



Article

Slightly Saline Water Improved Physiology, Growth, and Yield of Tomato Plants in Yellow Sand Substrate

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Abstract: Efficient utilization of saline water and yellow sand resources can enhance water and soil resource management while boosting crop yields in Xinjiang. This study conducted a two-season field experiment in Alar City, Xinjiang, from March to July 2023 and August 2023 to January 2024. The objective was to examine the effects of different irrigation water salinities (2, 3, 4, 5, and 6 g·L⁻¹) on the physiology, growth, and yield of sand-cultured tomatoes grown in yellow sand slag. Groundwater irrigation with salinity levels of 0.8–1 g·L⁻¹ was used as the control (CK). The results showed that the salinity of the substrate gradually increased with the salinity of irrigation water in each treatment. The salt accumulation increased by 59.5%, 82.5%, and 99.5% at the end of the experiment for T3 (4 g·L⁻¹), T4 (5 g·L⁻¹), and T5 (6 g·L⁻¹), respectively, compared to CK. As the salinity of irrigation water increased, plant height, stem thickness, chlorophyll content, net photosynthesis rate, stomatal conductance, transpiration rate, and total yield of tomato showed an increasing and then decreasing trend, in which the total tomato yield of the T2 (3 g·L⁻¹) treatment was significantly increased by 35.2% compared with that of CK between the two seasons. In contrast, as the salinity of irrigation water increased, the inter-cellular CO₂ concentration of tomato leaves showed a decreasing and then increasing trend, with the T2 treatment having the lowest inter-cellular CO₂ concentration. Pathway analysis revealed that appropriate salinity levels increased tomato yield by regulating inter-cellular CO₂ concentration. Based on these findings, a 3 g·L⁻¹ salinity level is recommended for irrigating sand-cultured tomatoes to maximize yellow sand resource use, address freshwater shortages, and optimize water and soil management in the Xinjiang region.



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Keywords: greenhouse tomato; growth and yield; irrigation water salinity; physiological characteristics; sand-cultured

1. Introduction

Southern Xinjiang, located at the northwestern border of China, typifies a dry climate characterized by low precipitation and high evaporation, typical of a temperate continental arid climate [1]. This region encounters a scarcity of freshwater resources but possesses abundant saline water resources. The judicious and scientific utilization of saline water resources can mitigate the freshwater resource crisis, ensuring a more stable water resource supply for residents and agricultural production. Moreover, it can enhance crop stress resistance, improve yield and quality, and promote sustainable agricultural development [2]. El-Mogy et al. established six NaCl salt concentrations and found that cherry tomato yield was not affected by irrigation water salinity of 0.26 dS·m⁻¹ compared to freshwater.

Furthermore, this salinity level improved the flavor index of the cherry tomatoes [3]. When the electrical conductivity (EC) $\geq 4.7 \text{ dS}\cdot\text{m}^{-1}$, it can substantially elevate the content of soluble solids, reducing sugars, organic acids, and vitamin C in tomatoes, with an optimal sugar–acid ratio (7.40–9.80) [4]. Irrigation water salinity of $0.30\text{--}0.50 \text{ g}\cdot\text{L}^{-1}$ significantly improved cucumbers' net photosynthetic rate, yield, and vitamin C content [5]. Nevertheless, Zhang et al. [6] observed that high-concentration saline water irrigation markedly elevated soil salinity in the cotton root zone through a 15-year field experiment, and the sodium adsorption ratio and pH in the 0–30 cm soil layer were significantly increased post-cotton harvest. The prolonged use of saline water irrigation can accumulate soil salt, leading to soil surface crusting, aggregate instability, and reduced permeability, severely constraining soil sustainability [7,8]. Additionally, high soil salinity reduces the water uptake capacity of the plant root system, inducing osmotic stress, ion toxicity, and oxidative damage to membrane systems. This can precipitate secondary oxidative stress and nutrient imbalance, which alters physiological indicators and negatively affects crop growth and yield [9,10].

In response to the issue of soil salinization caused by long-term saline water irrigation, many scholars have undertaken extensive theoretical research and practical efforts. Akhtar et al. [11] found that biochar can reduce the adverse effects of salinity by increasing soil moisture content and releasing mineral nutrients into the soil solution, reducing soil osmotic stress and reducing plant uptake of Na^+ . Li et al. [12] explored the effects of deep burial on water and salt dynamics in saline soil and found that these techniques effectively inhibit soil salt accumulation and improve water utilization efficiency. The application of soil amendments has been demonstrated to maintain the dynamic balance of soil water and salt, reduce pH, improve soil physicochemical properties, and thus significantly increase yields of tomatoes [13,14], cotton [15], and corn [16]. However, rational irrigation and drainage strategies, freshwater leaching, and soil amendments necessitate substantial investments in labor, materials, finances, and freshwater resources and fail to resolve soil salinization issues fundamentally [17]. Therefore, addressing the challenges of soil salinization and continuous cropping in protected agriculture to improve crop quality and yield simultaneously has become a global priority [18].

Substrate cultivation, recognized as an advanced mode of plant growth, holds extensive development prospects in China. This method can mitigate issues such as soil salinization and continuous cropping obstacles, provides a solution for saline water utilization, and improve crop yields and quality, thereby facilitating sustainable, healthy, and safe growth of the local fruit and vegetable industry [19]. Olubanjo et al. [20] contrasted protected cultivation employing two distinct organic substrates, rice husks and sawdust, with traditional soil cultivation. These study results indicated that tomatoes cultivated in rice husk and sawdust substrates demonstrated superior physiological morphology and growth than those cultivated in soil. The number of rhizobial microorganisms and the level of enzyme activity in tomato seedlings could be significantly increased when the volume ratio of peat—slag—vermiculite was 1:1:1, promoting the growth and development of tomatoes cultivated in protected areas [21]. Raja et al. [22] discovered that the mixtures of coconut peat and vermiculite in a 25:75 ratio, as well as the combination of coconut peat, perlite, and vermiculite in a 50:25:25 ratio, positively influence the growth and development of strawberries and enhance their quality. However, commercial lightweight substrates such as peat, perlite, and vermiculite are relatively costly, making their large-scale application and economic promotion burdensome. Wang et al. [23] found that incorporating yellow sand can effectively ameliorate soil structure, bolster water infiltration and retention capabilities, and consequently mitigate soil salinization. Slag exhibits remarkable water retention and robust adsorption abilities, effectively minimizing water evaporation [24]. Utilizing locally sourced materials like yellow sand and slag as growth substrates can augment plant chlorophyll content, stimulate photosynthesis, and elevate crop yield and quality [25].

Xinjiang is located on the northwestern border of China and has abundant deposits of yellow sand. The lack of freshwater resources and soil salinization are the main factors limiting agricultural production in Xinjiang and contributing to surface and groundwater being predominantly brackish. Therefore, how can abundant natural resources such as yellow sand and brackish water be utilized to establish a new agricultural technology model and provide a new direction for water and soil scarcity in Xinjiang? In this experiment, six groups with different irrigation water salinity were selected to analyze the following three problems: (1) to analyze the effects of different irrigation water salinity on the dynamic changes of substrate salinity; (2) to clarify the response mechanism of physiological growth and yield of sand-cultured tomatoes to distribute salinity in the substrate under different irrigation water salinity; and (3) to determine the threshold of irrigation water salinities suitable for the high yield and quality products of sand-cultured tomatoes in southern Xinjiang.

2. Materials and Methods

2.1. Experimental Materials

The experiment spanned from March to July 2023 and from August 2023 to January 2024 within a solar greenhouse at the Water-Saving Irrigation Experimental Base, College of Water Resources and Civil Engineering, Tarim University, situated in Alar City, Xinjiang Production and Construction Corps First Division ($40^{\circ}32'30''$ N, $81^{\circ}17'53''$ E, altitude 1020 m). The greenhouse length is 40 m, the width is 20 m, the ridge height is 5.5 m, and the eaves height is 4.8 m. The tomato variety “Dongsheng No. 1” was selected for this study. Yellow sand and furnace slag, employed as substrate materials, were sourced from the Ninth Regiment’s sand field and the Twelfth Regiment’s boiler room, respectively, belonging to the Xinjiang Production and Construction Corps First Division. The cultivation substrate was formulated by thoroughly mixing yellow sand and furnace slag at a volume ratio of 5:3 [25]. The basic physicochemical properties of the substrate included a bulk density of $1.28 \text{ g}\cdot\text{cm}^{-3}$, a total porosity of 26.9%, an EC value of $660.7 \mu\text{S}\cdot\text{cm}^{-1}$ and a pH value of 7.73. Temperature fluctuations within the greenhouse were tracked using a WS-C digital temperature and humidity recorder (as depicted in Figure S1).

2.2. Experimental Design

A sand-cultured cultivation model was utilized in the experiment, incorporating five salinity gradients: $2 \text{ g}\cdot\text{L}^{-1}$ (T1), $3 \text{ g}\cdot\text{L}^{-1}$ (T2), $4 \text{ g}\cdot\text{L}^{-1}$ (T3), $5 \text{ g}\cdot\text{L}^{-1}$ (T4), and $6 \text{ g}\cdot\text{L}^{-1}$ (T5). Local groundwater irrigation ($0.8\text{--}1 \text{ g}\cdot\text{L}^{-1}$) served as the control, creating six treatments. Each treatment was replicated three times, amounting to 18 experimental plots. Rigid PVC plastic cultivation troughs were employed, each measuring 5.90 m in length, 50 cm in width, and 30 cm in depth. A flow guide plate was installed at the end of each trough. The planting arrangement consisted of one row with two drip lines per trough (as depicted in Figure 1), maintaining a plant spacing of 0.20 m and a trough spacing of 1.00 m. Each cultivation trough accommodated 27 plants. The total irrigation volume throughout the growing season amounted to 310 mm [25]. Freshwater was used during the seedling stage, while saline water was used for subsequent growth and development stages. The $2 \text{ g}\cdot\text{L}^{-1}$ and other saline water treatments were prepared by mixing freshwater with chemical reagents Na_2SO_4 , NaCl , NaHCO_3 , CaCl_2 , and MgCl_2 in a mass ratio of 8:8:1:1:1 [26]. The specific growth stages are detailed in Table 1. The nutrient solution was formulated following the Yamazaki formula [27]. Inline emitter drip tapes were utilized, featuring emitter spacing of 0.20 m, a nominal working pressure of 0.05 MPa, and a nominal flow rate of $1.80 \text{ L}\cdot\text{h}^{-1}$.

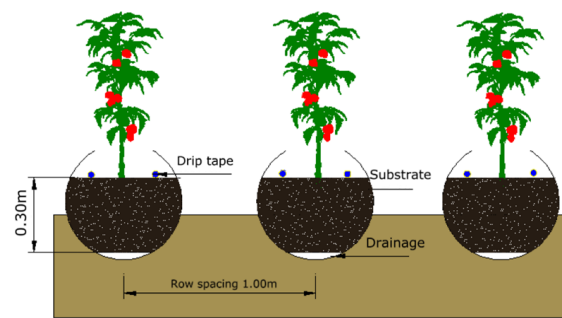


Figure 1. Planting pattern.

Table 1. Division of tomato fertility stage.

Growth Stage	Spring Start and End Times	Autumn Start and End Times
Seedling stage	24 March 2023–3 May (40 d)	27 August 2023–6 October (40 d)
Blooming stage	4 May 2023–11 May (7 d)	7 October 2023–14 October (7 d)
Fruiting stage	12 May 2023–13 June (32 d)	15 October 2023–20 November (36 d)
Fruit flourishing stage	14 June 2023–10 July (26 d)	21 November 2023–23 December (32 d)
Late stage	10 July 2023–18 July (8 d)	24 December 2023–5 January 2024 (12 d)

2.3. Measurement Items and Methods

2.3.1. Substrate Salinity Determination

After each tomato growth stage, vertical samples were collected beneath the drip irrigation belt using a small soil auger at depths of 5 cm, 15 cm, and 25 cm. The substrate samples were thoroughly mixed with water at a volume ratio of 5:1. Determination of the extracted liquid's electrical conductivity (EC) using the conductivity meter DDSJ-308A (Jiangsu Shenglan Instrument Manufacturing Co., Ltd., Changzhou, China). The substrate's salt content was calculated using the calibrated relationship between substrate salt content and EC ($y = 0.0037x - 0.3885$, $R^2 = 0.9925$).

2.3.2. Plant Growth Parameters Measurement

Ten days post the tomato seedling recovery stage, five seedlings exhibiting uniform growth were randomly selected and labeled for each treatment to measure plant height and stem diameter. Plant height was recorded using a ruler from the base of the root to the apical growing point, representing the natural height. Stem diameter was measured using the cross-sectional method with a vernier caliper positioned 2 cm above the ground.

The logistic crop growth model, which displays an “S”-shaped trend, was used, and the basic form of the fitting formula is [28]:

$$Y = Y_m / (1 + ae^{-bx}) \quad (1)$$

$$t_1 = -\frac{1}{b} \ln \left(\frac{2 + \sqrt{3}}{a} \right) \quad (2)$$

$$t_2 = -\frac{1}{b} \ln \left(\frac{2 - \sqrt{3}}{a} \right) \quad (3)$$

$$V_m = -\frac{bY_m}{4} \quad (4)$$

$$t_m = -\frac{\ln a}{b} \quad (5)$$

$$t = t_2 - t_1 \quad (6)$$

where Y is tomato growth indicators (plant height and stem diameter), Y_m is the theoretical maximum value of tomato growth indicators, a , b , and k represent growth parameters, t is the number of days after transplanting, t_1 is the start time of the fastest growth stage, t_2 is the end time of the rapid growth stage, V_m is the maximum relative growth rate, t_m is the time when it occurs, and t is the duration of rapid accumulation.

2.3.3. Plant Physiological Indicators Determination

Chlorophyll determination: Twenty-four hours post-irrigation during the flowering, fruit-setting, and peak fruit-bearing stages, leaves from three tomato plants were sampled for chlorophyll measurement. The fresh leaves were cleansed and segmented into small pieces, and chlorophyll content was assessed using the 95% ethanol extraction method.

Photosynthetic indices: Three representative plants from each treatment were randomly chosen. The net photosynthetic rate (P_n), transpiration rate (Tr), stomatal conductance (G_s), and inter-cellular CO_2 concentration (C_i) of the fourth functional leaf from the apex downward were measured utilizing a Li-6400 XT portable photosynthesis system between 11:00 am and 1:00 pm.

2.3.4. Yield and Path Analysis

Fruits were restricted to five clusters per plant, and each cluster was harvested individually at maturity. The weight of each cluster was recorded using an electronic scale with an accuracy of 0.01 kg. The yield per plant was computed, and the final yield was extrapolated based on planting density.

The following formula was used for the path analysis:

$$P_{ij} = r_{ij} \times P_{yj} \quad (7)$$

where P_{ij} is the indirect path coefficient (the effect of independent variable i on the dependent variable Y through independent variable j), r_{ij} is the correlation coefficient between i and j , and P_{yj} is the standardized coefficient (path coefficient) of j concerning the dependent variable.

2.4. Data Processing

The data were organized and analyzed using Microsoft Excel 2018. Graphical representations were created utilizing Origin 2021 software. Significant differences among treatments were determined through Duncan's multiple range test ($p < 0.05$) in SPSS 20.0.

3. Results and Analysis

3.1. Effects of Different Irrigation Water Salinity Levels on Salt Dynamics in Yellow Sand Substrate

Figure 2 illustrates the dynamic changes in salt content within the 0–25 cm substrate layer under varying irrigation water salinity levels during the spring and autumn seasons. It was observed that salt content decreased with depth in all treatments at different growth stages, with salinity remaining high in the surface layer. At the same irrigation rate, the average salinity of 0–25 cm substrate with different mineralization levels of irrigation water showed an increasing, decreasing and finally, increasing trend with fertility progressed, reaching a peak at the end of the fruiting stage. The average substrate salinity of the CK-T5 treatments reached 4.99, 5.99, 6.58, 8.13, 9.29, and 9.71 $g \cdot kg^{-1}$ between the two seasons, respectively. The average substrate salt content progressively increased with higher irrigation water salinity throughout the growth stage. The salt accumulation effect was more obvious in the T3, T4, and T5 treatments, with the average salinity of the substrate as high as 5.05, 5.78, and 6.32 $g \cdot kg^{-1}$, which increased by 59.5%, 82.5%, and 99.5% in T3, T4, and T5 treatments, respectively, as compared with the CK treatment between the two seasons. This indicated that the average substrate salt content progressively increased with higher irrigation water salinity throughout the growth stage.

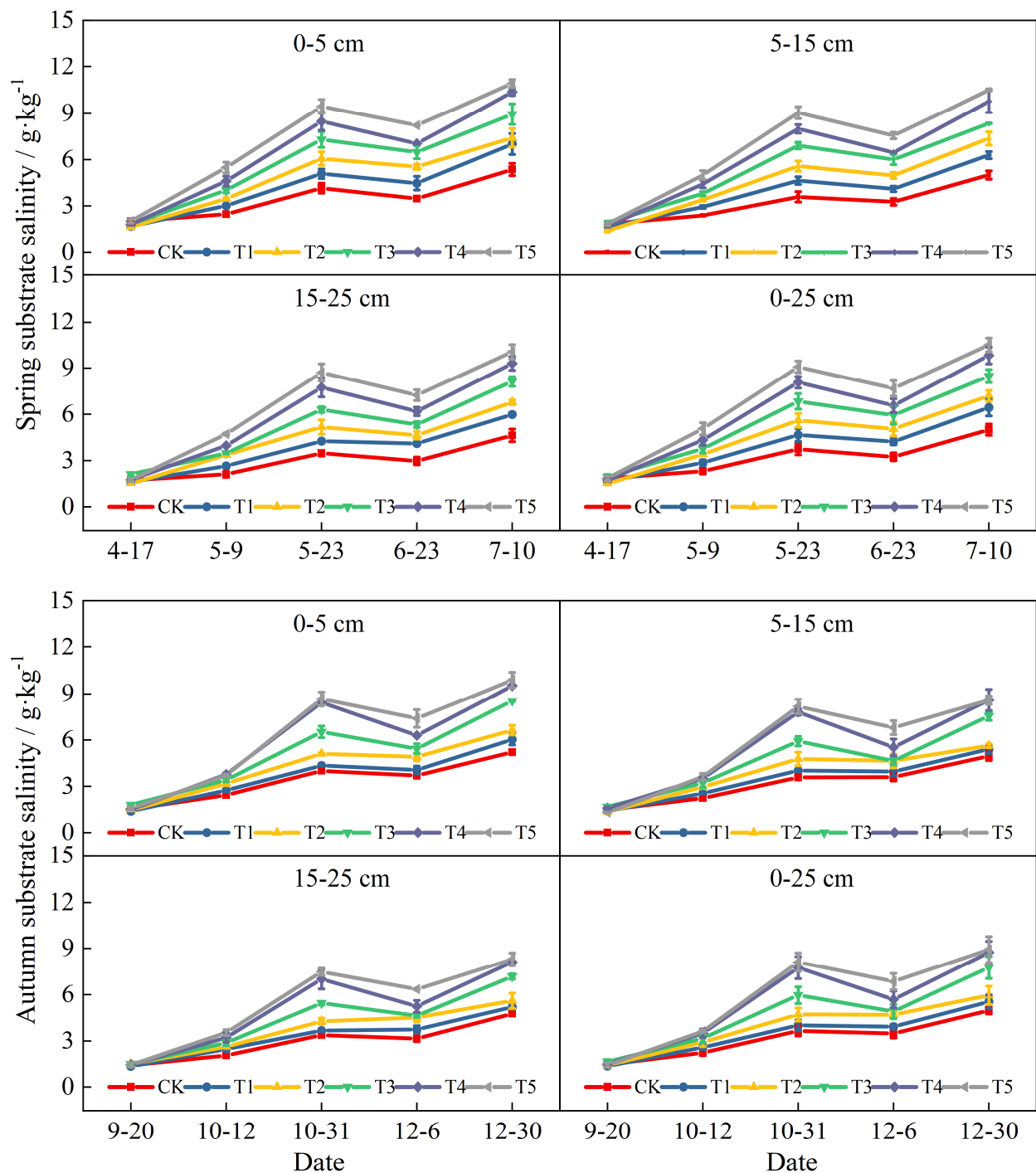


Figure 2. Salinity dynamics in the yellow sand substrate under different irrigation water salinity levels. (The values reported in Figure 2 are the mean of three replicates of substrate salinity. The error line indicates the standard error of the three replicate values.).

3.2. Effects of Different Irrigation Water Salinity Levels on Physiological Characteristics of Sand-Cultured Tomatoes

3.2.1. Dynamic Changes in Tomato Chlorophyll Content during the Growing Stage

Table 2 illustrates the changes in chlorophyll content in tomatoes over the spring and autumn seasons. Tomato entered the flowering stage, and the chlorophyll a, chlorophyll b, and carotenoid contents of tomato leaves in spring and fall showed an increasing and then decreasing trend with the increase of salinity of irrigation water. The chlorophyll a and chlorophyll b of the T3 treatment reached the maximum value, with no significant difference

compared with the CK's ($p > 0.05$). In contrast, the carotenoid content significantly increased by 17.8% compared with the CK treatment ($p < 0.05$) at the fruiting stage. The trends of chlorophyll a and b in all treatments showed that $T3 > T2 > T1 > CK > T4 > T5$. The chlorophyll a content of T1, T2, and T3 increased by 6.24%, 7.18%, and 11.3%, respectively, while the chlorophyll b content increased by 1.44%, 8.22%, and 11.0% compared with the CK treatment. Meanwhile, the chlorophyll a and b of the T4 (T5) treatment decreased by 3.97% (5.48%) and 9.07% (8.22%) compared with the CK treatment. The trends of the chlorophyll a, chlorophyll b, and carotenoid contents of all treatments showed $T2 > T1 > CK > T3 > T4 > T5$ during the fruit flourishing stage. Compared with CK, the chlorophyll a, chlorophyll b, and carotenoid contents of the T2 treatment increased by 11.7%, 25.0%, and 6.74%, respectively, and the T5 treatment significantly decreased by 13.8%, 18.0%, and 15.7% ($p < 0.05$).

Table 2. Dynamics of chlorophyll content in tomato during the reproductive stage.

Fertile Stage	Treatment	Spring			Autumn		
		Chlorophyll A	Chlorophyll B	Carotenoid	Chlorophyll A	Chlorophyll B	Carotenoid
The blooming stage	CK	2.26 ± 0.13 a	0.71 ± 0.01 a	0.46 ± 0.04 bc	1.99 ± 0.02 ab	0.53 ± 0.01 ab	0.44 ± 0.01 c
	T1	2.23 ± 0.14 a	0.64 ± 0.05 b	0.44 ± 0.04 bc	2.02 ± 0.16 ab	0.52 ± 0.04 ab	0.47 ± 0.04 bc
	T2	2.36 ± 0.18 a	0.74 ± 0.04 a	0.49 ± 0.03 ab	2.08 ± 0.02 a	0.54 ± 0.01 ab	0.51 ± 0.04 ab
	T3	2.43 ± 0.11 a	0.75 ± 0.05 a	0.52 ± 0.02 a	2.12 ± 0.04 a	0.55 ± 0.05 a	0.54 ± 0.03 a
	T4	1.99 ± 0.04 b	0.53 ± 0.01 c	0.40 ± 0.01 cd	1.97 ± 0.16 ab	0.52 ± 0.05 ab	0.43 ± 0.02 c
	T5	1.89 ± 0.12 b	0.54 ± 0.01 c	0.38 ± 0.03 d	1.86 ± 0.09 b	0.47 ± 0.02 b	0.42 ± 0.04 c
The fruiting stage	CK	2.87 ± 0.02 bcd	0.65 ± 0.00 bcd	0.73 ± 0.02 bc	2.42 ± 0.03 b	0.81 ± 0.08 abc	0.51 ± 0.03 bc
	T1	3.03 ± 0.17 abc	0.67 ± 0.02 abc	0.79 ± 0.06 ab	2.59 ± 0.08 a	0.81 ± 0.04 ab	0.54 ± 0.02 ab
	T2	3.06 ± 0.20 ab	0.70 ± 0.01 ab	0.81 ± 0.05 a	2.61 ± 0.16 a	0.88 ± 0.06 a	0.51 ± 0.04 bc
	T3	3.17 ± 0.07 a	0.72 ± 0.03 a	0.82 ± 0.00 a	2.72 ± 0.01 a	0.90 ± 0.01 a	0.57 ± 0.02 a
	T4	2.75 ± 0.15 cd	0.60 ± 0.06 cd	0.69 ± 0.04 cd	2.33 ± 0.14 b	0.78 ± 0.06 bc	0.47 ± 0.04 cd
	T5	2.65 ± 0.21 d	0.63 ± 0.02 d	0.65 ± 0.05 d	2.16 ± 0.01 c	0.71 ± 0.05 c	0.43 ± 0.01 d
The fruit flourishing stage	CK	2.24 ± 0.06 bc	0.58 ± 0.01 c	0.56 ± 0.02 ab	1.53 ± 0.03 bc	0.42 ± 0.02 bc	0.33 ± 0.01 bc
	T1	2.36 ± 0.14 ab	0.66 ± 0.05 b	0.56 ± 0.02 abc	1.63 ± 0.11 ab	0.44 ± 0.02 b	0.34 ± 0.02 ab
	T2	2.52 ± 0.12 a	0.72 ± 0.01 a	0.59 ± 0.02 a	1.69 ± 0.05 a	0.53 ± 0.01 a	0.36 ± 0.02 a
	T3	2.15 ± 0.10 cd	0.50 ± 0.00 d	0.52 ± 0.03 cd	1.43 ± 0.01 cd	0.41 ± 0.00 bc	0.31 ± 0.00 c
	T4	2.02 ± 0.05 d	0.49 ± 0.01 d	0.53 ± 0.02 bc	1.40 ± 0.09 d	0.39 ± 0.03 cd	0.30 ± 0.02 c
	T5	2.00 ± 0.08 d	0.47 ± 0.02 d	0.48 ± 0.01 d	1.25 ± 0.07 e	0.35 ± 0.03 d	0.27 ± 0.02 d

Note: The values reported in Table 2 are the mean and standard deviation of three replicates of each indicator. Different lowercase letters indicate significant differences among treatments at $p < 0.05$.

3.2.2. Changes in Photosynthetic Characteristics during the Growth Stage

As shown in Figure 3, the photosynthetic intensity of tomato leaves in both spring and fall followed an increasing and then decreasing trend as the growth stages progressed. During the fruiting stage, the net photosynthetic rate (Pn), stomatal conductance (Gs), inter-cellular CO₂ concentration (Ci), and transpiration rate (Tr) reached their maximum values. Throughout the flowering stage, the Pn, Gs, Ci, and Tr values showed an overall increase followed by a decrease as irrigation water salinity increased. In the T3 treatment, these indicators were slightly higher than in the other treatments during both seasons, with increases of 8.65%, 5.56%, 3.31%, and 5.38% compared to the CK treatment. When the tomatoes entered the fruiting stage, the values of Pn, Gs, and Tr for the T2 treatment increased by 15.6%, 10.3%, and 10.3%, respectively, compared to CK during both seasons. In contrast, the Pn, Gs, and Tr values for the T5 treatment decreased by 9.69%, 17.6%, and 10.6%, respectively, compared to CK, with significant differences between treatments ($p < 0.05$). The Ci value for tomato leaves reached a maximum of 319.7 $\mu\text{mol}\cdot\text{mol}^{-1}$ at T5 and a minimum of 274.3 $\mu\text{mol}\cdot\text{mol}^{-1}$ at T2. As the tomatoes entered the peak fruiting season, a relative decrease in Pn, Gs, Ci, and Tr values was observed across all treatments.

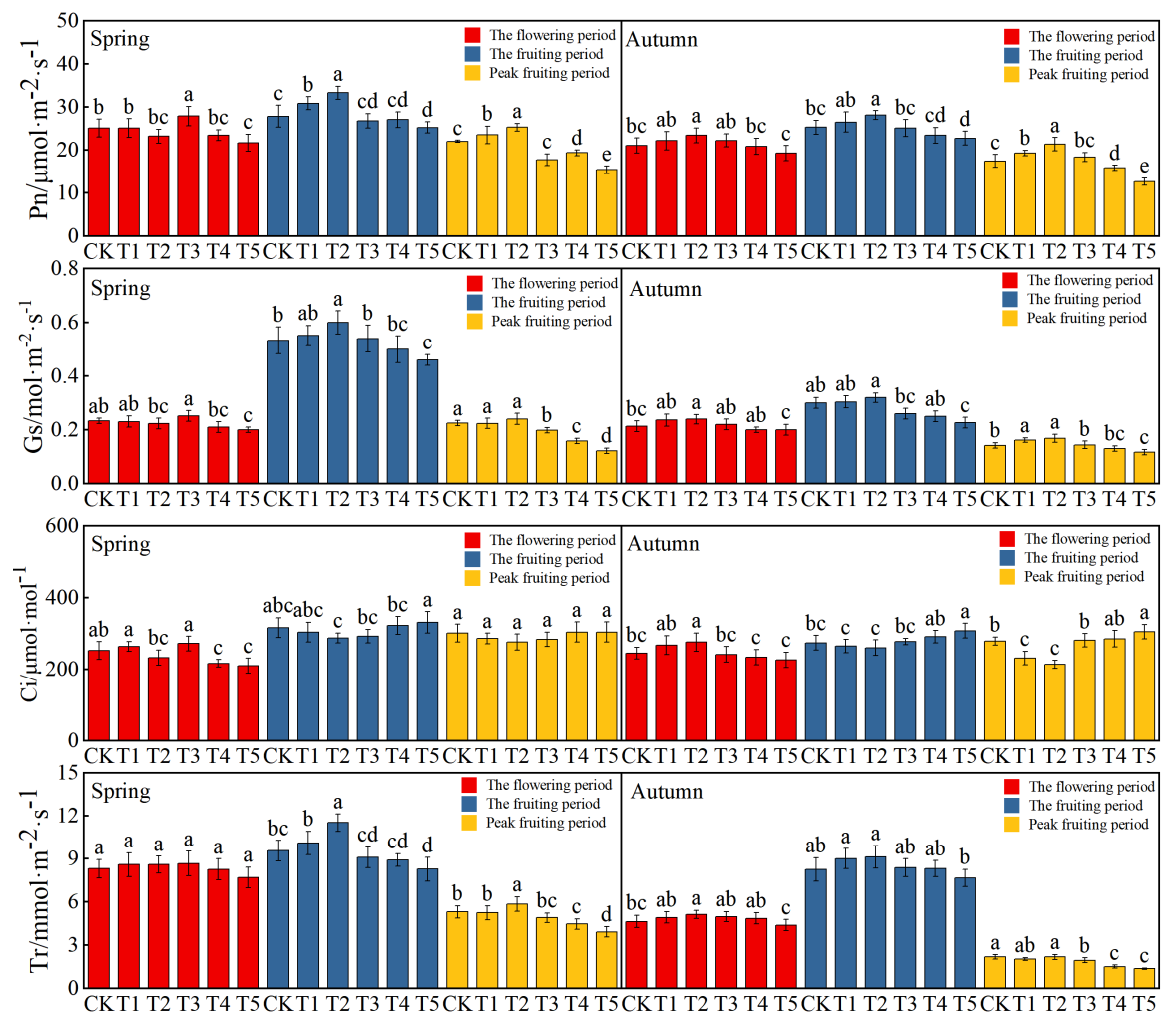


Figure 3. Effects of different irrigation water salinity levels on net photosynthetic rate, stomatal conductance, inter-cellular CO_2 concentration, and transpiration rate in leaves of tomato grown in sand culture during the spring and fall seasons. (The values reported in Figure 3 are the mean of three replicates of each indicator. The error line indicates the standard error of the three replicate values. Different lowercase letters indicate significant differences among treatments at $p < 0.05$).

3.3. Effects of Different Irrigation Water Salinity on the Growth and Yield of Sand-Cultured Tomatoes

3.3.1. Dynamic Changes in Tomato Plant Height and Model Development

Figure 4 depicts the dynamic variations in plant height of sand-cultured tomatoes throughout the growing stages under various irrigation water salinity levels for both spring and autumn seasons. It was shown that plant heights in all treatments followed the sequence $T2 > T1 > CK > T3 > T4 > T5$. At the end of the fruiting stage, the heights of T1 and T2 plants increased by 3.73% and 10.3%, respectively. In contrast, the heights of T3, T4, and T5 plants decreased by 6.64%, 15.7%, and 20.5%, respectively. Additionally, the height of T2 plants was significantly greater than that of T5-treated tomato plants, showing an increase of 38.7% compared to the CK treatment across both seasons. The growth trend of tomato plant height followed an “S” shape, gradually increasing and stabilizing as the growth stage advanced, consistent with the logistic model. By applying the measured plant height values from the spring experiment to the logistic growth model equation, the fitting equations and growth dynamic characteristic values for tomato plant height in the spring experiment were obtained (as depicted in Table 3). Under a fixed irrigation quota, the theoretical maximum plant height (Y_m) initially increased and then decreased as irrigation water salinity increased, peaking in the T2 treatment, where the

theoretical maximum plant height (Y_m) reached 152.9 cm. The rapid growth phase of tomato seedlings commenced 28 (t_1) days post-transplantation, lasting for 59 (t) days, with the maximum relative growth rate (V_m) of $1.71 \text{ cm} \cdot \text{d}^{-1}$ occurring at 58 days. The fitting equation for tomato plant height was derived by correlating the measured values from the autumn experiment with the simulated values from the spring plant height fitting equation, resulting in $y = 0.7908x - 16.3964$, with a coefficient of determination (R^2) of 0.9651, indicating a high fitting accuracy.

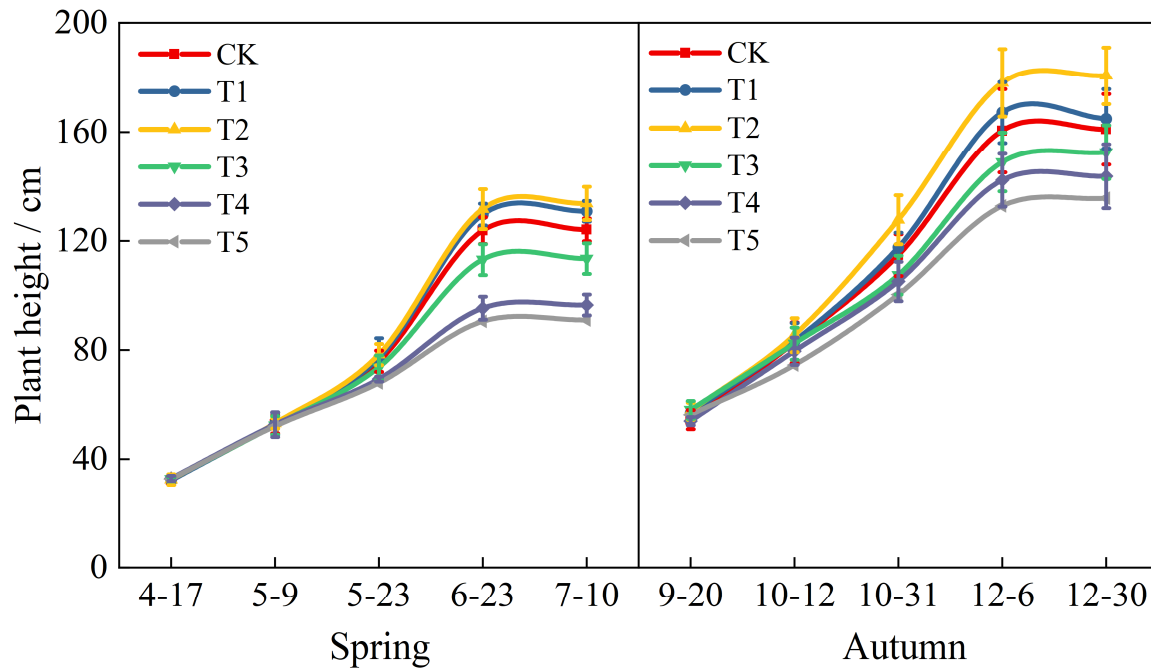


Figure 4. Dynamic changes in plant height during the reproductive stage of tomato in spring and fall and results of logistic model validation. (The values reported in Figure 4 are the mean and standard deviation of five replicates of tomato plant heights. The error line indicates the standard error of the five replicate values).

Table 3. Logistic model fitting equations and growth dynamic eigenvalues of tomato plant height at different irrigation water salinities.

Treatment	Mathematical Equation	Y_m/cm	R^2	Characteristic Parameter				
				t_1/d	t_2/d	$V_m/(\text{cm} \cdot \text{d}^{-1})$	t_m/d	t/d
T1	$y = 149.6 / (1 + 13.0 e^{-0.04 t})$	149.6	0.97	28	87	1.67	57	59
T2	$y = 152.9 / (1 + 13.2 e^{-0.04 t})$	152.9	0.97	28	87	1.71	58	59
T3	$y = 128.1 / (1 + 9.29 e^{-0.04 t})$	128.1	0.97	21	83	1.37	52	62
T4	$y = 105.5 / (1 + 6.39 e^{-0.04 t})$	105.5	0.99	13	76	1.10	44	63
T5	$y = 98.4 / (1 + 5.93 e^{-0.04 t})$	98.4	0.99	11	72	1.05	42	61
CK	$y = 141.3 / (1 + 11.5 e^{-0.04 t})$	141.3	0.97	26	85	1.56	55	60

3.3.2. Dynamic Changes and Model Development of Tomato Stem Diameter

The dynamic changes in stem thickness throughout the lifespan of spring and fall sand-cultured tomato plants with different irrigation water salinity are shown in Figure 5. The stem thickness of tomato plants showed a trend that increased and decreased with increasing irrigation water salinity. At the end of tomato fruiting, compared to the CK, the stem thickness of T1 and T2 increased by 1.69% and 4.73%, respectively, and in T3, T4, and T5 by 3.21%, 8.27% and 11.8%, respectively, from treatment between the two seasons. As shown in Table 4, the theoretical maximum value of tomato stem thickness (Y_m) increased by 4.24%. The maximum relative growth rate (V_m) increased by 9.62% in T2 treatment

compared to that of CK during the time of occurrence of the maximum relative rate (t_m) was delayed by 3 days. The duration of rapid growth (t) was shortened by 5 days. The equation for adjusting the thickness of tomato plant stems was determined by aligning the fall measurements with the simulated values from the spring adjustment equation for stem thickness. The resulting equation was $y = 1.219 0x - 2.0119$, with a determination coefficient (R^2) of 0.914 6, indicating a high degree of fit.

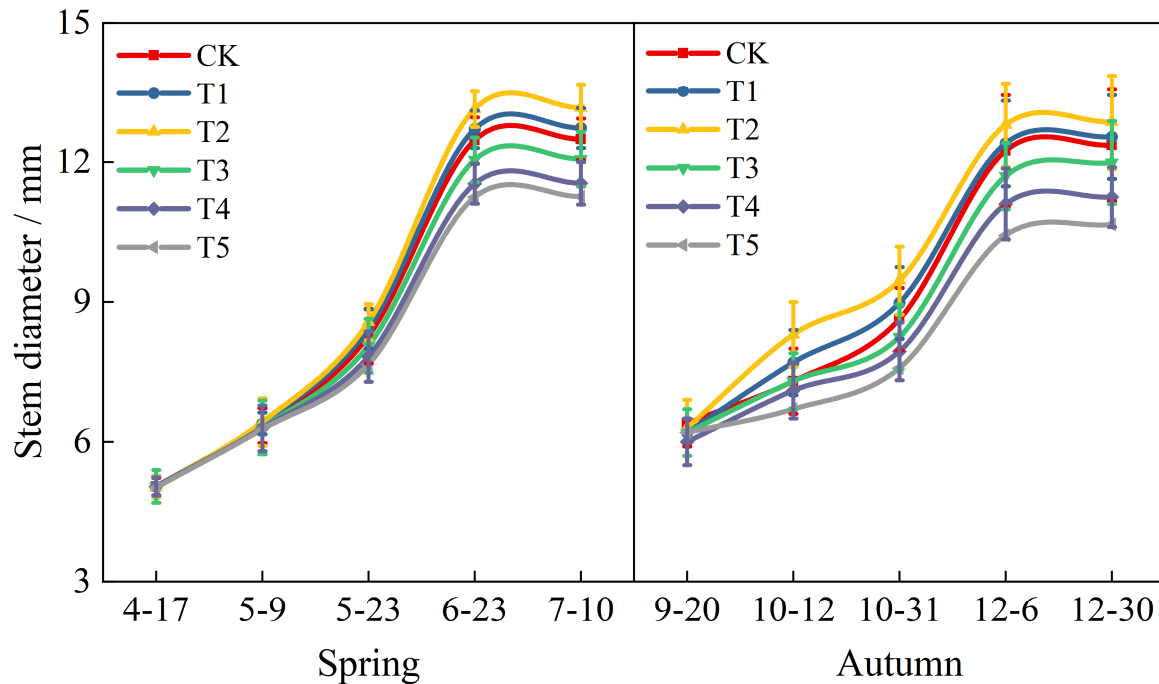


Figure 5. Dynamic changes in stem thickness during the reproductive stage of tomato in spring and fall and results of logistic model validation. (The values reported in Figure 5 are the mean and standard deviation of five replicates of tomato stem thickness. The error line indicates the standard error of the five replicate values).

Table 4. Fitting equations and growth dynamic eigenvalues of the logistic model for tomato stem thickness under different irrigation water salinities.

Treatment	Mathematical Equation	Y_m/mm	R^2	Characteristic Parameter				
				t_1/d	t_2/d	$V_m/(\text{mm} \cdot \text{d}^{-1})$	t_m/d	t/d
T1	$y = 16.0 / (1 + 5.05 e^{-0.03 t})$	16.0	0.94	10	99	0.12	55	89
T2	$y = 16.5 / (1 + 5.48 e^{-0.03 t})$	16.5	0.94	13	99	0.13	56	86
T3	$y = 15.4 / (1 + 4.50 e^{-0.03 t})$	15.4	0.94	7	103	0.11	55	96
T4	$y = 14.9 / (1 + 4.05 e^{-0.03 t})$	14.9	0.94	3	104	0.10	54	101
T5	$y = 14.6 / (1 + 3.87 e^{-0.03 t})$	14.6	0.94	1	105	0.09	53	104
CK	$y = 15.8 / (1 + 4.86 e^{-0.03 t})$	15.8	0.94	9	101	0.11	55	92

3.3.3. Effects of Different Irrigation Water Salinity Levels on Yield of Sand-Cultured Tomatoes

As can be seen from Table 5, with increasing irrigation water salinity, the number of individual plants, individual fruit weight, individual plant yield and total yield of tomato plants showed a trend that first increased and then decreased the total output from $T2 > T1 > CK > T3 > T4 > T5$. The number of tomato fruits per plant increased by 14.8% and 26.5% in T1 and T2 treatments, respectively, and the total yield increased by 21.4% and 35.2%, respectively, compared to CK between the two seasons, and the differences between treatments were significant ($p < 0.05$). T3 increased the number of fruits per plant by 4.84%

and decreased the total yield by 8.51% compared to the CK treatment, and the total yield of tomatoes was increased in the T4 and T5 treatments compared to the CK treatment by 24.9%, and 34.0% were significantly reduced ($p < 0.05$).

Table 5. Influence of different salinity of irrigation water on the yield components of tomatoes in spring and autumn.

Stage	Treatment	Single Plant Fruits (Number)	Single Fruit Weight (g)	Yield Per Plant (g)	Total Production ($\text{t} \cdot \text{hm}^{-2}$)
Spring	T1	$10.6 \pm 0.49 \text{ b}$	$92.7 \pm 4.52 \text{ a}$	$981.1 \pm 5.96 \text{ b}$	$43.9 \pm 0.27 \text{ b}$
	T2	$11.8 \pm 0.40 \text{ a}$	$89.4 \pm 3.57 \text{ ab}$	$1053.6 \pm 7.93 \text{ a}$	$47.2 \pm 0.35 \text{ a}$
	T3	$9.40 \pm 0.49 \text{ c}$	$86.0 \pm 4.39 \text{ b}$	$807.0 \pm 3.73 \text{ d}$	$36.1 \pm 0.17 \text{ d}$
	T4	$7.83 \pm 0.41 \text{ d}$	$75.6 \pm 3.62 \text{ c}$	$590.9 \pm 5.36 \text{ e}$	$26.5 \pm 0.24 \text{ e}$
	T5	$7.50 \pm 0.55 \text{ d}$	$69.9 \pm 4.58 \text{ d}$	$522.3 \pm 6.57 \text{ f}$	$23.4 \pm 0.29 \text{ f}$
	CK	$9.80 \pm 0.40 \text{ c}$	$90.9 \pm 3.2 \text{ ab}$	$889.9 \pm 9.65 \text{ c}$	$39.8 \pm 0.43 \text{ c}$
Autumn	T1	$14.8 \pm 1.17 \text{ b}$	$99.6 \pm 8.03 \text{ a}$	$1473.0 \pm 144.7 \text{ b}$	$65.9 \pm 6.48 \text{ b}$
	T2	$16.2 \pm 0.75 \text{ a}$	$104.0 \pm 8.26 \text{ a}$	$1680.0 \pm 92.6 \text{ a}$	$75.2 \pm 4.14 \text{ a}$
	T3	$13.8 \pm 0.75 \text{ c}$	$75.7 \pm 5.19 \text{ c}$	$1042.0 \pm 63.5 \text{ c}$	$46.7 \pm 2.84 \text{ c}$
	T4	$13.6 \pm 0.49 \text{ c}$	$68.3 \pm 6.48 \text{ cd}$	$928.4 \pm 77.3 \text{ d}$	$41.6 \pm 3.46 \text{ d}$
	T5	$12.8 \pm 0.78 \text{ d}$	$65.1 \pm 5.37 \text{ d}$	$811.4 \pm 60.2 \text{ e}$	$36.3 \pm 2.70 \text{ e}$
	CK	$12.3 \pm 1.03 \text{ d}$	$91.8 \pm 5.36 \text{ b}$	$1132.0 \pm 110.0 \text{ c}$	$50.7 \pm 4.93 \text{ c}$

Note: The values reported in Table 5 are the mean and standard deviation of five replicates of each indicator. Different lowercase letters indicate significant differences among treatments at $p < 0.05$.

3.4. Correlation Analysis of Tomato Physiological Indicators, Yield, and Yield Components

The relationships among physiological indicators, yield components, and total yield of tomatoes during peak fruiting stages in spring and autumn under varying irrigation water salinity levels in sand-cultured conditions are illustrated in Figure S2. The correlations for chlorophyll content, chlorophyll b content, carotenoid content, transpiration rate (Tr), and the number of fruits per plant were notably high, ranging from 0.640 to 0.979. Chlorophyll content exhibited a highly significant positive correlation with leaf Tr value ($p < 0.01$) and a highly significant negative correlation with the number of fruits per plant ($p < 0.01$). The correlation between total tomato yield and chlorophyll content, net photosynthetic rate (Pn), Tr, and stomatal conductance (Gs) was relatively low. Furthermore, a highly significant negative correlation was identified between total yield and inter-cellular CO_2 concentration (Ci) in tomato leaves ($p < 0.01$). Additionally, total yield displayed a highly significant positive correlation with the number of fruits per plant and single fruit weight ($p < 0.01$), with correlation values ranging from 0.77 to 0.80. A stepwise regression analysis was conducted using chlorophyll content, photosynthetic parameters, yield components, and total yield during the peak fruiting stage of tomatoes. The resulting regression equation was determined as $Y = -3.441 - 8.883X_2 + 0.426X_4 - 0.114X_6 + 3.373X_9$, with $R^2 = 0.99$, indicating a high degree of fit.

3.5. Path Analysis of Tomato Physiological Indicators, Yield, and Yield Components

A path analysis was conducted, with chlorophyll content, photosynthetic indexes, number of fruits per plant, and single fruit weight during the peak fruiting stage of tomatoes serving as independent variables and total tomato yield as the dependent variable. As illustrated in Table 6, a significant relationship ($p < 0.05$) was observed between the total tomato yield and the independent variables, although chlorophyll content, net photosynthetic rate (Pn), stomatal conductance (Gs), and transpiration rate (Tr) did not display notable direct linear relationships with the total yield ($p > 0.05$). Notably, the path coefficient between the number of fruits per plant and total yield was the highest at 0.626, indicating that this variable exerted the most substantial direct influence on total tomato yield. Conversely, the path coefficient between chlorophyll b content and total yield was the lowest at 0.067, indicating minimal direct impact. Utilizing Formula 7 to determine the indirect path coefficients between physiological indicators and yield and its components,

Table 6 reveals that the indirect path coefficient between inter-cellular CO₂ concentration and the number of fruits per plant was the highest at -0.454 . It suggests that brackish water irrigation can increase the number of fruiting tomato plants by regulating the inter-cellular CO₂ concentration of tomato leaves, thereby increasing the yield of greenhouse sand-cultured tomatoes.

Table 6. Passage analysis of tomato's physiological indices and yield components under different irrigation water salinity levels.

Independent Variable	Coefficient of Determination R^2	Direct Passage Coefficient	Indirect Passage Coefficient				Total Indirect Flux Coefficient
			X2→Y	X6→Y	X8→Y	X9→Y	
X2	0.999	0.067	—	0.081	-0.434	0.041	-0.312
X6	0.846	0.216	0.025	—	-0.454	-0.275	-0.704
X8	0.933	0.626	-0.046	-0.157	—	0.134	-0.069
X9	0.997	0.370	0.008	-0.160	0.227	—	0.075

Note: The total sample size for path analysis was 12 (6 in spring + 6 in autumn). X2, X6, X8 and X9 respectively represent chlorophyll b content, inter-cellular CO₂ concentration, the number of fruits per plant and individual fruit weight during the fruit flourishing stage of tomatoes. (spring and autumn, separately). Y represents the total yield at the end of the tomato fruiting stage (spring and autumn, separately).

4. Discussion

The long-term use of saline water for irrigation can lead to soil salt accumulation, disrupting plants' ionic balance and nutrient absorption capacity and ultimately affecting crop growth and yield [29,30]. In this experiment, it was found that the substrate salinity gradually increased with increasing salinity of irrigation water through sand culture tomato experiments in spring and autumn, which is consistent with the findings of Yuan et al. [31] about brackish water irrigation in tillage mode. The results of this study indicated that substrate salinity showed an increasing or decreasing trend as fertility progressed, which peaked in the late fruiting stage of tomato. The reduction in substrate salinity at the fruit flourishing stage may be due to the slag medium in the yellow sand substrate, which is rich in trace elements and has strong adsorption properties [24]. When the tomato enters the fruit flourishing stage, the plant's nutrient requirements increase significantly, and the nutrients and adsorbed salts in the slag are absorbed and utilized in large quantities, reducing salinity in the yellow sand substrate [32]. Research by Guan et al. [33] indicated that soil salt content gradually increases with depth, with higher salt concentrations in deeper layers. However, the present study yielded different results. This difference is because the sand substrate has better aeration and permeability than soil cultivation. In addition, the depth of the substrate in this experiment was only 30 cm. Under relatively low irrigation, the substrate salts could still be effectively leached by water, migrated to the bottom of the cultivation trough and discharged with the leachate, thus preventing salt accumulation in the deeper layers of the substrate.

Chlorophyll content not only reflects the photosynthetic capacity of plants but also indicates crops under salt stress [34]. Research by Taïbi K et al. [35] demonstrated that saline water irrigation can compromise the chloroplast structure of plants, significantly reducing chlorophyll content and inhibiting the synthesis of photosynthetic pigments, which in turn reduces the plant's photosynthetic capacity. This is different from the results of this present experimental study, which may be due to the different plant growth environments. Compared with soil, the pore space between the particles of a yellow sand matrix is large and has a strong infiltration capacity. A good pore structure can promote the leaching of matrix salts and reduce the pressure on plant growth caused by salt stress [36]. This experiment showed that irrigation water salinity of $2\text{--}3\text{ g}\cdot\text{L}^{-1}$ could enhance photosynthesis. However, when the salinity exceeded $3\text{ g}\cdot\text{L}^{-1}$, the net photosynthesis rate, stomatal conductance, transpiration rate, and inter-cellular CO₂ concentration significantly increased. These findings differ from the results reported by Chen et al. [37]. This can be

attributed to the fact that when the salinity of irrigation water reaches a certain level, Na^+ reacts with colloidal particles, altering the pore structure of the yellow sand substrate. This reduces permeability, inhibits hydraulic conductivity, and causes osmotic stress, leading to ionic toxicity and oxidative damage to the membrane system. As a result, these processes cause nutrient imbalances and secondary oxidative stress [9,10], which further damages the leaf thylakoid membrane, hinders the synthesis of photosynthetic pigments, weakens the light response, and increases the inter-cellular CO_2 concentration [38,39].

Salinity is one of the critical environmental factors influencing crop growth and development. Irrigation water with appropriate salinity can foster plant growth and enhance crop yields. However, surpassing the irrigation water salinity threshold can have adverse effects [40]. Wang et al. [41] conducted a three-year salt irrigation trial for spring corn was conducted, and it was found that corn yields gradually declined as irrigation water salinity increased. When the salinity was below $3 \text{ g}\cdot\text{L}^{-1}$, the yield reduction was no more than 10% compared to freshwater irrigation. However, long-term use of irrigation water with low salinity also led to significant yield losses over a longer period. This study revealed that irrigation water salinity levels of $2\text{--}3 \text{ g}\cdot\text{L}^{-1}$ positively impacted tomato plant height, stem diameter, and yield through the sand-cultured tomato experiments during the spring and autumn. When the irrigation water salinity reached $3 \text{ g}\cdot\text{L}^{-1}$ or higher, tomato plant growth and yield were significantly inhibited, and the degree of inhibition increased with increasing salinity. This may be due to the yellow sand's relatively good soil aeration and drainage, which can effectively prevent excessive accumulation of water and salts, and the slag contains nitrogen, phosphorus, potassium and trace elements, significantly inhibiting tomato growth and yield. It is also possible that the experiment used a trough cultivation mode, which can effectively leach salt and avoid the problem of soil succession barriers caused by long-term saline water irrigation, thus increasing crop yield [33,42].

5. Conclusions

Natural resources such as yellow sand and salt water are adapted to local conditions, and systematic studies on plant growth under saltwater irrigation systems are carried out. Combined with the salt tolerance of crop varieties, the integrated optimization of irrigation management strategies aims to achieve the dual goals of efficient use of soil and water resources and high crop yields and quality. In this study, we selected six groups of southern Xinjiang sand-cultured tomatoes with different irrigation water salinity as stress objects to understand better the response of substrate salinity distribution and physiological growth and yield of sand-cultured tomatoes under brackish water drip irrigation. The results showed that the appropriate salinity of irrigation water could create a favorable water-salt environment for tomato growth, and the salinity of $3 \text{ g}\cdot\text{L}^{-1}$ irrigation water could regulate the inter-cellular CO_2 concentration of tomato leaves, promote the production of photosynthesis, reduce the damage caused by salinity to tomato, and increase the overall yield of tomato. Therefore, an irrigation water salinity of $3 \text{ g}\cdot\text{L}^{-1}$ is an appropriate threshold for irrigation water salinity for sand-trained tomatoes in southern Xinjiang. In future research, we will further investigate the reaction mechanisms between the physicochemical properties of the yellow sand substrate and leaf enzyme activities, as well as osmoregulatory substances under long-term salinity stress. This will provide a scientific basis for the large-scale adoption of sand-cultured tomato technology.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy14102315/s1>, Figure S1: Meteorological data in the greenhouse during spring season and autumn season; Figure S2: Correlation analysis of physiological indices with yield and constitutive factors in fruit flourishing of tomato.

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