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Effects of Saline Irrigation Water Applications on Evapotranspiration Partitioning and Crop Coefficient of Tomato Grown in Mediterranean-Type Greenhouses

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Abstract: Accurate information regarding crop evapotranspiration (ET_c) and its components is essential for proper water management. Salinity has become increasingly serious in many parts of the world, affecting the use of saline water in irrigation for various biochemical processes, hence the importance of understanding the effects of soil and water salinity on ET_c. This study aimed to determine the transpiration (T_r) and soil evaporation (E_s) components that constitute ET_c in tomatoes irrigated by drip irrigation and to investigate the effects of irrigation water salinity levels on ET_c and its components, as well as on the crop coefficient (K_c) used to determine ET_c. In addition, the reference evapotranspiration (ET_o) values determined by the measurements obtained with the lysimeter system were compared with the ET_o values calculated using the Almeria (ET_{o_Alm}), FAO Radiation ($ET_{o_FAO\text{-}Rad}$), and Hargreaves (ET_{o_Harg}) models. During the spring growing period of 2022, tomatoes were cultivated under four different irrigation water salinity levels: S_0 = 0.7 (control), S_1 = 2.5 (low), S_2 = 5.0 (medium), and S_3 = 7.5 (high) dS m^{-1}. The T_r values in S_0, S_1, and S_2 treatments were measured by the sap flow method. Radiation-based ET_o prediction models had strong relationships with lysimeter-measured ET_o values ($R^2 > 0.977$ and RMSE < 0.53 mm). The results indicated that increasing salinity levels led to a decrease in both T_r and ET_c while causing an increase in E_s. In the S_0, S_1, and S_2 treatments, E_s accounted for 16.3, 45.0, and 36.2%, respectively. Actual K_c values also decreased with increasing salinity. The results indicate that different actual K_c values can be used when calculating evapotranspiration in decision-making processes in greenhouse tomato production in Antalya and when irrigation water with different salinity levels is used. Additionally, actual ET_c responses of tomatoes to salinity can be used to manage saline water in irrigation scheduling.

Keywords: crop coefficient; evaporation; salinity; sap flow sensors; transpiration

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1. Introduction

Over the last two decades, the global demands for crop production have increased significantly to meet the needs of the rapidly increasing human population [1]. Therefore, water use for agricultural purposes faces increasing competition from non-agricultural uses associated with the lowering of water table levels due to overexploitation of groundwater, overuse of surface water, water pollution, and soil salinization. All these factors threaten the sustainability of agricultural production and require the improvement of irrigation water-saving policies and practices [2].

In agricultural lands, almost all irrigation water is consumed through crop evapotranspiration (ET_c), which combines two important phenomena occurring simultaneously in

a planted area: transpiration (T_r) and evaporation from the soil (E_s) [3], since the amount of water used by plants for metabolic processes is insignificant. The ET_c knowledge is an important basis for optimizing irrigation water management strategies and improving crop water efficiency [4] and is necessary for sustainable development and environmentally friendly water management in the Mediterranean region [5].

The soil water balance method [6], weighed lysimeters [7], and sap flow measurement along with micro lysimeters [8] have been widely used to directly measure plant ET_c [9]. For a more comprehensive review of these methods, please refer to the literature, including the work by Allen et al. (2011) [10], which provides an extensive overview of alternative techniques. However, direct measurements of ET_c are costly and laborious. Therefore, many climate-based models have been developed to predict ET_c. The most commonly used models include the Penman-Monteith [11], the Priestley-Taylor [12], the Shuttle-Wallace [13], and the FAO56-crop coefficient (FAO_K_c-ET_o) [14].

The FAO_K_c-ET_o is the most widely used model in practice for estimating crop water requirements. The model is based on the formula $ET_c = ET_o \times K_c$ [15], which is the product of reference evapotranspiration (ET_o) and the crop coefficient (K_c) [16]. ET_o represents the evapotranspiration rate from a standardized reference crop, typically grass, under ideal water management and no-stress conditions [15] and can be estimated by numerous models developed using various climatic variables and levels of detail [17]. In general, K_c is estimated as the ratio of ET_c to ET_o and reflects the comprehensive influence of plant physiology between the reference surface and the real plant at different growth stages [15]. K_c is affected by management strategies like irrigation scheduling as well as plant characteristics at different growth stages, such as leaf area index, leaf physiological characteristics, and plant height [15].

The K_c can be determined by two approaches: single or dual. In the single approach, crop transpiration and evaporation from the soil are combined into a single K_c coefficient, while in the dual approach, K_c is divided into two separate coefficients; one is the basal plant coefficient (K_{cb}), which represents the transpiration of the plant, and the other is the soil-water evaporation coefficient (K_e), which represents the evaporation on the soil surface and is expressed as $K_c = K_{cb} + K_e$ [15]. This method, which uses separate estimates of plant and soil elements in the crop coefficient, allows both elements to be observed independently and compared with each other [18]. In FAO 56 [15], K_c and K_{cb} values are provided in tabular form, corresponding to the three growth stages (initial, mid-season, and late or end of season) of various plants. In addition to the K_c and K_{cb} values provided by FAO 56 [15], recent updates to these values for several vegetable crops have been published [19], which offer revised estimates and more accurate data for current applications.

The FAO_K_c-ET_o method can also be applied to greenhouse plants, where ET_o is estimated from the microclimate inside or outside the greenhouse [20]. It was demonstrated that the FAO56-PM equation with a constant aerodynamic resistance of 295 s m^{-1} is applicable in greenhouses due to the low wind speed [7], and this approach was used to calculate ET_o under greenhouse conditions in numerous studies [8,11,21].

E_s and T_r have different functions within the agricultural system. T_r is associated with plant growth and yield and plays an important role in photosynthesis and dry matter accumulation in plants. Therefore, it requires more attention [22]. In contrast, E_s is generally considered to be a water consumption that has no effect on yield formation and should be reduced as much as possible through plant management practices [23], which can be achieved through agricultural land management, such as applying mulch and using appropriate irrigation techniques [24]. T_r is significantly affected by microclimate and often correlates well with solar radiation, vapor pressure deficit, and air temperature, provided that soil moisture is sufficient [25]. However, the strength of the correlation between plant T_r and microclimate variables can vary depending on the type of plant, the conditions under which it is grown, the moisture content of the soil, and the agricultural methods used [26].

Sap flow sensors are widely used to measure plant transpiration [25]. If the variation in water storage in plants is negligible on a daily scale, then the daily total sap flow is equal to the T_r of the plant [27]. Accurate determination of ET_c and its components is critical for developing efficient and sensitive irrigation scheduling and increasing water use efficiency in greenhouses [23].

Lack of precipitation and drought in many parts of the world have reduced the surface water supply for irrigation purposes. This frequently encourages the use of saline water for irrigation [28], which can further increase salt accumulation near the soil surface [29]. Approximately 20% of the world's irrigated agricultural lands are negatively affected by soil salinization [30], a major environmental problem that threatens agriculture worldwide [31]. Problems related to soil salinization are exacerbated by increasing population and industry, degradation of the natural environment, poor irrigation practices, and climate changes [32]. As a result, the abiotic stresses and resulting nutritional imbalances triggered in plants can negatively affect yield and growth [33]. Improving plant acclimation to abiotic stresses is critical to meet the increasing food demand in sustainable agriculture, especially in an environment where salt water is increasingly used for irrigation in arid and semi-arid regions of the world [33].

Short-term exposure of plants to high salt concentrations causes osmotic stress, making it difficult for the roots to absorb water [34]. This leads to water deficiency, ion imbalance, ion toxicity, or a combination of any of these adverse factors [35]. Salinity-induced water uptake loss is regulated through plant transpiration by reducing stomatal opening and aperture [36]. This reduction is caused by the decrease in soil water potential [37]. Proper irrigation scheduling is fundamental for maximizing yield, and it requires a good understanding of the plant's response to soil water status [38] and the plant's tolerance to salinity [39]. In addition, Minhas et al. (2020) [40] provide a detailed study on managing salinity in irrigated agriculture, including a thorough analysis of crop evapotranspiration and water management issues related to salinity.

Tomato (*Solanum lycopersicum* L.) is a widely cultivated vegetable worldwide, with an annual production of 1.89×10^8 metric tons [41] and an important greenhouse crop in the semi-arid regions of the Mediterranean countries. In these regions, soil and groundwater salinity is a serious problem that affects tomato yield and quality [42]. Although tomatoes are moderately sensitive to salinity and can tolerate soil salinity (EC of saturated paste extract (EC_e)) up to 2.0 dS m^{-1}, their growth and yield are reduced at salinity above this level [43].

Numerous studies have been conducted on the calculation/measurement of ET_c and its components in tomatoes irrigated with drip irrigation, as well as the effect of soil salinity on ET_c. Möller and Assouline (2007) [44] calculated ET_o values inside the greenhouse using the FAO 56 method [15], while Fernandez et al. (2010) [7] measured them in drainage-type lysimeters. Both studies concluded that the ET_o value varied between 1 and 4 mm day^{-1}. Eliades and Orphanos (1986) [45] determined the ET_c of tomatoes in an unheated greenhouse in southern Cyprus using drainage-type lysimeters and found that the potential evapotranspiration varied between 0.5 and 6.7 mm day^{-1} in tomatoes by multiplying the evaporation from the pan placed outside the greenhouse by coefficients that varied throughout the season. In southern Italy, Quaglietta-Chiaranda and Zerbi (1981) [46] determined the water consumption of tomatoes to be 545 mm in the drainage-type lysimeter in the greenhouse, where the highest yield was obtained by irrigating when the cumulative Class A Pan evaporation was 20 mm. Zhao et al. (2013) [47] found that the water requirements of tomatoes irrigated with drip irrigation under greenhouse conditions increased with growth and decreased in the late-season growth stage, causing the daily ET_c to vary between 1.5 and 4.2 mm day^{-1}, and they concluded that mid-season and late-season K_c values, measured as 1.01 and 0.61, respectively, were 5% and 8% lower than the values recommended by FAO. Gallardo et al. (2013) [48] reported that the seasonal water requirements of tomatoes grown in greenhouses in spring and fall were 231 and 260 mm, respectively, and that the initial period, maximum, and late season K_c values were

0.2, 1.4, and 1.0, respectively. Harel et al. (2014) [49] found the K_c of tomatoes grown in greenhouses in Israel to be 0.3–1.0 in winter and 0.2–0.9 in summer for the period between seedling planting and first fruit harvest and 0.8 in both seasons for the last period. In China, the seasonal ET_c of tomatoes was found to vary between 249.1 and 388.0 mm under greenhouse conditions, where irrigation was scheduled according to the different levels of pan evaporation [6]. In addition, Gong et al. (2020) [50] determined the dual K_c values of tomatoes by comparing the ET_o calculated with different models with the use of sap flow sensors combined with a micro-lysimeter system in one experimental year and the ET_c values measured with a weighed lysimeter system in the other experimental year. They reported that the ET_c was 345 mm during the entire growth phase for tomatoes irrigated with drip irrigation.

Gong et al. (2020) [51] conducted another study focusing on ET_c and K_c values in greenhouse tomatoes under both full and limited water conditions. They determined that the total seasonal ET_c ranged from 310 to 350 mm under full irrigation. In addition, they proposed an individual crop coefficient model for predicting ET_c that considers factors such as leaf senescence, soil water stress, and canopy cover percentage. In another study, researchers measured the ET_c of drip-irrigated tomatoes grown in greenhouses with weighing lysimeters, E_s with micro lysimeters, and T_r with a sap flow monitoring system and found that the total seasonal ET_c of tomatoes was 315.1–350.8 mm, of which 15.4–26.5% was of E_s [23]. It is important to note that the ET_c and K_c values presented in these studies are indicative of and influenced by the type of greenhouse used (e.g., plastic vs. glass), particularly due to differences in material transmissivity. Additionally, the internal conditions of the greenhouse, such as temperature and humidity, further impact the ET_c.

Regarding salinity, Maggio et al. (2004) [52] compared tomato plants irrigated with 171 mM NaCl and control treatment, observing a decrease in leaf area, root turgor pressure, and root density, and stated that ET_c decreased with increasing irrigation water salinity. Tomato plants irrigated with a nutrient solution with a salinity of 9.1 dS m^{-1} consumed 40% less water than control-irrigated plants, and reductions in plant water uptake with increasing salinity varied between 3.5% and 5% per 1 dS m^{-1} among different tomato varieties [53]. Yang et al. (2020) [54] reported that while leaf photosynthesis rate, transpiration rate, and stomatal conductance remained unchanged up to an irrigation water salinity of 2 dS m^{-1}; ET_c decreased as salinity increased due to reductions in photosynthesis and transpiration rates.

Antalya province accounts for 38% of Türkiye's greenhouse agricultural area, which totals 82,000 hectares. Tomatoes are the most commonly cultivated crop in greenhouses, accounting for 45% of the total area [55]. In the Mediterranean Region of Türkiye, 20.9% of the irrigation water supply is provided by groundwater [56], with the electrical conductivity (EC) measurements of such waters employed in Antalya's greenhouses fluctuating between 0.85 dS m^{-1} and 4.1 dS m^{-1} in the winter month of November, and between 0.83 dS m^{-1} and 4.4 dS m^{-1} during the summer month of June. Evaluations conducted on the soil and the water used for irrigation in Demre's greenhouses, located in Antalya, revealed that the salinity is categorized within a range from moderate to high range [57].

To enhance water use efficiency through precise irrigation practices and automation in modern irrigated agriculture, it is crucial to separately determine the T_r and E_s components of the ET_c, as well as understand the effects of salinity on evapotranspiration in the decision-making process for irrigation at varying salinity levels. Therefore, this study aimed to assess the effects of different irrigation water salinity levels on ET_c and K_c values by separately evaluating the T_r and E_s components in spring tomato cultivation in Mediterranean-type greenhouses. Additionally, this study aimed to test the suitability of radiation-based methods in calculating reference crop evapotranspiration (ET_o).

2. Materials and Methods

2.1. Experimental Area

This study was carried out in the spring 2022 growing season in a Mediterranean-type greenhouse with a lysimeter system in Akdeniz University Agricultural Research and Implementation Area in Antalya (TR Türkiye, 36°53′15″ N latitude, 30°38′53″ E longitude; 12 m altitude a.s.l.). The greenhouse had a gothic roof design with a 4 m gutter height and a 6 m ridge height. It was 9.60 m wide and 25 m long and oriented in a north–south direction. It was naturally ventilated from both the side and roof and covered with polyethylene. It was covered with a three-layer polyethylene film of 180 µm thickness with a visible light transmission of 87–89% (Tarım Kredi İmece Plastik A.Ş., Antalya, Türkiye). The greenhouse was unheated and constructed from steel, which is typical of Mediterranean-type greenhouses found in the region. The lysimeters (15 in total) located inside the greenhouse had inner dimensions of 2.70 × 1.85 m and a depth of 0.80 m. It consisted of a top layer of 60 cm of soil and a bottom layer of 20 cm of gravel.

The region is characterized by a Mediterranean climate, experiencing warm, arid summers and rainy winters. Over the long term, the mean annual temperature stands at 18.8 °C, with the coldest and warmest monthly averages being 10.0 °C in January and 28.5 °C in July, as per the 2024 data from the Turkish State Meteorological Service (MGM 2024) (Figure 1).

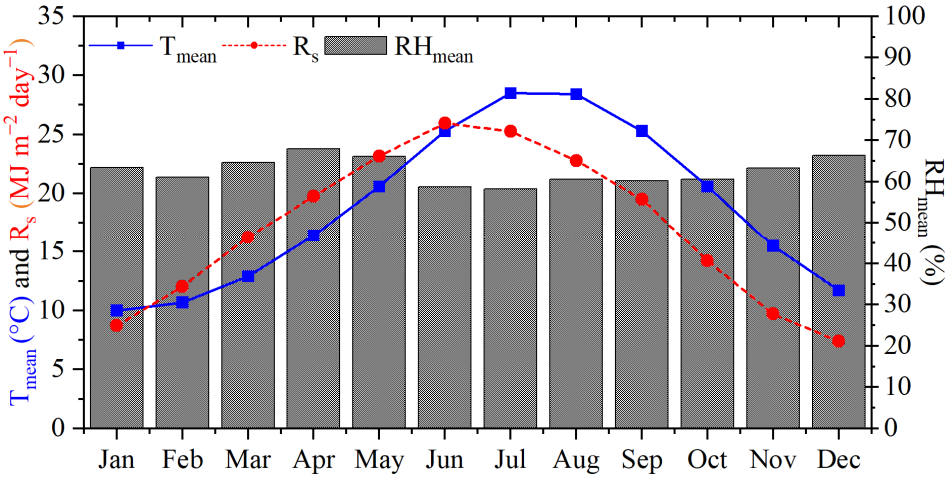


Figure 1. Long-term climate data for the Antalya Region. T_{mean} is the average monthly temperature (°C), R_s is the average monthly solar radiation (MJ m^{-2} day^{-1}), and RH_{mean} is the average monthly relative humidity (%).

2.2. Experimental Conditions, Design and Treatments

This study was conducted between 25 February and 27 June 2022 (122 days) and was arranged as a randomized complete block design with three replications for each salinity treatment. The experiment assessed four levels of irrigation water salinity (S), each characterized by distinct electrical conductivities (EC_i): S_0 = 0.7 dS m^{-1} (control), S_1 = 2.5 dS m^{-1} (low), S_2 = 5.0 dS m^{-1} (moderate), and S_3 = 7.5 dS m^{-1} (high). For all salinity treatments, the sodium adsorption rate (SAR) was kept as close as possible to that of the tap water source to eliminate the influence of the SAR on the results. For this purpose, the desired electrical conductivity values (EC_w) were prepared in the irrigation water for each treatment by mixing calculated amounts of $CaCl_2$, $MgSO_4$, and NaCl salts, and the EC_w values of the treatments were checked in the laboratory [58].

The soil was identified as a silty-clay loam consisting of 51% silt, 28% clay, and 21% sand with a bulk density of 1.38 g cm^{-3}. Additionally, the EC of soil determined by saturation extract was 0.5 dS m^{-1}, with field capacity and permanent wilting point measured at 31% and 14%, respectively. Lysimeter plots were irrigated with a drip irrigation system. The drip irrigation system was configured to ensure that each crop row was

serviced by one lateral equipped with pressure-compensating drippers. These drippers discharged water at a rate of 2 L h^{-1} under a pressure of 0.1 MPa and with a spacing of 0.2 m. The soil water pressure was observed using tensiometers (SR Series, Irrometer Company Inc., Riverside, CA, USA). After calibrating these instruments for the specific characteristics of lysimeter soils, they were installed uniformly in all lysimeter plots on 24 February 2022. The instruments were positioned proximal to the lateral pipes and located 0.10 m from the dripper at a depth of 20 cm. Irrigation applications were performed to replenish soil moisture levels to field capacity when tensiometer readings reached 20 cb (equivalent to 20% depletion of available water) at a depth of 0.60 m in the soil profile. The regulation of the amount of irrigation water was performed using both the water meter integrated into the primary pipeline and the individual valves assigned to each plot. To determine the amount of irrigation water distributed to the lysimeter plots, Equation (1) was used.

$$I = \frac{P_{V(FC)} - P_{V(AW)}}{100} \times D_s \times A \times P_a \quad (1)$$

where I is the amount of irrigation water (L), $P_{v(FC)}$ is the field capacity of the soil (cm^3 cm^{-3}), $P_{v(AW)}$ is the available water content in the soil (cm^3 cm^{-3}), D_s is the soil depth (mm), A is the parcel area (m^2), and P_a is the wetted area percentage (%).

The ÖZKAN F1 variety of tomatoes, which is commonly grown in Antalya, was cultivated in this experiment. The tomato seedlings were planted in lysimeter plots at intervals of 0.60 × 0.50 m. Once the tomato seedlings reached a height of 0.40 m, they were trained on a single stem and supported by ropes. New side shoots were periodically removed throughout the growing period. After eight clusters were formed, the top shoots of the plants were pruned. Leaf pruning was performed according to the method recommended by [59] and in accordance with local growers. The first leaf pruning operation was conducted on 9 May 2022, followed by 6 June 2022. To reduce the light intensity and temperature inside the greenhouse, whitening applications were applied on 22 April 2022 and 28 April 2022. For pollination, Bombus bees (NATUPOL Beehive, Koppert Türkiye, Antalya, Turkey) were placed in the greenhouse.

2.3. Measurements

The greenhouse's microclimate was monitored using a climate station positioned centrally above the crop canopy. This station was equipped with air temperature (PT100 1/3 Class B, Pessl Instruments, Weiz, Austria), relative humidity (Rotronic hygrometer IN-1, Pessl Instruments, Weiz, Austria), solar radiation sensors (LI-200SZ-IM506D, Pessl Instruments, Weiz, Austria), and net radiation (CNR4, Kipp & Zonen, Delft, The Netherlands). Net radiation data were recorded using a CR1000X data logger (Campbell Scientific, Inc., Logan, UT, USA) with a measuring interval of 5 min and a logging interval of 60 min. All other data were collected through an iMETOS 3.3 data logger (Pessl Instruments, Weiz, Austria) using the same measuring and logging intervals. Quality assessment and control of weather data have been carried out using the Python package agweather-qaqc python [60].

To determine the reference evapotranspiration (ET_o), the Tifway Sport Bermudagrass variety, known for its adaptability to greenhouse environments, was cultivated in three lysimeters within the greenhouse. Cultural practices were applied to the grasses based on the characteristics of a standard grass, as recommended by the authors of [15]. The amounts of ET_o and ET_c were calculated by using the equation for the water balance given in Equation (2) [7].

$$ET_o \text{ or } ET_c = (SWC_{t0} - SWC_{t1}) + I - D \quad (2)$$

where ET_o is the reference evapotranspiration, (mm), ET_c is the crop evapotranspiration (mm) measured between two measurement dates, ($SWC_{t0} - SWC_{t1}$) is the change in soil water content between two measurement dates (mm), I is the irrigation water (mm), and D is the total amount of water drained between two measurement dates (mm).

If any, the quantity of drainage water was recorded on a daily basis from the lysimeters. Since this study was conducted in a drainage-type lysimeter, weekly calculations of ET_o and

ET_c values were performed to ensure more accurate results. The mean values of ET_o and ET_c were derived from lysimeters located at different locations within the greenhouse. To mitigate any potential edge effects, the same plants were cultivated in pots placed between the lysimeters.

ET_o was also estimated using three different models commonly used in greenhouses [17], namely the Almeria (ET_{o_Alm}) [7], FAO24-Radiation ($ET_{o_FAO\text{-}Rad}$) [61], and Hargreaves (ET_{o_Harg}) [62] models, which are given in Equations (3)–(5), respectively.

$$\begin{array}{c} For\ JD \leq 220\ ET_o = ((0.288 + 0.0019JD)R_s)/2.45 \\ For\ JD > 220\ ET_o = ((1.339 - 0.00288JD)R_s)/2.45 \end{array} \quad (3)$$

$$\begin{array}{c} ET_o = b \times \left(\frac{\Delta}{\Delta+\gamma}\right)R_s - 0.3 \\ b = 1.066 - 0.0013RH + 0.045 \times U_d - 0.0002RH \times U_d - 0.315 \times 10^{-4} \times RH^2 - 0.0011 \times {U_d}^2 \end{array} \quad (4)$$

$$ET_o = \left(0.0023R_s(T_{max} - T_{min})^{0.5}(T_{avg} + 17.8)\right)/2.45 \quad (5)$$

where ET_o is the reference evapotranspiration (mm day^{-1}), JD is the Julian days, R_s is the solar radiation (MJ m^{-2} day^{-1}), Δ is the slope of the saturation vapor pressure temperature relationship (kPa °C^{-1}), γ is the psychrometric constant (kPa °C^{-1}), RH is mean air relative humidity (%), U_d is daytime wind speed (m s^{-1}), T_{max} is the maximum daily temperature (°C), T_{min} is the minimum daily temperature (°C), and T_{avg} is the mean daily temperature (°C).

To estimate the plant transpiration, rates of sap flow (F_s, g h^{-1}) of individual plants were measured using the stem heat balance (SHB) technique [63,64]. F_s was continuously monitored on 2–3 plants per treatment, once the plants reached a stem diameter close to sensor one (around 12 mm—25 April 2022) and till the end of the experimental period (growing season) using SHB sap flow sensors (Dynamax Inc., Houston, TX, USA) of stem diameter *SGEX13*. Sensors were not installed on plants in the S_3 treatment due to the data logger's inadequate capacity for collecting sap flow system data. The sensors were mounted at a height of 0.30–0.40 m above the collar and installed following the manufacturer's instructions (cfr. https://youtu.be/s7Zz5aNApLI, accessed on 25 July 2024).

Sap flow sensor data were gathered every 30 s using a datalogger (model CR1000, Campbell Scientific Inc., Logan, UT, USA), and the averages over 15 min periods were documented. The sap flow rates (F_s) were derived from the collected data by applying the formulas provided by Baker and van Bavel (1987) [64], utilizing the datalogger's companion software, PC400 version 4.7 (Campbell Scientific Inc., Logan, UT, USA).

To calculate the T_r per unit of ground area (T_r, mm day^{-1}) for each treatment, the T_r of the entire plant was estimated by summing the F_s contributions from all stems (in the case under consideration, the plants were single stems). The sap flow rate per unit of stem area (F_i; g m^{-2} h^{-1}) for the ith stem was obtained by dividing its F_s rate (F_{si}; g h^{-1}) by the stem area (A_{si}; m^2). The sum of all F_i was multiplied by the ratio of the average stem area at 0.40 m of ten plants per treatment ($A_{s\text{-}avg}$; m^2) to the ground surface area per plant (SA; m^2). Finally, the result was transformed to kg m^{-2} h^{-1} and, therefore, to mm of water column per hour (mm h^{-1}), as follows in Equation (6) [65]:

$$T_r = \sum_{i}^{n} \frac{F_{si}}{A_{si}} \times \frac{A_{s-avg}}{SA} \times 10^{-3} \frac{kg}{g} \quad (6)$$

where i = stem number and n = the number of stems per plant. Subsequently, the hourly T_r was cumulated for each day to calculate the daily T_r per unit of ground area (T_r; mm day^{-1}). Additionally, the stem cross-sectional area (A_s) and its average ($A_{s\text{-}avg}$) were determined at a height of 0.40 m using a dendrometer caliper. The SA was predicted based on the plant density of 3 plants m^{-2}. Soil evaporation (E) values were calculated by subtracting T_r values from ET_c.

The crop coefficient (K_c) values were calculated as the average over measurement periods using the ET_o and ET_c values collected from the lysimeters within the greenhouse, as shown in Equation (7) [15].

$$K_c = ET_c / ET_o \quad (7)$$

where K_c is the crop coefficient, ET_o is the reference crop evapotranspiration (mm), and ET_c is the crop evapotranspiration (mm). Throughout the manuscript, crop evapotranspiration and the crop coefficient in the control treatment (S_0) are expressed as ET_c and K_c, respectively, whereas under salt stress, they are referred to as actual ET_c and K_c, respectively.

To monitor soil salinity, soil samples were collected from the lysimeters monthly throughout the study. Saturated extracts were prepared with each soil sample passed through a 2 mm sieve in air-dry form, and EC_e was measured with an EC meter [66].

2.4. Statistical Analysis

The mean differences among the data obtained from different irrigation water salinity levels were assessed using a one-way analysis of variance (ANOVA) after verifying for normality and homoscedasticity through the Shapiro–Wilk and Levene tests, respectively. Subsequently, multiple comparisons (LSD) were performed at a significance level of $p < 0.05$ to examine these mean differences.

A two-sample t-test was used to compare the ET_o values measured from the lysimeter with those predicted by the models. Additionally, a scatter plot was generated to illustrate the distribution of the measured and predicted ET_o data around the 1:1 line through linear regression analysis, as detailed in Equation (8).

$$y = ax \quad (8)$$

where y is the measured ET_o, x is the predicted ET_o, and a is the slope of the fitted line.

The predictive performance of ET_o was evaluated using the coefficient of determination (R^2) and root mean square error ($RMSE$) as described in Equations (9) and (10).

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(X_i - \overline{X_i}\right)\left(Y_i - \overline{Y_i}\right)\right]}{\sum_{i=1}^{n}\left(X_i - \overline{X_i}\right)^2 \sum_{i=1}^{n}\left(Y_i - \overline{Y_i}\right)^2} \quad (9)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{n}} \quad (10)$$

where n is the number of observations, X_i is the predicted ET_o, Y_i is the measured ET_o, $\overline{X_i}$ is the average of the predicted ET_o, and $\bar{Y}_i$ is the average of the measured ET_o. R^2 and NSE values equal to 1 and $RMSE$ values equal to 0 indicate the best possible regression relationship. Statistical analyses were performed, and figures were formed using OriginPro v2024 (OriginLab Corporation, Northampton, MA, USA).

3. Results and Discussion

Figure 2 shows the temperatures (T_{max}, T_{min}, and T_{avg}) and relative humidity (RH_{max}, RH_{min}, and RH_{avg}) inside the greenhouse during the cropping period, as well as the average daily solar radiation inside and outside the greenhouse.

The data indicated a consistent increase in both T and R_s throughout the cropping period, which was consistent with the expected pattern for the spring season.

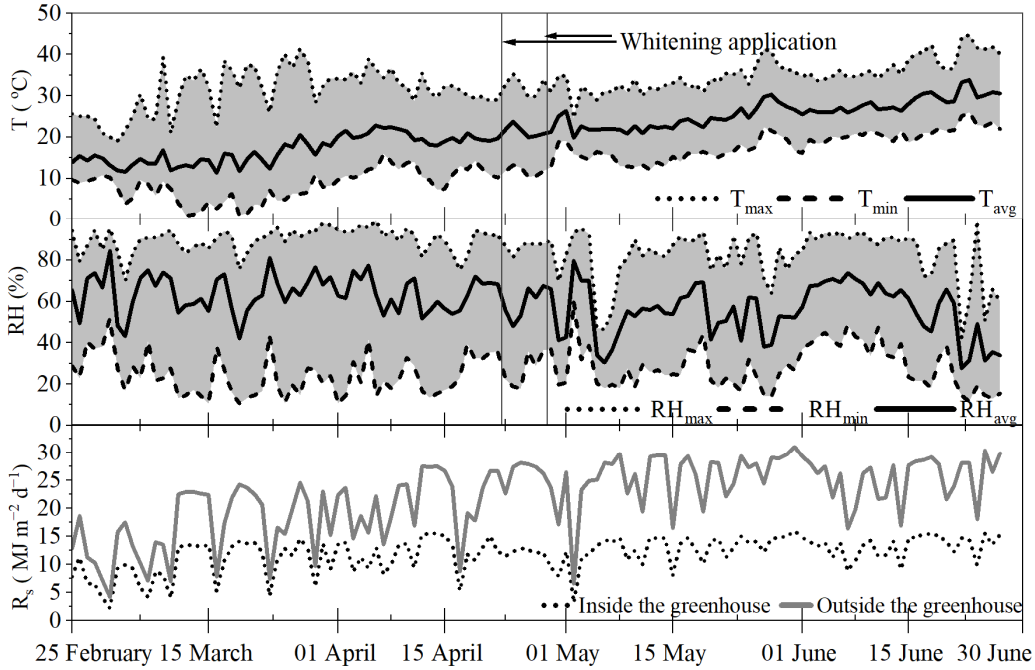


Figure 2. Diurnal variations in greenhouse temperature (*T*), relative humidity (*RH*), and solar radiation (R_s) throughout the cropping period.

3.1. Soil Salinity

The statistical analysis results of irrigation water salinity and sampling time on soil salinity throughout the experimental period are presented in Table 1.

Table 1. Comparative assessment of soil salinity responses to varied irrigation water salinity levels and temporal sampling intervals during the cropping period.

Sampling Time (T)	Water Salinity Treatment (S) (dS m^{-1})							
	S_0 (Control-0.7 dS m^{-1})		S_1 (Low-2.5 dS m^{-1})		S_2 (Moderate-5.0 dS m^{-1})		S_3 (High-7.5 dS m^{-1})	
23 February 2022	0.67 †	l ‡	0.89	kl	1.76	ik	2.04	hj
26 March 2022	1.07	jl	1.69	ik	2.35	gi	3.48	ef
26 April 2022	1.02	kl	2.32	gi	3.53	ef	5.31	d
22 May 2022	1.60	il	3.13	fg	6.05	cd	6.55	bc
27 June 2022	2.76	fh	4.26	e	7.32	ab	7.90	a
Significant Level	S: $p < 0.01$, T: $p < 0.05$, S × T: $p < 0.01$							

†: Each value is the mean of three replications. ‡: means followed by the same letter are not significantly different at the 5% level according to LSD multiple range tests.

Statistical analysis of the soil salinity data showed that there was an interaction between the sampling time (T) and irrigation water salinity level (S) as the main factors ($p < 0.01$). For this reason, in the evaluation of soil salinity results, each factor was not considered separately but was evaluated as a two-way interaction of the main factors. Naturally, soil salinity increases in parallel with an increase in irrigation water salinity levels. During the cropping period, soil salinity tended to increase more dramatically, especially under moderate and high water salinity treatments [67]. At the beginning of the experiment, the soil in each lysimeter was subjected to leaching to ensure homogeneity in the growing environment, but it was determined that there were slight variations in soil salinity levels at the beginning of the season among the irrigation water salinity treatments. Despite this, sharp differences in the soil salinity values among all irrigation water salinity treatments emerged on 26 April 2022. This significant difference in soil

salinity levels among treatments was also observed at the end of the growing season (27 June 2022). Due to increasing salt accumulation in the soil over time, the highest soil salinity values (7.32 and 7.90 dS m^{-1}) were determined on 27 June 2022 under S_2 and S_3 treatments, without any statistical difference between them (Table 1). It was calculated that soil salinity increased by 3.87, 4.16, 4.79, and 4.12 times under the high, medium, low, and control irrigation water salinity treatments, respectively. At the end of the growing period, soil salinity under S_1, S_2, and S_3 treatments were 1.54, 2.65, and 2.86 times, respectively, of the S_0 (control) treatment.

During the growing season, irrigation water salinity was observed to increase significantly towards the end of the growing season compared to the initial sampling date under different conditions categorized as control, low, medium, and high. In scenarios without sufficient leaching, soil salinity tended to increase progressively, even with low-salinity irrigation water [68]. This was attributed to the accumulation of salts in the root zone, as plant uptake of salts is minimal relative to the amount introduced into the soil. In parallel, under non-leaching conditions, soil salinity increased with increasing irrigation volume, which resulted in reduced salinity in the irrigation water itself [69]. Another study showed that at the end of the growing season, the electrical conductivity of the soil extract (EC_e) under irrigation water with salinities of 0.6, 2.0, 3.0, 4.0, and 6.0 dS m^{-1} was 1.73, 2.50, 3.42, 4.11, and 8.38 dS m^{-1} respectively [54].

3.2. Comparison of Measured and Estimated Reference Evapotranspiration Values

The ET_o values measured on lysimeters and those predicted by models during the growing season of tomatoes cultivation under greenhouse conditions are shown in Figure 3. The relationships between the ET_o values measured in the greenhouse (ET_{o_Mea}) and those calculated using the Almeria (ET_{o_Alm}), FAO Radiation ($ET_{o_FAO\text{-}Rad}$), and Hargreaves (ET_{o_Harg}) models during the growing season are in Figure 4.

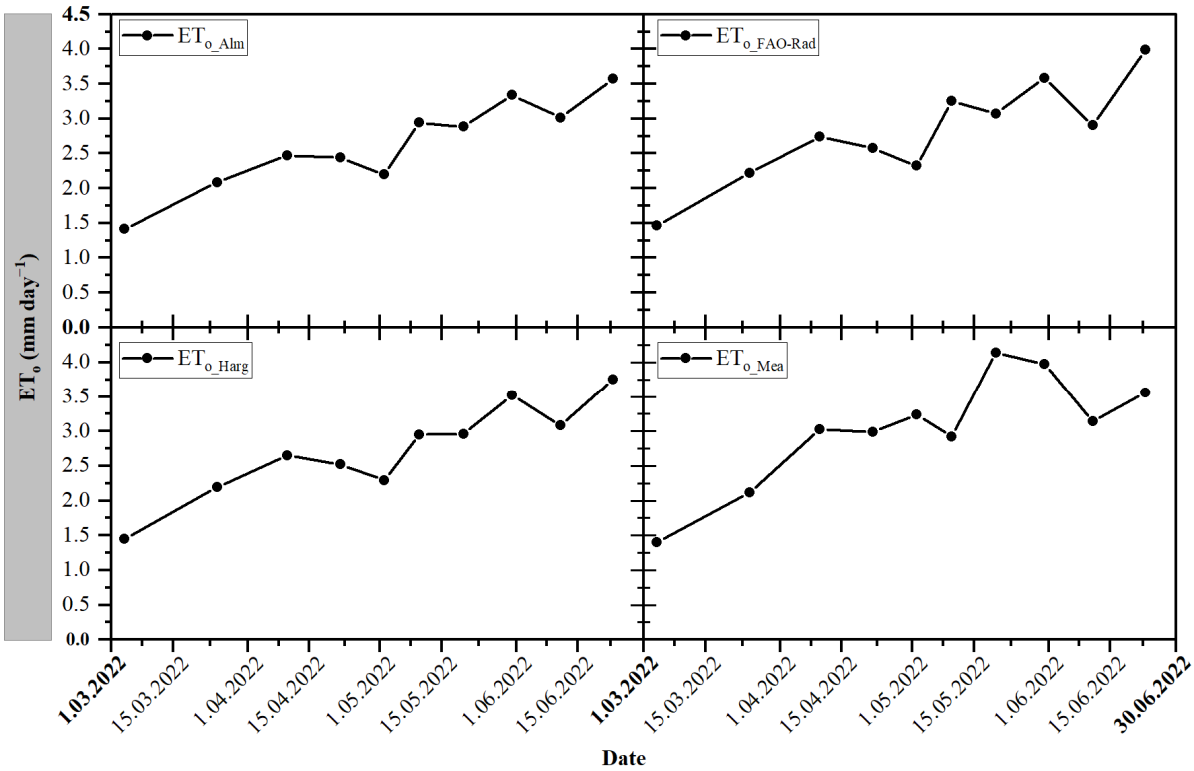


Figure 3. Reference crop evapotranspiration (ET_o) values measured (ET_{o_Mea}) and calculated with Almeria (ET_{o_Alm}), FAO Radiation ($ET_{o_FAO\text{-}Rad}$), and Hargreaves (ET_{o_Harg}) models during the growing season of tomato in the greenhouse.

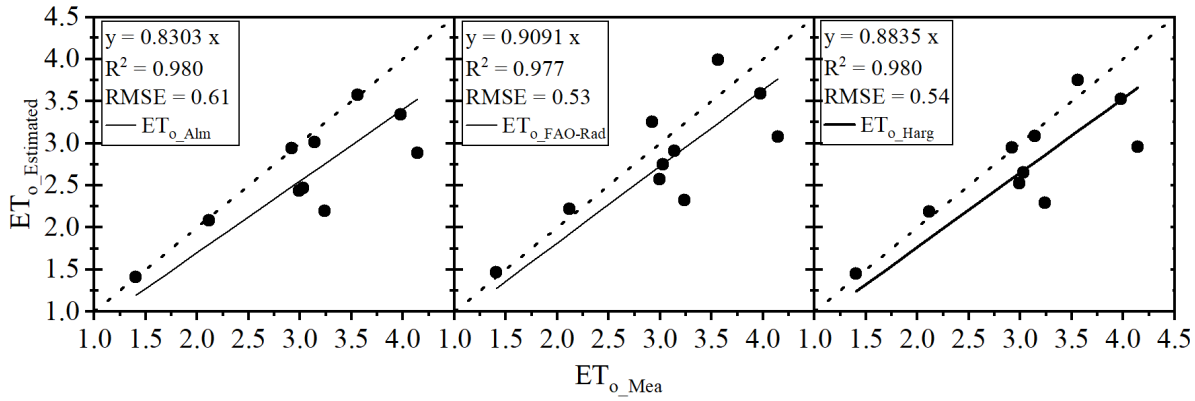


Figure 4. Average daily reference crop evapotranspiration (ET_o) relationships during the growing season, measured (ET_{o_Mea}) and calculated with the Almeria (ET_{o_Alm}), FAO Radiation ($ET_{o_FAO\text{-}Rad}$), and Hargreaves (ET_{o_Harg}) models. The dashed lines represent the 1/1 line of the graph, and the solid lines indicate the slope line.

The daily mean ET_o values, both measured and calculated by the Almeria, FAO Radiation, and Hargreaves models, showed similar upward trends throughout the growing season. The measured ET_o values varied between 1.41 and 4.14 mm day^{-1}, while the ET_o values calculated with the models varied between 1.41 and 3.99 mm day^{-1} (Figure 3). Generally, the daily ET_o value, which reached its maximum in the second half of May, increased again at the end of the season after a slight decrease. The R^2 values of the relationships between the measured ET_o values and the ET_o values estimated by the Almeria, FAO Radiation, and Hargreaves models using the climate values measured in the greenhouse were 0.980, 0.977 and 0.980, respectively, and the *RMSE* were 0.61 mm, 0.53 mm, and 0.54 mm, respectively. (Figure 4). It can be concluded that the R^2 values of all three models are close to each other because they are based on radiation. Additionally, given the results about the good correlations obtained among ET_o measured and ET_o from models, a very interesting result is that all the models underestimate the ET_o measured, but FAO Radiation and Hargreaves are closer than Almeria to 1.

These findings are consistent with Möller and Assouline (2007) [44], who determined that the ET_o value inside the greenhouse varies between 1 and 4 mm day^{-1} from measured meteorological data. It is also consistent with those of Fernandez et al. (2010) [7], who found that ET_o values measured in Spain, under similar conditions as in our study, varied from just under 1 mm day^{-1} in the winter and rising to about 4 mm day^{-1} during the summer. Finally, they were also consistent with the findings of Gong et al. (2020) [50], who found the daily ET_o values to be 3.22 mm d^{-1} as an average of two experimental years.

On the other hand, the plastic cover of the greenhouse was coated with whitening substances on April 22 and 28. This treatment was applied to shield the plants from solar damage and diminish the internal T_{avg} and R_s within the greenhouse (Figure 2), which explains the relative decrease in the ET_o after the second half of May. Möller and Assouline (2007) [44] used the FAO-56 [15] method to calculate the ET_o. Fernandez et al. (2010) [7] compared the values measured in drainage-type lysimeters in a greenhouse with the values they found by calculation and concluded that the best ranking method was FAO 56 Penman-Monteith with a constant aerodynamic resistance (r_a) of 150 s m^{-1}, FAO 24 Pan with a constant pan coefficient of 0.79, and the locally calibrated Radiation and Hargreaves Method. Gong et al. (2020) [50] found that Radiation and Pan evaporation models tend to overestimate ET_o values, whereas the Penman-Monteith and Priestley-Taylor models provide more accurate predictions for ET_o. They concluded that considering its robustness and simplicity, the Priestley-Taylor model would be recommended for estimating ET_o for greenhouse tomatoes. Since solar radiation is the most important factor affecting evapotranspiration in the Mediterranean region, it is understandable that radiation-based methods generally provide more accurate results for calculating evapotranspiration. An

important advantage of the Hargreaves equation is that it requires fewer climate parameters than other equations [17].

3.3. Measured Crop Evapotranspiration (ET_c) and Transpiration (T_r)

The seasonal daily actual ET_c and T_r values of tomatoes at different irrigation water salinities are illustrated in Figure 5. Average daily actual ET_c, T_r values, and proportional values of ET_c components measured for tomatoes grown under different irrigation water salinities are presented in Table 2.

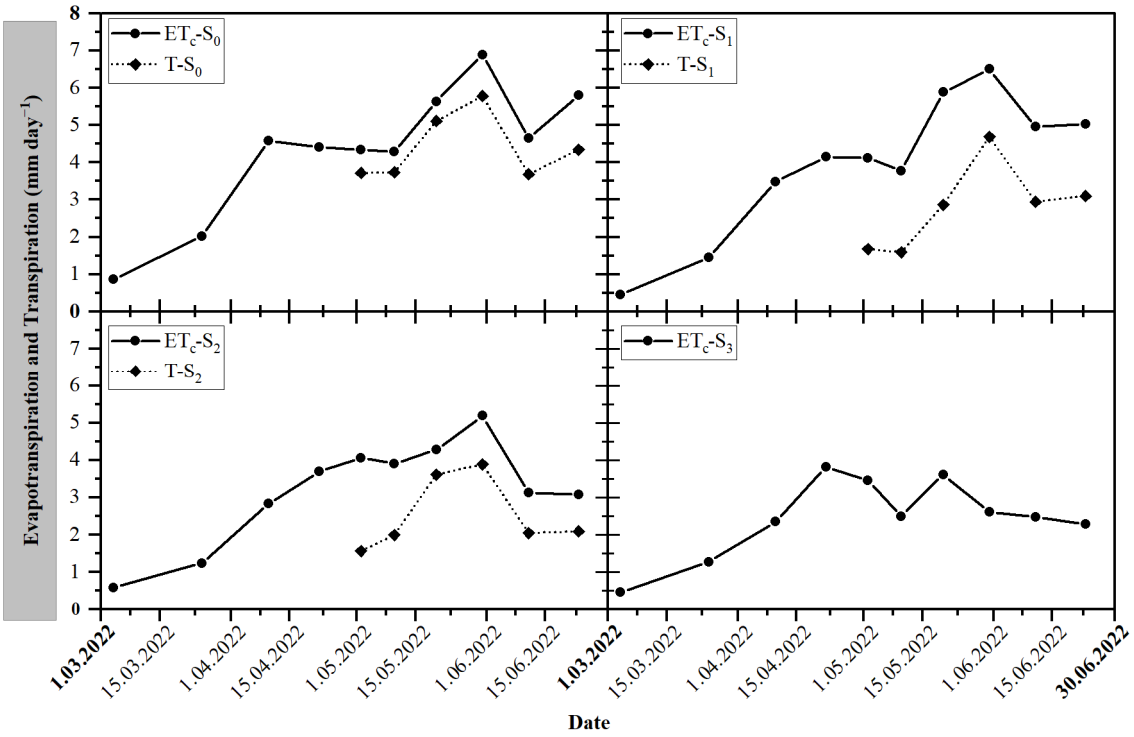


Figure 5. Seasonal daily actual crop evapotranspiration (ET_c) and transpiration (T_r) values of tomatoes under different irrigation water salinities. The S_0, S_1, S_2, and S_3 represent the irrigation water levels of 0.7, 2.5, 5.0, and 7.5 dS m^{-1}, respectively.

Table 2. Throughout the growing season, the transpiration rate (T_r/ET_c) and the evaporation rate from the soil (E_s/ET_c) of tomatoes under different irrigation water salinities. The S_0, S_1, S_2, and S_3 represent the irrigation water levels of 0.7, 2.5, 5.0, and 7.5 dS m^{-1}, respectively.

Measurement Calculation Period		Transpiration Rate T_r/ET_c (%)			Evaporation Rate E_s/ET_c (%)		
Start	**End**	**S_0**	**S_1**	**S_2**	**S_0**	**S_1**	**S_2**
27 April	5 May	85.68	40.78	38.77	14.32	59.22	61.23
6 May	14 May	87.38	42.18	51.28	12.62	57.82	48.72
15 May	24 May	90.76	48.64	84.35	9.24	51.36	15.65
25 May	4 June	83.89	72.15	74.95	16.11	27.85	25.05
5 June	16 June	79.35	59.39	65.50	20.65	40.61	34.50
17 June	27 June	75.00	61.43	68.08	25.00	38.57	31.92
Mean		83.68	55.00	63.82	16.32	45.00	36.18

As shown in Figure 2, the increase in plant growth and incoming R_s resulted in a corresponding rise in the average daily actual ET_c across all salinity treatments. This trend persisted until the end of the growing period, reaching a peak around June, as depicted in

Figure 5. The seasonal average of the actual ET_c values varied between 2.48 and 4.35 mm day$^{-1,}$ depending on the irrigation water salinity treatments. The highest average daily actual ET_c throughout the season was observed under control conditions (S_0 = 0.7 dS m^{-1}), and the lowest average daily actual ET_c was observed under high irrigation water salinity (S_3 = 7.5 dS m^{-1}) (Figure 5). The daily average actual ET_c for low (S_1), moderate (S_2), and high (S_3) irrigation water salinity treatments compared to control (S_0) treatment decreased by 8, 26, and 43%, respectively.

Table 2 and Figure 5 indicate that the transpiration rates (T_r/ET_c) observed for the control, low, and moderate salinity treatments were 83.68%, 55.00%, and 63.82%, respectively, while the evaporation rate from the soil (E_s/ET_c) was determined as 16.32, 45.00, and 36.18%. In other words, in general, as salinity increased, the T_r component of actual ET_c decreased, and evaporation from the soil increased. With the increase in salinity levels of irrigation water, a decrease in T_r/ET_c is observed; however, no clear trend has emerged. Interestingly, in the S_2 treatment, an increase in the T_r/ET_c was observed, contrary to the expected decrease. Moreover, the decline in the T_r/ET_c under the S_1 treatment is notably sharp. Actually, the increase observed in the S_2 treatment compared to the S_1 is due to the sharp decline in the S_1 treatment. T_r occurs through the leaves. The leaf area indices for the S_1 and S_2 treatments do not show a sharp decline when compared to the S_0 treatment or when compared to each other. Similarly, there is no significant difference in stomatal conductance between the saline irrigation water treatments [67]. On the other hand, Yang et al. (2022) [70] stated that T_r can be strongly affected by the ambient microclimate, while other researchers [25,71] reported that, in most cases, plant transpiration is well correlated with solar radiation, vapor pressure deficit, and air temperature under adequate soil water conditions. The extant scientific literature offers limited studies addressing the transpiration response of tomatoes or other vegetable crops under greenhouse cultivation. To our knowledge, information on tomato transpiration under saline conditions is scarce. Therefore, further research is needed on the partitioning of T_r on vegetables in general and saline irrigation waters in particular.

In different studies, it has been reported that the seasonal ET_c of greenhouse tomatoes varies between 231 and 545 mm [6,23,48,50], and the daily ET_c value varies between 0.5 and 6.7 mm day^{-1} [45,47]. The seasonal total and daily average ET_c values under the control irrigation water salinity treatment in this study were within this range (Figure 5). ET_c may vary depending on characteristics such as greenhouse growing periods and indoor air conditioning differences. Low-cost, unheated, and naturally ventilated plastic greenhouses, which are common in countries with a Mediterranean climate where the average annual temperature is 10–20 °C, are affected by external weather conditions [67]. Therefore, R_s and T_{avg} are the driving forces that influence crop growth and increase ET_c. However, the use of saline water in irrigation results in a decrease in T_r [72], which ultimately leads to a decrease in ET_c. The T_{avg} and R_s showed an increasing trend from the beginning to the end of the cropping period (Figure 2), causing most of the seasonal ET_c to occur during the second half of the spring season [67]. Although there is a similar increasing trend in all salinity treatments, this increasing trend slows as salinity increases. Increasing T_{avg} and R_s in the last quarter of the cropping period, increased evaporation demand, and continued saline water applications throughout the growing season led to salt accumulation in the plant root zone. Therefore, under medium and high water salinity treatments, tomato plants could not uptake sufficient water from the root zone, causing the daily average of the actual ET_c to decrease, thereby decreasing the seasonal total actual ET_c (Table 2 and Figure 4). This indicates that increasing salt in the plant root zone and increasing evaporation demand due to greenhouse climate are two factors that constantly affect each other. The physiological drought effect caused by salinity has led to the evaporation of water that cannot be taken up by the crop and used in transpiration as salinity increases. Tomatoes are a moderately salt-sensitive crop, and irrigation with saline water negatively affects their growth and actual ET_c [70]. Cumulative crop water uptake was found to decrease with increasing NaCl concentrations in the nutrient solution, and the differences between the treatments

increased over time after salinization [73]. It was reported that tomato plants irrigated with a salinity nutrient solution of 9.1 dS m^{-1} consumed 40% less water than control irrigated plants, and among tomato varieties, the decreases in plant water uptake with increasing salinity varied between 3.5% and 5% per unit salinity [53]. The close negative correlation between plant water consumption and EC revealed that as EC increases, less water is used [54].

In light of the physiological impact of salinity, which can be characterized as a form of physiological drought, it is evident that the soil salinity levels remained consistent with the seasonal ET_c values across all salinity treatments. The reduction in water uptake has been attributed to a decline in the hydraulic conductivity of the root system [74] and lower water availability [40]. Furthermore, plants are known to undergo osmotic adaptation mechanisms, characterized by an elevation in solute concentration and a consequent reduction in water potential, aimed at mitigating osmotic imbalances and maintaining cellular turgor [75]. Indeed, studies have demonstrated a linear reduction in evapotranspiration rates in tomato plants in response to alterations in the electrical conductivity of the irrigation water [76,77].

Gong et al. (2019) [21] concluded that under greenhouse conditions, the cumulative soil evaporation in drip-irrigated tomatoes accounted for 25% of the total ET_c over the entire growth period, with a gradual reduction observed as canopy cover increased. In a separate study, Gong et al. (2020) [50] employed various measurement techniques, including weighing lysimeters for ET_c, micro lysimeters for E_s, and a sap flow monitoring system for T_r. Their findings indicated that the E_s component constitutes approximately 15.4–26.5% of the total seasonal ET_c of tomatoes.

In our study, the E_s component, derived by deducting T_r measured via the sap flow method from ET_c measured in lysimeters, constituted approximately 16.32% of ET_c under the control salinity. This proportion increased due to the evaporation of water that remained unavailable for plants owing to salinity stress, reaching 45.00% and 36.18% in low and medium salinity conditions, respectively. Various methodologies have been used to compute the E_s and T_r components of the ET_c in prior studies. Zhang et al. (2013) [78] used SIMDualKc, Gong et al. (2019) [21] adopted the Shuttleworth–Wallace Dual vegetation coefficient, and Gong et al. (2021) [23] used the Priestley–Taylor model. Consequently, the E_s component of ET_c is expected to exhibit variability under diverse environmental contexts, including the influence of different modeling techniques and variations between open-field and greenhouse conditions. Furthermore, the effect of pruning towards the conclusion of the growing season may also be significant. As a matter of fact, the importance of irrigation frequency and plant cover in controlling E_s has been emphasized [78]. Notably, E_s represents a physical process that is closely correlated with soil moisture dynamics [79]. Nevertheless, the distinct responses of evaporation and yield to osmotic and ionic stresses remain incompletely elucidated [54].

3.4. Change in Crop Coefficient (K_c) Values

The variation in actual K_c values of tomatoes during the cropping period under different irrigation water salinity treatments is given in Figure 6.

The change in actual K_c values with irrigation water salinity had the same tendency as the change in actual ET_c. Under S_0, S_1, S_2, and S_3 treatments, the lowest actual K_c values were 0.61, 0.33, 0.42, and 0.32, respectively, whereas the highest values were 1.73, 1.63, 1.34, and 1.28, respectively. The actual K_c values decreased with increasing salinity (Figure 6). The K_c values recommended for outdoor-field tomatoes in FAO56 [15] are given as 0.60, 1.15, and 0.70–0.90 for the beginning, middle, and late periods, respectively. Gallardo et al. (2013) [48] found that under greenhouse conditions in Almeria (Spain), tomatoes had K_c values of 0.2, 1.4, and 1.0 at the initial, maximum, and end-of-season stages, respectively. In their study, Harel et al. (2014) [49] observed K_c values ranging from 0.3 to 1.0 in winter and 0.2 to 0.9 in summer between seedling planting and first fruit harvest, with a consistent value of 0.8 for both seasons in the final growth stage. Zhao et al. (2013) [47] reported

K_c values of 1.01 for the mid-season and 0.61 for the late season. Gong et al. (2020) [51] measured K_c values of 0.53, 1.13, and 0.90 for the early, middle, and late stages, respectively, under full irrigation conditions. As can be seen, the K_c values obtained in our study were higher than the mentioned values. Orgaz et al. (2005) [80] determined K_c values for the mid-season and final growth stages of common greenhouse plants (melon, green beans, watermelon, and pepper) under Mediterranean conditions as 0.2, 1.1–1.4, and 0.9–1.2, respectively. They stated that the reason for the high K_c values may be due to the fact that the plants supported with a string are more open-structured and taller, regular pruning creates open canopies, leaf area indexes are higher, and the radiation rate emitted in the greenhouse is high. In a previous study, high LAI values were obtained for the tomatoes [67]. The LAI is a plant characteristic that represents the rate of photosynthesis within the plant canopy, transpiration levels, and overall plant growth, thereby influencing K_c values [15]. Climate conditions can notably influence canopy development rates, particularly during the spring, when weekly temperatures can vary across years. Furthermore, row spacing and plant density after thinning also affect the canopy development rate [81]. Additionally, most plants grown out of season in the greenhouse have to be harvested without being exposed to low temperatures, which causes the maximum K_c values to decrease due to market concerns [48]. Consequently, this accounts for the higher K_c values observed at the end of the season.

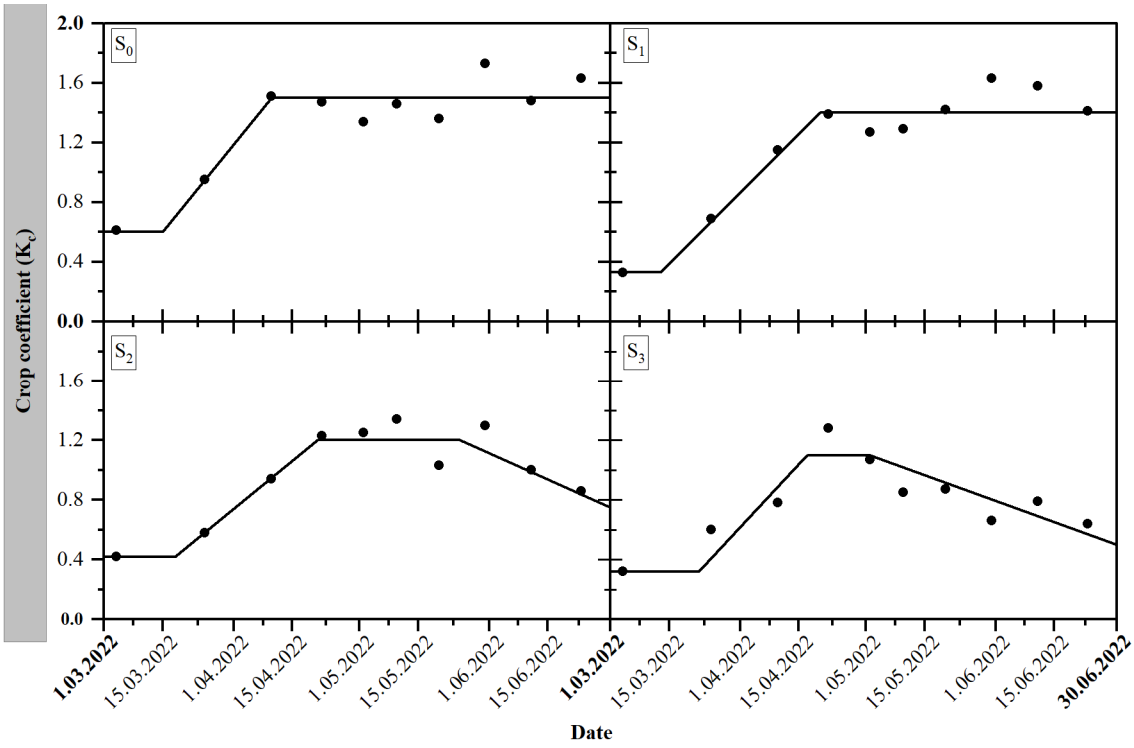


Figure 6. Change in K_c values of tomatoes under different irrigation water salinities treatments during the growing season. The S_0, S_1, S_2, and S_3 represent the irrigation water levels of 0.7, 2.5, 5.0, and 7.5 dS m^{-1}, respectively.

In our study, while the decrease in actual K_c values with increasing salinity was not evident at the beginning of the season, actual K_c differences under different salinity treatments became evident towards the end of the season. This phenomenon can be explained by the fact that the physiological drought effect increases over time with the accumulation of salts in the soil, which slows down the plant's water uptake. As salinity increased, there was a corresponding decrease in actual K_c values, with a similar trend observed in ET_c. The seasonal average actual K_c values were determined as 1.35, 1.22, 1.00, and 0.79 in S_0, S_1, S_2, and S_3 treatments, respectively. Actual K_c was mainly affected by

salinity, greenhouse climate, and phenological stage. A reduction in actual K_c values is indicative of a decrease in actual ET_c, which is reflected in a deceleration in plant growth and a less dense canopy [82]. In the context of a high irrigation water salinity treatment, the relatively constant K_c value observed throughout the growing season suggests that plants are affected by high salinity. The differences in the initial crop growth stage and development stage durations between the control (S_0) and treatments (S_1, S_2, and S_3) (Figure 6). These differences were attributed to the varying salinity levels of the irrigation water used in each treatment. While plant growth continued until the end of the growing season in both the S_0 and S_1 treatments, the impact of increased salinity in the S_2 and S_3 treatments resulted in progressively shorter development stages. Salinity levels negatively affected the crop growth rate, leading to earlier maturation and reduced development periods in the higher salinity treatments (S_2 and S_3).

A significant limitation of this study is the application of various approaches to estimate the ET_o under greenhouse conditions. Unlike open field environments, greenhouses present unique microclimatic conditions, including controlled humidity and significantly lower wind speeds, which affect the accuracy and applicability of standard K_c adjustment formulas, such as those discussed by Allen et al. (2011) [10] and Pereira et al. (2020) [83]. These formulas generally do not exceed the K_c values of 1.20–1.30 in arid and semi-arid climates under open field conditions. However, in greenhouses, the lack of standardization in ET_o estimation methods and the presence of local advection conditions or the "clothesline effect" can lead to higher K_c values. The reliance of this study on lysimeter grass ET as a benchmark for comparing various ET_o equations highlights the need to develop and validate specific K_c values tailored to greenhouse conditions. Future research should focus on establishing standardized methods for ET_o estimation in greenhouses to improve the accuracy of the K_c values and their applicability in controlled environments.

This study provides an in-depth evaluation of different ET_o estimation methods in greenhouse environments and offers important insights into their effectiveness and constraints. We believe that several factors mitigate these potential limitations. First, the experiment was conducted under controlled greenhouse conditions to minimize the variability that can arise from external factors, thereby enhancing the consistency and reliability of our results. Second, high-tech sensors were used for monitoring and measurement purposes. These advanced sensors provide high precision and accuracy, thereby ensuring the quality and reproducibility of the collected data. Third, our study focused on tomatoes, which are an annual crop. Because tomatoes are replanted in each growing season, there are no cumulative effects that might vary year by year, as could be the case with perennial crops. However, a notable limitation of this study is that it was conducted within a single crop season. Therefore, under different climatic conditions, the corresponding results may differ from those of the experimental season and do not fully support the conclusions drawn. Expanding the dataset to include multiple crop seasons and varying climatic conditions would provide more robust support for these results. The findings of this study are an initial step towards understanding ET_o estimation methods under greenhouse conditions, and further research is necessary to generalize these results across different environments and growing seasons.

4. Conclusions

This study focused on the effects of irrigation water salinity on the T_r and E_s components of actual ET_c as well as actual K_c values in tomatoes irrigated with the drip irrigation method during the spring growing season. Additionally, the study compared several radiation-based methods used to compute reference evapotranspiration. During the growing period, the average indoor and outdoor temperature and solar radiation generally exhibited an upward trend, influenced by seasonal variations. Soil salinities consistently showed a sharp increase under moderate (5 dS m^{-1}) and high (7.5 dS m^{-1}) treatments, while there was a relatively lower increase under the control (0.7 dS m^{-1}) and low (2.5 dS m^{-1}) treatments. Significant differences in soil salinity under saline irrigation began to

exist in the middle of the season. All irrigation water salinity levels caused varying degrees of increase in soil salinity. At the end of the growing season, soil salinity was significantly different among the irrigation water salinity treatments.

Although there was a highly significant linear relationship between the actual ET_o values measured on lysimeters under greenhouse conditions and the ET_o values calculated by the radiation-based Almeria, FAO Radiation, and Hargreaves models ($R^2 > 0.977$ and $RMSE < 0.53$ mm), there was no significant difference between the prediction methods of these models. In comparison to the control treatment, the daily average ET_c values for the S_1, S_2, and S_3 treatments exhibited reductions of 8%, 26%, and 43%, respectively. In general, the T_r component of actual ET_c decreased, and the E_s component from the soil increased with increasing water salinity levels throughout the season. The E_s/ET_c for S_0, S_1, and S_2 treatments were determined as 16.32%, 45.00%, and 36.18%. K_c values followed the same trend as daily actual ET_c. As salinity increased, plant coefficient values decreased.

It is, therefore, important to ensure that the correct amount of water is used for irrigation with saline water sources. The ET_c of greenhouse tomatoes is highly affected by climatic conditions inside the greenhouse. Therefore, it can be concluded that the K_c values calculated on a local (experimental) basis can be used perfectly in irrigation management applications such as precision irrigation and automation of irrigation, thus making rational use of fresh and saline irrigation water possible and high irrigation efficiency can be achieved.

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Data Availability Statement: The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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