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Effects of Alternating Fresh and Saline Water Irrigation on Soil Salinity and Chlorophyll Fluorescence of Summer Maize

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Abstract: Saline groundwater irrigation is an important way to alleviate the shortage of fresh water resources. In order to find a reasonable saline irrigation method for farmland, an irrigation experiment was conducted with fresh water and saline water at the seedling, jointing, heading, and filling stages. The soil salinity, growth, chlorophyll fluorescence, and yield of summer maize were measured. The results showed that alternating fresh and saline water irrigation led to a smaller increase in soil salinity relative to that irrigation with saline water alone. In addition, different sequences of alternating irrigation also significantly affected the accumulation of soil salinity. The maximum quantum yield, effective quantum yield of photochemical energy conversion, photochemical quenching, and non-photochemical quenching varied greatly at the jointing stage and heading stage. Furthermore, the yield of maize that was irrigated with fresh water at the heading stage (8.53 t ha^{-1}) was greater than that at the jointing (7.69 t ha^{-1}) and filling stages (7.45 t ha^{-1}). Therefore, these findings indicate that in areas where fresh water is scarce, priority should be given to the application of fresh water at the heading stages for summer maize irrigation.

Keywords: alternating irrigation; soil salinity; maize yield; saline water; chlorophyll fluorescence

1. Introduction

With the growth of the world population and the rapid development of the social economy, the demand for water resources is increasing day by day [1,2]. Groundwater has been widely used for many countries to resolve water shortage [3,4], for example, groundwater is an important source of freshwater for agricultural in some arid or semi-arid areas [5,6]. However, excessive exploitation of groundwater causes the groundwater level to decline [7], which leads to the intrusion of seawater into the terrestrial fresh groundwater and causes the problem of groundwater salinization [8,9]. Although some studies have found that saline groundwater irrigation can increase soil moisture and provide water needed for crop growth [10,11], it also brings problems such as increased soil salinity [12], compaction of soil [13], decreased soil fertility [14], and reduction in crop yield [15]. In order to reduce the problems caused by saline water irrigation, some researchers have carried out experimental research on mixed irrigation of saline and fresh water. They found that mixed irrigation with saline and fresh water significantly improved the irrigation water quality, reduced the impact of irrigation water quality on soil salinization [16], and increased crop yield compared with irrigation with saline water [17]. However, the salt sensitivity of crops at different growth stages was not considered in the mixed irrigation with saline and fresh water.

Abdel et al. (2005) reported that the use of fresh water during the sensitive stages of plant growth and saline water during the non-sensitive stages could increase the irrigation utilization rate of saline water [18]. Under the same irrigation system and management method, Malash et al. (2005) found that the total tomato yield irrigated with a ratio of 80% fresh water and 20% saline water was not significantly different from irrigated fresh water alone [19]. Minhas (1996) reported that the yields of mustard and wheat under alternating irrigation were higher than those under mixed irrigation at the same level of salt [20]. Still, evidences of the benefit of alternating saline and freshwater irrigation are limited and no guideline of the alternating use has been presented. Consequently, it is necessary to research on alternating irrigation with fresh and saline water.

Maize, the third important crop in the world [21], is classified as a moderately salt sensitive crop [22] and it is important to promote the utilization efficiency of saline water and maintain maize production. To date, many studies of saline water irrigated maize have mainly focused on the effects of saline water irrigation or saline and fresh water mixed irrigation on parameters such as soil salt transport [23,24], the maize growth index [25–27], and yield [28,29]. For example, the experimental designs by Huang et al. (2019) and Zhu et al. (2017) about alternating fresh and saline water irrigation for maize [30,31] mainly focused on once irrigation with saline water in the three periods of seedling, jointing and tasseling, and after tasseling. While maize is most sensitive to irrigation water quality at seedling stage [32], during which irrigation with saline water will significantly reduce the emergence rate of maize [33], and the lower emergence rate is not conducive to the study of saline water irrigation on the growth of maize in later stage. Moreover, the strategy of once irrigation with saline water in the whole growth period is obviously unfavorable for areas where saline groundwater is the main source of irrigation. Meanwhile, compared with saline water irrigation or saline and fresh water mixed irrigation, few studies focused on the effects of alternating fresh and saline water irrigation on the soil salinity and growth of maize, especially on soil salinity and fluorescence parameters of maize under alternating fresh and saline water irrigation. Salt stress affects the normal growth of plants and reduces yield by disrupting physiological processes, especially photosynthesis [34]. Furthermore, chlorophyll fluorescence reflects the efficiency of photochemical reactions in the plant [35], which has a direct effect on the absorption, transmission, and conversion of light energy in plant photosynthesis.

Thus, the effects of alternating fresh and saline water irrigation on soil salinity and fluorescence parameters of maize needs warrant study. The purposes of this study were (1) to investigate the soil salt distribution under alternating fresh and saline water furrow irrigation; (2) to investigate the effects of alternating irrigation with fresh and saline water on the growth index, fluorescence characteristics, and water use efficiency of maize; (3) to provide a theoretical basis and technical reference for alternating irrigation; and (4) to increase the saline water utilization ratio and reduce the consumption of freshwater resources.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted in a greenhouse under natural light conditions at the Nanpi Eco-Agricultural Experimental Station (38°00′ N, 116°40′ E) in Hebei Province, China (Figure 1). The annual average temperature of the study location is 12.3 °C and the mean annual total sunshine duration is 2318 h. The area has a typical semi-humid warm-temperate continental monsoon climate with an annual precipitation of 480 mm and a mean annual free surface evaporation is of 1900–2200 mm.

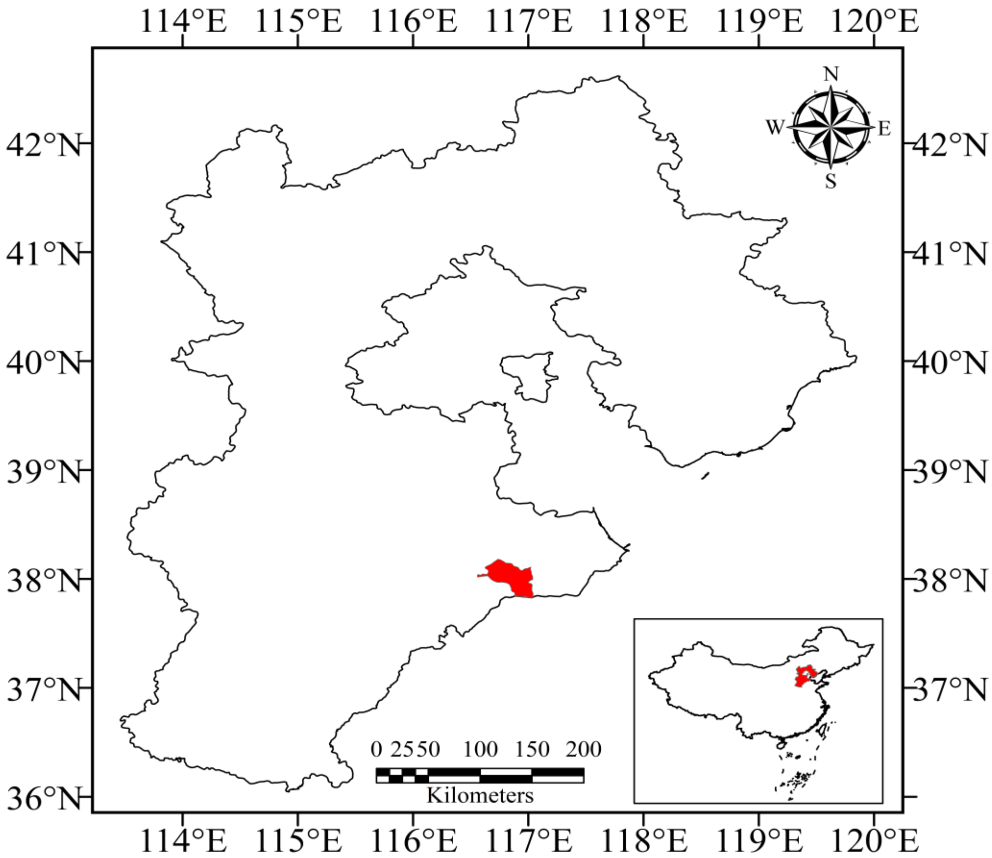


Figure 1. Location of the experiment site.

The groundwater level varies from 5 to 7 m below the soil surface, and the overlying shallow aquifer is saline water bearing. The climate and unique geographical conditions of this region make it susceptible to salt accumulation on the soil surface. The soil texture was silt loam soil (Table 1), which had a pH of 8.91, a depth of 0–20 cm, and contents of organic matter of 16.75 g kg^{-1}, available nitrogen (N) of 83.98 mg kg^{-1}, available phosphorus (P) of 16.97 mg kg^{-1}, and available potassium (K) of 104.98 mg kg^{-1}.

Table 1. Basic physical properties of initial soil profile.

Soil Layers (cm)	Soil Mechanical Composition (%)			Soil Texture	Soil Bulk Density (g cm^{-3})	Field Capacity (cm^3 cm^{-3})
	Clay (<0.002 mm)	Silt (0.002–0.02 mm)	Sand (0.02–2 mm)			
0–10	7.60	58.30	34.09	Silt loam	1.33	32.57
10–20	9.01	62.26	28.73	Silt loam	1.47	34.41
20–40	10.61	66.07	23.31	Silt loam	1.53	36.21
40–60	12.82	67.25	19.94	Silt loam	1.56	37.68
60–80	15.30	68.06	16.65	Silt loam	1.58	36.45
80–100	16.56	66.01	17.43	Silt loam	1.53	35.13

Note: Soil bulk density and field capacity were measured using the gravimetric method. Soil mechanical composition were detected by LS13320 laser diffraction particle size analyzer (LS13320, Beckman Coulter, Inc. Brea, CA, USA).

2.2. Experimental Design

An alternative furrow irrigation system was used to deliver fresh and saline water to summer maize. The salt content of the fresh water and saline water was 0.1–0.3 g L^{-1} and 4.0–4.4 g L^{-1}, respectively. Irrigation was performed four times per treatment, once at each of the seeding, jointing, heading, and filling stages, with 50 mm irrigation provided at each stage. Fresh water was used for irrigation in all treatments at the seedling stage. Five irrigation treatments were established (with fresh water and/or saline water) at three plant growth stages (jointing, heading, and filling) (Table 2): (i) FFF, in which maize was irrigated with fresh water at jointing, heading and filling stage (ii) SFS, in which maize was irrigated with fresh water at heading stage and irrigated with saline water at jointing and filling stage, (iii) FSS, in which maize was irrigated with fresh water at jointing stage and irrigated with saline water at heading and filling stage, (iv) SSF, in which maize was irrigated with fresh water at filling stage and irrigated with saline water at jointing and heading stage, (v) SSS, in which maize was irrigated with saline water at jointing, heading and filling stage.. A randomized complete block design was used, and three replicates were established in fifteen plots. The size of each plot was 3 × 2.2 m. Each plot consisted of 3 rows of summer maize planted on 3 raised ridges (Figure 2a). The ridge and furrow for ridge tillage were 20 cm wide (20 cm high) and 40 cm wide (20 cm high) (Figure 2b), respectively. At the end of the plot, the furrows were closed to intercept water. To accurately determine the effects of alternating furrow irrigation with fresh and saline water on soil salinity and chlorophyll fluorescence parameters, a transparent plastic rain shelter was used when there was precipitation during the growing season of summer maize.

Table 2. Irrigation treatments due to different crop growth stages.

Treatments	Jointing Stage	Heading Stage	Filling Stage
FFF	Freshwater	Freshwater	Freshwater
SFS	Saline water	Freshwater	Saline water
FSS	Freshwater	Saline water	Saline water
SSF	Saline water	Saline water	Freshwater
SSS	Saline water	Saline water	Saline water

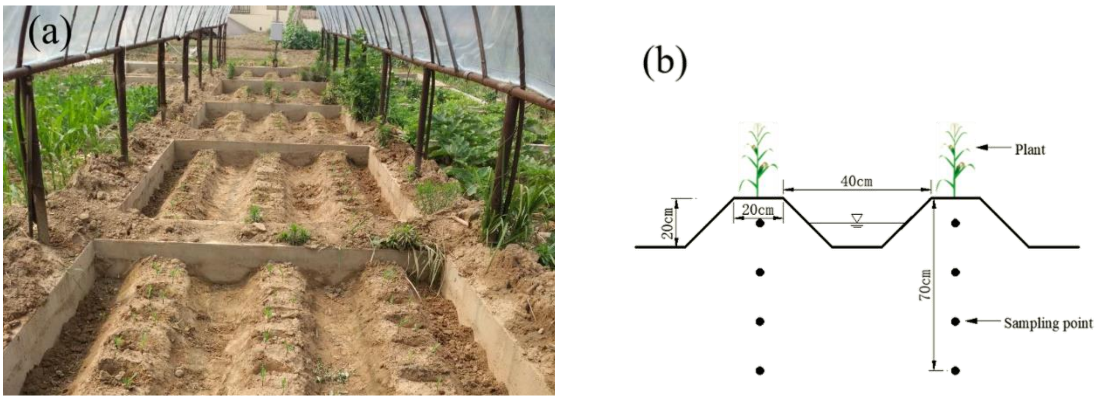


Figure 2. (**a**) Dimensions of ridge-furrow and the position of soil samples, and (**b**) view of experimental plot.

Standard amounts of fertilizer were applied, with the same amounts applied across the treatments. A basal dose of 600 kg ha^{-1} of a compound fertilizer (N: P_2O_5: K_2O = 15%: 15%: 15%) was applied uniformly to the plots when the beds were raised, and urea was applied at a rate of 240 kg ha^{-1} with the second irrigation in all treatments at the jointing stage. The maize cultivar was Zheng-dan 958. The maize was seeded with 60 × 30 cm hill spacing on 23 June and harvested on 3 October, 2017.

2.3. Data Collection and Analysis

2.3.1. Soil Samples

During the growth period of summer maize, soil samples were collected at depths of 0–20, 20–40, 40–60, and 60–80 cm using a soil auger before and after irrigation and at harvest (Figure 2b). The determinization of each soil sample includes two indexes: water content and electrical conductivity. Water content was measured by the gravimetric method. Electrical conductivity was measured by the conductivity meter method, the prepared soil samples were dissolved at soil-to-water ratio of 1:5, and the electrical conductivity $EC_{1:5}$ of soil leachates were measured by DDS-307A conductivity meter (Shanghai Precision and Scientific Instrument Co., Ltd., Shanghai, China).

2.3.2. Plant Height and Leaf Area

Plant height was measured by the vertical line method, the height from the highest point of the plant to the soil surface [36]. Leaf area was measured by length × width method, measured the leaf length and leaf width of the second unfolded leave with a ruler, and calculated with the length × width × coefficient [37].

2.3.3. Chlorophyll Fluorescence Parameters

Fluorescence indices were measured with an OS5P Chlorophyll Fluorometer (Opti-Sciences, Hudson, NH, USA). Chlorophyll fluorescence parameters were calculated as follows [38]:

Maximal quantum yield of *PSII* (F_v/F_m):

$$\frac{F_v}{F_m} = \frac{F_m - F_0}{F_m}. \tag{1}$$

Effective quantum yield of photochemical energy conversion in *PSII* (*PHI PSII*):

$$\Phi PSII = \frac{F_m{}' - F_s}{F_m{}'}. \tag{2}$$

Photochemical quenching (qP):

$$qP = \frac{F_m{}' - F_s}{F_m{}' - F_0{}'}. \tag{3}$$

Non-photochemical quenching (NPQ):

$$NPQ = \frac{F_m - F_m{}'}{F_m{}'}, \tag{4}$$

where F_0 is minimal fluorescence; F_m is maximal fluorescence; F_s is steady-state chlorophyll fluorescence; $F_0{}'$ is the minimal fluorescence of light adapted *PSII*; and $F_m{}'$ is the maximum fluorescence of adapted *PSII*.

2.3.4. Water Use Efficiency and Irrigation Water Use Efficiency

Evapotranspiration (ET) was calculated using the soil water balance equation for the growing season as follows:

$$ET = P + I - \Delta W + G - R - D, \tag{5}$$

$$\Delta W = 10\gamma H(W_1 - W_0), \tag{6}$$

where ET are evaporation and transpiration, mm; P is precipitation, mm; I is irrigation, mm; ΔW is the change of soil water storage in the measured soil depth, mm; G is recharge of groundwater to summer maize roots, mm, when the groundwater table is lower than 4 m below the ground surface, G is negligible [39]; R is surface runoff, mm, there was no surface runoff during the test, $R = 0$; D is deep percolation, irrigated 50 mm each stage, D is negligible. H is calculation depth of soil layer, cm; γ is soil bulk density, g cm^{-3}.

Water use efficiency (WUE) is calculated as:

$$WUE = \frac{Y}{ET}. \tag{7}$$

Irrigation water use efficiency ($IWUE$) is expressed as:

$$IWUE = \frac{Y}{I}, \tag{8}$$

where Y is maize yield, kg m^{-2}.

2.4. Statistical Analysis

All data were subjected to least significant difference (LSD) tests with SPSS software version 20.0 (IBM, Armonk, New York, NY, USA). Significance was evaluated at $p \leq 0.05$. Figures were produced using Origin 2018 (OriginLab, Northampton, MA, USA).

3. Results

3.1. Dynamics of Soil Salinity ($EC_{1:5}$)

The dynamics of soil salinity at the different depths of the root zone in the five treatments are shown in Figure 3. Before sowing and after harvesting, the salt contents in all areas were mainly surface-accumulated, and the $EC_{1:5}$ values in the 0–20 cm layer were much higher than those in other soil layers. The irrigation water treatment had a significant influence on $EC_{1:5}$ in the different layers. In the 0–80 cm soil layer, the average $EC_{1:5}$ values were increased by 292.2, 383.6, 158.6, and 599.2 µs cm^{-1} under the SFS, FSS, SSF, and SSS treatments, respectively, and decreased by 115.6 µs cm^{-1} in the FFF treatment. Our data indicate that the increases in $EC_{1:5}$ in the root zone following alternating fresh and saline water furrow irrigation (SFS, FSS, and SSF) were between those under fresh water irrigation (FFF) and saline water irrigation (SSS), and the application of alternating irrigation with fresh and saline water increased salt accumulation under water-stress conditions, whereas, the increase of salt content caused by SSF and SFS was significantly lower than that of FSS treatment.

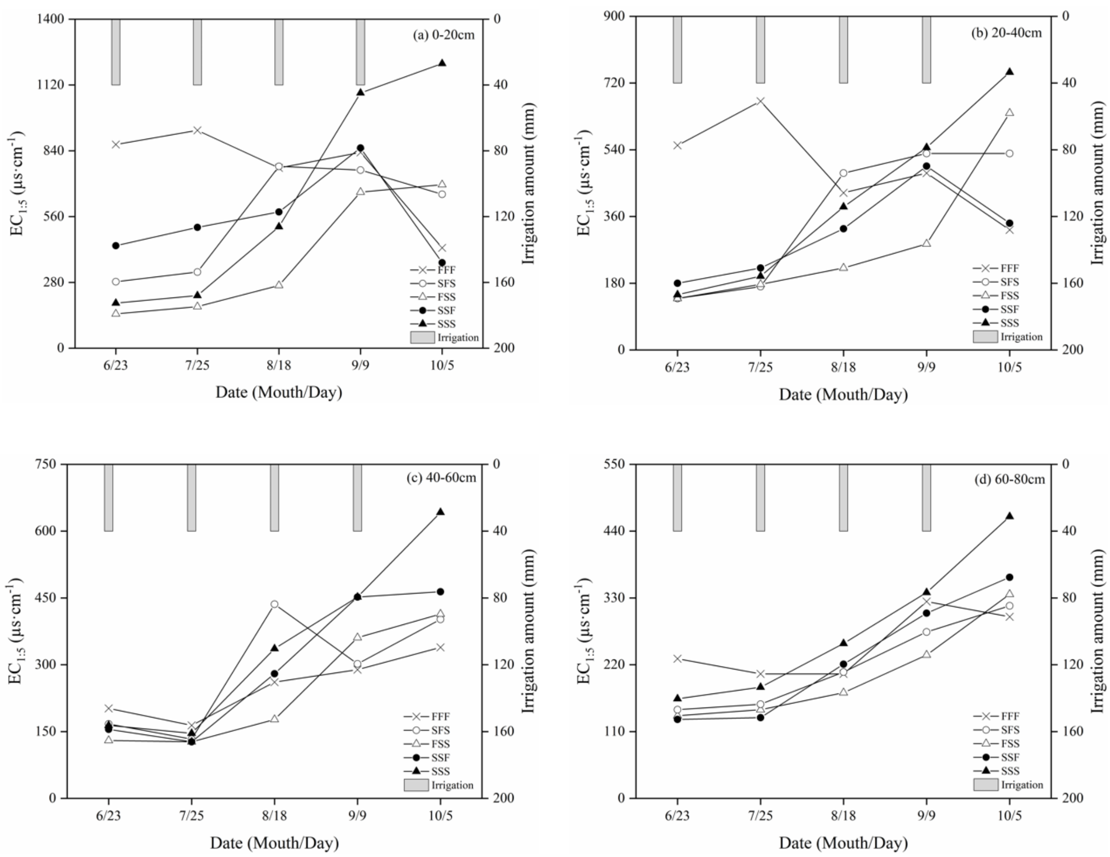
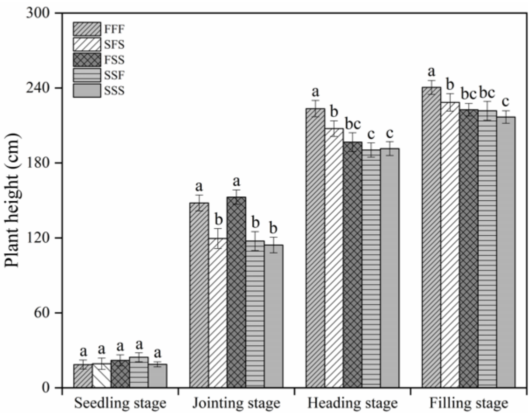


Figure 3. The average $EC_{1:5}$ value at the depths of 0–20, 20–40, 40–60, and 60–80 cm layers of experimental plots before four irrigation events and at harvest.

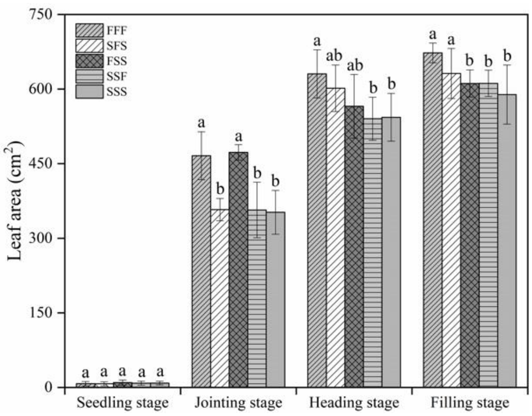
In the 0–20 cm soil layer, the salt content in FFF decreased gradually over the growing period, whereas that in SSS increased throughout the growing period, and the salt contents in SSF, SFS, and FSS first increased and then decreased. Relative to the soil salinity before sowing, the soil salinity after harvesting decreased by 440.6 and 71.9 μs cm^{-1} in FFF and SSF, respectively, and increased by 371.9, 550.0, and 1018.8 μs cm^{-1} in SFS, FSS, and SSS, respectively. In the 20–40 cm soil layer, the dynamics of soil salinity in the different treatments were similar to those in the 0–20 cm soil layer. Relative to the soil salinity before sowing, the soil salinity after harvesting had decreased by 228.1 μs cm^{-1} in FFF and increased by 390.6, 500.0, and 162.5 μs cm^{-1} in SFS, FSS, and SSF, respectively. In the 40–60 cm soil layer, the soil salinity in each treatment was lowest before the jointing-stage irrigation. In the 60–80 cm soil layer, in all treatments, soil salt content increased over the entire growing season. The salt accumulation rate in the 60–80 cm soil layer ranged from 25.9% to 148.26% in the different treatments.

3.2. Plant Height and Leaf Area

Figure 4 shows that plant height did not significantly differ among the treatments at the seedling stage. At the jointing stage, plant height in the FFF and FSS treatments was significantly greater than that in the SFS, SSF, and SSS treatments. It is possible that salt stress caused by low quality salt water severely inhabited cell division and growth during this period. At the heading stage, the growth rate of plants in the SFS treatment had recovered considerably, and was 8.36% higher than that in the SSS treatment. However, plant growth in the FSS treatment was significantly inhibited, with a growth rate 2.72% higher than that in the SSS treatment, and 11.99% lower than that in the FFF treatment.



(**a**) Variation of plant height



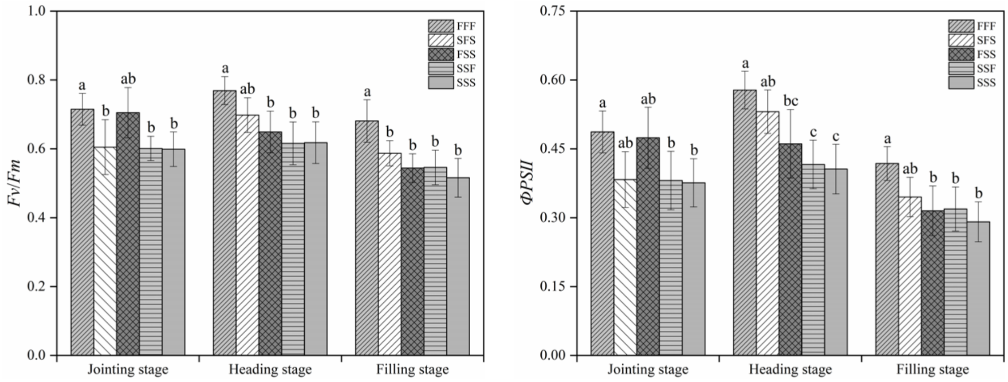
(**b**) Variation of leaf area

Figure 4. Plant height (**a**) and leaf area (**b**) dynamics of maize at different crop growth stages under designed irrigation treatments. Values are mean ± standard deviation. a, b and c values with the same letter within a column are not significantly different (LSD's test at $p = 0.05$).

At the filling stage, plant height in the different treatments followed the order FFF > SFS > FSS > SSF > SSS. Plant height in the SFS, FSS, and SSF treatments were 5.40%, 2.68%, and 2.31% higher, respectively, than that under SSS, and 4.99%, 7.44%, and 7.78% lower, respectively, than that under FFF. These results indicated that the plant height of maize was higher under SFS treatment than under the other patterns of alternating fresh and saline water irrigation. It is possible that the effect on plant height at jointing stage and heading stage were greater than other growth stages during the whole growth period of summer maize; saline water irrigation at the jointing stage lowed the cellular osmotic potential and water use efficiency, and thereby inhibited the absorption and transport of ions needed for maize. There were similar trends of the variations in the leaf area and plant height of maize in the different irrigation treatments.

3.3. Maximal Quantum Yield (F_v/F_m) and Effective Quantum Yield of Photochemical Energy Conversion (ΦPSII)

As shown in Figure 5, the trends in the F_v/F_m and *ΦPSII* of maize leaves across the different irrigation treatments were similar. Over the growth period, F_v/F_m and *ΦPSII* in the FFF, SFS, SSF, and SSS treatments first increased and then decreased with time, peaking at the heading stage. The maximum values of F_v/F_m in FFF, SFS, SSF, and SSS were 0.769, 0.698, 0.616, and 0.618, respectively, and the maximum values of *ΦPSII* in FFF, SFS, SSF, and SSS were 0.578, 0.531, 0.416, and 0.406, respectively. In the FSS treatment, downward trends in the F_v/F_m and *ΦPSII* throughout the growth period were observed, with the highest values observed at jointing, which were 0.705 and 0.474, respectively.



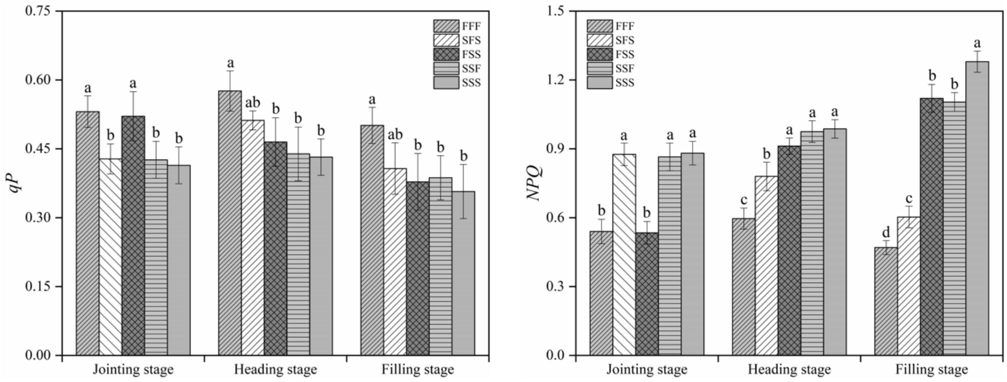
(**a**) Variation of F_v/F_m (**b**) Variation of *ΦPSII*

Figure 5. F_v/F_m (**a**) and *ΦPSII* (**b**) dynamics of maize at different crop growth stages under designed irrigation treatments. Values are mean ± standard deviation. a, b and c values with the same letter within a column are not significantly different (LSD's test at $p = 0.05$).

Relative to the corresponding values under FFF, the F_v/F_m values under the SFS treatment were decreased by 15.38% (jointing stage), 9.23% (heading stage), and 13.80% (filling stage), and the *ΦPSII* values under the SFS treatment were decreased by 21.36% (jointing stage), 8.13% (heading stage), and 17.46% (filling stage). Irrigation with fresh water can significantly mitigate the effects of salinity on maize. Relative to the corresponding values under FFF, F_v/F_m under FSS was reduced by 1.40% (jointing stage), 15.60% (heading stage), and 20.12% (filling stage), and *ΦPSII* under FSS was reduced by 2.67% (jointing stage), 20.24% (heading stage), and 24.64% (filling stage). Furthermore, F_v/F_m and *ΦPSII* values in the SSF or SSS treatment were significantly lower than those in the other treatments, indicating that the electron transfer rate and photochemical efficiency were mainly affected by salt stress mainly at the jointing and heading stages.

3.4. Photochemical Quenching (qP) and Non-Photochemical Quenching (NPQ)

Figures 5 and 6 show that the *qP*, F_v/F_m, and *ΦPSII* of maize leaves under the different irrigation treatments followed the same patterns. Relative to *qP* under FFF, *qP* in the SFS, FSS, SSF, and SSS treatment was reduced by 19.40%, 1.88%, 19.77%, and 22.03%, respectively, at the jointing stage, by 11.11%, 19.27%, 23.78%, and 25.00%, respectively, at the heading stage, and by 18.76%, 24.55%, 22.75%, and 28.74%, respectively, in the filling stage. However, *NPQ* showed a trend dissimilar to that of *qP*, F_v/F_m, or *ΦPSII*, showing upward trends over the whole growth period in all treatments except SFS. Under the SFS treatment, the *NPQ* at jointing stage, at heading stage and filling stage were 0.876, 0.780, and 0.603, respectively. In the SFS treatment, *NPQ* exhibited a downward trend throughout the growth period. Salt stress decreased *qP* and increased *NPQ*. At the filling stage, relative to *NPQ* in FFF, *NPQ* was enhanced by 20.83% in SFS, 138.30% in FSS, 134.89% in SFF, and 172.34% in SSS.



(**a**) Variation of qP (**b**) Variation of NPQ

Figure 6. qP (**a**) and NPQ (**b**) dynamics of maize at different crop growth stages under designed irrigation treatments. Values are mean ± standard deviation. a, b c and d values with the same letter within a column are not significantly different (LSD's test at $p = 0.05$).

3.5. Yield and Its Components

The effects of the different irrigation sequence on maize yield were significant (Table 3). The highest yield among the treatments (11.35 t ha^{-1}) was achieved under the FFF treatment. Relative to the yield under FFF, the greatest reduction in yield was 44.49%, in SSS, and the lowest reduction was 24.85%, in SFS. The corresponding yield reductions of maize in FSS and SSF were 32.25% and 34.36%, respectively. SFS achieved the best results among saline water treatments. This finding indicates that SFS reduced the use of freshwater compared with FFF while enhancing the yield of maize compared with FSS, SSF, and SSS.

Table 3. Maize yields and its components of different treatments.

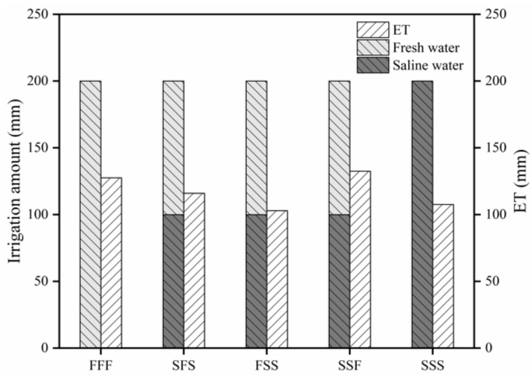
Treatment	Spike Number (10^{4} ha^{-1})	Number of Kernels per Ear	100-Kernel Weight (g)	Grain YIELD (t ha^{-1})
FFF	4.55 ^{a}	592 ^{a}	46.87 ^{a}	11.35 ^{a}
SFS	3.94 ^{b}	540 ^{b}	44.57 ^{a}	8.53 ^{b}
FSS	3.79 ^{b,c}	505 ^{c}	44.66 ^{a}	7.69 ^{b,c}
SSF	3.79 ^{b,c}	480 ^{c,d}	45.56 ^{a}	7.45 ^{c}
SSS	3.64 ^{c}	468 ^{d}	41.08 ^{b}	6.30 ^{d}

Note: ^{a,b,c,d} values with the same letter within a column are not significantly different (LSD's test at $p = 0.05$).

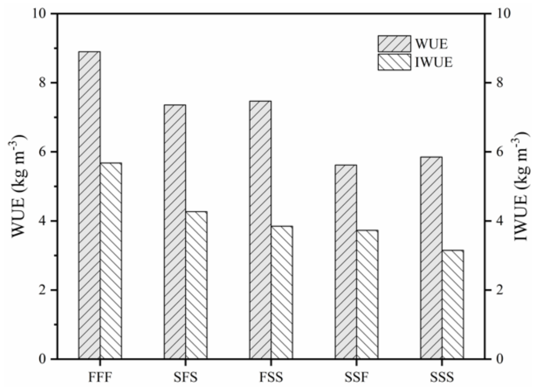
Table 3 shows that the spike number, number of kernels per ear, and 100-kernel weight following alternating fresh and saline water furrow irrigation (SFS, FSS, and SSF) were between those observed under fresh water irrigation (FFF) and saline water irrigation (SSS). Spike number, number of kernels per ear, and 100-kernel weight were largest in the FFF treatment and lowest in SSS. Among SFS, FSS, and SSF treatments, SFS yielded the highest spike number and number of kernels per ear and the lowest 100-kernel weight. Compared with SFS, spike number in the FSS and SSF treatment was reduced by 3.81% and 3.81%, respectively, number of kernels per ear in the FSS and SSF treatment was reduced by 6.48% and 11.11%, respectively, and 100-kernel weight in the FSS and SSF treatment was increased by 0.20% and 2.22%, respectively.

3.6. ET, WUE and IWUE

Figure 7 shows that *ET*, *WUE*, and *IWUE* for all treatments. Except for SSF, *ET* values in SFS and FSS were between those in FFF and SSS. *WUE* and *IWUE* in SFS, FSS, and SSF were between those in FFF and SSS. *ET*, *WUE*, and *IWUE* of FFF treatment were higher than SSS treatment. *ET*, *WUE*, and *IWUE* in FFF exceeded that in SSS by 18.52%, 52.14%, and 80.32%. *ET* in the different treatments followed the order SSF > SFS > FSS, with corresponding values of 132.48, 115.95, 102.91 mm, respectively. *WUE* in the different treatments followed the order FSS > SFS > SSF, with corresponding values of 7.47, 7.36, 5.62 kg m^{-3}, respectively. *IWUE* in the different treatments followed the order SFS > FSS > SSF, with corresponding values of 4.27, 3.85, 3.73 kg m^{-3}, respectively. This indicated that the sequence of alternating irrigation affected the *ET*, *WUE*, and *IWUE* of maize. *WUE* in SFS and FSS exceeded that in SSF by 30.96% and 32.92%. *IWUE* in SFS and FSS exceeded that in SSF by 14.48% and 3.22%. These results indicate that early irrigation of fresh water can reduce *ET* and increase *WUE* and *IWUE* of maize in alternating furrow irrigation with saline and fresh water. In *IWUE*, SFS treatment was significantly better than FSS.



(**a**) Irrigation and *ET*



(**b**) *WUE* and *IWUE*

Figure 7. *ET*, *WUE*, and *IWUE* under designed irrigation treatments.

4. Discussion

Soil salinity during maize cultivation was closely related to the irrigation times and the pattern of fresh and saline water alternation. There was a positive correlation between soil salt accumulation and saline water irrigation times, and that specific effect was greater in saline water irrigation than in any of the fresh/saline water irrigation alternation patterns. Irrespective of the experimental treatments, the salt content in the upper layer was higher than that in the lower layer, and the highest in 0–20 cm soil layer (Figure 3). This was mainly due to the high levels of crop transpiration and evaporation, causing water and salts to move upwards from the bottom layers along with the evaporation of water [40]. Under the same alternating irrigation times of salt water and fresh water, the alternating irrigation sequence of fresh and saline water application had a significant effect in lowering soil salinity and that an appropriate irrigation sequence can help reduce the risk of soil salinization of the root zone [41]. In all treatments, irrigation of fresh water at seedling stage promoted salt leaching [42], formed a desalting region at 0–60 cm and salt accumulation region at 60–80 cm, similarly to results reported by Jin [43].

Under alternating irrigation of fresh and saline water during different growth phases of maize, plant height was the most sensitive to irrigation water quality at jointing stage [11,44], and salt stress imposed by saline water inhibited the absorption and transport of ions needed for maize. However, the application of fresh water for irrigation at the heading stage resulted in plants recovering from earlier stress and growth inhibition after saline water applied at jointing stage [25]. The trends of the variations in the leaf area and plant height were similar, which may be due to the similar mechanisms of salt stress on leaf area and plant height.

Our study shows that fresh water irrigation would be beneficial to the F_v/F_m and *ΦPSII*, while saline water irrigation negatively affected the F_v/F_m and *ΦPSII*. Qu et al. (2012) also found that salt stress can reduce the maximum quantum yield (F_v/F_m) of maize plants [45]. As soil salt stress increased, electron transport and photochemical activity of *PSII* decreased. *ΦPSII* was the actual *PSII* efficiency, which decreased inevitably [46]. Furthermore, Chaum et al. (2009) also indicated that salt stress inhibited the photosynthetic electron transfer rate and actual photochemical efficiency of *PSII*, and reduced the conversion efficiency of photosynthetic light energy [47]. Our data indicate that the aggravation of salt stress caused the increase of *NPQ*. A potential reason is due to salt stress, the over- excitation in *ΦPSII* increased, and therefore to avoid the damage from excess light, the excess energy was dissipated in the form of heat by nonphotochemical quenching.

In our study, the yields in different treatments followed the order SFS > FSS > SSF, with corresponding values of 8.53, 7.69, 7.45 t ha^{-1}, respectively. The result proves that the maize grain yield is particularly sensitive to water quality during the heading period, and poor water quality reduces the yield of maize [48,49]. Among SFS, FSS, and SSF treatments, SFS yielded the highest spike number and number of kernels per ear and the lowest 100-kernel weight. This result is due to the irrigation with freshwater at the heading stage in SFS, which increased water availability and the absorption and transport of ions needed by maize, thereby increased spike number and number of kernels per ear. However, saline water irrigation was carried out at the filling stage, which intensified soil salt stress, and caused the crop water deficit and decreased the 100-kernel weight [50,51].

ET values in the FFF and SSF treatments were higher than that in the SFS, FSS, and SSS treatments. This is mainly due to that a large amount of water has been consumed by maize at the filling stage [52], and the irrigation water quality also affected plant evapotranspiration. Among the treatments, *WUE* and *IWUE* of the FFF treatment was higher than those of SFS, FSS, SSF, and SSS treatments. This shows that saline water irrigation inevitably reduced *WUE* and *IWUE* compared to fresh water irrigation. However, this does not negate the use of saline water for irrigation. In our study, although the yield in SFS was 75.15% of that in FFF, SFS saved 50% of fresh water, while Zhang et al. (2018) also found a similar result in the study of alternating irrigation of fresh and saline water [53]. Therefore, it should be noted that alternating irrigation should be a recommended irrigation practice in areas with severe freshwater shortage.

5. Conclusions

Obtained results in the present study indicate that the increases of salinity in the root zone soil layer under alternating fresh and saline water irrigation (SFS, FSS, and SSF) were between the increase under fresh water irrigation and that under saline water irrigation. SSF and SFS were more effective than FSS in reducing negative effects of soil salinization in the maize root layer.

Saline water irrigation strongly inhibited plant growth. However, alternating fresh and saline water furrow irrigation can mitigate the growth inhibition due to saline water irrigation. Plant height in SFS, FSS, and SSF was 5.40%, 2.68%, and 2.31% higher than that in SSS, respectively, but 4.99%, 7.44%, and 7.78% lower than that in FFF, respectively. Irrigation water quality had the greatest impacts on plant height at the jointing and heading stages. The changes of leaf area and plant height in maize were similar across the different irrigation treatments.

The trends in the F_v/F_m, $\Phi PSII$, and qP of maize leaves were similar across the different irrigation treatments. However, NPQ exhibited a trend dissimilar to that of qP, F_v/F_m, or $\Phi PSII$. This result indicated that fluorescence parameters were one of the processes that was most inhibited under saline stress and suggests that the mechanism underlying the inhibition of F_v/F_m, $\Phi PSII$, and qP by salt stress differed from that underlying the salt stress-driven inhibition of NPQ.

In case of shortage of fresh water for irrigation during maize cultivation, the correct alternating application of fresh and saline water in consecutive growth stages results in improving plant growth and *WUE* without reducing yield and grain quality. The sequence of SFS allowed to obtain the highest yield (8.53 t ha^{-1}) among the treatments employing alternating fresh and saline water irrigation, although the yield in SFS was 75.15% of that in FFF, SFS saved 50% of fresh water. In addition, SFS can enhance *IWUE* under the scarcity of fresh water stress and could thus be an effective irrigation management practice for summer maize production under conditions of drought.

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