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A Trade-Off between the Growing Performance and Sowing Density of Sunflower (*Helianthus annuus* L.) under Fertigation in an Arid Saline Area

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Abstract: Sunflower is one of the pioneer crops cultivated in salt-affected arid areas. The influences of sowing density on the growth performance of this crop under fertigation conditions have not been well studied. This study arranged four sowing density treatments, 41,667, 35,714, 31,250, and 27,778 plants ha$^{-1,}$ marked as D30, D35, D40, and D45, respectively, to reveal the relationships between soil salinity, growth performance, and sowing density under drip fertigation conditions. The results showed that the electrical conductivity of saturated paste extracts (ECe) decreased during the growing seasons but increased on the topsoil during the non-growing seasons in all of the treatments. The sowing densities had remarkable influences on the ECe in the 0–40 cm soil layer (ECe-40). The average ECe-40 during the two seasons for treatments D30–D45 correspondingly decreased by 7.0%, 33.9%, 11.1%, and 15.8% when compared to the original value. The soil pH in the 0–40 cm soil layer during the two seasons for treatments D30–D45 correspondingly decreased by −0.03, 0.20, 0.20, and 0.27 when compared to the original value. Increasing the spacing in the rows could promote the stem diameter, plant biomass, and proportion of biomass allocated underground. The yield and related yield components in this experiment under fertigation were significantly higher than those under surface irrigation. A sowing density between 31,250 and 35,714 plants ha^{-1} could ensure both the high yield and high morphological quality of the seeds, which could be recommended for sunflower cultivation under drip fertigation conditions.

Keywords: sunflower; sowing density; fertigation; saline soil; yield components

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1. Introduction

Sunflower is an annual oilseed crop globally cultivated on 24.77 million hectares, and it has an 8% share in the world oilseed market [1]. This crop is a pioneer crop cultivated in salt-affected arid areas [2,3]. On most occasions, sunflower is cultivated under rainfed conditions, and surface irrigation is conducted before sowing in arid or semiarid areas [4]. The Hetao Irrigation District, located in northwest China, is a representative arid area that has approximately half of the irrigated land salt affected [5]. Thus, another surface irrigation event, aiming to leach salt, occurs after the sunflower harvest. More than 600 mm of applied water is needed for sunflower cultivation in this area [6]. However, water competition among different users, caused by water shortages, will predominantly change irrigated lands to rain-fed systems and ultimately increase salinization and decrease sunflower yield. Therefore, the efficient utilization of limited water resources is needed for agricultural production in these arid or semiarid regions.

Drip fertigation has the ability to apply small but frequent irrigation with soluble nutrients and chemicals, which has been found to be superior to the flood method in terms of the potential to save water, increase yield, improve quality, and enhance water and fertilizer use efficiency [7,8]. It has been reported that drip fertigation can improve crop yield by enhancing individual performance, water use efficiency, and seed quality and can support higher plant densities [7,9,10]. The optimal sowing density and yield of sunflower under drip fertigation will be quite different from those under conventional surface irrigation. Further studies on sunflower sowing density under fertigation conditions are needed to increase yields.

Regulating sowing density is an important practice to improve crop yield. Individual shoot biomass and yield decreased with density, while total biomass per area and yield increased with sowing density for grain crops, which was reported by several publications [11,12]. However, the total biomass in a given area was linearly proportional to the sowing density up to a critical density beyond which the total yield did not increase. Eventually, biomass allocation to reproduction may be reduced as well, causing a lower harvest index at very high sowing densities [11,13]. Sowing density also altered plant root distribution, biomass allocation, nutrient uptake, and cell morphology [14–16].

A wide range of sowing densities for the achievement of optimum yields in sunflower can be found in the literature [17,18]. The optimum sowing density for sunflower is influenced by several factors, such as temperature, soil fertility, water availability, and genotype [19,20]. The optimal sowing density to achieve high grain quality and high total yield under drip fertigation conditions remains unclear. Moreover, soil salinity is another important factor that affects agronomic practices. It was reported that an optimal sowing density could form full cover on the ground; on the one hand, it could inhibit weeds [21,22] and, on the other hand, it could reduce soil surface evaporation and prevent salt accumulation in the topsoil (0–20 cm) [3]. The evapotranspiration (ET) in the crop land was correlated with the sowing density, which influenced the soil water content, leaching fraction, and crop water productivity [23]. However, very little attention has been given to the interactions among planting density, soil salinity, yield, and yield components in the literature. Therefore, the objective of this research was to investigate the influence of sowing density on the soil salinity in saline soil and reveal the interactions among sowing density, soil salinity, yield, and yield components under drip fertigation conditions.

2. Materials and Methods

2.1. Experimental Site

Field experiments were conducted in a saline area (41°3′ N, 108°20′ E) from 2018 to 2019 in Wuyuan County, Inner Mongolia Autonomous Region, China. This area has a temperate continental arid climate with annual rainfall and potential evaporation of approximately 170 mm and 2500 mm, respectively. The EC of groundwater was greater than 7.8 dS m^{-1}, and its depth was generally less than 1.5 m. The physical and chemical properties of the tested soil are shown in Table 1. The 0–40 cm soil was silt loam, and the average electrical conductivity of saturated paste extracts (ECe) and the pH in 0–40 cm were 5.7 dS m^{-1} and 8.69, respectively, and the soil was classified as moderately alkaline saline soil [24].

Table 1. The initial physical and chemical properties of the experimental soil.

Soil Depth (cm)	mm for Soil Mechanical Composition (%)			Soil Texture	ECe (dS m^{-1})	pH	Bulk Density (g cm^{-3})
	<0.002	0.002–0.05	0.05–2				
0–10	7.76	73.16	19.07	Silt loam	6.7	8.61	1.51
10–20	7.79	73.03	19.17	Silt loam	5.5	8.68	1.61
20–30	7.84	73.34	18.82	Silt loam	5.2	8.68	1.46
30–40	7.67	73.21	19.12	Silt loam	5.3	8.77	1.54

2.2. Experimental Arrangement

The field experiment consisted of four sowing density treatments, of which the spacing between the sunflower plants in the same row was 30, 35, 40, and 45 cm represented as D30, D35, D40, and D45, respectively, and the distance between the rows was 80 cm for all of the treatments. Thus, the sowing densities corresponding to the above treatments were 41,667, 35,714, 31,250, and 27,778 plants ha^{-1}, respectively. The four treatments, each consisting of three replicated plots, were in a random block arrangement. Each plot had an area of 28 m $\times$ 8 m, and there was a one-meter-wide isolation belt between the two adjacent plots. The sunflower cultivar was hybrid sunflower SH363 in this experiment, and the seeds were sown on 28 May 2018 and on 10 June 2019.

Before the experiment, the soil was ploughed and levelled first. Then, the soil was ridged with drip tape buried under the plastic mulches by a multifunction machine (Figure 1A). The top width and height of a ridge were 0.4 m and 0.15 m, respectively, the same as in former studies [25,26]. The intervals between the adjacent ridges were 0.8 m, and the sunflower seeds were sown manually in a single row on the top of each ridge at an interval of the setting spacing according to each treatment. A tensiometer was buried at exactly 0.2 m under the drip emitter, which was nearest to a robust sunflower, in the second replicate plot to schedule drip irrigation (Figure 1A). Thus, there were four tensiometers in this experiment.

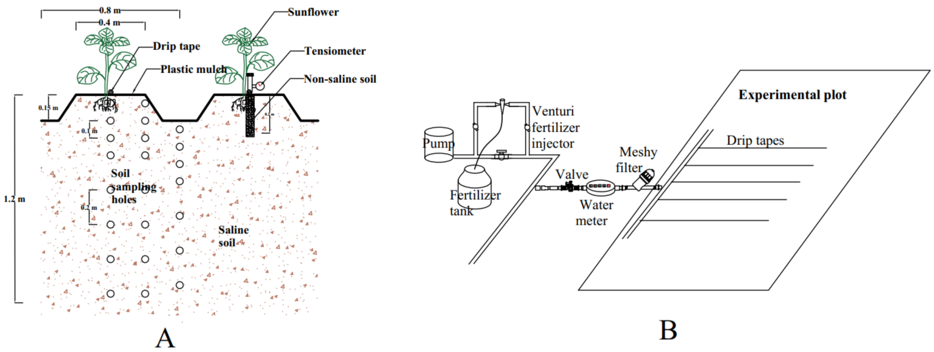

Figure 1. Schematic of the experimental design. (**A**) fertigation system in the experiment and (**B**) ridge planting pattern under drip irrigation.

2.3. Fertigation Scheduling

The irrigation water was pumped from a well with an EC of 1.3 dS m^{-1}. Based on previous studies, 30 mm water was immediately applied after sowing [26]. After the emergence of seedlings, irrigation was scheduled by a soil matric potential (SMP) monitored by tensiometers. The SMP thresholds were set at -10 kPa in the first year and -20 kPa in the second year for salt leaching [27,28]. When more than two of the four monitored SMP values fell below the set threshold, 7 mm water was applied in all of the treatments through a drip irrigation system (Figure 1B). The fertilizer amounts consisted of 180 kg ha^{-1} total N, 100 kg ha^{-1} total P, and 160 kg ha^{-1} total K, which were the same in all of the treatments according to the local conditions. These soluble fertilizers were applied through a venturi fertilizer injector during each irrigation event, according to daily usage [25,29].

2.4. Measurements

2.4.1. SMP

The SMP values monitored by tensiometers at a 0.2 m depth were recorded daily at 15:00 to initiate drip irrigation.

2.4.2. Soil Sampling and ECe

Soil cores were obtained from each plot in all of the treatments using an auger (4.0 cm diameter, 20 cm high) at the beginning and at the end of each growing season (May and September in 2018 and in 2019). Soil samples were obtained at lateral distances of 0, 20, and

40 cm from the emitters. The soil sampling locations and distribution in a profile are shown in Figure 1A. All of the soil samples were air-dried and sieved through a 2 mm sieve. Then, 25 g of sieved soil from each sample was mixed with about 20–25 mL of distilled water to make saturated soil paste according to the standard method [30,31]. To be noted, the amount of the distilled water for the different soil samples might be different as the soil texture affected the water amount that was used to make the saturated soil paste. After 8 h, the extract solution was obtained by centrifuging the saturated soil paste. The electrical conductivity of the saturated soil extracts (ECe) and the pH of the saturated soil extracts were determined by a conductivity meter (DDS-11A, Yulong, Shanghai, China) and a pH meter (pH-3C, Yulong, Shanghai, China), respectively.

2.4.3. Growth Performance

During the flowering stage in the 2018 growing season, whole sunflower bodies were collected to investigate growth performance. Three plants were collected randomly, with both aboveground bodies and whole roots taken into the laboratory, in each replicate plot. Then, the height, ground diameter, and area of each leaf were measured manually. The leaf area was measured based on 1 cm × 1 cm grid paper with coordinates, and the leaf area index (LAI) was calculated according to the measured leaf area and sowing density. The roots separated from the plants were placed into a net bag, soaked in water, and cleaned carefully until all the soil was washed away. Finally, the plant bodies and roots were dried at 65 °C in an oven to estimate the aboveground dry matter weight (AW) and the underground dry matter weight (UW) [32].

2.4.4. Yield and Its Components

Two quadrats (1.6 m × 4 m) in each plot of all of the treatments were selected randomly to estimate the sunflower yield. When the sunflower seeds were ripe, all the sunflower heads in the quadrats were collected manually. The diameter of each head was measured. Seeds were peeled from the heads and naturally wind-dried. The market yield (with immature seeds and impurities extracted), the thousand seed weight (TSW), and the seed setting percentage were measured based on the selected quadrats. Specifically, all of the seeds collected from a repeating plot were mixed in the 2018 season, and the seed length and width were determined based on 100 random seeds in each plot. The irrigation water productivity (IWP) was defined as the ratio of market yield and irrigation water amount [33].

2.5. Data analyses and Statistics

All data gathered in the research were recorded and classified in Microsoft Office Excel 2016. Analyses of variance (ANOVA) were carried out by SPSS 19.0 statistical software (IBM SPSS Inc., Armonk NY, USA). The significant differences in ECe, pH, growth performance, yield, and yield components between the treatments were compared by Tukey's test ($p < 0.05$). Figures were drawn by Surfer 14 (Golden Software Inc., Golden, CO, USA) and SigmaPlot 12.5 (Systat Software Inc., San Jose, CA, USA). The equations adopted in this study are as follows [33–35]:

$$\text{Soil matric potential (SMP, kPa)} = \Psi_{\text{tensiometer}} - \Psi_{\text{gravity}} \tag{1}$$

where $\Psi_{\text{tensiometer}}$ is the reading of a tensiometer dial and Ψ_{gravity} is the gravitational potential between a dial and porous ceramic cup.

$$\text{Leaf area index (LAI)} = A_{\text{leaves}} \times P \tag{2}$$

where A_{leaves} is the total leaf area of one plant and P is the sowing density of the sunflower.

$$\text{Irrigation water productivity (IWP, kg ha}^{-1}\text{ mm}^{-1}) = \frac{Y}{W} \tag{3}$$

where Y is the grain yield of the sunflower and W is the total quantity of water irrigated in the sunflower life circle.

3. Results

3.1. Rainfall, Irrigation, and Soil Matric Potentials

The rainfall amount in the 2018 growing season was 180 mm, which was almost twice that in the 2019 growing season (Table 2). The average annual rainfall in this area was 170 mm, indicating that the climate in 2018 was wetter, while it was drier in 2019 when compared with normal years. Rainfall influenced the amount of applied irrigation water. Basically, the applied irrigation water amount increased as the SMP threshold increased [36]. However, the applied irrigation water amount in 2018, scheduled at −10 kPa, was less than that in 2019, which was scheduled at −20 kPa. More rainfall in 2018 resulted in less applied irrigation water.

Table 2. Amounts of rainfall and irrigation in the 2018 and 2019 growing seasons.

Growing Season	Rainfall (mm)	Applied Irrigation Water Amount (mm)	Total Water Amount (mm)
2018	180	287	467
2019	69	322	491

Interestingly, the total water amounts in these two seasons were between 450 and 500 mm. Daily SMP dynamics (Figure 2) showed that the SMPs in the two seasons all fluctuated around their thresholds, −10 and −20 kPa, respectively, and the vibration amplitude in 2019 was larger than that in the 2018 season, indicating that the SMPs in these two seasons were well controlled through SMP threshold scheduling as anticipated.

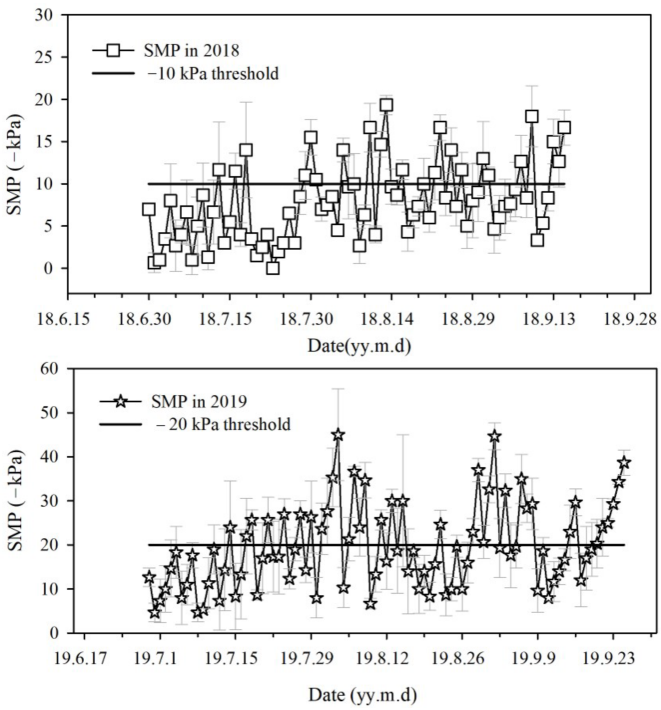

Figure 2. Daily soil matric potential (SMP) dynamics in the 2018 and 2019 growing seasons.

3.2. ECe and pH

The original soil ECe distributions before this experiment showed that the soil salinity decreased with the soil depth (Figure 3A1), and the average ECe within the whole depth indicated that the soil was moderately alkaline saline soil [24]. At the end of the first growing season (Figure 3B1 and Table 3), the ECe in the whole soil profile had firm decreases, and the average ECe showed that the soil changed to mildly alkaline saline soil (Table 3). Significant differences were found between the different treatments for the ECe in the 0–40 cm soil layer (ECe-40) and the ECe in the 0–120 cm soil layer (ECe-120). The D30 treatment had the largest ECe-40 and ECe-120, while the D45 treatment had the lowest ECe-40 and ECe-120.

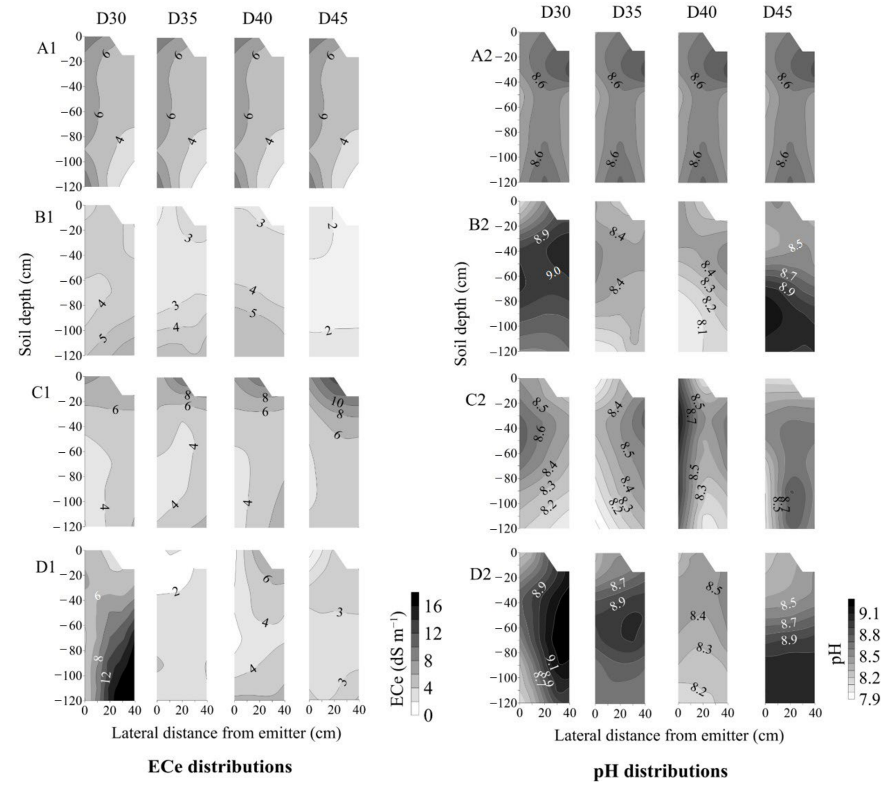

Figure 3. Spatial and temporal distributions of the electrical conductivity of the saturated soil extracts (ECe) and the pH of the saturated soil extracts (pH) in the different treatments. (**A1**,**A2**) May in 2018; (**B1**,**B2**) September in 2018; (**C1**,**C2**) May in 2019; (**D1**,**D2**) September in 2019. **D30**, **D35**, **D40**, and **D45** indicated treatments with sowing densities of 41,667, 35,714, 31,250, and 27,778 plants ha^{-1}, respectively.

Table 3. The average ECe in the 0–40 cm and 0–120 cm soil layers during the different sampling periods.

Treatments	0–40 cm ECe (dS m^{-1})				0–120 cm ECe (dS m^{-1})			
	May. 2018	Sep. 2018	Apr. 2019	Sep. 2019	May. 2018	Sep. 2018	Apr. 2019	Sep. 2019
D30	5.7 ^{Aab}	4.3 ^{Ab}	6.6 ^{Aa}	5.0 ^{Aab}	5.2 ^{Aa}	4.4 ^{Aa}	4.9 ^{Aa}	8.8 ^{Aa}
D35	5.7 ^{Aa}	2.9 ^{Bb}	6.5 ^{Aa}	1.9 ^{Bb}	5.2 ^{Aa}	3.2 ^{Bb}	5.0 ^{Aa}	2.9 ^{Bb}
D40	5.7 ^{Aa}	3.3 ^{Bb}	7.0 ^{Aa}	4.9 ^{Aab}	5.2 ^{Aa}	4.1 ^{Aa}	5.4 ^{Aa}	4.3 ^{Ba}
D45	5.7 ^{Ab}	2.0 ^{Cc}	9.1 ^{Aa}	3.3 ^{ABc}	5.2 ^{Aa}	1.8 ^{Cb}	6.3 ^{Aa}	2.9 ^{Bb}

Note: Different lowercase letters following the data in the same row in the same soil layer indicate significant differences at $p < 0.05$ among the different sampling periods; different capital letters following the data in the same column indicate significant differences at $p < 0.05$ among different treatments according to Tukey's test.

After one non-growing season (Figure 3C1), salt accumulated in the topsoil. The ECe-40 even became larger than the original value in all of the treatments, and the ECe-120 also increased to its original level. The ECe in the soil profiles in the D35, D40, and D45 treatments all decreased, while that in the D30 treatment increased when the second growing season terminated.

Overall, the average ECe-40 values during the two seasons for treatments D30–D45 were 5.3, 3.8, 5.1, and 4.8 dS m^{-1}, which were correspondingly decreased by 7.0%, 33.9%, 11.1%, and 15.8% when compared with the original value. The average ECe-120 values for treatments D30–D45 were 6.0, 3.7, 4.6, and 3.7 dS m^{-1}, with corresponding decreasing ratios of −16.0%, 28.8%, 11.5%, and 29.5%, respectively. In terms of spatial and temporal changes, the D35, D40, and D45 treatments had more advantages in controlling soil salinity than the D30 treatments.

The pH dynamics varied from the ECe. During the first growing season, the pH values in the 0–40 cm soil layer (pH-40) and in the 0–120 cm soil layer (pH-120) in the D35 and D40 treatments decreased firmly, but they increased in D30 and D45 (Figure 3B, right and Table 4). In contrast to the ECe dynamics, the pH decreased or remained stable instead of increasing after one non-growing season (Figure 3C2). At the end of the second growing season, noticeable pH increments occurred in the D35 and D45 treatments along with the salt leaching process (Figure 3D2). Overall, the average pH-40 during the two seasons for treatments D30–D45 correspondingly decreased by −0.03, 0.20, 0.20, and 0.27 when compared to the original value. The average pH-120 for treatments D30–D45 correspondingly decreased by −0.17, 0.05, 0.16, and −0.11.

Table 4. The average pH in the 0–40 cm and 0–120 cm soil layers during the different sampling periods.

Treatments	0–40 cm pH				0–120 cm pH			
	May. 2018	Sep. 2018	Apr. 2019	Sep. 2019	May. 2018	Sep. 2018	Apr. 2019	Sep. 2019
D30	8.69 Aab	8.79 Aab	8.48 Ab	8.88 Aa	8.55 Abc	8.84 Aab	8.41 Ac	8.90 Aa
D35	8.69 Aa	8.39 Bb	8.43 Ab	8.65 Ba	8.55 Ab	8.36 Cc	8.36 Ac	8.78 Aa
D40	8.69 Aa	8.38 Bb	8.62 Aa	8.47 BCa	8.55 Aa	8.27 Db	8.53 Aa	8.37 Ba
D45	8.69 Aa	8.43 Bb	8.44 Ab	8.39 Cb	8.55 Aab	8.74 Ba	8.51 Ab	8.74 Aa

Note: Different lowercase letters following the data in the same row in the same soil layer indicate significant differences at $p < 0.05$ among the different sampling periods; different capital letters following the data in the same column indicate significant differences at $p < 0.05$ among the different treatments.

3.3. Growth Performance

The sunflower growing parameters during the flowering stage in the 2018 season are shown in Table 5. The plant height (H) first increased and then decreased with increasing spacing in the rows, but non-significant differences were found between the treatments. The ground diameter (GD) increased as the spacing in rows increased, and those in the D35–D45 treatments were remarkably larger than those in the D30 treatment. The H/GD ratio decreased as the spacing in the rows increased, and the ratios in the D35–D45 treatments were significantly lower than those in the D30 treatment. The LAI values in the D30 and D35 treatments were statistically larger than those in the D40 treatment but not significantly different from those in the D45 treatment. The aboveground dry matter weight (AW) and underground dry matter weight (UW) for an individual plant both increased as the spacing in the rows increased, and the UW/AW ratio exhibited the same trend.

Table 5. The main growing parameters during the flowering stage among treatments in the 2018 growing season. H, GD, LAI, AW, and UW are abbreviations for height, ground diameter, leaf area index, aboveground dry matter weight, and underground dry matter weight for an individual plant, respectively.

Treatments	H (cm)	GD (mm)	H/GD	LAI	AW (g)	UW (g)	UW/AW
D30	177.3 a	26.4 b	67.5 a	2.8 a	170.8 c	49.4 b	0.29 b
D35	180.0 a	33.7 a	54.3 b	2.6 a	264.7 b	83.8 b	0.32 ab
D40	182.0 a	33.5 a	54.4 b	2.1 b	269.6 b	85.2 b	0.32 ab
D45	177.3 a	35.6 a	49.9 b	2.4 ab	324.8 a	135.5 a	0.41 a

Note: Different lowercase letters following the data in the same column indicate significant differences at $p < 0.05$ among the different treatments.

The dry biomass parameters in the D45 treatment were significantly larger than those in the rest of the treatments, and the D30 treatment achieved the lowest dry biomass among all of the treatments. The comprehensive growing parameters indicated that increasing the space in the rows could increase the plant ground diameter and the whole plant biomass, especially promoting root growth, which might enhance the ability of plants to absorb water and nutrients and their ability to resist lodging.

3.4. Yield and Its Components

The sunflower market yields in the two seasons both increased first and then decreased as the spacing in the rows increased (Figure 4). The trend curves suggested that the yields in all of the treatments in the 2019 season were higher than those in the 2018 season, and the yields ascended to their peaks, larger than 4000 kg ha^{-1}, when the spacing in the rows was between 35 and 40 cm. The statistical analysis showed that the yield in the D40 treatment in 2019 was higher than those in the D30 and D45 treatments in 2018 and those in the D30 treatment in 2019 and the yield did not vary from the rest of the treatments (Table 6). Notably, the average yields in the two seasons of the D30–D45 treatments firmly increased by 18.0%, 28.9%, 29.7%, and 18.0%, respectively, when compared with the 5-year average yield under surface irrigation.

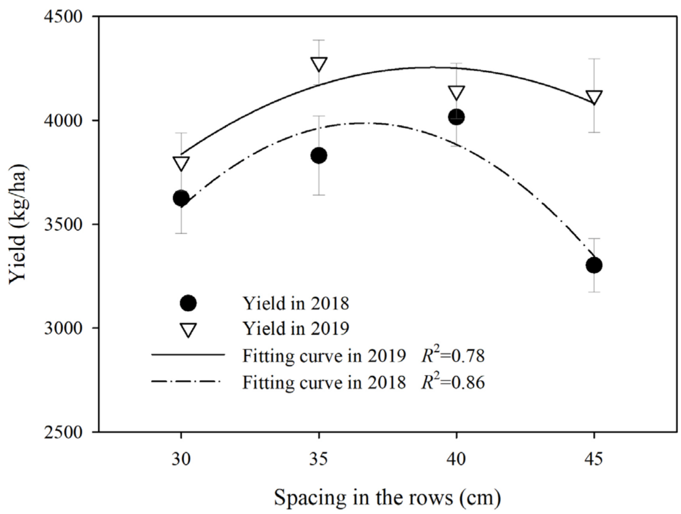

Figure 4. Sunflower yields in the two growing seasons under different treatments (different spacing in the rows). (Error bars indicate the standard deviation).

The irrigation water productivity (IWP) in the D40 treatment in 2018 was 14.0 kg ha^{-1} mm^{-1}, which was the largest and significantly larger than those in the D45 treatment in 2018 and the D30 treatment in 2019, with corresponding IWPs of 11.5 and 11.8 kg ha^{-1} mm^{-1}, respectively. The IWP in each treatment was more than twice that under surface irrigation.

The head diameter and the thousand seed weight (TSW) in the D40 treatment in both of the seasons were the highest, while the lowest values in the D30 treatment were even higher than those under surface irrigation. The setting percentages of seeds in all of the treatments remained comparable with each other, except that in the D30 treatment in the 2018 season the percentage was significantly lower than that in the rest of the treatments. The seed length and width indicated that the seed sizes in the D40 and D45 treatments were apparently larger than those in the D30 and D35 treatments. Overall, it was easy to conclude that the spacing in the rows between 35–40 cm could ensure both the high yield and the high morphological quality of the seeds.

Table 6. Sunflower yield and its components in different treatments in the two growing seasons. IWP and TSW are abbreviations for irrigation water productivity and thousand seed weight, respectively.

Growing Seasons	Treatments	Yield and Its Components						
		Market Yield (kg ha^{-1})	IWP (kg ha^{-1} mm^{-1})	Head Diameter (cm)	TSW (g)	Setting Percentage (%)	* Seed Length (mm)	* Seed Width (mm)
2018	D30	3626.1 ^{cd}	12.6 ^{abc}	19.7 ^{c}	212.3 ^{d}	61.9 ^{c}	22.0 ^{b}	9.2 ^{b}
	D35	3830.9 ^{abc}	13.3 ^{ab}	20.8 ^{bc}	210.5 ^{d}	74.6 ^{ab}	22.6 ^{b}	9.3 ^{b}
	D40	4015.8 ^{abc}	14.0 ^{a}	23.4 ^{a}	237.4 ^{c}	76.2 ^{ab}	23.4 ^{a}	9.9 ^{a}
	D45	3302.5 ^{de}	11.5 ^{c}	21.8 ^{b}	211.5 ^{d}	74.2 ^{b}	23.4 ^{a}	10.2 ^{a}
2019	D30	3800.4 ^{bc}	11.8 ^{bc}	19.9 ^{c}	209.9 ^{d}	76.5 ^{ab}	—	—
	D35	4279.0 ^{a}	13.3 ^{ab}	23.6 ^{a}	243.0 ^{bc}	80.8 ^{a}	—	—
	D40	4141.7 ^{ab}	12.9 ^{abc}	24.6 ^{a}	260.2 ^{ab}	75.7 ^{ab}	—	—
	D45	4118.8 ^{ab}	12.8 ^{abc}	25.0 ^{a}	270.9 ^{a}	78.3 ^{ab}	—	—
† 2016–2020	Surface irrigation	3145.7 ^{e}	5.1 ^{d}	20.6 ^{bc}	165.1 ^{e}	—	—	—

Note: Different lowercase letters following the data in the same column indicate significant differences among the treatments at $p < 0.05$; * the seed length and seed width were not recorded in the 2019 season; † the data of traditional surface irrigation during 2016–2020 were collected from the available publications [5,6,37–40].

4. Discussion

4.1. Influence of Sowing Density on Soil Salinity

This study found that sowing density had a significant influence on soil salinity, which was in accordance with several available publications. Li et al. [41] found that different sowing densities led to differences in soil evaporation and crop transpiration, which caused differences in soil salt accumulation. The crop leaf area index (LAI) increased as the sowing density increased [41,42], and the leaf area duration increased as the sowing density increased. However, high sowing density changed the canopy structure (leaf area distribution) and increased water consumption [13,43]. Our results were consistent with these findings. The sunflower LAI under the D30 treatment (the highest sowing density) was the largest, which might encourage the water consumed by sunflower leaves (known as transpiration) and finally increase the sum of transpiration and soil surface evaporation (known as evapotranspiration, ET) [41]. Since all of the treatments received the same amounts of rainfall and irrigation water, the water for salt leaching decreased as the ET increased. This explained the remarkable salt accumulation phenomenon in the D30 treatment in the 2019 season. However, the salt accumulation phenomenon in the D30 treatment in the 2018 season was not apparent. The SMP threshold for scheduled fertigation in the 2018 season (−10 kPa) was higher than that in the 2019 season (−20 kPa), which changed the vertical water potential gradient. It was calculated that the salt leaching fraction under the condition that irrigation was scheduled by an SMP threshold of −10 kPa was 240% higher than that under −20 kPa [36]. Thus, the soil salinity in the D30 treatment increased when the SMP threshold decreased from −10 kPa in the 2018 season to −20 kPa in the 2019 season. The sowing density had remarkable influences on soil salinity dynamics, the mechanism of which was likely conducted by regulating crop LAI and ET.

4.2. Interactions between Sowing Density and Growth Performance under Fertigation

Individual crop shoot biomass and yield decreased with density, while total biomass per area and yield were linearly proportional to sowing density up to a critical density beyond which the harvest index did not increase [11,12]. High sowing density had a negative influence on individual crop performance when the sowing density was larger than the sowing density threshold. It was reported that poor individual morphological features, such as fewer productive tillers, shorter plants, thinner stalks, reduced hundred-grain weight, and fewer seeds per ear for grain crops would be achieved under a high sowing density [44–47]. A significant decrease in the leaf dry mass, leaf total chlorophyll content, and leaf nitrogen content per leaf area occurred with increasing planting density in each growth stage of maize [16]. In comparison, the total growing performances for the population, such as the LAI, total ear, and biomass, had far greater increasing potentials with increasing planting density [44,48], which meant that a larger sowing density was needed to achieve its peak. The total growth performance for the population was far more sensitive to increasing planting density than individual performance. This was because plants could adjust their growth to their environment through means ranging from whole-plant morphological changes to alterations in the stoichiometry of the photosynthetic apparatus [45]. Nevertheless, these advantages of population growth performance did not translate into yield advantages. Competition for water, nutrients, light, and expanding space altered the plant nutrient allocation, which encouraged more energy to flow to the vegetative organs rather than the reproductive organs [49,50]. Thus, the optimal sowing density for peak yield was normally between the sowing density for the best individual performance and the sowing density for the best population performance. However, peak yield did not achieve the highest economic benefits for crops such as sunflower because seed quality (seed size and hundred-seed weight) had remarkable influences on market price. Thus, a trade-off between seed quality and total yield should be made to determine the optimum sowing density.

The limitations of crop competition for resources under high-density cultivation may be overcome through efficient fertigation practices [51]. Li et al. [41] conducted a five-sowing density experiment for sunflower cultivation under drip fertigation conditions and found that the individual performances decreased less with increasing density, but population performance and yield increased with increasing density. The density corresponding to peak yield and the best population growing performances reached 55,556 plants ha^{-1}, which was much higher than the population density under surface irrigation in this area (normally less than 30,000 plants ha^{-1}), indicating that fertigation could increase yield by supporting more crop density. This result was consistent with our study and together revealed the interactions among sowing density, individual crop performance, total population performance, and yield under drip fertigation conditions.

5. Conclusions

Sowing density had a significant influence on soil salinity, and high-density planting caused salt accumulation in the vertical soil profile during the growing season. The individual growth performance and yield components of sunflower, such as stem diameter, plant biomass, head diameter, thousand-seed weight, and the proportion of biomass allocated underground, decreased remarkably as the sowing density increased. However, the total population growth performance and yield increased with increasing sowing density before a critical density threshold, beyond which the total yield did not increase. The height yield was a dynamic optimal solution that was determined by the sowing density, individual crop performance, total population performance, and irrigation practice. A sowing density between 31,250 and 35,714 plants ha^{-1} is recommended for sunflower cultivation under drip fertigation in arid saline areas with similar conditions.

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