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Effects of Different Salinity Levels in Drip Irrigation with Brackish Water on Soil Water-Salt Transport and Yield of Protected Tomato (*Solanum lycopersicum*)

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Abstract: The effective exploration and utilization of brackish water resources are crucial to alleviating the scarcity of freshwater in arid regions. This study focused on protected tomato plants and set up four irrigation salinity levels: T1 (2 g·L^{-1}), T2 (4 g·L^{-1}), T3 (6 g·L^{-1}), and T4 (8 g·L^{-1}), with freshwater irrigation as a control (CK). The aim was to investigate the effects of continuous brackish water irrigation on soil water-salt transport and tomato yield. The outcomes highlighted that the moisture content in different layers of soil exhibited a "high in the middle, low at both ends" pattern, with the primary accumulation of soil moisture occurring at the 40 cm depth. The range and moisture content of the soil wetted zone increased with elevated salinity levels. Under continuous brackish water irrigation, the range of the soil wetted zone expanded further for the autumn crops, and the moisture content significantly increased compared to the spring crops. The concentration of soil salt gradually decreased with increasing soil depth, exhibiting greater levels in the 0–20 cm layer compared to the 40–80 cm layer. The average salt concentration in the soil at the end of the growth period was significantly higher than before transplantation, and this phenomenon became more pronounced with increasing salinity levels. Initial irrigation with brackish water with a salinity level of 2–4 g·L^{-1} promoted the growth of the tomatoes planted in the spring and the plant height and stem diameter reached the peak values of 1.68 m and 1.08 mm for the T2 treatment, respectively, which were 7.1% and 9.2% higher than that of the CK treatment, ensuring efficient yield and water usage. However, continuous irrigation with brackish water with a salinity level of 2–4 g·L^{-1} inhibited the growth and yield of the tomatoes planted in autumn, while the T1 and T2 treatments only yielded 24,427.42 and 16,774.86 kg·hm^{-2}, respectively, showing a decline of 32.2% and 46.1% compared to the yields of the spring season. Considering the soil water-salt and yield indicators, under the conditions of non-continuous brackish water irrigation, using water with a salinity level of 2–4 g·L^{-1} is recommended for drip irrigation of protected tomatoes.

Keywords: brackish water irrigation; protected tomato; soil water-salt; growth characteristics; yield

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1. Introduction

Water resources are one of the most fundamental natural resources for sustaining economic and social development and ecological balance [1]. Based on the "2020 China Water Resources Bulletin", Xinjiang had a total water resource volume of 80.10 billion m^3 in 2020, with agricultural water consumption of 49.62 billion m^3, ranking first among the 31 provinces in China in terms of agricultural water use [2]. Typically, Xinjiang is an extremely arid region with intense evaporation, scarce rainfall, and limited water resources. Roughly 95% of the overall water consumption is attributed to agricultural water usage [3]. With the rapid development of industry, agriculture and the increasing population in Xinjiang in recent years, the contradiction between water supply and demand has become increasingly prominent. Therefore, the rational development and effective usage of saline water resources for irrigation are considered essential means to address the crisis of freshwater resources.

For centuries, brackish water, which is a prevalent unconventional water resource, has been used as a viable alternative to freshwater for agricultural irrigation [4], particularly in arid and semi-arid regions. However, improper brackish water irrigation can result in the buildup of salt ions in the surface soil, adversely affecting crop growth, yield, and quality [5,6]. Additionally, brackish water irrigation is a contributor to secondary soil salinization [7]. Extensive national and international research has shown the relevance between the quality of brackish water irrigation and soil water-salt transport as well as the response of crops. Distinct salinity levels in irrigation water inevitably result in varying degrees of interaction between the introduced salt ions after entering the soil and the original soil ions, thereby affecting the migration process of soil moisture [8,9]. Yuan et al. [10] found that soil moisture content gradually elevated with the increase in irrigation water salinity, and this phenomenon became more pronounced as the growth period progressed. This indicates that the salt introduced into the soil by brackish water irrigation reduces soil water potential, resulting in salt stress on crops and affecting their water uptake by roots. However, brackish water irrigation would benefit crops in some cases. For example, Mu et al. [11] found that the salt accumulation of the scheme of fresh water + fresh water + brackish (3 $g\cdot L^{-1}$) water was 0.0552 $g\cdot kg^{-1}$; this scheme could not only supplement soil water but also accumulate less salt. Cavalcante et al. [12] found that under drought and extreme drought conditions, saline water irrigation can reduce crop water stress, avoid the excessive accumulation of salt in soil, and promote water productivity, which is 3.03 times that of non-saline water treatment under severe drought conditions.

Plant growth status is the most intuitional indicator of their response to environmental stress. The impact of brackish water irrigation on crop growth has been investigated extensively. For instance, the cotton emergence rate drops significantly when the irrigation water salinity exceeds 5 $g\cdot L^{-1}$ [13], while brackish water irrigation promotes the growth of plant height of tomatoes [14] and wheat [15]. However, the salt tolerance levels and responses of different crops to salt vary. Therefore, it is crucial to understand the relative salt thresholds for different crops. With technological advancements, some researchers have developed crop models that quantitatively analyze and simulate dynamic plant growth based on mathematical analysis methods combined with field test results [16]. A logistic model, commonly used to simulate the dynamic growth of crops [17], can accurately model the dynamic changes in plant height and stem diameter. Liu et al. [18] developed comprehensive and fully correlated logistic models for four crops. The results showed that the fully correlated logistic growth model better reflected the basic characteristics of crop growth and the characteristics of each growth stage compared to the semi-correlated model. Furthermore, the fully correlated model provided a good fit for the growth patterns of all four crops. Fang et al. [19] used the commonly used Gompertz and logistic curves to establish growth models, taking the days after transplanting and cumulative growing degree days as independent variables to simulate the correlation between these variables and five growth indices. The results indicated that the logistic model estimated critical points were closer to the expected values than the Gompertz model and were more suitable for tomato crops in Taiwan. Chen et al. [15] reported the impact of saline irrigation on winter wheat and summer maize and revealed that the maximum yield of wheat and maize was attained at a water salinity level of 2 $g\cdot L^{-1}$. Magán et al. [20] discovered that tomato total yield gradually decreased with increasing salt concentration beyond a threshold, mainly due to a decrease in fruit weight. Li et al. [21] discovered that tomato yield reduced as the salt concentration in irrigation water increased, especially when the salinity exceeded the salt tolerance threshold. Once the soil's electrical conductivity (EC) within the root zone surpasses 2.5 dS·m^{-1}, each incremental increase of 1 dS·m^{-1} in irrigation water salinity leads to a 10% reduction in tomato yield.

Tomato is currently one of the world's most widely grown vegetable crops that are rich in vitamin C, lycopene, flavonoids, polyphenols and pectin, etc., which play an important role in the prevention of cancer and hyperlipidemia, anti-radiation and aging, and the regulation of cardiovascular disease [22]. The planting area of fresh tomato in Xinjiang is 92,000 hm^2, which is divided into greenhouse cultivation and open-air cultivation. It can produce 910 $\times$ 10^4 kg fresh fruit [23]. Li et al. [24] proposed that compared with open field cultivation, the biggest advantage of facility cultivation technology is that it can regulate the temperature environment to a certain extent, can carry out early spring, late autumn and overwintering production, and realize annual production, but can easily lead to high temperatures, high humidity and weak light environments. Tomato is a light and temperature-loving crop, and its facility cultivation technology focuses on the regulation of temperature, light and humidity. In order to better control the operability of the experiment, tomato cultivation was carried out in solar greenhouses.

In summary, numerous scholars have conducted extensive research on the impact of saline irrigation on the growth of crops, yielding many results and conclusions. However, irrigation with saline water inevitably leads to an increase in soil salinity, which can cause secondary soil salinization issues, especially in arid regions with low rainfall, like southern Xinjiang. Therefore, this study attempts to explore the rational development and utilization of saline water resources in precision-controlled protected tomato cultivation. It analyzes the impact of irrigation with saline water on the soil water-salt environment and crop growth and determines the appropriate salinity range for irrigation in arid regions to offer a foundational understanding of the rational utilization of saline water resources in arid regions.

2. Materials and Methods

2.1. Overview of the Experimental Site

The experimental took place between March 2021 and January 2022 in the multi-span greenhouse in the Water-saving Irrigation Test Base (40°20′47″–41°47′18″ N, 79°22′33″–81°53′45″ E) of the Key Laboratory of Modern Agriculture at Tarim University, College of Water Conservancy and Architectural Engineering, Southern Xinjiang. The greenhouse covered an area of 800 m^2 (40 m long and 20 m wide). The experimental site is located at an elevation of 1020 m, characterized by a warm temperate extreme continental arid desert climate with maximum evaporation and scarce precipitation. The annual temperature fluctuates between 10.8 and 14.5 °C, accompanied by annual precipitation spanning from 40.1 to 82.5 mm and annual evaporation ranging from 1976.6 to 2558.9 mm. The soil at the experimental site is sandy loam, with an average bulk density of 1.43 g·cm^{-3} from 0 to 80 cm depth, an average field capacity of 0.26 g·g^{-1}, and an average initial soil salinity of 1.06 g·kg^{-1}.

2.2. Experimental Design

The local conventional variety "Qin ling Shu Yue" was selected for tomato cultivation. The planting method used was ridge cultivation with one ridge, two rows, and one strip. The ridge shoulder width was 60 cm, ridge height was 20 cm, and ridge spacing was 60 cm. Tomato seedlings were planted on both sides of the ridge with a row spacing of 30 $\times$ 40 cm. Drip irrigation was adopted using a drip tape with an inner flat emitter with a drip head spacing of 30 cm and a flow rate of 3.0 L·h^{-1}. The total area of each plot was 250 m^2, with dimensions of 4.2 m in length and 4 m in width, as shown in Figure 1.

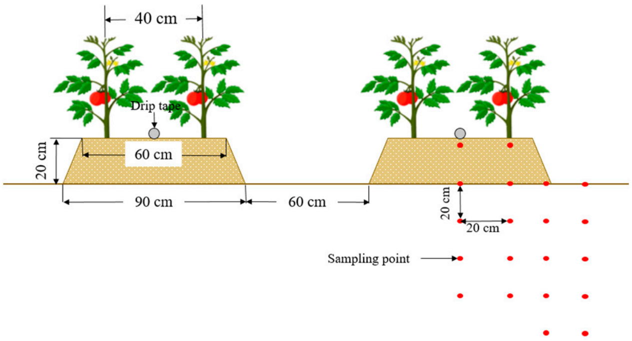

Figure 1. Planting patterns.

According to the underground brackish water ion composition in Southern Xinjiang, the irrigation water was prepared by mixing freshwater (1.0~1.2 g·L^{-1}) with chemicals Na_2SO_4, NaCl, $NaHCO_3$, $CaCl_2$, and $MgCl_2$ in a mass ratio of 8:8:1:1:1 [25]. Freshwater irrigation was used as the control (CK), and four different gradients of saline water irrigation treatments were established, namely T1 (2 g·L^{-1}), T2 (4 g·L^{-1}), T3 (6 g·L^{-1}), and T4 (8 g·L^{-1}). Each treatment had three replicates. Both tomato crops were irrigated with 300 mm of irrigation over the entire life cycle, divided into eight irrigation groups [26]. Integrated water and fertilizer management was applied, with a balanced fertilizer (N-P_2O_5-K_2O ratio of 15-15-15) used during the vegetative growth stage and a high-potassium fertilizer (N-P_2O_5-K_2O ratio of 12-6-40) used during the flowering and fruiting stages, with a dosage of 45 kg·hm^{-2}. Field management practices were consistent with local production practices. The tomato growth period was 122–125 days, with planting dates on 10 March and 28 August, respectively, as demonstrated in Table 1.

Table 1. Duration of tomato growth period.

	Growth Period	Start and End Date (y-m-d)	Duration/d
Spring stubble	Seedling period	10 March 2021–19 April 2021	1~40
	Blooming period	20 April 2021–26 April 2021	41~47
	Blooming and fruit period	27 April 2021–30 May 2021	48~81
	Blooming and fruit flourishing period	31 May 2021–30 June 2021	82~112
	Late period	1 July 2021–10 July 2021	113~122
Autumn stubble	Seedling period	7 September 2021–17 October 2021	1~40
	Blooming period	18 October 2021–24 October 2021	41~47
	Blooming and fruit period	25 October 2021–27 November 2021	48~81
	Blooming and fruit flourishing period	28 November 2021–28 December 2021	82~112
	Late period	29 December 2021–10 January 2022	113~125

2.3. Measurement Items and Methods

2.3.1. Soil Moisture and Salinity

Moisture content in the soil was assessed utilizing the following drying method: after each 24 h period of irrigation, soil samples were acquired utilizing a soil borer at distances of 0, 20, 40, and 60 cm from the drip tape, at depths of 10, 20, 40, 60, and 80 cm, respectively. Samples were collected during the flowering and fruiting periods (spring: 3 May, autumn: 28 October) and at the end of fruiting (spring: 3 July, autumn: 31 December) for analysis. Soil salinity was determined using the following conductivity method: sampling was carried out in each growth period of spring and autumn; dried soil samples were ground and sieved through a 20-mesh sieve, then a 5:1 water-to-soil ratio extract was made, and the electrical conductivity (EC) of the extract was measured using a portable conductivity meter

(DDP-210). Subsequently, the connection between soil salinity and electrical conductivity was calibrated employing the drying method, enabling the calculation of soil salinity. The calibration outcomes are depicted in Figure 2.

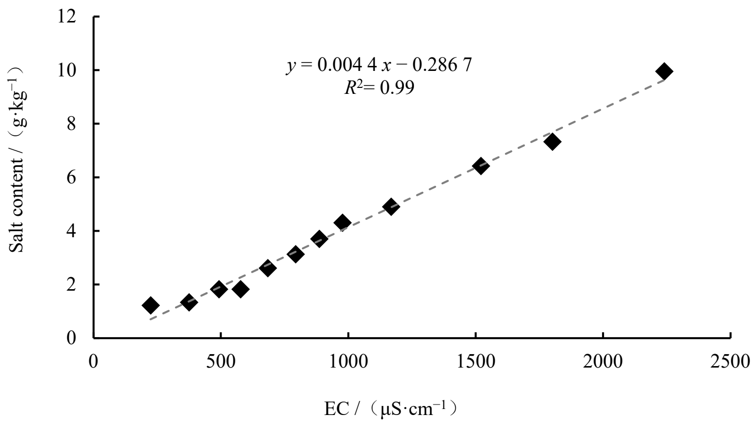

Figure 2. Calibration results of drying method.

2.3.2. Plant Growth Indicators

Plant height, stem diameter, and the mass of dry matter were measured; towards the end of the growth phase (spring: 3 July 2021, Autumn stubble: 7 January 2022), ten tomato plants with consistent growth were randomly selected from each plot. Plant height was determined with a measuring tape starting at the base of the plant. Stem diameter was measured using electronic calipers and the cross-intersection method, and the average value was taken. Plants were cut at the base and dried at 105 °C for 30 min, and then dried again 65 to 75 °C for 48 h (DHG-9625A, Shanghai Yiheng Scientific Instruments Co., Ltd., Shanghai, China), then the mass of dry matter was weighed and calculated [27].

2.3.3. Evaluation Indices of the Logistic Model

The logistic model was used to simulate the stem diameter and plant height of protected tomatoes throughout the reproductive period [28].

The growth rate equation is as follows:

$$V = \frac{abce^{-cx}}{\left(1 + be^{-cx}\right)^2} \tag{1}$$

This is derived from the first-order derivative of the logistic model equation $y = a/(1 + be{-}^{cx})$, and the growth rate equation takes the first-order derivative and makes it zero, yielding the maximum growth rate:

$$V_1 = \frac{ac}{4} \tag{2}$$

The time it takes to reach the maximum growth rate can be calculated using the following equation:

$$T_1 = \ln\frac{b}{c} \tag{3}$$

On the basis of the growth rate equation for the second-order derivative being zero, it is possible to obtain the growth curve for the T_2 and T_3 inflection points, from planting at T_2 and T_3 to the ripening tomato growth rate associated with incremental growth and a slow increase in growth, in addition to the growth rate in the T_2–T_3 in the period of rapid growth.

$$T_2 = \frac{\left[\ln b - \ln\left(2 + 3^{\frac{1}{2}}\right)\right]}{c} \tag{4}$$

$$T_3 = \frac{\left[\ln b - \ln\left(2 - 3^{\frac{1}{2}}\right)\right]}{c} \tag{5}$$

The evaluation indices are as follows:

(1) Root mean square error (RMSE)

$$\mathrm{RMSE} = \left[\sum_{i=1}^{n} \frac{(P_i - S_i)^2}{n}\right]^{0.5} \tag{6}$$

where RMSE represents the root mean square error (the smaller the RMSE value, the more accurate the simulation), P_i represents the simulated value, S_i represents the measured value, and n represents the number of samples.

(2) Normalized root mean square error (nRMSE)

$$\mathrm{nRMSE} = \left[\sum_{i=1}^{n} \frac{(P_i - S_i)^2}{n}\right]^{0.5} \times \frac{100}{\overline{S}} \tag{7}$$

where $\overline{S}$ represents the average of measured values (nRMSE < 10% indicates that the model performs extremely well; 10% < nRMSE < 20% indicates that the model performs well; 20% < nRMSE < 30% shows moderate performance of the model; nRMSE > 30% represents poor model performance).

(3) Synergy index d

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - S_i)^2}{\sum_{i=1}^{n}\left(\left|P_i - \overline{S}\right| + \left|S_i - \overline{S}\right|\right)^2}\right] \tag{8}$$

where d represents the synergy index (the closer the d value is to 1, the better the simulation effect).

(4) Coefficient of determination R^2

$$R^2 = \frac{\left[\sum_{i=1}^{n}(P_i - \overline{P})(S_i - \overline{S})\right]^2}{\sum_{i=1}^{n}(P_i - \overline{P})^2 \sum_{i=1}^{n}(S_i - \overline{S})^2} \tag{9}$$

where R^2 represents the coefficient of determination (the closer the R^2 value is to 1, the higher the model's credibility).

2.3.4. Tomato Yield

In each experiment, 15 tomato plants were harvested from each block. Fruits of tomato plants from the first to the fourth layer were measured in turn, and then the total fresh weights of these four layers fruit were calculated as the total yield for each plant [27].

2.4. Calculation of Irrigation Water Use Efficiency

The calculation formula of irrigation water use efficiency (IWUE) is as follows [29]:

$$IWUE = Y/I \tag{10}$$

where Y represents the tomato yield ($kg \cdot hm^{-2}$) and I represents the irrigation water supply during the growth period ($m^3 \cdot hm^{-2}$).

2.5. Data Processing and Analysis

Microsoft Excel (v. 2018; Micorosoft Corporation, Redmond, WA, USA) was utilized for data reduction and analysis, while plotting was carried out using Origin (v. 2018; Origin Lab, Northampton, MA, USA), and SPSS (v. 20.0; SPSS Inc., Chicago, IL, USA). Duncan's method was employed to test the significant differences between treatments.

3. Results

3.1. Soil Moisture Distribution Characteristics

Figure 3 depicts the spatial distribution of soil moisture during the flowering stage of protected tomatoes in spring and autumn. The figure shows that the soil moisture in different treatments for the spring tomatoes gradually increases in the 0–40 cm soil layer while decreasing in the 40–80 cm layer, exhibiting a "high in the middle and low on both ends" pattern. The soil moisture primarily accumulates at a depth of 40 cm. Horizontally, there is an observable pattern of initially increasing and subsequently decreasing with the distance from the drip irrigation tape. In all treatments, an elliptical wet area developed in the soil layer at a distance of 30–50 cm from the drip irrigation tape at a 20–40 cm depth. With the rise in salinity of the irrigation water, the wet area gradually expands away from the drip irrigation tape, and the soil moisture content within the wet area increases with elevated water salinity. Compared with the CK treatment, the average soil moisture content of the T1 and T2 treatments decreased by 0.27% and 0.23%, respectively, while that of T3 and T4 treatments increased by 4.14% and 7.88%, respectively. The distribution pattern of soil moisture content for tomatoes planted in the autumn is similar to that in the spring, but continuous saline water irrigation further expands the wet area and significantly increases the soil moisture content compared to tomatoes planted in spring. The average soil moisture content of the T1–T4 treatments was higher than that of the CK treatment.

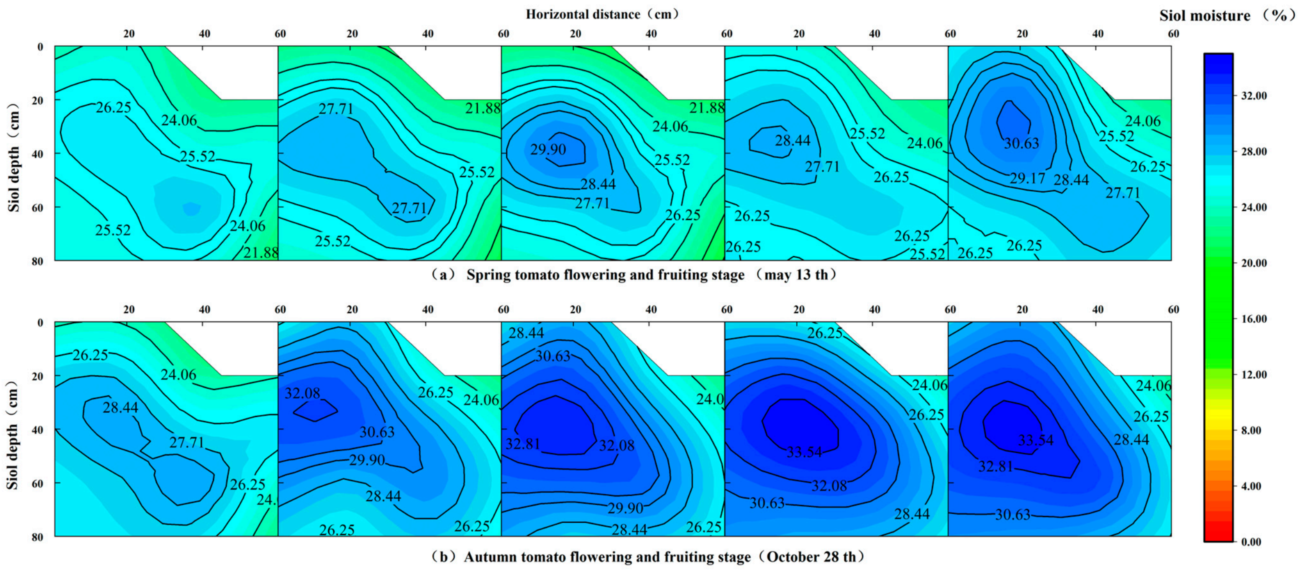

Figure 3. Soil moisture content during the growth period.

3.2. Soil Salinity Distribution

Figure 4 depicts the variation in soil salinity in different soil layers during the growth period under different irrigation salinities. The figure shows that the soil salinity generally decreases with increasing soil depth, with the salinity in the 0–20 cm layer is significantly higher than that in the 40–80 cm layer. With the passage of the growth period, the soil salinity in the 0–20 cm layer gradually increased following the various saline water irrigation treatments. In particular, for the T1–T4 treatments, the salinity in the 10 cm layer increased by 7.39%, 112.94%, 206.37%, and 222.90%, respectively, at the final stage compared to the initial stage after transplanting. The increase for the 20 cm layer was 95.10%, 256.22%, 417.52%, and 647.22%, indicating a more significant salt accumulation with increasing irrigation salinity. The soil salinity in the 40–80 cm layer showed no significant change for the T1 and T2 treatments during the growth period. However, for the T3 and T4 treatments, a significant increase was noted after the flowering and fruiting period. Specifically, at the final stage, the salinity increased by 620.01% and 680.62% in the 40 cm layer, 587.68% and 819.28% in the 40 cm and 60 cm layers, and 971.62% and 1043.97% in the 80 cm layer, respectively. Greater irrigation salinity corresponds to more pronounced salt accumulation in the deeper soil layers. Comparison of the average salinity in the 0–80 cm soil layers among different treatments showed a positive correlation between the soil salinity and irrigation mineralization. Compared to the CK treatment, the final average salinity in the T1−T4 treatments increased by 84.70%, 153.17%, 362.89%, and 480.79%, respectively, indicating significant salt accumulation.

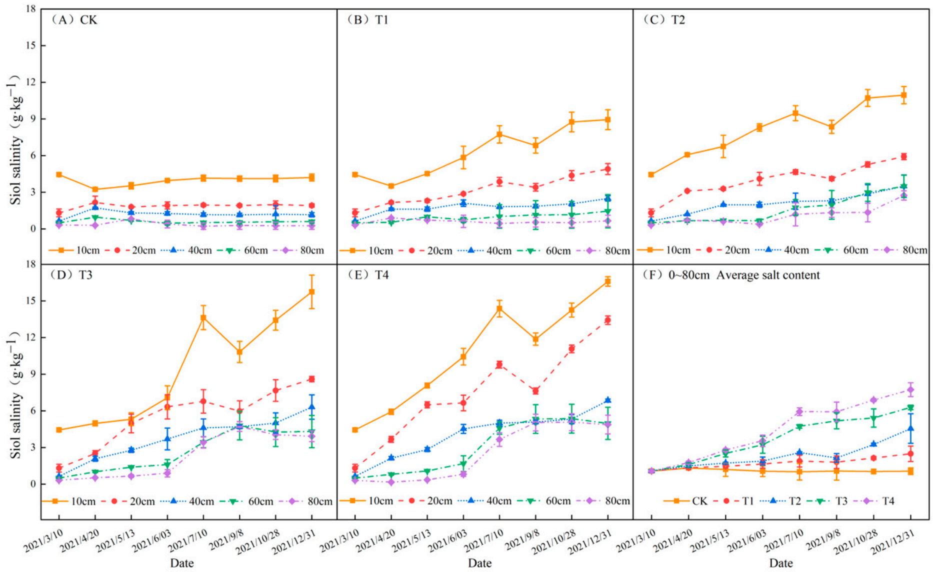

Figure 4. Salt content of soil during the growth period.

The variation pattern of soil salinity in the autumn crops is consistent with that of the spring crops. During the seedling stage (8 September), the salt concentration in the surface layer (0–20 cm) was lower than that in the final stage of the spring tomatoes (10 July). This is because water with low salinity was drip irrigated after the autumn crop was transplanted, causing the salts to leach below 40 cm. Continuous irrigation of saline water during the growth period increased the soil salinity further when compared to the spring crop. The maximum average soil salinity at the final stage for the T3 and T4 treatments reached 6.28 g·kg^{-1} and 7.74 g·kg^{-1}, respectively.

3.3. The Impact of Irrigation with Saline Water on Growth Parameters of Spring Tomatoes

Figure 5 depicts the stem diameter and plant height of protected tomatoes in different brackish water drip irrigation treatments for the spring and autumn. Table 2 shows the dry matter accumulation of tomato under different treatments in spring and autumn. The total dry matter and leaf dry matter at the end of the growth period of spring tomatoes gradually declined as the salinity of irrigation water increased. In the T4 treatment, values of 30.49 g and 13.37 g were recorded, respectively, with a decrease of 75.08% and 85.1% compared to the CK treatment, significantly lower than the other treatments. The stem dry matter amount showed an increasing and then decreasing trend with the increase in irrigation water salinity. The TI treatment had the most considerable amount of stem dry matter, reaching 48.23 g, substantially higher than the other treatments, and increased by 48.58% compared to the CK treatment. The growth in plant height and stem diameter displayed an initial surge, succeeded by a reduction as the salinity of irrigation water rose. Plant height and stem diameter reached their peak values for the T2 treatment, measuring 1.68 m and 1.08 mm, respectively, which were 7.1% and 9.2% higher than the CK treatment and significantly higher than other treatments. With persistent brackish water irrigation, the plant height and stem diameter of autumn tomatoes exhibited a progressive decrease as the irrigation water salinity increased. Compared to the spring tomatoes, a substantial decrease was observed in all treatments, and the extent of the decline increased with the increase in water salinity. As the growth phase concluded, the plant height in the T3 and T4 treatments was only 0.86 m and 0.54 m, respectively, showing a decline of 33.90% and 38.90% compared to the spring season. The stem diameter was 0.66 cm and 0.64 cm, respectively, reducing by 32.65% and 33.61% compared to the spring season.

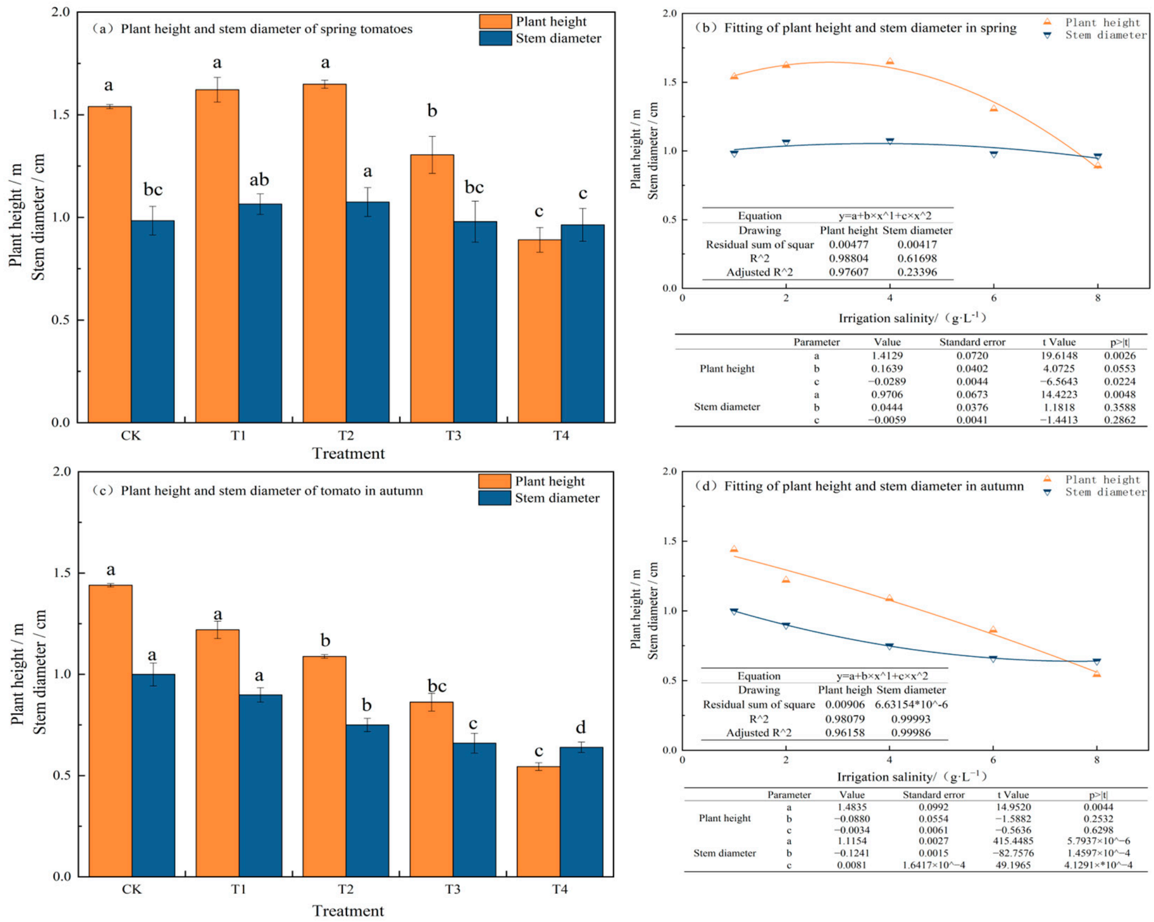

Figure 5. Changes in plant height and stem diameter at the end of the growth period.

Table 2. Dry matter accumulation of tomato under different treatments.

	Treatments	Stem/g	Leaf/g	Dry Matter Accumulation/g
Spring	CK	32.46 ± 0.19 b	89.93 ± 1.4 a	122.39 ± 1.23 a
	T1	48.23 ± 0.66 a	61.77 ± 0.5 b	110.00 ± 1.12 a
	T2	30.38 ± 0.87 c	55.10 ± 2.96 c	85.48 ± 3.16 b
	T3	22.23 ± 0.97 d	33.09 ± 0.71 d	55.32 ± 1.65 c
	T4	17.11 ± 0.74 e	13.37 ± 0.84 e	30.48 ± 1.56 d
Autumn	CK	32.14 ± 0.95 b	89.03 ± 1.14 a	121.17 ± 2.03 a
	T1	47.17 ± 1.27 a	60.41 ± 0.35 b	107.58 ± 1.58 a
	T2	26.27 ± 1.11 c	47.66 ± 1.37 c	73.94 ± 2.51 b
	T3	18.11 ± 0.47 d	26.96 ± 0.34 d	45.09 ± 0.84 c
	T4	12.38 ± 0.83 e	9.68 ± 0.26 e	22.07 ± 1.05 c

The same alphabet on the right side of the same list shows no significance ($p > 0.05$), in contrast, having significance ($p < 0.05$).

Taking the irrigation salinity as the independent variable, the plant height and stem diameter at the end of the growth period of the two crops of protected tomatoes as the dependent variables, a quadratic regression equation was established. The fitting curves of plant height and stem diameter in spring were parabolic, and the fitting curves of dry matter accumulation were linear. The determination coefficients were 0.988 and 0.617, respectively, and the plant height and stem diameter reached their peak at 4 g·L^{-1}. The fitting curve of stem diameter in autumn stubble was open upward parabolic distribution, and tended to be stable when it was greater than 6 g·L^{-1}, and the determination coefficient was 0.999.

In conclusion, within an appropriate salinity range, initial irrigation with brackish water at a concentration of 2–4 g·L^{-1} can promote plant growth. Plant growth is notably hindered when the irrigation water salinity surpasses 4 g·L^{-1}. However, under continuous brackish water irrigation, the overall soil salinity increases, leading to decreased water absorption capacity of the crops, which is unfavorable for plant growth.

3.4. Dynamic Simulation of Plant Height and Stem Diameter of Tomatoes

The overall growth process of crops shows a trend of "gradual growth-rapid growth-slow growth", forming an "S"-shaped curve [30], which is supported by the logistic model [19]. Therefore, this model was used to quantitatively analyze the dynamic development of plant height and stem diameter of protected tomatoes under different irrigation water salinities.

Table 3 presents the parameters of the logistic model for plant height and days of growth for each treatment. The correlation coefficient R^2 between the fitted values and measured values of the logistic model for all treatments is not less than 0.99. The parameters a_1 and b_1 varied greatly among different treatments. In contrast, the parameter c_1 changed slightly when the irrigation water salinity was less than 6 g·L^{-1} but increased significantly when it reached 6 g·L^{-1} or higher. The maximum plant heights obtained by fitting the logistic model for CK, T1, T2, T3, and T4 treatments were 158.36 cm, 165.55 cm, 169.32 cm, 133.41 cm, and 88.89 cm, respectively. The maximum growth rate of plant height V_{1max} increased initially and then decreased with the increase in irrigation water salinity, reaching its maximum at 54.51 days. The growth rate of plant height was in the growth stage, accelerating from 39.87 days after planting and entering the growth stage, decelerating from 69.14 days after planting until maturity. Rapid growth presented from 39.87 days to 69.14 days.

Table 3. Parameters of the logistic model for plant height of tomato in spring crops.

Treatment	Parameter Equation			R^2	Characteristic Parameter			
	a_1	b_1	c_1		V_1max	T_{11}	T_{21}	T_{31}
CK	158.36	124.41	0.08	0.99	3.17	60.29	43.83	76.76
T1	165.55	175.45	0.09	0.99	3.72	57.42	42.78	72.05
T2	169.32	160.27	0.09	0.99	3.81	56.41	41.78	71.04
T3	133.41	86.02	0.08	0.99	2.67	55.68	39.22	72.14
T4	88.89	168.52	0.12	0.99	2.67	42.73	31.75	53.70
Average	143.11	142.93	0.09	0.99	3.21	54.51	39.87	69.14

Table 4 depicts the parameters of the logistic model for stem diameter and development days. The correlation coefficients (R^2) between the fitted values and measured values of the logistic model for all treatments were not less than 0.99. The parameter c_2 showed slight variation, while the parameters a_2 and b_2 varied significantly among different treatments. For CK, T1, T2, T3, and T4 treatments, the maximum stem diameters of tomatoes fitted by the logistic model were 9.82 mm, 10.71 mm, 10.82 mm, 9.77 mm, and 9.61 mm, respectively. The maximum growth rate of stem diameter (V_{2max}) increased initially and then decreased with the increase in irrigation salinity, reaching its peak at 39.87 days. The growth rate of tomato stem diameter was in an accelerating phase 27.03 days after planting. Growth deceleration presented from 52.71 days after planting to the maturity stage, whereas the rapid growth period presented from day 27.03 to day 52.71.

Table 4. Parameters of logistic model for stem diameter of spring tomato.

Treatment	Parameter Equation			R^2	Characteristic Parameter			
	a_2	b_2	c_2		V_2max	T_{12}	T_{22}	T_{32}
CK	9.82	64.19	0.11	0.99	0.27	37.83	25.86	49.81
T1	10.71	50.46	0.09	0.99	0.24	43.57	28.94	58.20
T2	10.82	47.14	0.09	0.99	0.24	42.81	28.18	57.45
T3	9.77	61.44	0.11	0.99	0.27	37.44	25.46	49.41
T4	9.61	92.21	0.12	0.99	0.29	37.70	26.73	48.68
Average	10.15	63.09	0.10	0.99	0.26	39.87	27.03	52.71

3.5. The Impact of Saline Water Irrigation on Tomato Yield and Its Components

For tomatoes planted in the spring, the yield in each treatment showed a pattern of initial increase followed by a decrease as irrigation water salinity increased. The T1 treatment group demonstrated a substantial increase of 9.99% ($p < 0.05$), reaching 36,046.90 $Kg{\cdot}hm^{-2}$ compared to the CK group (control), while the T2–T4 treatment groups demonstrated a substantial reduction in yield ($p < 0.05$) compared to the CK group. The T4 treatment group had the lowest yield, with a decrease of 51.61%. The trends of individual plant yield and fruit set per plant were consistent with the overall yield. Irrigation with saline water at 2~4 $g{\cdot}L^{-1}$ considerably improved the fruit set per plant. Initially, the irrigation water use efficiency (IWUE) rose, followed by a subsequent decline as irrigation water salinity increased. The T1 treatment group had the highest IWUE, with an increase of 10.05%, while the lowest IWUE was observed in the T4 treatment group, with a decrease of 51.64%. Under continuous saline water irrigation, the yield indicators and IWUE of tomatoes planted in the autumn season significantly decreased. The T1 and T2 treatment groups only yielded 24,427.42 and 16,774.86 $Kg{\cdot}hm^{-2}$, respectively, showing a decline of 32.2% and 46.1% compared to the spring season. With increasing irrigation water salinity, the yield reduction became more pronounced. The T4 treatment resulted in almost no yield.

In Figure 6, the linear regression equation and the quadratic regression equation were established by taking the tomato yield as the dependent variable and the irrigation salinity as the independent variable. The fitting curve of spring crop yield and irrigation salinity was open downward parabolic distribution, the coefficient of determination was 0.951, and reached the peak at 2 $g{\cdot}L^{-1}$. However, the fitting curve of autumn crop yield and irrigation salinity was open upward parabolic distribution, the coefficient of determination was 0.980, and crops in the autumn season almost had no yield when the irrigation salinity was over 8 $g{\cdot}L^{-1}$. It was further indicated that the initial irrigation salinity of 2 $g{\cdot}L^{-1}$ saline water irrigation could significantly increase tomato yield, but continuous saline water irrigation would lead to yield reduction.

These results revealed that initial irrigation with saline water at a 2–4 $g{\cdot}L^{-1}$ salinity level can ensure tomato yield and IWUE. However, irrigation with saline water exceeding 4 $g{\cdot}L^{-1}$ significantly inhibited crop growth and significantly decreased the yield. Additionally, continuous irrigation with saline water at 2–4 $g{\cdot}L^{-1}$ also adversely affected crop growth (Table 5).

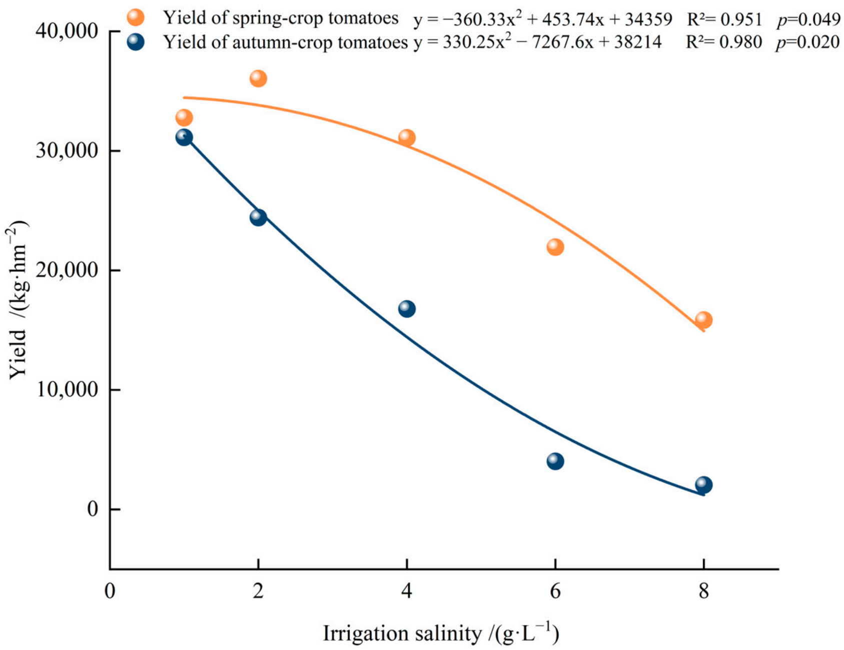

Figure 6. Relationship between tomato yield and irrigation salinity in greenhouse.

Table 5. Yield components and irrigation water use efficiency of tomato in spring.

	Treatment	Fruit Number per Plant /ind	Fruit Weight /g	Yield per Tree /g	Yield /(Kg·hm^{-2})	IWUE /(Kg·m^{-3})	Yield Rank
Spring	T1	8.0 ± 0.02 a	90.43 ± 3.63 b	720.92 ± 6.8 a	36,046.90 ± 36.88 a	12.04 ± 0.06 a	1
	T2	7.9 ± 0.11 a	78.82 ± 4.13 c	621.80 ± 7.82 c	31,093.40 ± 39.45 c	10.38 ± 0.32 b	3
	T3	6.7 ± 0.01 c	73.18 ± 1.85 d	439.08 ± 6.52 d	21,954.14 ± 32.20 d	7.31 ± 0.38 c	4
	T4	5.2 ± 0.26 d	60.20 ± 5.65 e	317.10 ± 2.15 e	15,855.83 ± 41.83 e	5.29 ± 0.01 d	5
	CK	6.6 ± 0.40 b	99.37 ± 3.41 a	655.44 ± 2.66 b	32,772.02 ± 37.11 b	10.94 ± 0.36 b	2
Autumn	T1	6.7 ± 0.14 b	72.91 ± 3.63 b	488.55 ± 3.63 b	24,427.42 ± 22.75 b	8.16 ± 0.02 b	2
	T2	5.9 ± 0.35 c	56.86 ± 3.63 c	335.50 ± 3.63 c	16,774.86 ± 18.12 c	5.61 ± 0.07 c	3
	T3	3.5 ± 0.02 d	22.99 ± 3.63 d	80.49 ± 3.63 d	4024.98 ± 8.77 d	1.36 ± 0.04 d	4
	T4	2.2 ± 0.03 e	18.65 ± 3.63 e	41.03 ± 3.63 e	2051.54 ± 9.14 e	0.70 ± 0.01 e	5
	CK	6.4 ± 0.21 a	97.29 ± 3.63 a	622.67 ± 3.63 a	31,133.42 ± 15.33 a	10.39 ± 0.05 a	1

The same alphabet on the right side of the same list shows no significance ($p > 0.05$), in contrast, having significance ($p < 0.05$).

4. Discussion

4.1. Impact of Saline Irrigation on Soil Water and Salt Concentration

Irrigation with saline water can relieve the contradiction between water supply and demand to some extent but leads to soil salinization, which affects crop growth and yield [14]. Soil salt concentration undergoes dynamic accumulation and leaching processes impacted by various factors including irrigation and evaporation. The current report revealed that the soil moisture in the 0–80 cm depth range initially increases and then decreases. Compared to freshwater irrigation, saline irrigation significantly increases soil moisture content, consistent with the outcomes reported by Guo et al. [31]. This can be attributed to the fact that the infiltration depth of drip irrigation for protecting tomatoes mainly concentrates in the soil layer above 60 cm. Under the effect of evaporation, surface soil moisture is lost rapidly, while deep soil is less affected. Furthermore, as irrigation salinity increases, soil salt concentration also significantly increases, indirectly reducing the water uptake capacity of crop roots and leading to the accumulation of unused soil moisture in the root zone. Li et al. [21] observed that deep soil moisture content was significantly higher than shallow soil moisture content, which is different from the results of this study showing an initial augmentation followed by a reduction in soil moisture content with depth. This variance may be attributed to the shallow groundwater depth in the previous study areas, which greatly influenced soil moisture content. However, in our experiment, the groundwater level was 3.5 m or more below the ground, resulting in less impact on soil moisture content in the tillage layer. Salt concentration decreases gradually with an increase in depth, with most salt accumulation occurring in the shallow soil layer.

Moreover, salt concentration increases with the augmentation in irrigation salinity, indicating that saline irrigation increases soil salt concentration. Moreover, evaporation from soil leads to the accumulation of salts at the soil surface [32]. This study found that salt concentration in the shallow soil layer fluctuated and elevated to varying degrees during the growth period. This can be attributed to the leaching effect of saline irrigation on soil salts, which washes excessive salt into the deeper soil layers [33]. The shallow soil layer undergoes varying degrees of fluctuation and elevation during the growth period due to the combined effects of salt leaching from irrigation and salt accumulation from evaporation. In contrast, the deep soil experiences less leaching from irrigation, leading to a continuous increase in salt concentration. The higher the salinity level, the more pronounced the salt accumulation in the deep soil. Although different salinity gradient treatments were used in various studies on saline irrigation, the overall result indicates that the average soil salt concentration increases with the increase in irrigation salinity [34]. However, Li et al. [21] found that saline irrigation did not increase soil salt concentration but instead redistributed the existing salts within the soil. This was due to significant rainfall during their experimental period, which resulted in the leaching of soil salts to deeper soil layers, weakening the impact of saline irrigation on soil salt concentration. In our experiment conducted in a greenhouse without rainfall interference, soil salt concentration significantly increased after multiple saline irrigation events.

4.2. Impact of Saline Irrigation on Tomato Growth

Soil is the material foundation for crop survival. Under saline irrigation conditions, especially high-frequency saline drip irrigation, the salinity in the soil solution within a certain range around the plant's root zone is primarily affected by the salt introduced by irrigation water [21]. After continuous saline irrigation, different irrigation salinity levels result in significant variance in the soil water and salt environment, affecting plant growth and yield to varying degrees [35]. Yang et al. [36] observed that when the salinity level of irrigation water was between 1 and 3 $g \cdot L^{-1}$, it promoted crop growth, and the trends in plant height and stem diameter growth were consistent. However, when the salinity level reached 5 $g \cdot L^{-1}$, plant height and stem diameter growth were significantly inhibited, which aligns with the results of this study. The findings of this research revealed that the salinity of irrigation water greatly impacts plant growth, with significant differences observed among the treatments ($p < 0.05$). Overall, using slightly saline water with a salinity level of 2–4 $g \cdot L^{-1}$ promotes the height and stem diameter growth of tomato plants, while a salinity level of 6–8 $g \cdot L^{-1}$ has a noticeable inhibitory effect. This aligns with earlier research [37], which concluded that irrigation with slightly saline water within an appropriate salinity range can promote tomato growth. Furthermore, the height and stem diameter of tomato plants in the autumn season were significantly lower than those in the spring season, indicating that an appropriate salinity level in irrigation water promotes crop growth to some extent, while continuous saline water irrigation leads to severe soil salt accumulation, which is detrimental to crop growth.

In most cases, the growth rate of crops starts slow, then accelerates, and eventually slows down until the growth rate reaches zero [38]. Scholars have proposed several S-shaped growth curves to describe this growth pattern of organisms. Among these models, the logistic model is comparatively simple and reliable [39,40]. In the present report, the logistic model was used to simulate the dynamic growth process of protected tomato plants under saline water irrigation conditions, and the fitting accuracy with an R^2 value greater than 0.99 was high. Therefore, the logistic model can accurately describe the dynamic growth process of protected tomato plants under different saline water irrigation conditions.

On the whole, when the salinity of irrigation water was less than 4 g·L^{-1}, it could promote the absorption of water by crops to a certain extent, and then promote the growth of plant height and stem diameter, and this promotion effect gradually decreased with the increase in salinity of irrigation water. When the salinity of irrigation water is greater than 4 g·L^{-1}, it has a certain inhibition effect on the water absorption capacity of crops, which in turn inhibits the growth of plants, resulting in some water remaining in the soil and unable to be absorbed and utilized, and this inhibitory effect gradually increases with the increase in irrigation salinity. Under the condition of continuous saline water irrigation, the continuous accumulation of soil salt content leads to the inhibition of plant growth, which decreases with the increase in irrigation salinity.

4.3. The Impact of Saline Water Irrigation on Tomato Yield and Its Components

Numerous experiments have elucidated that for some salt-tolerant crops, saline or slightly saline water can achieve yields comparable to or even approaching freshwater irrigation [41]. However, long-term continuous saline water irrigation has the potential to cause the accumulation of salt, altering the water–salt movement in the soil and the soil environment in farmland and ultimately reducing crop productivity by impeding water absorption [42,43]. Wan et al. [44] found that as the salinity of irrigation water increased, the water use efficiency of okra decreased. Yao et al. [45] investigated how saline water drip irrigation impacted the water use efficiency of preserved vegetables. They found a significant decrease in yield under saline water stress conditions with the same amount of irrigation.

Similarly, this study found that as the salinity level of irrigation water exceeded 2 g·L^{-1}, water use efficiency (WUE) and dry matter accumulation gradually decreased. However, some studies suggested that irrigation with slightly saline water can stimulate crop growth within a specific range without significantly reducing or increasing crop yields and improve water resource utilization efficiency [10]. It is consistent with the findings of this study that when the irrigation water salinity is 2 g·L^{-1}, the growth indicators, yield, and water use efficiency of protected tomatoes in the spring season are higher than those under freshwater irrigation.

Salt stress has a negative impact on crop growth and yield, which aligns with the outcomes of prior reports [46,47]. The findings of this study show that when the salinity level of irrigation water exceeds 4 g·L^{-1}, salt stress has a considerably negative affect on crops, and all treatments of long-term saline water irrigation significantly reduce tomato yield. When salinity exceeds 4 g·L^{-1}, tomato production approaches zero. Yang et al. [36] believed that saline water at 1–3 g·L^{-1} promotes crop growth, and the trends in plant height and stem diameter growth are consistent, namely rapid growth presented during the flowering and fruiting stages, followed by a stable growth phase towards the end of the growth stage. When the salinity level reaches 5 g·L^{-1}, plant height and stem diameter are significantly inferior compared to those treated with a salinity level of 1–3 g·L^{-1}, which is consistent with the outcomes of this report. However, their study showed no significant effect of different irrigation water salinity levels on tomato yield. This differs from the findings of this study that irrigation with saline water at 2–4 g·L^{-1} ensures a high tomato yield, while a salinity level of 6–8 g·L^{-1} significantly reduces the yield. This discrepancy may be because they adopted drip irrigation under the plastic film method, which allowed salt to leach into the deep soil layers and between furrows after irrigation. However, mulching effectively suppressed evaporation from the soil, reducing the accumulation of salts in the root zone of the crops and weakening the impact of water salinity on crops. In addition, the maximum salinity level of its irrigation water is relatively low, only 5 g·L^{-1}. In previous studies, the threshold for the effect of irrigation water salinity on crop yield failed to be identified. The different tomato varieties used in the experiment may have varying salt tolerance. All of these contribute to diverse research outcomes. Single fruit weight is an important indicator of tomato yield. In our experiment, no significant difference was observed in single fruit quality between saline and freshwater irrigation when the irrigation water salinity level was less than 2 g·L^{-1}. However, the single fruit quality significantly decreased when the irrigation water salinity level exceeded 4 g·L^{-1}. This outcome aligns with those of Zhai et al. [48]. The decrease in single fruit weight also led to a decline in crop yield [49]. Moreover, this experiment found that although irrigation with 2–4 g·L^{-1} saline water ensured high spring yields and water use efficiency, continuous irrigation with less saline water also significantly accumulated salts in the soil. This inhibited the water absorption capacity of crop roots, leading to unfavorable consequences for both crop growth and yield.

5. Conclusions

(1) Soil moisture content showed a gradual increase in the 0–40 cm soil layer and a gradual decrease in the 40–80 cm soil layer, presenting a "high in the middle and low at both ends" pattern. Soil moisture primarily accumulated at a depth of 40 cm, with relatively lower moisture content in the surface and deep soil layers. Horizontally, the soil moisture content of each treatment initially increased and then decreased with the distance from the drip irrigation belt. The extent of the wet area and soil moisture content gradually increased with the increase in salinity level. Under continuous saline water irrigation, the range of moist soil area expanded during autumn, and the moisture content significantly increased compared to spring.

(2) Soil salinity decreased gradually with soil depth, with significantly higher salt concentration in the 0–20 cm soil layer compared to the 40–80 cm soil layer. As the growth stage progressed, the salt concentration in the 0–20 cm soil layer increased gradually for different saline water irrigation treatments. The higher the salinity level, the more apparent the accumulation of salts in the shallow soil layer. Treatment T3 and T4, which had higher salinity levels, showed a continuous increase in salt concentration in the 40–80 cm soil layer during the growth stage, indicating significant salt accumulation. The soil salt concentration of the profile was positively correlated with the irrigation water salinity level, with an increase of 84.70%, 153.17%, 362.89%, and 480.79%, respectively, for different saline water drip irrigation treatments compared to the control group (CK). Under continuous saline water irrigation, soil salinity in different soil layers continued to increase for tomatoes planted in autumn, with the maximum average soil salt concentration reaching 6.28 and 7.74 g·kg^{-1} for treatments T3 and T4, respectively.

(3) The plant height and stem diameter of protected tomato planted in spring followed the order T2 > T1 > CK > T3 > T4. The cumulative dry matter decreased gradually with the increase in the irrigation water salinity level, with the order at the end of the growth stage being CK > T1 > T2 > T3 > T4. Generally, when the irrigation water salinity level was less than 4 g·L^{-1}, it promoted tomato plant growth without significantly impacting dry matter. However, plant growth was inhibited when the salinity level exceeded 4 g·L^{-1}. Appropriate salinity levels for saline water irrigation were beneficial for crop growth, while continuous saline water irrigation inhibited plant growth in all treatments.

(4) The first period of irrigation with 2 g·L^{-1} saline water significantly increased the yield of spring tomatoes and promoted the absorption and utilization of water by plants. However, the yield began to decline when the irrigation water salinity level exceeded 4 g·L^{-1}. A significant positive correlation was noted between yield and the number of fruits per plant and single fruit weight. Under continuous saline water irrigation, tomatoes planted in autumn showed a significant decrease in yield compared to those planted in spring for all the treatments.

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