP;

Contribution rate of vegetative organ photosynthate after pollination to grain (CRA) = TAA/Grain dry weight at maturity × 100%;

Dry matter accumulation after pollination (DMAP, g/plant) = dry matter at maturity − DMF;

Percentage of dry matter accumulated after pollination (PDMA) = DMAP/dry matter at maturity.

2.3.5. Grain Yield

At the physiological maturity stage, all ears from each plot were harvested. After harvesting, the ears of corn were weighed, manually shucked and the grain weighed. Samples were taken from each batch to calculate grain moisture content. The samples were dried in an oven at 80 °C. All yields refer to 14% moisture content (GB/T, 2013) on a wet weight basis.

2.3.6. Water Productivity

Soil moisture content was measured to depth of 100 cm at 20 cm interval with the gravimetric method detailed in Guo et al. [33]. Three soil samples were collected randomly from each plot before planting and after harvest.

Total crop water consumption (ET, mm) was determined during the growing season using the soil water balance equation as follows [22]:

$$\text{ET (mm)} = I_w + P_w + U\text{-}R\text{-}D_w \pm \Delta S$$

where ET (mm) refers to the total water consumption during the growing season; I_w (mm) refers to the amount of irrigation; P_w (mm) refers to the amount of precipitation during the growing season; U refers to upward capillary flow from the root zone (mm); R refers to the runoff (mm); and D_w refers to the amount of drainage water below the 200 cm soil layer (mm). ΔS refers to the change from planting to harvesting in soil water storage in the 0–100 cm soil layer (mm). P was considered zero because no natural rain fell on the experiment during corn growth under the rainout shelter. No runoff and no capillary rise occurred in all treatments, so U and R were not taken into account. Downward drainage out of the root zone was measured previously in NCP and the associated value in the above equation was therefore neglected [38].

Water productivity was calculated by Arbat, G. P. et al. [39] as:

$$WP = GY/ET \tag{1}$$

where WP refers to water productivity (kg/m^3), GY refers to the grain yield (kg/ha) and ET refers to crop evapotranspiration (mm).

2.4. Statistical Analysis

Figures used the SigmaPlot 12.5 program. Analysis of variance was performed for ET, P_n, G_s, C_i, L_s, WP, GY, DMA and PAT/PT by using DPS 9.5. All treatments were compared based on statistical significance using the least significant difference (LSD) test and 5% (α = 0.05) significance level.

3. Results

3.1. Corn Growing Season Duration

The growing season duration (from sowing date to physiological maturity) was delayed somewhat by increasing irrigation levels (Table 2). SDI treatment attained physiological maturity about 1–2 days later than FI treatment. DH518 silked in 47 days in 2020 and 48–49 days in 2021 after planting, while DH605 required 49 days in 2020 and 52–54 days in 2021to reach the silking stage. The growing season length for DH518 decreased 6–7 days in 2020 and 8–9 days in 2021, compared to DH605. Similar results were obtained in 2020 and 2021, and only minor differences were observed between years.

3.2. Grain Yield, Crop Evapotranspiration and Water Productivity

Effects of different irrigation treatments on corn GY, ET and WP were shown in Table 4. The overall yields differed significantly across hybrids, irrigation methods and irrigation levels. In both years, GY and ET increased from T1 to T3 while WP decreased from T1 to T3. Compared to T3, the decreases (mean of both years) for DH518 in GY were 20.95% under T1 and 10.66 % under T2, the decreases (mean of both years) for DH605 in GY were 19.19% under T1 and 10.48% under T2, respectively. Compared to DH605, the decreases (mean of both years) for DH518 in GY and ET were 7.22% and 12.34%, respectively. While the increase (mean of both years) in WP for DH518 was 6.2%. Compared to FI, the increases mean of both years in GY and WP for SDI were 21.49% and 51.34%, respectively, while the decrease in ET for SDI was 18.24%. Similar results were obtained in 2020 and 2021, and only minor differences were observed between years.

Table 4. Effects of different irrigation treatments on GY, ET and WP of two corn hybrids differing in maturity.

Hybrid	Treatment	GY (kg/ha)		ET (mm)		WP (kg/m^3)	
		2020	2021	2020	2021	2020	2021
DH605	FIT1	7633.96 ^{f}	7545.84 ^{g,h}	300.21 ^{f}	270.49 ^{h}	2.54 ^{f}	2.79 ^{d,e}
	FIT2	8644.06 ^{e}	8930.90 ^{e,f}	435.34 ^{c}	422.55 ^{d}	1.99 ^{h}	2.11 ^{f}
	FIT3	10,022.11 ^{c}	10,234.76 ^{c,d}	511.38 ^{a}	511.24 ^{a}	1.96 ^{h}	2.00 ^{f}
DH605	SDIT1	10,025.70 ^{c}	10,335.53 ^{d,e}	239.36 ^{h}	248.73 ^{i}	4.19 ^{b}	4.16 ^{b}
	SDIT2	10,653.39 ^{b}	11,002.89 ^{b,c}	351.07 ^{e}	334.08 ^{f}	3.03 ^{d}	3.29 ^{c}
	SDIT3	11,634.14 ^{a}	11,837.52 ^{a}	439.29 ^{c}	436.53 ^{c}	2.65 ^{e,f}	2.71 ^{e}
DH518	FIT1	7178.49 ^{g}	6994.09 ^{h}	262.82 ^{g}	237.14 ^{j}	2.73 ^{e}	2.94 ^{d,e}
	FIT2	8432.08 ^{e}	8258.38 ^{f,g}	391.83 ^{d}	380.37 ^{e}	2.15 ^{g}	2.17 ^{f}
	FIT3	9457.15 ^{d}	9593.72 ^{d,e}	464.21 ^{b}	472.60 ^{b}	2.04 ^{g,h}	2.02 ^{f}
DH518	SDIT1	9181.67 ^{d}	9148.61 ^{e}	203.30 ^{i}	208.18 ^{k}	4.52 ^{a}	4.70 ^{a}
	SDIT2	9908.46 ^{c}	10,002.39 ^{d}	302.85 ^{f}	282.75 ^{g}	3.27 ^{c}	3.53 ^{c}
	SDIT3	10,684.36 ^{b}	11,189.23 ^{a,b}	389.58 ^{d}	372.27 ^{e}	2.74 ^{e}	3.00 ^{d}

Numbers followed by same alphabets along the column are not significantly different at $p < 0.05$. The same as below.

3.3. Dry Matter Accumulation and Translocation

The dynamic changes in plant DMA throughout the corn developmental stages in 2020 and 2021 were presented in Figure 1. The dry matter gradually increased from the V6 to R6 stage and peaked at maturity in both growing seasons. In 2020, DMA of DH518 at the R6 stage was 7.53% lower than that of DH605 by average. DMA increased as the irrigation levels increased, and the over trend was T3 > T2 > T1. The DMA was significant and substantially decreased under T1 (by 14.61%, averagely) and T2 (by 8.28%, averagely), compared to that under T3. DMA of SDI was 16.24% higher than that of FI by average. Similar results were obtained in 2020 and 2021, and only minor differences were observed between years.

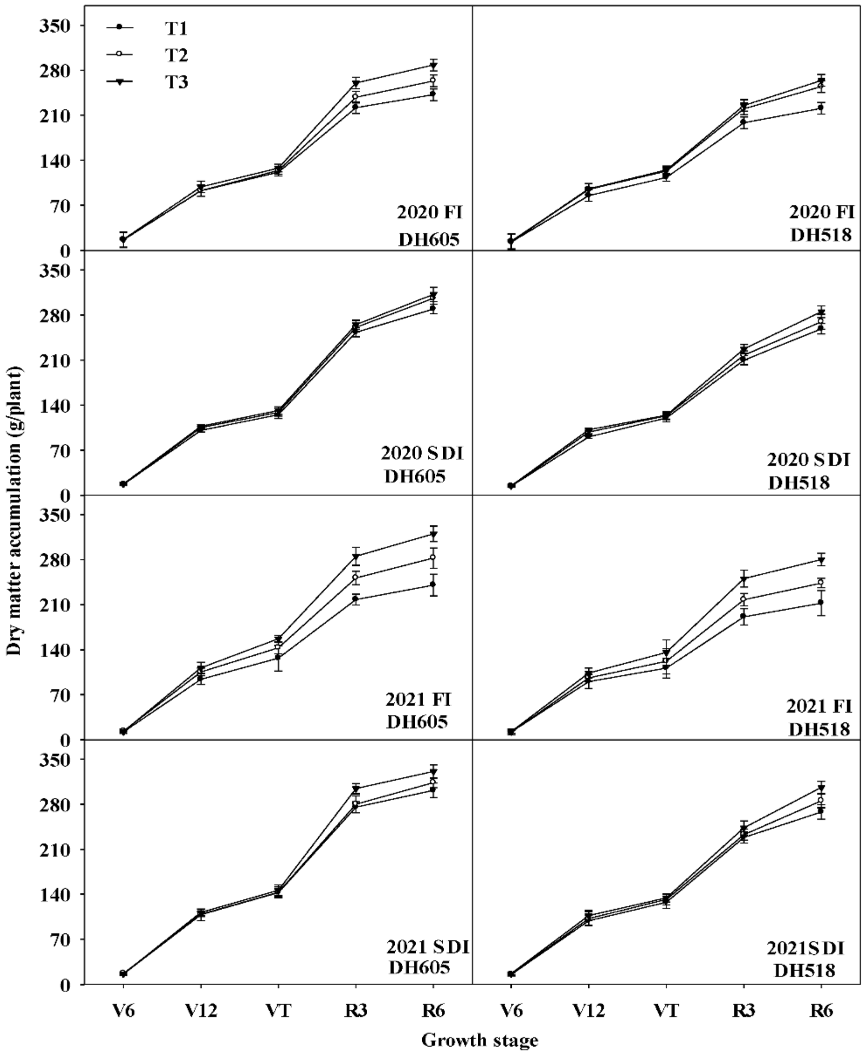

Figure 1. Effects of different irrigation treatments on dynamic changes in plant dry weight at different growth stages of two corn hybrids differing in maturity.

As shown in Table 5, the parameters of PAT/PT were affected by hybrids, irrigation amounts and irrigation methods. In 2020, TAA and CRA of DH605 at the R6 stage were 8.19%and 1.22% higher than those of DH518 by average, respectively. APA and CRA increased as irrigation levels increased, and the over trend was T3 > T2 > T1. TAA and CRA were significant and substantially decreased under T1 (by 20.10% and 4.21%, averagely and, respectively) and T2 (by 10.34% and 1.77%, averagely and, respectively), compared to those under T3. TAA, CRA of SDI were 25.23% and 6.14% higher than those of FI on average, respectively. Compared with T3, T2 increased TAP and CRP by 4.41% and 16.56%, and T1 increased TAP and CRP by 10.88% and 34.61% for DH605. Compared with the T3, T2 increased TAP and CRP by 1.34% and 11.03%, and T1 increased TAP and CRP by 4.64% and 29.87% for DH518. TAP and CRP of DH605 were 2.43% and 8.51% lower than those of DH518 on average. TAP and CRP of SDI were 19.24% and 32.72% lower than those of FI on average. Similar results were obtained in 2020 and 2021, and only minor differences were observed between the two years.

Table 5. Effects of different irrigation treatments on dry matter distribution and PAT/PT for two corn hybrids differing in maturity.

Year	Hybrid	Treatment	TAP (g/plant)	CRP (%)	TAA (g/plant)	CRA (%)
2020	DH605	FIT1	9.86 ^{a,b,c}	8.71 ^{b,c}	103.35 ^{g}	91.29 ^{b,c}
		FIT2	8.26 ^{b,c,d}	6.45 ^{b,c,d}	119.82 ^{e}	93.55 ^{a,b,c}
		FIT3	7.80 ^{b,c,d}	5.26 ^{c,d}	140.54 ^{c}	94.74 ^{a,b}
		SDIT1	4.76 ^{c,d}	3.20 ^{d}	143.85 ^{c}	96.80 ^{a}
		SDIT2	4.38 ^{d}	2.78 ^{d}	153.46 ^{b}	97.22 ^{a}
		SDIT3	3.96 ^{d}	2.29 ^{d}	168.42 ^{a}	97.71 ^{a}
	DH518	FIT1	15.13 ^{a}	14.23 ^{a}	91.22 ^{h}	85.77 ^{d}
		FIT2	12.02 ^{a,b}	9.62 ^{b}	113.01 ^{f}	90.38 ^{c}
		FIT3	11.66 ^{a,b}	8.25 ^{b,c}	129.71 ^{d}	91.75 ^{b,c}
		SDIT1	8.78 ^{b,c,d}	6.45 ^{b,c,d}	127.40 ^{d}	93.55 ^{a,b,c}
		SDIT2	8.02 ^{b,c,d}	5.45 ^{b,c,d}	138.92 ^{c}	94.55 ^{a,b,c}
		SDIT3	7.71 ^{b,c,d}	4.87 ^{c,d}	150.69 ^{b}	95.13 ^{a,b}
2021	DH605	FIT1	20.20 ^{a}	18.07 ^{a,b}	91.59 ^{i}	81.93 ^{f,g}
		FIT2	18.68 ^{a,b}	14.10 ^{c,d}	113.81 ^{g}	85.90 ^{d,e}
		FIT3	17.83 ^{a,b,c,d}	11.66 ^{d,e,f}	135.13 ^{c,d}	88.34 ^{b,c,d}
		SDIT1	15.67 ^{b,c,d}	10.24 ^{e,f,g}	137.39 ^{c}	89.76 ^{a,b,c}
		SDIT2	15.03 ^{c,d}	9.21 ^{f,g}	148.16 ^{b}	90.79 ^{a,b}
		SDIT3	14.45 ^{d}	8.22 ^{g}	161.43 ^{a}	91.78 ^{a}
	DH518	FIT1	20.15 ^{a}	19.45 ^{a}	83.47 ^{j}	80.55 ^{g}
		FIT2	19.03 ^{a,b}	15.53 ^{b,c}	103.49 ^{h}	84.47 ^{e,f}
		FIT3	18.18 ^{a,b,c}	12.76 ^{d,e}	124.29 ^{e}	87.24 ^{c,d}
		SDIT1	15.56 ^{b,c,d}	11.45 ^{e,f}	120.33 ^{f}	88.55 ^{b,c}
		SDIT2	15.49 ^{b,c,d}	10.45 ^{e,f,g}	132.69 ^{d}	89.55 ^{a,b,c}
		SDIT3	15.83 ^{b,c,d}	9.53 ^{f,g}	150.34 ^{b}	90.47 ^{a,b}
ANOVA						
Y			*	*	*	*
H			*	*	*	*
IA			NS	*	*	*
IM			*	*	*	*
H × IA			NS	NS	NS	NS
H × IM			NS	NS	*	NS
IA × IM			NS	NS	*	**
H × IA × IM			NS	NS	NS	NS

Note: TAP, translocation amount of vegetative organ photosynthate before pollination; CRP: contribution rate of vegetative organs photosynthate before pollination to grain weight; TAA: translocation amount of vegetative organs photosynthate after pollination; CRA: contribution rate of vegetative organs photosynthate after pollination to grain weight; PDMA: percentage of dry matter accumulated after pollination. NS, not significant. ** and * indicate significant difference at the 0.01 and 0.05 levels of probability, respectively. Numbers followed by same alphabets along the column are not significantly different at $p < 0.05$.

3.4. Leaf Gas Exchange Parameters

As shown in Table 6, P_n showed a decreasing trend after VT. The average decline rate of P_n was relatively slow from the VT to R2 stage (13.23 % in 2020 and 17.42 % in 2021) and the average decline rate from the R2 to R5 stage was 61.76% in 2020 and 67.09 % in 2021. The average P_n of FI was reduced by 11.93% in 2020 and 16.34% in 2021 at the VT stage compared with that of SDI. At the R2 stage, the average P_n of DH605 was 7.07% higher in 2020 and 22.72% higher in 2021 than that of DH518. At the R3 stage, the average P_n of DH605 was 11.03% higher in 2020 and 49.49% higher in 2021 than that of DH518. It suggested that P_n of DH518 was generally lower and declined rapidly after the VT stage than that of DH605. Similar results were obtained in G_s and only minor differences were observed (Table 7).

Table 6. Net photosynthetic rate (P_n) of two corn hybrids differing in maturity under different irrigation treatments (μmol $CO_2/(m^2$ s)).

Hybrid	Treatment	Days after Anthesis (Days)									
		2020					2021				
		0	20	30	40	50	0	20	30	40	50
DH605	FIT1	31.50	24.64	16.97	8.38	5.25	30.49	24.04	16.36	12.22	8.18
	FIT2	37.26	33.02	25.74	14.34	8.59	35.84	29.89	22.32	14.95	11.72
	FIT3	40.69	35.95	30.69	19.09	10.40	38.77	33.42	26.86	20.50	14.34
DH605	SDIT1	39.08	35.34	30.29	19.39	11.51	37.66	34.43	27.56	19.90	9.29
	SDIT2	42.41	40.09	36.05	22.62	13.13	44.83	39.48	36.55	22.32	11.11
	SDIT3	43.72	42.31	38.27	27.36	14.75	47.76	43.62	39.68	26.75	11.82
DH518	FIT1	29.78	22.22	12.73	7.98	5.15	29.18	18.48	12.22	8.28	6.46
	FIT2	32.31	26.45	18.99	10.30	6.77	33.12	23.53	16.46	12.22	9.90
	FIT3	38.77	33.02	24.24	14.24	7.88	36.15	27.76	20.50	15.45	11.41
DH518	SDIT1	35.54	29.68	21.21	12.52	8.28	32.92	27.36	17.68	10.91	7.78
	SDIT2	37.76	33.32	24.44	15.55	11.51	39.08	33.62	21.01	12.63	8.48
	SDIT3	39.88	36.15	28.77	18.48	12.73	41.70	37.76	23.84	13.94	9.60

Table 7. Stomatal conductance (G_s) of two corn hybrids differing in maturity under different irrigation treatments (μmol $H_2O/(m^2$ s)).

Hybrid	Treatment	Days after Anthesis (Days)									
		2020					2021				
		0	20	30	40	50	0	20	30	40	50
DH605	FIT1	392.55	287.72	192.69	115.33	73.42	390.53	296.81	225.71	169.05	99.78
	FIT2	436.99	317.61	262.17	168.25	98.26	425.98	319.41	271.36	182.59	120.89
	FIT3	466.87	382.14	328.62	218.75	137.96	451.73	370.83	312.87	238.84	140.65
DH605	SDIT1	491.11	413.55	349.93	243.89	136.64	526.66	457.68	372.04	268.12	134.32
	SDIT2	516.77	447.59	408.10	274.79	146.24	561.90	513.43	385.88	276.20	158.04
	SDIT3	466.87	381.84	328.62	218.75	137.35	569.28	552.32	440.82	349.63	195.41
DH518	FIT1	363.86	271.26	196.63	121.69	63.32	305.70	214.71	170.27	107.76	55.03
	FIT2	407.49	316.91	227.84	155.82	91.60	386.99	289.94	227.63	133.01	62.31
	FIT3	420.83	358.71	263.38	176.43	95.64	407.09	343.98	265.20	159.26	83.11
DH518	SDIT1	473.74	396.38	282.47	199.66	85.23	501.41	433.75	325.49	212.38	103.51
	SDIT2	509.29	450.52	330.44	212.18	121.49	538.78	477.88	376.29	301.45	128.62
	SDIT3	530.10	479.80	381.74	272.16	134.02	630.79	586.85	427.80	328.62	203.49

The increases in C_i and decreases in L_s could be the turning point of photosynthesis which changed from being driven by SL to NSL. As shown in Tables 8 and 9, C_i increased under T1 treatment while L_s decreased from the VT to R5 stage in both growing seasons. NSL was the main factor leading to the reduction of photosynthesis under T1 treatment during the reproductive stage. The P_n and G_s of two hybrids under T2 and T3 treatments decreased gradually, C_i from the VT to R2 stage were consistent with only minor variations and increased gradually after the R2 stage. As for L_s, only minor differences were observed from the VT–R2 stage, and it decreased gradually after the R2 stage. These findings indicated that the limiting factors for photosynthesis under T2 and T3 treatments gradually changed from SL to NSL during the reproductive stage. The photosynthesis for both hybrids under T2 treatment changed from being limited by SL to NSL at the R2 stage while that change mainly occurred at the R2–R3 stage under T3 treatment, respectively.

Table 8. Intercellular CO_2 concentration (C_i) of two corn hybrids differing in maturity under different irrigation treatments (CO_2 μmol/mol).

Hybrid	Treatment	Days after Anthesis (Days)									
				2020					2021		
		0	20	30	40	50	0	20	30	40	50
DH605	FIT1	129.69	132.58	153.10	171.38	207.33	141.40	145.02	152.66	158.52	162.45
	FIT2	155.15	148.33	144.52	171.98	215.51	144.61	150.30	154.77	163.05	169.67
	FIT3	158.79	155.94	146.44	180.77	222.68	165.32	166.35	169.93	168.72	177.86
DH605	SDIT1	167.89	167.47	172.89	180.37	201.88	194.36	193.56	200.83	205.68	207.70
	SDIT2	175.65	172.99	177.54	191.68	204.40	210.12	211.94	213.76	218.00	219.40
	SDIT3	182.50	181.32	178.35	187.13	210.87	214.36	216.38	218.60	222.84	227.48
DH518	FIT1	127.90	136.19	150.28	174.00	221.98	137.18	144.56	150.13	154.49	156.98
	FIT2	151.11	149.80	163.70	187.74	231.27	142.59	147.31	156.34	159.92	166.73
	FIT3	163.93	163.44	174.31	199.35	234.30	157.35	156.27	160.88	164.52	172.15
DH518	SDIT1	152.83	149.81	157.34	177.13	193.29	188.30	183.47	190.73	196.79	208.91
	SDIT2	171.24	5.05	169.15	182.69	209.66	199.21	193.15	194.77	204.06	211.74
	SDIT3	176.90	175.32	177.34	189.46	213.59	208.50	202.85	197.39	199.21	217.80

Table 9. The stomatal limitation value (L_s) of two corn hybrids differing in maturity under different irrigation treatments.

Hybrid	Treatment	Days after Anthesis (Days)									
				2020					2021		
		0	20	30	40	50	0	20	30	40	50
DH605	FIT1	0.68	0.67	0.62	0.58	0.49	0.65	0.64	0.62	0.61	0.60
	FIT2	0.62	0.63	0.64	0.57	0.47	0.64	0.63	0.62	0.60	0.58
	FIT3	0.61	0.61	0.64	0.55	0.45	0.59	0.59	0.58	0.58	0.56
DH605	SDIT1	0.58	0.59	0.57	0.55	0.50	0.52	0.52	0.50	0.49	0.49
	SDIT2	0.57	0.57	0.56	0.53	0.49	0.48	0.48	0.47	0.46	0.46
	SDIT3	0.55	0.55	0.56	0.54	0.48	0.47	0.46	0.46	0.45	0.44
DH518	FIT1	0.68	0.66	0.63	0.57	0.45	0.66	0.64	0.63	0.62	0.61
	FIT2	0.63	0.63	0.59	0.54	0.43	0.65	0.64	0.61	0.60	0.59
	FIT3	0.59	0.60	0.57	0.51	0.42	0.61	0.61	0.60	0.59	0.57
DH518	SDIT1	0.62	0.63	0.61	0.56	0.52	0.53	0.55	0.53	0.51	0.48
	SDIT2	0.58	0.99	0.58	0.55	0.48	0.51	0.52	0.52	0.49	0.48
	SDIT3	0.56	0.57	0.56	0.53	0.47	0.48	0.50	0.51	0.51	0.46

3.5. SPAD Value

As shown in Figure 2, the SPAD value increased from the V6 to V12 stage and peaked at the VT stage. Furthermore, the SPAD value declined gradually. SPAD value increased when irrigation amounts increased during both growing seasons. In 2020, the SPAD value of SDI was 27.54% higher at the VT stage compared with that of FI. DH518 reached the highest SPAD value of 65.69 under SDIT3, while SPAD value of DH605 at the VT stage was 4.43% higher at the VT stage, compared to DH518. At the R3 stage, average SPAD value of DH605 was 7.58% higher than those of DH518. SPAD value of DH518 was generally lower and declined rapidly after the VT stage. Similar results were obtained in 2020 and 2021, and only minor differences were observed between the two years.

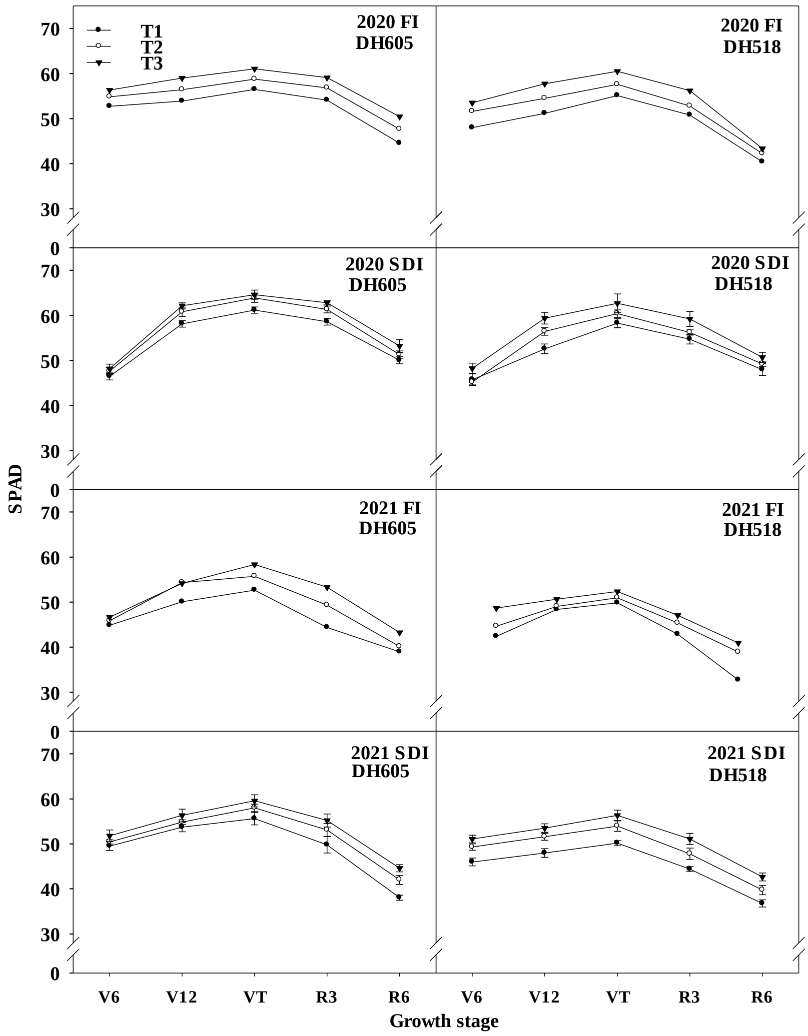

Figure 2. SPAD value of two corn hybrids differing in maturity under different irrigation treatments.

4. Discussions

As the climate inevitably became warm, droughts and heatwaves occurred frequently during the growth period, which inhibited corn growth and development [40,41]. Water supply is one of the most important factors affecting crop production. The different ways of crop response on water stress were dependent on drought severity, timing and duration [42,43]. In this study, water stress decreased the SPAD value (Figure 2) and P_n (Table 6) during the reproductive stage, resulting in significant yield losses. WP could be improved either by increasing yields or reducing crop evapotranspiration [44]. We found the increases (mean of all treatments in SDIT1 and SDIT2) in GY and WP were 24.92% and 57.58%, compared to FIT1 and FIT2 (Table 4). Based on these results, we therefore demonstrated that SDI could be environmentally necessary in the NCP, especially in the areas where water shortages had become the main factor which limited agricultural sustainable development. In addition to adequate irrigation treatments, the use of longer season hybrids has been shown to lead to higher yields, but the ET was much higher, resulting in lower WP, compared to DH518. Furthermore, DH518 attained physiological maturity about 6–9 days earlier than DH605 (Table 3). Given that the reduction in grain moisture content at harvest was of great significance for improving the quality of mechanical harvesting [45], a shortening of hybrid maturity could dry down for early harvest and meet the requirements of high-quality mechanical harvesting.

Photosynthesis is one of the most important physiological processes affecting corn yield. In the present study, DMA (Figure 1) and GY (Table 4) demonstrated significant reductions at the R6 stage due to water shortage under T1 and T2 treatments, which were associated with significant decreases in SPAD value and P_n of ear leaves at the VT stage. These results also showed that water stress significantly decreased the C_i and G_s in corn, which had a negative effect on photosynthesis and ultimately reduced corn production. Shen et al. [46] showed that the optimal irrigation management increases photosynthetic rate and DMA of corn under drip irrigation, resulting in an increase in corn production. These results were consistent with our findings, in this study SDI increased the SPAD value, delayed the senescence process and had a positive effect on DMA. In addition, severe water stress had serious degradation on photosynthetic pigments, resulting in the damage of the photosynthetic electron transfer system and the physiological functions of photosynthetic organs [47]. C_i increased while L_s decreased from the VT to R5 stage under T1 treatment (Tables 8 and 9), suggesting that non-stomatal limitation contributed to the major decreases in corn photosynthesis. Under mild water stress, G_s and C_i decreased gradually from the VT to R2 stage, indicating that the opening of the stomata decreased. After the R2 stage, physiological functions of mesophyll cells were impaired with senescence in whole plant [48], resulting in the increase in C_i from the R2 to R5 stage and the decrease in L_s from the R2 to R5 stage. At this stage, the reduction in photosynthesis was caused by NSL factors. The photosynthesis for DH518 under T3 treatment changed from being limited by SL to NSL at the R2 stage while the photosynthesis for DH605 under T3 treatment was changed from being limited by SL to NSL at the R2–R3 stage. These results could be explained by the fact that there were differences in senescence of corn hybrids of different maturities at a later growth stage, ultimately leading to the differences in photosynthetic capacity [49]. In general, our data suggested that the photosynthesis of two corn hybrids was mainly limited by NSL factors caused by damage to photosynthetic organs during reproductive stage.

Water supply is one of the most important factors for regulating DMA [50]. GY depends on efficient photosynthesis and dry matter reserved in vegetative tissues during the vegetative stage [51]. Results obtained in this study demonstrated that water deficit during both vegetative and reproductive stages increased TAP and CRP, while severe water stress led to the least TAA, CRA and DMA, resulting in yield loss. (Figure 1 and Table 4). These results indicated that assimilation from photosynthesis after pollination could not meet the requirement of grain filling under drought condition and more dry matter reserved in vegetative organs would be remobilized to the grains during reproductive stage. We also found that increasing DMA was projected to achieve higher yields and CRA accounted for more than 70% in both growing seasons. Such results were consistent with previous research showing that the assimilation from photosynthesis at the reproductive stage was the main factor leading to higher yields [52]. In addition, we noticed that yields obtained with short-season hybrids were more dependent on the larger translocation existed in vegetative organs before flowering, because short-season hybrids were characterized by decreasing grain-filling period and senescing quickly [53], resulting in lower photosynthetic capacity at reproductive stage and procuring a lower amount of assimilation for grain development (Tables 4–9). There was also evidence that explained that the higher GY by DH605 over DH518 at the planting density used in this experiment (67500 plants/ha) was mainly due to the greater leaf photosynthetic capacity and DMA from the VT to R6 stages. Prior studies reported that hybrid maturity was a key factor that influenced the yield–density relationship in corn production [54]. The yield potentials of short-season hybrids were similar to those of full-season hybrids through effective agronomic managements and the plant density for maximum yield was greater for short-season hybrids rather than the full-season hybrids [55,56]. As such, whether similar GY or higher WP could be obtained through increasing density under optimum irrigation management for short-season hybrids should be further investigated.

5. Conclusions

In this study, irrigation levels and methods greatly affect corn yields, photosynthetic characteristics and biomass. Applying the optimum irrigation level (T3) improved leaf photosynthetic capacity, which had positive effects on increasing biomass and grain yield. The use of surface drip irrigation was suitable for achieving both a relatively high yield and water productivity. The yields and water consumption amounts obtained with the medium- and full-season hybrids were significantly higher than those obtained with the short-season hybrids, but it presented lower water productivity. The higher yield obtained by medium- and full-season hybrids over short-season hybrids was mainly due to the greater leaf photosynthetic capacity and dry matter accumulation throughout the growing seasons. Farmers in the North China Plain will benefit more from planting short-season hybrids with the development of high-quality mechanical grain harvesting. We recommended that SDIT3 (irrigating while the soil relative water content of the tested soil layer reduced to 75% ± 5% of the field capacity by surface drip irrigation) treatment could obtain higher grain yield and water productivity.

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