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Responses of Tomato Crop and Water Productivity to Deficit Irrigation Strategies and Salinity Stress in Greenhouse

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Abstract: Saudi Arabia faces water scarcity and inadequate sustainable sources, particularly in agriculture, necessitating efficient irrigation water management to improve productivity amidst rising demand. The study investigated the impact of irrigation levels and water salinity on tomato plants in greenhouses, covering four irrigation levels (100%, 80%, 60%, and 40% of ET_c) and three water sources (FW (0.9 $dS{\cdot}m^{-1}$), SW (3.6 $dS{\cdot}m^{-1}$) and MW (2.25 $dS{\cdot}m^{-1}$)). Salinity impacts crop yield, physiological responses, and fruit quality. The photosynthesis, stomatal conductance, transpiration, and chlorophyll content decrease with MW and SW, negatively affecting morphological characteristics. For MW, it was recommended to apply 60% deficit irrigation with a yield of 98 $kg{\cdot}ha^{-1}$, and water productivity (WP) improved to 21.93 $kg{\cdot}m^{-3}$ compared to 13.65 $kg{\cdot}m^{-3}$ at full irrigation (FI). In SW, 80% irrigation was suggested, as there was no significant difference in yield compared to FI. For FW, 60% deficit irrigation produced the best water conservation (104.58 $kg{\cdot}ha^{-1}$ yield and 23.19 $kg{\cdot}m^{-3}$ WP), while FI produced the highest yield per unit area (123.48 $kg{\cdot}ha^{-1}$ yield and 16.51 $kg{\cdot}m^{-3}$ WP). Nonetheless, greater water and salinity stress was associated with increased fruit quality measures such as total acidity, vitamin C, and soluble solids. The results show that implementing deficit irrigation with salinity strategies in greenhouse tomatoes could improve crop adaptability, yield, and water productivity in the face of water scarcity and salinity variability.

Keywords: deficit irrigation; salinity; tomato; greenhouse; fruit quality; water productivity

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1. Introduction

The problem of scarce water within arid regions such as the Kingdom of Saudi Arabia (KSA) has been exacerbated by climatic change and the speedy expansion of residential, industrial, and agricultural water consumption. Consequently, the United Nations (UN) has cataloged KSA as a nation grappling with a severe water crisis [1]. In KSA, groundwater extraction has significantly increased during the last three decades, reaching over 17 billion cubic meters annually [2]. Approximately 80% of Saudi Arabia's water needs are satisfied through groundwater sources [3]. Arid and semi-arid regions frequently encounter extreme climate conditions that cause groundwater salinization [4]. In Al-Kharj, Saudi Arabia, around 69.4% of wells are classed as slightly to moderately saline (0.7–3 dS m^{-1}) and the rest are categorized as severely saline (>3 dS m^{-1}). These groundwater sources can still be utilized for irrigation despite the salinity issues, but with certain restrictions [2]. In contrast to these withdrawal rates, the annual net recharge of groundwater remains relatively low [5,6]. This underscores the imperative necessity for the formulation of enduring water management strategies to address KSA's water scarcity challenges—for example, apply a deficit irrigation strategy, which entails using less water than the crop needs—while the effects on yield are less dramatic. Concurrently, this becomes increasingly challenging as water quality deteriorates. The utilization of saline irrigation water adversely impacts the interactions among soil, water, and plants, frequently seriously hampering crops' typical physiological functions and productive potential [7,8]. Nonetheless, cultivating salty soil crops or applying saline water for irrigation has become necessary for supplying the rising food brought on by population growth, particularly in regions where water resources are consistently limited [9]. Consequently, salinity and deficit have gained widespread prevalence in the farm field.

Controlled environment agriculture, including greenhouse cultivation, has gained global popularity [10]. Protected agriculture, focusing on year-round, high-density vegetable production, offers sustainable solutions in arid regions [11–13]. Harmanto et al. [13] demonstrated a 20–25% water use reduction for tomatoes compared to field cultivation. Saudi Arabia has 5968 hectares of greenhouses, with 2305 hectares dedicated to tomatoes, yielding 258,214 tons [14]. Drip irrigation is currently often used in greenhouse water supplement systems due to its effectiveness in conserving water. Crop quality and productivity can be carried off using drip irrigation systems, since they can supply water and fertilizer to the crop's root zone in a regular and suitable amount based on the crop's water needs [15].

Tomato (*Solanum lycopersicum* L.) holds a preeminent position as a horticultural crop worldwide. Its economic and nutritional significance has grown in tandem with increasing harvested areas and yields, with a global harvested surface surpassing 5 million hectares annually and an average production of approximately 189.1 million tons per year [16]. In Saudi Arabia, cultivating high-yield tomatoes is important to meet the surging food demand. In Riyadh region, tomato production reached 49,128.7 tons, with 46,388.1 tons sold, as per MEWA [17]. Tomatoes, an abundant source of vitamins A and C, are a beloved vegetable worldwide. Their versatility in culinary applications is noteworthy, offering many consumption possibilities. Tomatoes contain minerals and antioxidants, including phenols, lycopene, and vitamin C (VC) [18]. Tomatoes also contribute color and flavor to dishes while offering a wealth of nutrients helpful for human health, containing fiber, vitamins, potassium, phosphorus, and phenolic compounds [19–23].

Salinity stress induces diverse plant changes, encompassing morphological, physiological, biochemical, and molecular dimensions, primarily through elevated sodium and chlorine ion levels in plant cells. It adversely affects plant growth and production, subjecting plants to osmotic, ionic, and oxidative stresses and nutritional and hormonal imbalances [24–26]. Salinity exacerbates its impact on plants by negatively affecting photosynthetic machinery, transpiration, and gas exchange, manifested by reduced chlorophyll and carotenoid concentrations, a distorted chloroplast ultrastructure, decreased stomatal conductance, and subsequent PSII system disruption [27]. Additionally, salinity prompts the accumulation of reactive oxygen species (ROS) in plant cells, causing oxidative stress with detrimental effects, including lipid peroxidation, membrane degradation, DNA damage, and protein damage [28]. Plant responses to salt stress are intricate, contingent upon factors like solute type and concentration, genetic potential, plant developmental stage, and the nature and intensity of the stress [29].

Farooq et al. [30] noted that the impact of drought stress on yield ranges from 13–94% based on its severity and interval. Interestingly, water stress, while decreasing productivity, can enhance water productivity [31]. Tomato plants undergo adaptations when exposed to drought conditions, often decreasing leaf area and photosynthesis rate, resulting in diminished accumulation of biomass and yield. Moreover, studies have found that certain amounts of water lack can improve WUE [32,33].

Despite extensive research on the effects of salinity and deficit irrigation on tomato yield, there is a research gap regarding their combined impact on greenhouse tomato yield and fruit quality. Therefore, this study aims to fill this gap. The hypothesis that salinity irrigation at the optimal level of deficit would enhance greenhouse tomato fruit quality and water productivity with marginally reducing yield is one that our research endeavors to investigate. The variation in water availability and salinity concentration applied to the tomato makes the practical application of this hypothesis challenging. As a result, these factors and their potential interactions with deficit irrigation strategies were evaluated.

The aim of this research was to evaluate the impact of varying deficit irrigation and salinity levels on the physiological responses and fruit quality characteristics of tomato plants cultivated in greenhouses. Additionally, the research sought to assess the intricate relationships between irrigation water quality and water stress concerning crop yield and water productivity.

2. Materials and Methods

2.1. Experimental Design and Growth Conditions

In a greenhouse, trials were conducted for two consecutive seasons of growing tomato crops: 23 September 2021, to 30 May 2022, for the first season, and 9 September 2022, to 16 May 2023, for the second, for 249 days of cultivation in the Thadaq district, Riyadh, Saudi Arabia (altitude 722 m above mean sea level, latitude 25°17′40″ N and longitude 45°52′55″). The chemical and physical characteristics of the soil taken from surface and subsurface layers, as well as irrigated water, are explained in Tables 1 and 2.

Table 1. Physical and chemical parameters of the soil at the trial site.

Soil Physical Parameters										
Soil Depth (cm)	ρ_b (g cm^{-3})	$CaCO_3$ (%)	OM (%)	Mechanical Analysis (%)				θ_S%	θ_{FC}%	θ_{WP}%
				Sand	Silt	Clay	Soil Texture			
0–15	1.6	15.8	0.4	88.8	5.0	6.8	Loamy sand	24.4	17.5	8.7
15–30	1.6	19.4	0.8	83.5	8.8	8.1	Loamy sand	25.2	18.3	9.9
30–50	1.6	23.0	1.1	78.2	12.5	9.3	Sandy loam	26.0	19.0	11.0
Chemical Analysis										
Soil Depth (cm)	**pH**	**EC_e (dS m^{-1})**	**Cations (meq L^{-1})**				**Anions (meq L^{-1})**			**SAR**
			Ca^{+2}	**Mg^{+2}**	**Na^+**	**K^+**	**SO_4^{2-}**	**HCO_3^-**	**Cl^-**	
0–15	7.39	4.01	8.17	2.26	18.4	14	25.38	12	25.83	2.03
15–30	7.36	3.94	11.17	1.8	16.0	3.9	18.23	18	18.46	3.09
30–50	7.32	3.87	14.17	1.31	13.6	9.9	11.08	24	11.08	4.14

Bulk density (ρb), field capacity (θ_{FC}), wilting point (θ_{WP}), saturated moisture content (θs), soil electrical conductivity (EC_e), organic matter (OM), acidity or basicity of water solution (pH), and sodium adsorption ratio (SAR).

Table 2. Chemical parameters of the irrigated water at the trial site.

Water Sample	pH	EC (dS m^{-1})	Cations (meq L^{-1})				Anions (meq L^{-1})			SAR
			Ca^{+2}	Mg^{+2}	Na^+	K^+	CO_3^{-2}	HCO_3^-	Cl^-	
FW	7.10	0.90	4.20	2.4	7.3	0.13	0.00	2.00	7.20	4.02
MW	7.31	2.25	3.50	2.30	19.67	3.94	0.00	2.44	19.25	12.14
SW	7.52	3.60	2.80	2.2	32.04	0.29	0.00	2.87	31.29	20.26

Fresh-Water (FW), Mixture-Water (MW), Saline-Water (SW), and water electrical conductivity (EC).

The experiment consisted of twelve treatments that combined three different saline water treatments; namely Fresh-Water (FW) (0.9 dS m^{-1}), Saline-Water (SW) (3.6 dS m^{-1}), and a mixture of fresh and saline water by 1:1 (MW) (2.3 dS m^{-1}), and four irrigation levels, namely full irrigation 100% of tomato evapotranspiration ET_c (FI), and three deficit irrigation (DI) levels (0.8, 0.6, and 0.4 of ET_c). Trials were designed as a randomized complete block (Split-Plot Design) with three replicates. Saline water treatments were the main factor, and irrigation levels were sub-factors, with 36 total experimental units, as shown in Figure 1.

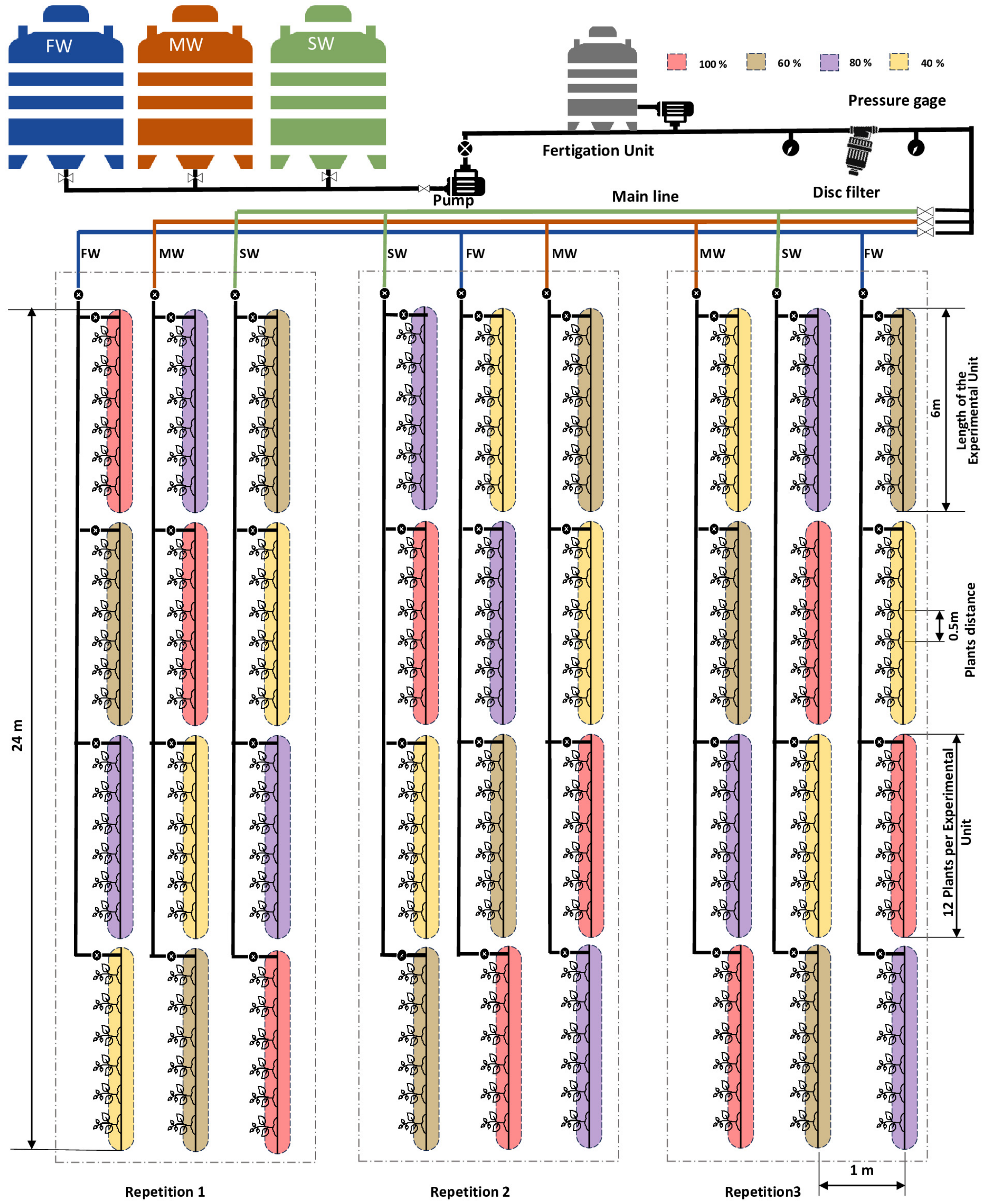

Figure 1. The experimental layout and the randomization of treatment conditions.

The tomato (*Solanum lycopersicum* L.) was seeded directly in the ground in the greenhouse. The experimental unit was six × 1 m, and the planting lines were spaced 1 m. The distance between plants was 50 cm. The plants were grown until they reached a height of 2 m, at which point the stem was laid and buried whenever it exceeded this limit. The irrigation system was designed using a UPVC 63 mm diameter pipe starting from the pump (Pentair STA-RITE, Manufactures Edge, Inc., Farmingdale, NJ, USA, Q_{max} = 14.5 m^3 h^{-1}, H_{max} = 36 m, and power = 1.5 HP) outside the greenhouse and ending with lateral of PE 16mm diameter pipes extending in two directions from the center of the greenhouse. The pressure compensating emitters used in this study were of the type of TURBO PC with a rate of discharge of 4 L h^{-1}, manufactured by (Jain Irrigation Systems Ltd. from Jalgaon, India), and were spaced 50 cm apart along the length of the lateral.

Standard agricultural procedures, such as applying fertilizer, control of pests, and soil sanitation, were used in the context of commercial greenhouse tomato cultivation. Mainly, N, P, and K fertilization were carried out at rates of 285, 142, and 238 kg ha^{-1}, respectively.

The measurements of the multi-span fiberglass greenhouse were 40 m × 54 m. It was divided into five spans, each 10.8 m in width and 4.5 m in height. Conventional cooling was applied to withdraw the excess sensible heat by ventilation and evaporative cooling. Each span has a pad and air system consisting of a cellulose pad wall (8 m × 2 m × 15 cm) and 3 fans with capacity of 40,000 m^3/h each (EOS50 fans, Termotecnica Pericoli, Albenga, Italy, 1.5 HP motors). During the cultivation seasons, a weather station was installed outside the greenhouse to continuously measure climate variables such as air temperature (T), relative humidity (RH). Their daily average values of two consecutive seasons are shown in Figure 2. The sustainable greenhouse's T and RH were maintained at 26 ± 1 °C in the daytime, 19 ± 1 °C at night, and at 75 ± 2% RH. The RH and T within the greenhouse were monitored using an analogue thermo-hygrometer 45-2000 (Fischer Instruments, Sindelfingen, Germany, with the accuracy of ±5% for RH and ±1 °C for T).

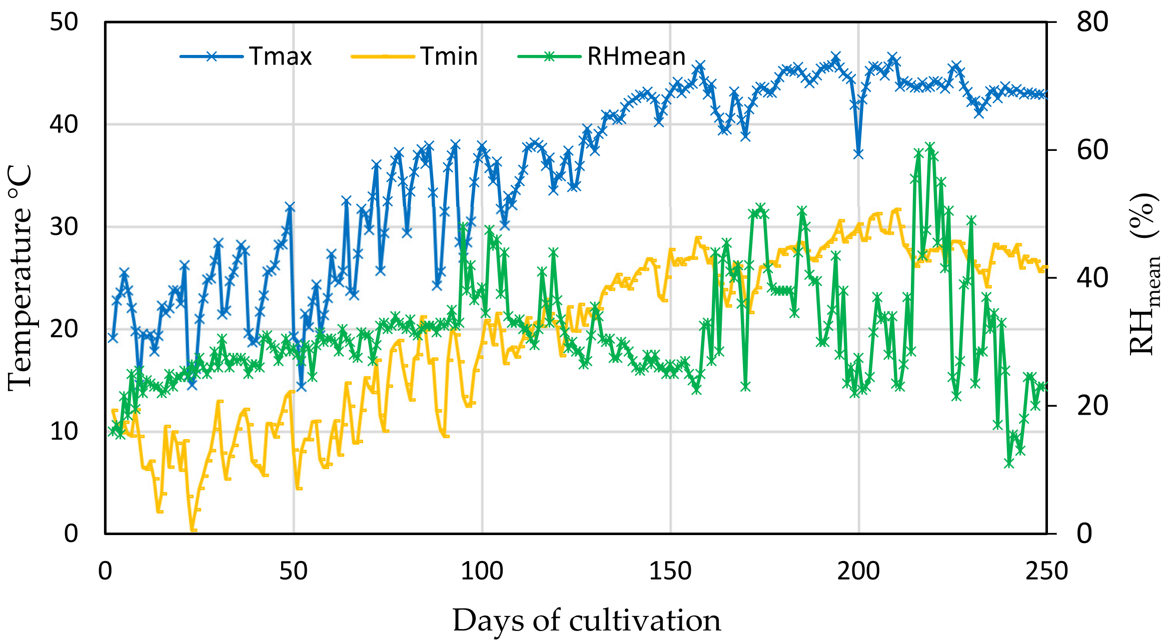

Figure 2. Minimum (T_{min}) and maximum (T_{max}) daily air temperatures, and mean daily relative humidity (RH_{mean}) for average data of two consecutive seasons of tomato growth.

2.2. The Measurements

2.2.1. Applied Irrigation Water

Pan reference evapotranspiration ($ET_{o\text{-}pan}$) within the greenhouse was estimated based on the FAO-56 recommendations [34] for Class A evaporation pans installed on bare soil (Case "B"). The evaporation pan apparatus was positioned at 1 m away from the plant, conforming to the specified guidelines. The calculation of the $ET_{o\text{-}pan}$ was implemented as

$$\begin{aligned} ET_{o-pan} = E_{pan} \quad & (0.61 + 0.00341 \cdot RH_{mean} - 0.000162 \cdot u_2 \cdot RH_{mean} \\ & -0.00000959 \cdot u_2 \cdot FET + 0.00327 \\ & \cdot u_2 \cdot \ln(FET) - 0.00289 \cdot u_2 \cdot \ln(86.4u_2) \\ & -0.0106 \cdot \ln(86.4u_2) \cdot \ln(FET) + 0.00063 \\ & \cdot [\ln(FET)]^2 \cdot \ln(86.4u_2) \end{aligned} \tag{1}$$

where RH_{mean} is the average daily relative humidity (%), u_2 is the wind speed at 2 m above the ground (m s^{-1}), and FET is the fetch or distance of the identified surface type (bare soil for case B upwind of the evaporation pan). Figure 3 shows the average daily values of $ET_{o\text{-}pan}$ for two consecutive seasons of growing tomato crops.

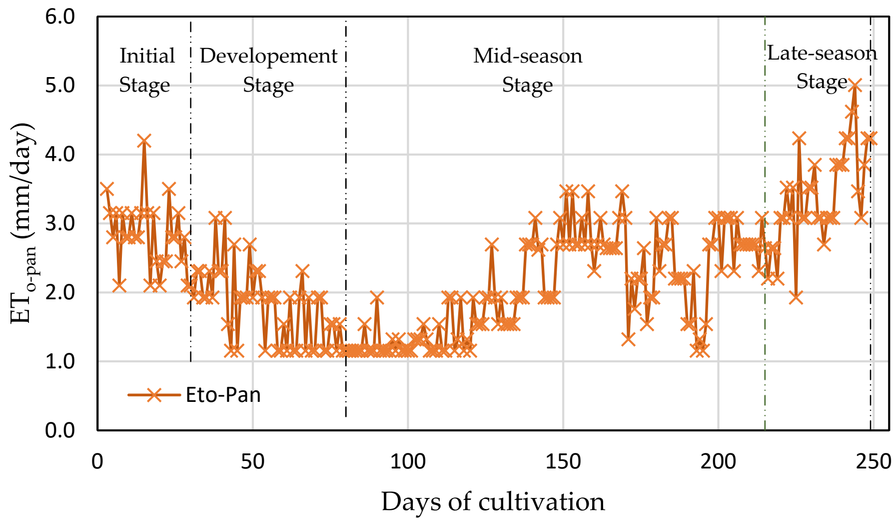

Figure 3. Average daily $ET_{o\text{-}pan}$ values at each stage of greenhouse tomato growth for two seasons.

The crop water requirements (ET_c) were calculated utilizing Equation (2),

$$ET_c = ET_o \cdot K_c \tag{2}$$

where ET_c is the crop water requirement (crop evapotranspiration; mm day^{-1}), and K_c is the crop coefficient. During four different develop stages of the crop, namely initial, development, mid-season, and late-season stages, the duration of each stage was 30, 50, 135, and 33 days, respectively. For each stage, different K_c values were applied: 0.60 for the initial stage, 1.22 for the mid-season, and 0.80 for the late season, as specified by Allen et al. [34]. Furthermore, the K_c values were modified according to the approach described by Allen et al. [34], taking into consideration factors such as relative humidity and wind speed at 2 meters. Subsequently, $K_{c\text{-ini}}$ was adjusted based on the average interval between wetting events, potential evaporation (ET_o), and the fraction of the surface wetted by irrigation, as follows:

$$K_{c-ini-adj} = f_w \cdot K_{c-ini(Fig)} \tag{3}$$

where f_w is the fraction of surfaced wetted by irrigation, $K_{c\text{-ini-(Fig)}}$ is the obtained initial crop coefficient from Figure 29 at FAO-56 [34] (p. 117) depending on the time period of wetting events, amount of the wetting event, and the level of ET_o.

Meanwhile $Kc_{\text{-mid}}$ and $K_{c\text{-end}}$ were adjusted (designated as $K_{c\text{-mid-adj}}$ and $K_{c\text{-end-adj}}$ for mid-season and end-season) utilizing the formula given by Allen et al. [34]:

$$K_{c-mid/end-adj} = K_{c-mid/end-tab} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \tag{4}$$

where $K_{c\text{-tab}}$ is the value for standard K_c of mid- or end-season as specified in FAO-56 [34], and RH_{min}, u_2 and h are the mean values calculated over the duration of the stage period for daily minimum air relative humidity, wind speed and crop height, respectively.

2.2.2. Growth and Physiological Characteristics

Various plant growth characteristics were recorded, consisting of plant height, stem diameter, and leaf area. Martin et al. [35] concluded that ImageJ software is a viable alternative to the leaf area meter (LI-3100—LI-COR) for oat crops. Similarly, leaf area integrator methods for bean crops were found to be effective by Martin et al. [36]. Therefore, leaf area measurements were derived from digital images and processed using ImageJ [37] software version 1.51j8 during the mid-season stage, on 31 March 2022, the 190th day after planting for the first season, and on 4 March 2023, the 177th day after planting for the second season. The contrast colors were applied to the leaves, rendering them darker (black) for enhanced analysis. Additionally, the plant's wet and dry weights, encompassing leaves and stems, were determined. The weight was measured by a digital scale in drying at 70 °C until constant weight was achieved in a forced-air oven.

For the assessment of stomatal conductance (g_s), photosynthesis rate (P_n), and transpiration rate (T_r), from each crop's above canopy, three mature leaves were carefully chosen for every trial unit. Measurements were conducted utilizing an LI-6400XT portable photosynthesis system (LiCor Inc., Lincoln, NE, USA). The samples for the various treatments were collected from functional leaves between 8:00 a.m. and 10:00 a.m. local time. For the first season, this occurred on 18 November 2021, corresponding to the 57th day after planting. In the second season, the data collection took place on 9 November 2022, which corresponds to the 62nd day after planting. Gas exchange data were recorded during the developmental stage of the crop. The evaluation of the chlorophyll index by the soil plant analysis development (SPAD) chlorophyll meter was conducted through the utilization of the SPAD 502 Plus Chlorophyll Meter, which is manufactured by Minolta Co., Ltd. (Osaka, Japan). This assessment took place during the mid-season stage, specifically on 31 March 2022, which corresponds to the 190th day after the planting for the first season. Furthermore, the evaluation was also conducted on 4 March 2023, which corresponded to the 177th day after planting for the second season. The SPAD 502 Plus Chlorophyll Meter, being a handheld device, provides a rapid and precise estimation of leaf chlorophyll levels. Additionally, this device offers a non-destructive approach by detecting the red (650 nm) and infrared (940 nm) radiation emitted by the leaves [38].

As part of the evaluation, the quality of the fruits was assessed based on their total soluble solids (TSS, %), vitamin C (VC, mg 100 g^{-1}), and titratable acidity (TA, % citric acid) parameters. For this purpose, samples were collected from three fully grown crops for every treatment in the growing season. The evaluation was conducted in-depth to ensure accurate results. Each tomato was meticulously blended and filtered to extract the flesh, and the TSS was determined employed a digital refractometer (PR-101 model, ATAGO, Tokyo, Japan) within standard analysis methods [39]. While TA was ascertained using the procedure described by Caruso et al. [40]. The measurement of VC in the extracted juice was conducted using 2,6-dichlorophenol-indophenol dye [41].

2.2.3. Total Yield and Water Productivity (WP)

Total fresh tomato yields (Y) were meticulously measured by directly harvesting and weighing fruits from the various treatments for all produced tomato yield. The objective of irrigation deficits is to enhance water productivity (WP), which was calculated as the ratio of the crop yield (Y, kg m^{-2}) to the amount of applied water (W, m^3 m^{-2}) [42,43] as

$$WP = \frac{Y}{W} \tag{5}$$

The tomato crop yield and applied water (Y–W) relationship was expressed as a quadratic polynomial function (one dependent variable; W) [43,44] for different irrigation levels and water salinity as follows:

$$Y = a_o + a_1 W + a_2 W^2 \tag{6}$$

where a_0, a_1, and a_2 are fitting constants for a given irrigation level and water salinity.

Furthermore, a second-order polynomial two independent variables (W and S) relationship that integrates water amount (W, m^3 m^{-2}) and salinity (S, dS m^{-1}) for tomato yield prediction (Y, kg m^{-2}) was formed using the Statistix 9 software [45] as

$$Y = b_o + b_1 W + b_2 S + b_3 WS + b_4 W^2 + b_5 S^2 \tag{7}$$

where b_0, b_1, b_2, b_3, b_4, and b_5 are fitting constants for a given irrigation level and water salinity.

The yield reduction (YR) and the WP improvement (IWP) were estimated by Formulas (8) and (9) [46,47] as

$$YR(\%) = \frac{Y_c - Y}{Y_c} \times 100 \tag{8}$$

$$IWP(\%) = \frac{WP - WP_c}{WP_c} \times 100 \tag{9}$$

where (Y_c, WP_c) are the yield and water productivity of a control treatment, and (Y, WP) are yield and water productivity of a given irrigation level and water salinity teatment.

2.3. Statistical Analysis

The layout of the experiment that we used was a randomized complete block with a split-plot arrangement and three repetitions. The results were reported as the mean ± standard error (S.E). We conducted ANOVA analysis and the revised least significant difference (LSD) test at a degree of trust of 0.05 to investigate the statistical importance of differences among the main components. Data analysis was performed using the Costat program version 6.311 [48].

3. Results and Discussion

3.1. Physiological Responses of Tomato Plants to Water Quality and Irrigation Levels

In the investigation of the influence of salinity stress on the physiological traits on greenhouse-grown tomato plants, namely photosynthesis (P_n), transpiration (T_r), and stomatal conductance (g_s), it was evident that their mean values exhibited an increase when utilizing Fresh-Water (FW), while these values witnessed a decline with escalating irrigation water salinity across all studied traits (Table 3). Specifically, the highest average P_n rate was recorded at 14.83 µmol CO_2 m^{-2} s^{-1} when utilizing FW, depicting a subsequent reduction of 10.7% and 17.7% with the adoption of Mixed-Water (MW) and Salinity-Water (SW), respectively. Concurrently, the values for (g_s) and (T_r) decreased by approximately 22% at SW when compared with FW, which were 3.35 and 1.15 mmol H_2O m^{-2} s^{-1}, respectively. Similarly, these values decreased due to water stress, reaching their lowest levels at the level of 40% irrigation application (10.56 µmol CO_2 m^{-2} s^{-1}, 2.07 and 0.84 mmol H_2O m^{-2} s^{-1} for P_n, T_r, and g_s, respectively).

Table 3. The impact of water quality and irrigation water levels on stomatal conductance (g_s), photosynthesis (P_n), transpiration (T_r), and chlorophyll index for tomato crop.

Treatments		**P_n * (µmol CO_2 m^{-2} s^{-1})**	**T_r * (mmol H_2O m^{-2} s^{-1})**	**g_s * (mmol H_2O m^{-2} s^{-1})**	**Chlorophyll ** (SPAD)**
Quality	FW	14.83 a	3.35 a	1.15 a	41.88 a
	MW	13.25 b	2.93 b	0.95 b	36.02 b
	SW	12.2 c	2.6 c	0.89 c	33.53 c
	p-value	0.000	0.000	0.000	0.000
	LSD	0.064	0.113	0.053	0.861
RDI	100%	15.64 a	3.84 a	1.18 a	42.02 a
	80%	14.52 b	3.06 b	1.03 b	39.68 b
	60%	12.99 c	2.86 c	0.93 c	34.76 c
	40%	10.56 d	2.07 d	0.84 d	32.11 d
	p-value	0.000	0.000	0.000	0.000
	LSD	0.093	0.098	0.045	0.555
Quality × RDI	*p*-value	0.000	0.079	0.032	0.000
	LSD	0.162	0.169	0.078	0.961

The LSD test: values that share the same letter are not considered significantly different at the 0.05 probability level. Data from two consecutive seasons of tomato crop growth were analyzed. * and ** indicate the data measured during development and mid-season stages, respectively.

In Figure 4a, the interaction between salinity and water stresses had a significant impact on P_n. Under full irrigation conditions with FW, P_n values were significantly higher compared to WM and SW water sources. At a 40% irrigation level, it exhibited a substantial reduction of approximately 41%. However, the significance diminished for g_s, and there was no significant effect observed for T_r at a 0.05 significance level (Table 3). Similarly, g_s values experienced a notable decrease of 42.8% with MW and 46.4% with SW (Figure 4b). T_r values showed a noteworthy decrease of 52.5% with MW and 59.2% with SW at the 40% irrigation level compared to full irrigation with FW (Figure 4c). In this, the values of P_n, T_r, and g_s under full irrigation with FW were 17.1 (μmol CO_2 m^{-2} s^{-1}), 3.37 and 1.32 (mmol H_2O m^{-2} s^{-1}), respectively.

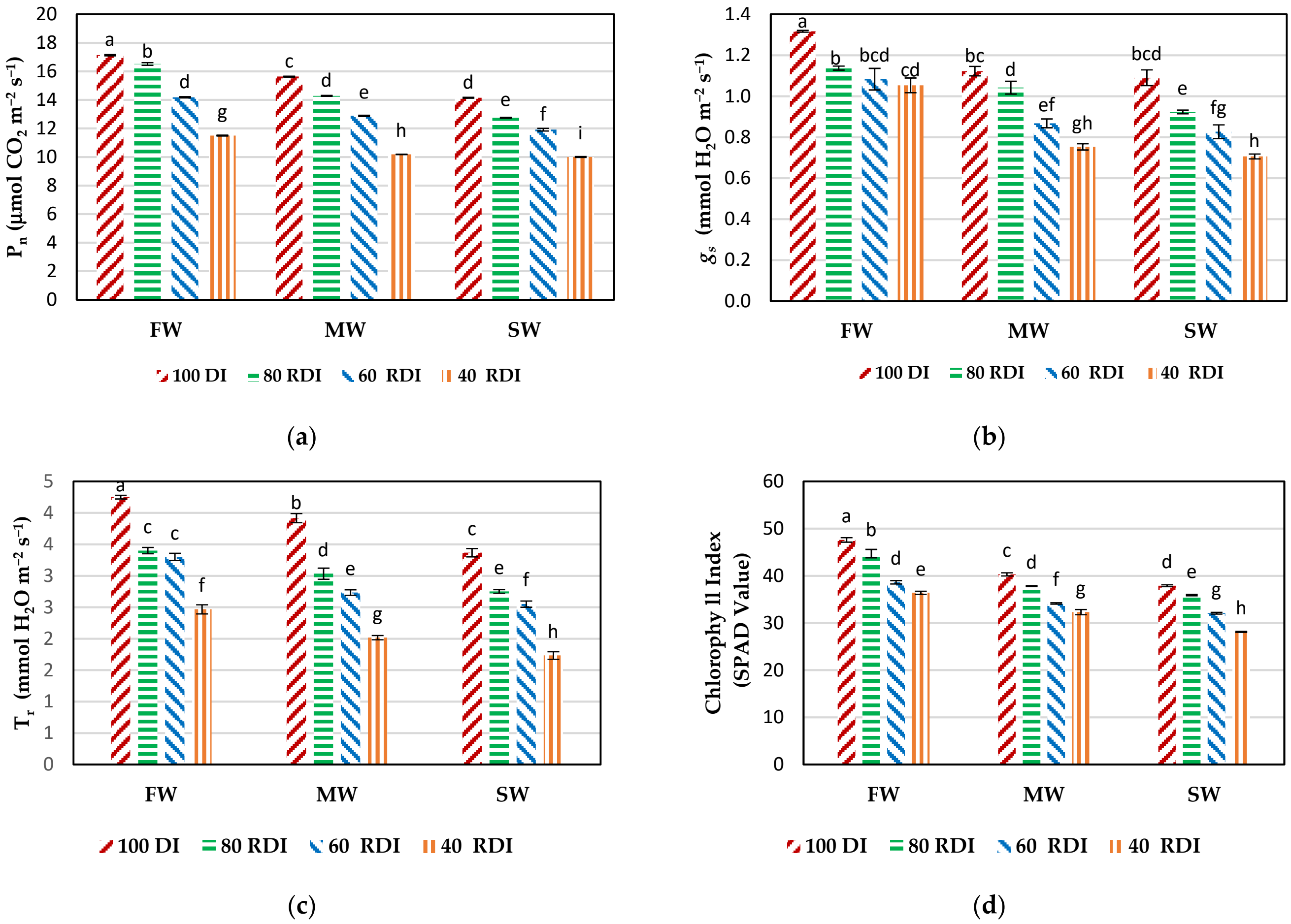

Figure 4. Interaction effects between water quality and irrigation water levels on (**a**) photosynthesis (P_n), (**b**) stomatal conductance (g_s), (**c**) transpiration (T_r), (**d**) chlorophyll index (SPAD Value), for FW (Fresh-Water); MW (Mixed-Water); SW (Salinity-Water); 100% Full irrigation; and 80%, 60%, and 40% potential ET_c. The data are the mean value ± standard error and based on the LSD test at the 5% level ($p < 0.05$), distinct letters represent significant differences within treatments.

Previous research results are consistent with the findings of this investigation: Ors et al. [49] revealed that a heightened salt concentration led to diminished gas exchange in tomato seedling leaves. In addition, water stress induces a decline in photosynthetic rates by instigating stomatal closure, a mechanism deployed to mitigate water loss and subsequently reduce carbon dioxide uptake. Earlier studies have found a relationship between water stress and reduced photosynthesis [50–52]. Wong et al. [53] and Tuzet et al. [54] showed that P_n and T_r are regulated by g_s, and they reciprocally impact each other. Additionally, Hao et al. [55] found out a significant positive linear association between net photosynthetic rate and both transpiration rate and stomatal conductance, while Liu et al. [56] noted that when plants are water-stressed, g_s decreases as stomata close to maintain leaf water status.

Furthermore, conflicting results were found regarding stomatal closure mechanisms [57]. According to various research studies, chemical cues such as abscisic acid (ABA) and pH were responsible, while others propose hydraulic signals like soil, root, and shoot resistances [56,58,59]. Despite numerous studies mechanisms, questions persist regarding the precise stomatal closure mechanism [57]. As highlighted by Farooq et al. [30], stomatal closure reduces CO_2 intake into parenchyma cells, thereby affecting photosynthesis efficiency through diminished CO_2 availability and reduced light intake, and Table 3 and Figure 4 reflect what has been discussed.

Table 3 and Figure 4d provide information on the chlorophyll II content in tomatoes by showing the impact of several factors and how these interact. The chlorophyll content appears to be significantly considerably impacted by the quality of irrigation water applied. Notably, the highest average chlorophyll content of 41.88 is observed when Fresh-Water (FW) is employed for irrigation. In contrast, when tomato plants are irrigated with Mixed-Water (MW) and Salinity-Water (SW), the chlorophyll content decreases by 14 and 20%, respectively.

Additionally, the data indicate a relationship between irrigation levels and chlorophyll content, with higher irrigation levels corresponding to reduce water stress and resulting in higher chlorophyll content. For instance, under full irrigation (RDI 100), the chlorophyll content reaches 42.02, while at lower irrigation levels (80, 60, and 40), the content progressively decreases by 5.6%, 17.18%, and 23.58% compared to full irrigation, respectively. Water stress exerts an impact on photosynthesis that extends beyond stomatal closure: it leads to chlorophyll degradation, decreased activity of enzymes like Rubisco, and the diminished photochemical efficiency of Photosystem II (PS II) [54]. Chlorophyll quantity declines as a result of chloroplast membrane degradation, the photo-oxidation of chlorophyll, enhanced chlorophyllase function, and inhibition of chlorophyll biosynthesis [60]. Additionally, water stress harms the entire photosynthetic apparatus, which is one of the reasons discussed in the review of potential indicators for crop water stress in vegetable crops [57].

Moreover, the chlorophyll interaction between the quality of water and irrigation levels is statistically significant. Specifically, chlorophyll values experienced a decrease of 32.14% with MW and 40.93% with SW at the 40% irrigation level compared to full irrigation with FW, whose value was 47.6. The considerable impact observed on the chlorophyll content due to the intricate interplay between water quality and water stress levels signifies the complexity of these factors in affecting plant physiology. The reduction in the amount of chlorophyll could be the result of osmotic stress, which leads to substantial damage to chloroplast layers by increasing membrane permeability [61]. These findings resonate with established research, affirming that environmental stressors like salt stress and drought exert a proven propensity to deplete photosynthetic pigments in tomato leaves [62].

3.2. Characteristics of Tomato Plants' Morphology

Irrigation levels have a pronounced effect on the leaf area, with a clear positive relationship between the volume of water applied and a rise in leaf area. However, the quality of water and its interaction with the level of water stress did not yield any significant effects at a significant level of 0.05, as illustrated in Table 4. However, there was a 'noteworthy decrease in leaf area by 37.61% and 32.56% at the 40% irrigation level when MW and SW were employed, respectively, in comparison to full irrigation with FW, where the leaf area measured 1449.59 cm^2 (Figure 5a).

Observations indicated that plant characteristics, including plant length, stem diameter, and both wet and dry stem weights, exhibited a decline when irrigation water salinity increased. The maximum of these characteristics was observed at FW, reaching 441.59 cm for plant length, 9.28 mm for stem diameter, and 417.87 g and 44.4 g for wet and dry stem weights, respectively.

Table 4. The analysis of the effects of water quality and irrigation water levels on the morphological characteristics of tomato plants.

Treatments		Leaf Area (cm^2)	Plant Length (cm)	Stem Diameter (mm)	Stem Fresh Weight (g)	Stem Dry Weight (g)
Quality	FW	1227.38 a	441.59 a	9.28 a	417.83 a	44.4 a
	MW	1195.2 a	412.16 b	7.73 b	353.14 b	40.85 b
	SW	1151.38 a	364.83 c	7.4 c	290.79 c	38.15 c
	p-value	0.132	0.000	0.000	0.000	0.000
	LSD	79.989	6.115	0.113	3.677	0.717
RDI	100%	1431.01 a	482.59 a	9.59 a	469.58 a	48.11 a
	80%	1293.84 b	428.6 b	8.64 b	341.94 b	41.97 b
	60%	1074.84 c	390.56 c	7.56 c	336.88 b	39.83 c
	40%	965.59 d	323.03 d	6.74 d	267.27 c	34.63 d
	p-value	0.000	0.000	0.000	0.000	0.000
	LSD	55.889	5.911	0.138	7.153	0.715
Quality × RDI	*p*-value	0.920	0.000	0.000	0.000	0.067
	LSD	96.803	10.239	0.238	12.390	1.239

According to the LSD test, values that share the same letter are not considered significantly different at the 0.05 probability level. Data from two consecutive seasons of tomato crop growth were analyzed.

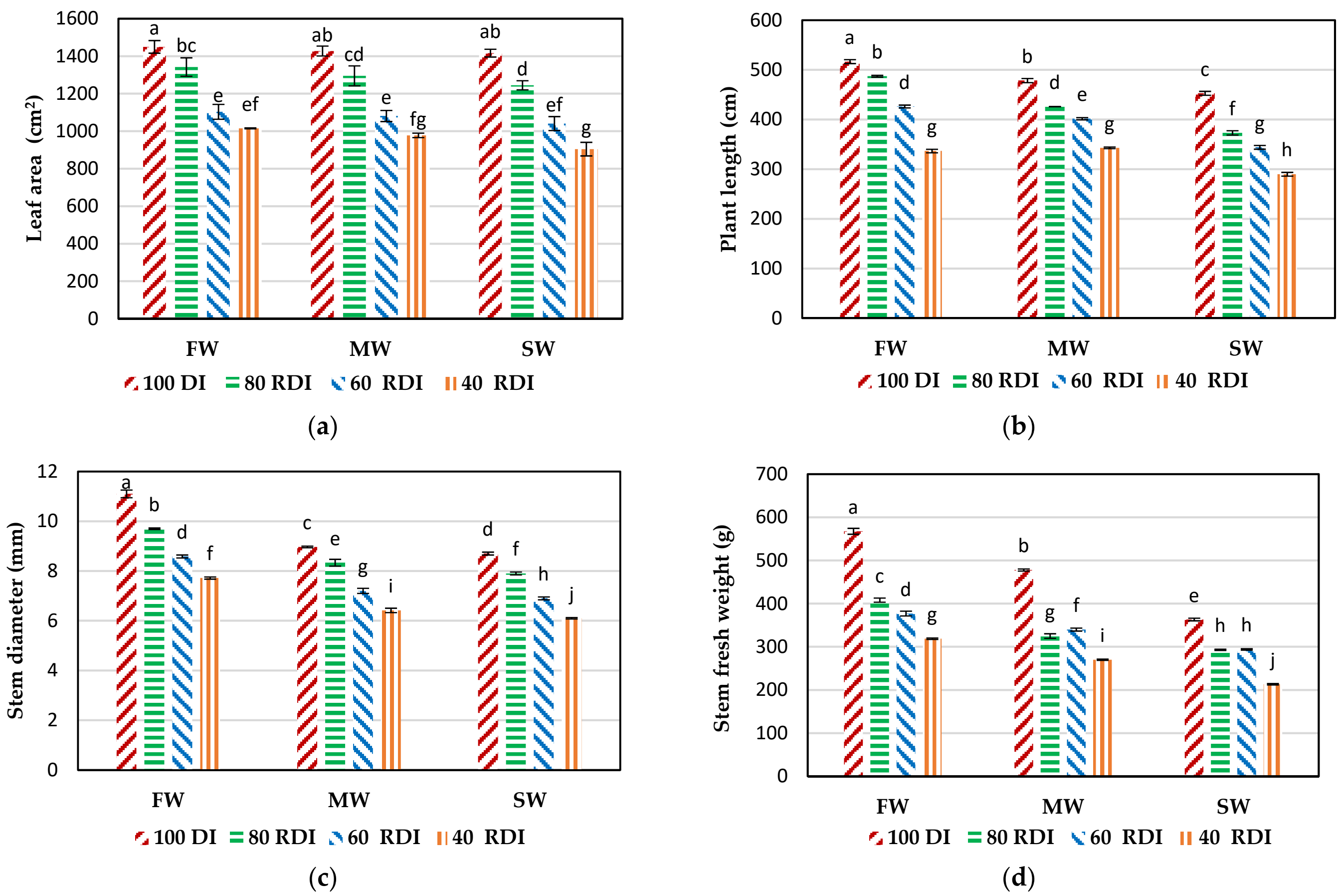

Figure 5. Interaction effects between water quality and irrigation water levels on (**a**) leaf area, (**b**) plant length, (**c**) stem diameter, and (**d**) stem fresh weight, for FW (Fresh-Water), MW (Mixed-Water), SW (Salinity-Water); 100% Full irrigation; 80%, 60%, and 40% potential ET_c. The data are the mean value ± standard error, and the LSD test was conducted at the 5% level ($p < 0.05$), and distinct letters in the figure indicate significant differences within treatments.

Examining various irrigation levels showed a significant impact on various characteristics. The application of more water resulted in an improvement in these characteristics. However, when the irrigation level was at 40%, there was a notable decrease of 33.06%, 29.7%, 28%, and 43.1% in plant length, stem diameter, wet weight, and dry weight of the stem, respectively, compared to full irrigation. Additionally, when considering both water and salt stress together, a significant effect was observed on plant length, stem diameter, and stem wet weight. Plant height peaked at 516.6 cm under full irrigation with FW and dropped to 289.72 cm when utilizing SW at the 40% irrigation level. The stem diameter and wet weight of the stem were the least at the 40% irrigation level, depending on water quality, being highest at FW and lowest at SW, as depicted in Figure 5.

As the irrigation water's salinity increased, these plant characteristics were observed to decrease. This phenomenon could be ascribed to the impact of saline water on plant vegetative growth attributes, primarily resulting from nutritional imbalances, as suggested by Gabhi et al. [63]. Due to this, excessive salt concentrations might impede the growth of plants because of osmotic stress and ion toxicity [64]. Additionally, This finding is in line with earlier studies by Reina-Sánchez et al. [65], Colimba-Limaico et al. [66], and Wu et al. [67], which indicate that salinity and water stress cause a considerable loss of many morphological characteristics. The level and duration of the irrigation stress influence the magnitude of this reduction.

3.3. Crop Yield and Water Management Indicators

According to the results, as irrigation water salinity increased, yield reduced to 10.13% and 24.92% for MW and SW, respectively, compared to FW, which produced 102.43 t ha^{-1}. This reduction was accompanied by 9.4% and 30.43% decreased water productivity (WP) for MW and SW, respectively, compared to the FW water productivity of 20.46 kg m^{-3} (Table 5). Additionally, yield decreased from 105.34 t ha^{-1} under full irrigation (FI) about 6.1%, 13.7%, and 36.7% under deficit irrigation levels of 80%, 60%, and 40%, respectively. Conversely, deficit irrigation increased WP by 15%, 30.8%, and 36.9% compared to FI, which had a WP of 14.07 kg m^{-3}, as shown in Table 5.

Table 5. The analysis of the effects of water quality and irrigation water levels on total fruit yield (Y), yield reduction (YR), water productivity (WP), and improved WUE for tomato plants.

Treatments		Y (t ha^{-1})	YR (%)	WP (kg m^{-3})	IWP (%)
Quality	FW	102.43 a	0.00	20.49 a	0.00
	MW	92.05 b	10.13	18.73 b	−9.40
	SW	76.9 c	24.92	15.71 c	−30.43
	p-value	0.000	-	0.000	-
	LSD	2.501	-	0.393	-
RDI	100%	105.34 a	0.00	14.07 d	0.00
	80%	98.89 b	6.12	16.56 c	15.04
	60%	90.92 c	13.69	20.32 b	30.76
	40%	66.69 d	36.69	22.3 a	36.91
	p-value	0.000	-	0.000	-
	LSD	1.581	-	0.340	-
Quality × RDI	*p*-value	0.000	-	0.000	-
	LSD	2.738	-	2.499	-

According to the LSD test, values that share the same letter are not considered significantly different at the 0.05 probability level. Data from two consecutive seasons of tomato crop were analyzed.

As illustrated in Figure 6a, when FI was executed with FW, the yield reached 123.48 t ha^{-1}. Furthermore, an examination of crop performance indicated that irrigation at 60% with FW outperformed complete irrigation with MW. Also, the yield experienced a decline of

46.42% and 50.94% utilizing salinity water MW and SW, respectively, at an irrigation level of 40%, compared to FI under FW.

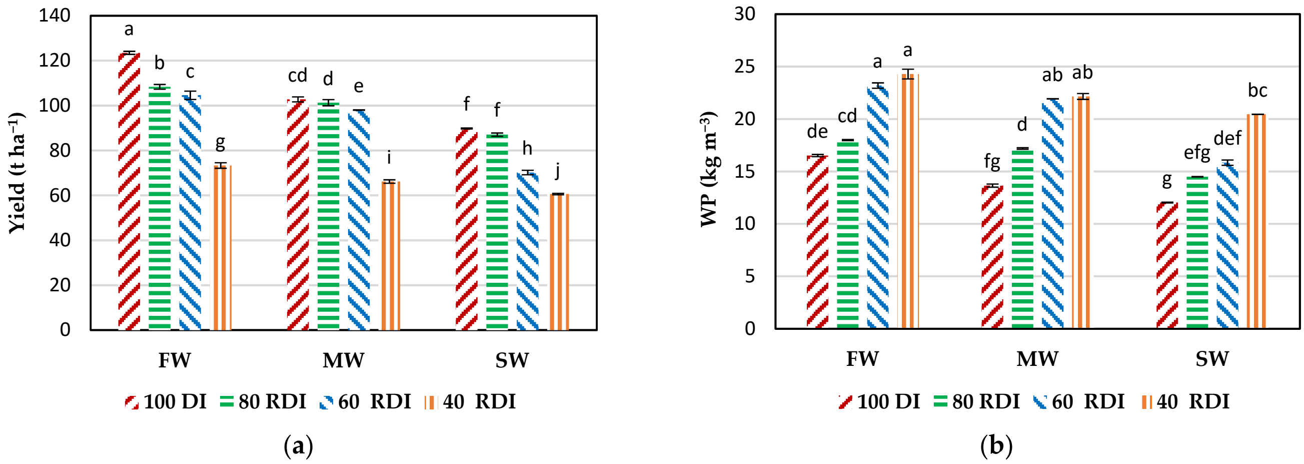

Figure 6. Interaction effects between water quality and irrigation water levels on (**a**) total fruit yield (t ha^{-1}) and (**b**) water productivity (WP), for FW (Fresh-Water); MW (Mixed-Water); SW (Salinity-Water); 100% Full irrigation; and 80%, 60%, and 40% potential ET_c. The data are the mean value ± standard error and the LSD test was conducted at the 5% level ($p < 0.05$), and distinct letters in the figure indicate significant differences between treatments.

The WP suggested an obvious and statistically significant relationship between the level of water stress and irrigation water quality. When FW was used, the WP averaged 23.74 kg m^{-3} at irrigation levels of 40% and 60%. In contrast, when SW and MW were used under FI conditions, WP decreased by 50.43% and 43.78%, respectively, compared to the 40% irrigation level using FW, as shown in Figure 6b.

These findings are consistent with the conclusions presented by Al-Harbi et al. [68], who found a significant 24.3% reduction in total fruit products due to irrigation with salinity water, with an electrical conductivity of 4.7 dS m^{-1}. Additionally, a recent meta-analysis by Gao et al. [69] found that the changes in tomato yield due to saltwater irrigation varied widely, ranging from a decrease of 96.8% to 36.2%. This comprehensive meta-analysis included data from 988 pairs of comparisons collected from 69 different articles. In a study by Yang et al. [70], tomato yield decreased as salt stress increased, with significant yield declines of 32.9% and 89.1% with salinity of 3‰ and 9‰ under deficit irrigation 2/3 of full irrigation compared to treatment with salinity of 0‰. Many studies indicate lower water quality and stress lead to reduced productivity [71,72]. Lu et al. [12] used meta-analysis to analyze 25 research articles; overall, RDI reduced tomato production by 18.61 t ha^{-1} on average, consistent with our findings. In accordance with the review Tura and Tolossa [71], utilizing 50% ET_c with good-quality water may be sufficient for tomato production. Furthermore, the data reviewed by Chand et al. [72] support the notion that RDI can save up to 50% of water, although yield reduction can range from 9% to 46%, depending on the degree and timing of water stress. This result is similar to the findings of Kirda et al. [73] and Wang et al. [74].

Yield—Applied Irrigation Water Functions

Figure 7 and Table 6 show the relationships between applied water (W) and tomato yield (Y) at various salinity levels (S). For each salinity level, the quadratic polynomial regression function (Y(W)) could be efficiently used with a good determination coefficient (R^2) of 0.94. Results indicate that crop yield improved when irrigation water was applied up to its maximum level and decreased as more water was supplied. It is noteworthy that the Y(W) curve significantly reduced compared to the FW curve as salinity increased. The results of this investigation were consistent with those of Yang et al. [75],Yang et al. [76], and Chand et al. [77] who reported that crop yield enhanced with irrigation quantity to its maximum level and declined with the excess water.

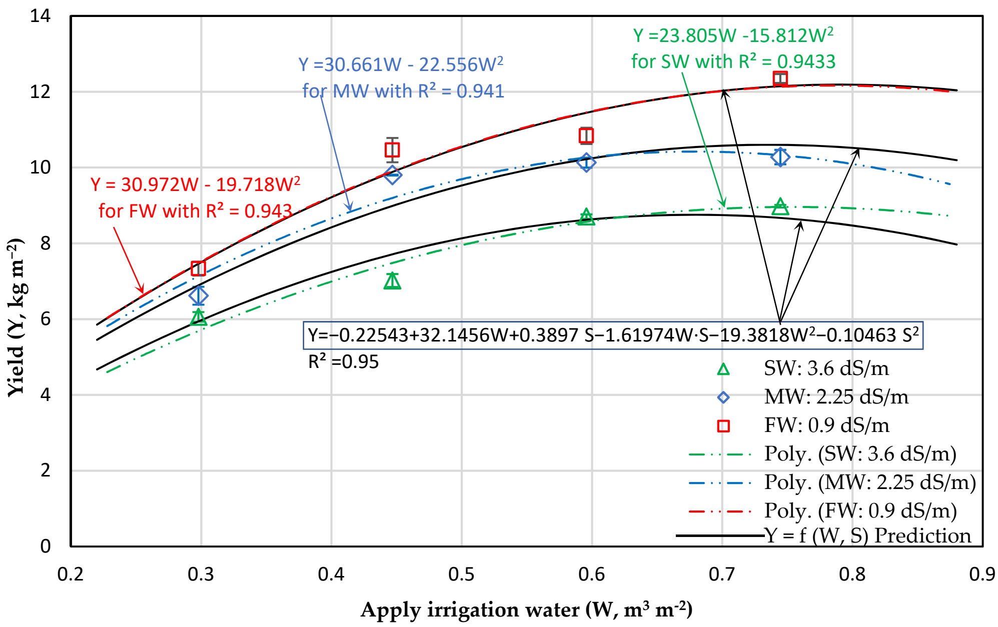

Figure 7. The relationships between crop yield and applied water under different water quality: FW (Fresh-Water), MW (Mixed-Water), and SW (Salinity-Water). The data are the mean value ± standard error.

Table 6. The yield (Y)—irrigation quantity (W) and water quality (S) relationships.

Quality of Water (S)	Equations	R^2
Quadratic polynomial function (one independent variable; W)		
FW = 0.9 dS m^{-1}	$Y = 30.972W - 19.718W^2$	0.94
MW = 2.25 dS m^{-1}	$Y = 30.661W - 22.556W^2$	0.94
SW = 3.6 dS m^{-1}	$Y = 23.805W - 15.812W^2$	0.94
2nd-order polynomial function (two independent variables; W and S)		
$Y = -0.22543 + 32.1456W + 0.3897S - 1.61974W{\cdot}S - 19.3818W^2 - 0.10463S^2$		0.95

Water quality has a significant effect on tomato yield; so, incorporating water quality into the Y(W) relationship, yield can be predicted by the 2nd order polynomial regression function (Y(W,S)) of two independent variables (W and S). The results indicate a good agreement between the three Y(W) functions at different salinity and the Y(W,S) function. For FW, the Y(W) and Y(W,S) curves are exactly identical. For MW and SW, only at irrigation level of 80%, the both curves are identical. While at MW, the Y(W) curve was slightly higher than Y(W,S) curve at lower 80% irrigation levels, and it decreased when that level was exceeded; at SW, the opposite was observed.

3.4. Impact of Water Quality and Irrigation Levels on Tomato Fruits Quality

The study analyzed the quality of tomato fruit, including total acidity (TA), vitamin C (VC), and total soluble solids (TSS), in relation to irrigation water quality; the findings demonstrated a notable rise in these attributes as water salinity increased. Specifically, using SW increased TA and TSS by 16.1% and 15.5%, respectively compared to FW, while VC reached 33.67 (mg/100 g), signifying improved fruit quality (Table 7). The study also showed that decreasing irrigation levels enhanced fruit quality significantly, with 40% RDI increasing TA, VC, and TSS by 36.5%, 16.7%, and 28.8%, respectively, compared to 100% RDI, as shown in Table 7.

Table 7. The analysis of the impacts of water quality and irrigation water levels on total acidity (TA), vitamin C (VC), and total soluble solids (TSS) for tomato fruits.

Treatments		TA (% Citric Acid)	VC (mg 100 g^{-1})	TSS (%)
Quality	FW	4.22c	30.42c	4.13c
	MW	4.49b	32.83b	4.33b
	SW	4.9a	33.67a	4.77a
	p-value	0.000	0.000	0.000
	LSD	0.078	0.274	0.054
RDI	100%	3.89d	29.31d	3.85d
	80%	4.41c	32.26c	4.08c
	60%	4.54b	33.43b	4.75b
	40%	5.31a	34.22a	4.96a
	p-value	0.000	0.000	0.000
	LSD	0.071	0.293	0.084
Quality × RDI	*p*-value	0.000	0.118	0.009
	LSD	0.124	0.507	0.146

According to the LSD test, values that share the same letter are not considered significantly different at the 0.05 probability level. Data from two consecutive seasons of tomato crop were analyzed.

The investigation of the interaction effect of water and salt stresses on fruit quality found that both TA and TSS are significantly affected at a 0.05 level. As the intensity of these stresses increases, these values increase as well. When using SW, the highest TSS values were recorded at 40% and 60% irrigation levels, reaching 5.45% and 5.15%, respectively. However, the 40% RDI irrigation levels had the highest TA values of 5.38 for MW and SW, as shown in Figure 8. Reducing irrigation amounts seems to have an inverse relationship with improving fruit quality. This observation aligns with similar research, which noted that water-stressed conditions can enhance fruit quality compared to full irrigation conditions [12,66,72,74,78,79]. In the situation of soil water deficit, there could be a reduction in water flow from the xylem to the fruit [80,81]. As a result, the translocation of phloem sap to the fruit is hindered, leading to an increase in solute concentration in the sap, contributing to improved fruit quality [80,82,83]. However, Yang et al. [70] and Wu et al. [84] revealed that the combination of water and salinity stress had no significant effect on certain fruit quality indices, such as VC.

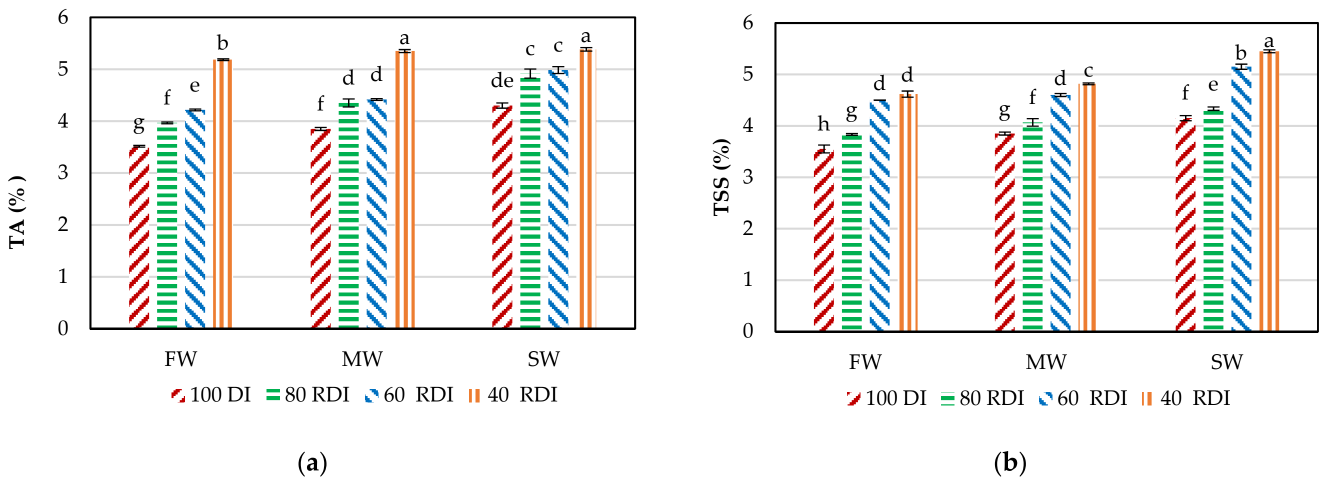

Figure 8. Interaction effects between water quality and irrigation water levels on (**a**) total acidity (TA), and (**b**) total soluble solids (TSS). The LSD test was conducted at the 5% level ($p < 0.05$), and distinct letters in the figure indicate significant differences between treatments.

4. Conclusions

Investigating the effects of water and salt stresses on tomato crop yield, morphological and physiological properties, and water productivity in a greenhouse led to the following conclusions:

- Salinity has a negative impact on stomatal conductance (g_s) and transpiration (T_r), as observed by the significant reductions in these physiological parameters with salinity of 3.6 m ds^{-1} (SW) compared to freshwater (FW: 0.9 m ds^{-1}).
- Also, FW had the greatest chlorophyll content, which indicates the plant's morphological characteristics were improving.
- Depending on the availability and quality of the water source, specific irrigation levels should be recommended.
- For salinity of 2.25 m ds^{-1}, a 60% deficit irrigation is ideal, resulting in similar yields to full irrigation (FI) with significantly improved water productivity. In contrast, for SW, an 80% irrigation level is recommended, as it does not significantly reduce yield compared to FI.
- For FW, FI should be used for optimal yield per unit area, although those wishing to preserve water can profit from 60% deficit irrigation.
- Under deficit irrigation and salinity stress, fruit quality indices such total acidity (TA), vitamin C (VC), and total soluble solids (TSS) increased, indicating that improving water management practices can improve fruit quality.

The research found that salinity has a negative impact on critical physiological variables in tomato crops, emphasizing the importance of these irrigation strategies. When greenhouse horticulture is stressed by water and salinity, the results indicate that altering irrigation levels according to water quality helps reduce yield losses, increase water productivity, and improve fruit quality. Future investigations in this field should delve into enhancing and improving deficit irrigation strategies in greenhouse horticulture to lessen the negative impacts of salinity stress on tomato crops. The exploration of particular irrigation scheduling methods, technologies for monitoring soil moisture, and practices for managing crops that are customized to different water quality conditions has the potential to strengthen further the ability of tomato crops to withstand physiological stress caused by salinity.

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