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Water Requirement of Solar Greenhouse Tomatoes with Drip Irrigation under Mulch in the Southwest of the Taklimakan Desert

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Abstract: Understanding crop water requirements is important for establishing irrigation schedules, and improving water use efficiency (WUE), crop yield and crop quality. In order to reveal the optimal water requirement of tomatoes in various growth stages, the responses of the water requirement, crop coefficient, fruit yield and quality of tomato to different irrigation levels were studied in a solar greenhouse in Hetian, Southwestern Taklimakan Desert, China from August 2019 to June 2020. The medium irrigation quota (Ia) was calculated in different tomato growth stages based on the root distribution range, suitable soil moisture content of high yield, and the planned wetted percentage of drip irrigation. Five irrigation levels (60%, 80%, 100%, 120% and 140% I_a) were used. The technique for order preference by similarity to ideal solution (TOPSIS) results showed that 120% I_a was the optimal irrigation quota for the yield, water use efficiency (WUE), and fruit quality of tomato. The daily water requirement of 120% I_a were 2.26, 4.28, and 2.35 mm·d^{-1} in three growth stages in the autumn–winter season, while it was 1.96, 3.99, and 3.80 mm·d^{-1} in the winter–spring season. The crop coefficients of the three stages in each growth season were 0.49, 1.10, and 0.76, and 0.61, 1.09, and 0.78, respectively. The results could provide guideliens for improving the productivity of protected agriculture in the Southwestern Taklimakan Desert or other similar regions.

Keywords: tomato; water requirement; crop coefficient; drip irrigation; WUE

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1. Introduction

As an important form of protected agriculture, solar greenhouses have been widely developed and applied in the arid areas of Northern China [1]. It is very important to produce vegetables in winter without any auxiliary heating [2,3]. A solar greenhouse is different from a conventional greenhouse. Specifically, heat-storing materials are used to retain solar heat in order to receive the maximum solar heat during the winter, and large amounts of insulation are used where there is little or no direct sunlight [4,5]. Hetian is located in the southwest part of the Taklimakan desert, and it is rich in photothermal resources; in other words, this region is one of the most advantageous areas for the development of protected agriculture in Xinjiang, China [6]. The oasis area in Hetian only accounts for 3.7% of the total area, the per capita cultivated land area is less than 0.087 ha, and the average water resource per unit of land is only 390 m^3·ha^{-1} [7]. Obviously, poor soil and water resources have seriously hindered the development of the local agricultural economy. In recent years, this area has developed the protected agriculture with high-value non-field crops. This is one of the most successful and effective means to solve the above problems, by utilizing superior photothermal resources and developing drip irrigation under mulch technology in the local agricultural production system.

Presently, a total of 136 thousand solar greenhouses and other facilities have been built in Hetian, China. The protected agriculture area is approximately 3.30 thousand ha. Tomato (*Lycopersicon esculentum* Mill.), one of the main vegetables in the Hetian area, is widely cultivated. Due to the serious lack of cultivated land, the development and utilization of non-cultivated land resources have become an important means in increasing the cultivated area, such as developing oasis desert agriculture [8]. The local protected agriculture industry is mostly built on the edge of the oasis desert, and the soil layer of protected agriculture is mainly composed of an aeolian sandy soil with a loose structure, large porosity values, and poor water and fertilizer retention [9]. Drip irrigation under mulch offers many advantages, including improved yield and WUE [10], so it has been widely used in protected agriculture. A previous study indicated that drip irrigation under mulch was beneficial for crop growth [11,12], but there is a lack of scientific understanding about the water requirement characteristics of facility tomatoes under aeolian sandy soil planting conditions. The irrigation system of local protected agriculture is not perfect, which leads to the serious problem of deep percolation, and further aggravates the prominent problem of "high input and low output". Therefore, it is urgent and necessary to carry out research on the tomato water requirement in this region.

Many studies have been carried out on the water requirements of tomatoes in solar greenhouses. Harmanto et al. found that the water requirement of cherry tomatoes in tropical greenhouses is approximately 75% of crop evapotranspiration (ET_c), and the actual irrigation amount is about 4.1~5.6 $mm{\cdot}d^{-1}$ [13]. Guo et al. studied the water requirements of cherry tomatoes in solar greenhouses using a large-scale weighing lysimeter, and obtained the daily ET_c, crop coefficient (K_c), and pan coefficient for cherry tomatoes at different growth stages [14]. Liu et al. developed a suitable irrigation schedule for tomatoes in greenhouses based on the 20 cm evaporation pan. The irrigation quota was 10 mm, the irrigation interval was 2~6 days, and the pan coefficient was 0.9 [15]. Mohmed et al. found that 100% ET_c was the optimal irrigation amount for ensuring tomato yield and quality in a greenhouse based on the Penman–Monteith equation [16]. Li et al. studied tomato water requirements in the winter–spring and autumn–winter seasons and concluded that the daily water requirements of tomatoes increased first and then decreased with the change in reproductive period [17]. In addition, the peak water requirement for tomatoes in the autumn–winter season occurred earlier than that in the winter–spring season, but the total water requirement of tomatoes was high in the winter–spring season. Gong et al. studied the evapotranspiration and K_c of the tomato in a solar greenhouse under deficit irrigation (DI) and regulated deficit irrigation (RDI) conditions and showed that the single crop coefficient model could accurately estimate the K_c value at different growth stages [18]. Moreover, Tal Saadon et al. [19]. found that the net radiation can be used to predict the evapotranspiration of crops in greenhouses after introducing the cloud effect coefficient.

Although many studies on the water requirement of greenhouse vegetables have been conducted, the water requirement of the same vegetable varies a lot in different regions because the water requirement of greenhouse vegetables is affected by various factors, such as vegetable varieties, soil characteristics, meteorological factors, agricultural cultivation measures, greenhouse ventilation methods. However, whether the key results such as the water requirement and crop coefficient can be directly applied to the southwestern region of the Taklimakan Desert still needs to be studied.

There is also a lack of research on the water requirement of vegetables in greenhouses located in extremely arid areas. Therefore, to fill this gap in knowledge, we studied the response of the water requirement, crop coefficient, fruit yield and quality of tomato to the different irrigation levels in a solar greenhouse in Hetian, Southwestern Taklimakan Desert. Thus, the main objective of this study is to determine the water requirement and the crop coefficient of tomato in solar greenhouses in extremely arid desert area.

Novelty: The water requirements of tomatoes in a solar greenhouse located in extremely arid desert regions were studied in this study, of which the findings could further complement existing research. The research could provide guidelines for improving the productivity of protected agriculture in the Southwestern Taklimakan Desert and could also be applied in other desert areas for water management in protected agriculture.

2. Materials and Methods

2.1. Experimental Plot

The experiment was performed in a solar greenhouse in Hetian County, Hetian area, Southwestern Taklimakan Desert, China (37°16′ N, 79°52′ E) from August 2019 to June 2020. The experimental plot was in the warm temperate zone and had a continental climate with low rainfall and high evaporation. The annual average temperature and precipitation are 12.2 °C and 33.5 mm, respectively. The annual potential evaporation is above 2600 mm (measured using a 20 cm evaporation dish) and the annual total radiation is within the range of 138.1~151.5 KJ·cm^{-2}. A 60 m × 9 m steel arch plastic film solar greenhouse that ran east to west was used for the experiment. The transparent cover material in the greenhouse was an ethylene vinyl acetate copolymer (EVA) double protective film, and the greenhouse wall, rear roof, and insulation were covered with the material (glue-spreading cotton with a thickness of 5 cm and a density of 700 g·m^{-2}), as shown in Figure 1. The solar greenhouse was located on the edge of the desert, and the soil in the cultivated layer was mainly aeolian sandy soil with a good uniformity. Soil texture and soil hydraulic property at the experimental site were shown in Table 1. The average soil pH and organic content of the soil at 0~100 cm depth were 8.12 and 1.25%, respectively. The available nitrogen, phosphorus, and potassium contents in the topsoil were 0.046, 0.007, and 0.205 g·kg^{-1}, respectively, and the soil's salt content varied between 0.06% and 0.09%. Groundwater at a depth greater than 6 m was used for irrigation, with the total dissolved solids (TDS) of 1.625 g·L^{-1}.

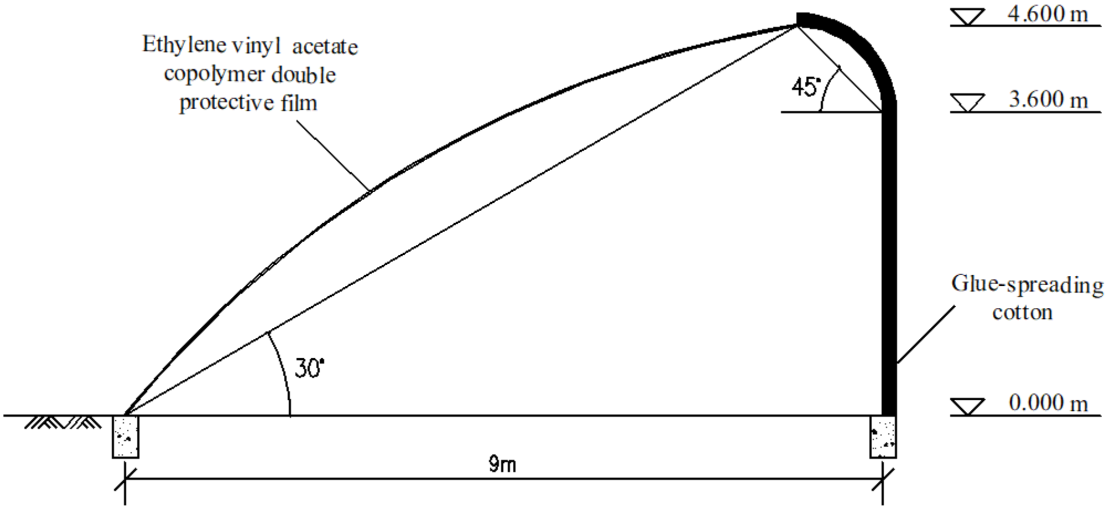

Figure 1. Cross section of the solar greenhouse.

Table 1. Soil texture and soil hydraulic property at the experimental site.

Soil Depth cm	Dry Bulk Density g·cm^{-3}	Soil Particle Size Composition (%) <0.002 mm	0.002–0.02 mm	0.02–2 mm	>2 mm	Field Capacity cm^3·cm^{-3}	Soil Texture
0–30	1.59	2.62	7.58	89.80	0.00	0.19	Sandy
30–70	1.58	2.79	7.97	89.24	0.00	0.20	Sandy
70–100	1.57	2.95	7.81	89.24	0.00	0.21	Sandy

2.2. Plant Material

Tomato (*Solanum lycopersicum* L., "Nongge 520") was selected for this study; we chose an early maturing variety with the unlimited and medium plant growth. The tomato variety had a strong continuous fruit setting capacity and a high yield, with a single fruit weight of approximately 280 g. It was suitable for autumn–winter and winter–spring cultivation. The tomatoes in the experiment were cultivated by ridge planting and film mulching. Plant and row spacing were 20 cm and 40 cm, respectively. The specific planting pattern for the tomatoes is shown in Figure 2.

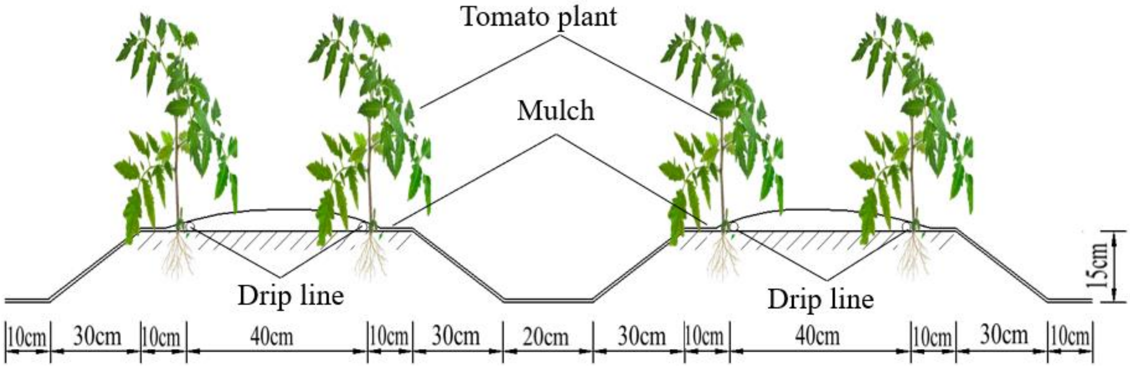

Figure 2. Tomato planting pattern.

Tomatoes in the autumn–winter season were transplanted on 4 August 2019 and last harvested on 22 November 2019, with a total growth period of around 111 days. Tomatoes in the winter–spring season were transplanted on 10 January 2020 and last harvested on 25 May 2020, with a total growth period of around 137 days.

2.3. Irrigation Treatment Design

The total tomato growth period can be divided into three stages: the seedling stage (transplanting to flowering of first fruit), the flowering and fruiting stage (flowering of first fruit to ripening of first fruit), and the maturation stage (ripening of first fruit to seedling pulling). The specific divisions of the total tomato growth period in the two seasons are shown in Table 2.

Table 2. Division of tomato growth periods in a solar greenhouse.

Season	Year	Beginning and Ending Date		
		Seedling Stage	**Flowering and Fruiting Stage**	**Maturation Stage**
Autumn–winter	2019	4 August–2 September	3 September–24 October	25 October–22 November
Winter–spring	2020	10 January–24 February	25 February–23 April	24 April–25 May

The root depth of the tomato at the seedling, flowering and maturation stages is usually 20, 40, and 40 cm, respectively [1,20,21]. The suitable soil moisture interval for the three growth stages of high-yield tomatoes were 60~100%, 70~100%, and 70~100% FC, respectively [22,23]. The corresponding wetted percentages (the percentage of the surface area wetted by the drip irrigation system compared to the entire cropped area) of the three growth periods could be estimated as 52%, 74%, and 74%, according to the soil texture and the root depth for each of three growth stages [21]. Therefore, the formula (Equation (1)) was used to calculate a medium irrigation quota (I_a) [24].

$$I_a = HP(\theta_1 - \theta_2) \tag{1}$$

where I_a is the medium irrigation quota, mm. H is the root depth, and the value of H is 200, 400, and 400 mm in the seedling, flowering, fruiting, and maturation stages. p is the wetted percentage, and the value of p in the three stages is 52%, 74%, and 74%. θ_1 is the field capacity (FC = 20.0%). θ_2 is the suitable soil moisture content, and the value of θ_2 in the three stages is 60%, 70%, and 70% FC.

The I_a was 8.3, 17.8, and 17.8 mm in the three tomato growth periods, respectively. Five irrigation treatments were designed, and the irrigation quotas of five treatments were

60%, 80%, 100%, 120%, and 140% I_a, respectively (Table 3). All treatments were arranged randomly with three replications for each treatment in a block.

Table 3. Irrigation amounts (mm) applied to the experimental tomatoes during each growth stage and for the whole growth period.

Treatment	Irrigation	Autumn–Winter Season				Winter–Spring Season			
		Seedling Stage	Flowering and Fruiting Stage	Maturation Stage	Whole Growth Period	Seedling Stage	Flowering and Fruiting Stage	Maturation Stage	Whole Growth Period
T1	60% I_a	63.2	127.9	53.3	244.3	61.5	149.2	74.6	285.3
T2	80% I_a	73.1	170.5	71.0	314.7	76.5	198.9	99.5	374.9
T3	100% I_a	83.1	213.1	88.8	385.0	91.5	248.6	124.3	464.4
T4	120% I_a	93.1	255.7	106.6	455.4	106.5	298.4	149.2	554.0
T5	140% I_a	103.1	298.4	124.3	525.8	121.4	348.1	174.0	643.6

Note: I_a in Table 3 represents medium irrigation quota, and it is 8.3, 17.8 and 17.8 mm at the seedling, flowering and fruiting, and maturity stage, respectively.

The drip lines were laid under the mulch film and the layout method was one row with one drip line. The drip line used in the experiment was a single wing side slit type with an emitter flow rate of 3.2 $L \cdot h^{-1}$ and an emitter space of 20 cm. Within 10 days of transplantation, the I_a was used for irrigation, and then the irrigation treatment started. The irrigation levels in each growth period and the whole growth period is shown in Table 3.

2.4. Agronomic Management

First, 22.5 $t \cdot ha^{-1}$ dry chicken manure and 1.05 $t \cdot ha^{-1}$ compound fertilizer (N-P_2O_5-K_2O (15-15-15)) were applied as a basal fertilizer before tomato transplanting. There were five fertilizations during the whole growth period. Urea ($N \geq 46\%$) was applied twice during the seedling stage, and the amount of each application was 45 $kg \cdot ha^{-1}$. Flowering and fruiting stage were fertilized with balanced fertilizer (N-P_2O_5-K_2O-Fe-Zn-B-Cu-Mn = 15-20-20-0.05-0.5-0.5-0.5-0.05), and the amount of each application was 45 $kg \cdot ha^{-1}$. Potassium dihydrogen phosphate was applied once during the late flowering and maturation, and the mid-fruiting stage at 60 $kg \cdot ha^{-1}$.

During the late seedling stage, the tomato was suspended on a wire above the greenhouse with a thin rope to ensure the upward growth of the plant. The tomato branches were also trimmed from time to time to ensure the growth of the main stem. After flowering, tomatoes were artificially pollinated once every 5 days, and tip pruning began after the fourth order-fruit had set, to limit the apical dominance of the tomato plants.

2.5. Parameter Determinations

2.5.1. Meteorological Data

The meteorological data were measured using an automated weather station (Watchdog, Spectrum Technologies, Inc., Aurora, IL, USA) installed in the solar greenhouse. The monitored meteorological parameters are solar radiation, air temperature, air humidity, wind speed and direction, and rainfall. Average daily air temperature (T) and relative humidity (RH) in the solar greenhouse during the whole tomato growth period from 2019 to 2020 are shown in Figure 3a, and total radiations (Rs) are shown in Figure 3b.

2.5.2. Irrigation Amount

A water meter was set at the pipeline entrance of each experimental plot to control the irrigation amount.

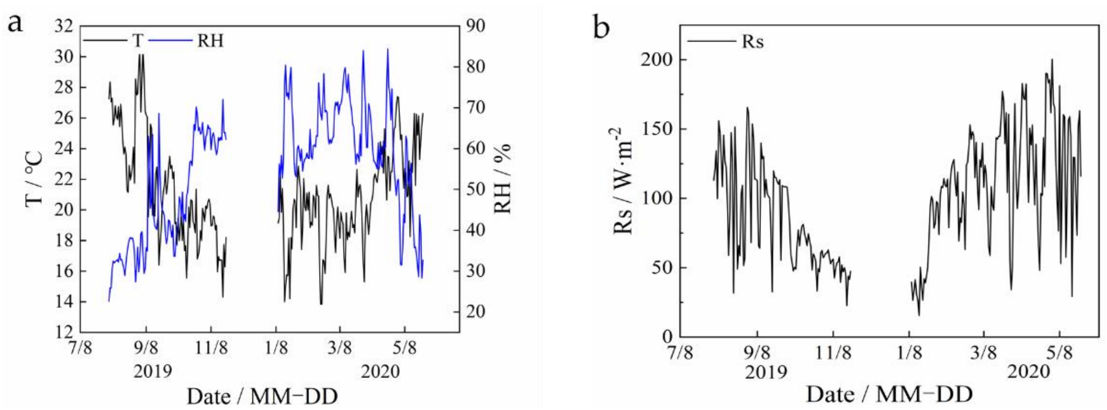

Figure 3. (**a**) Average daily air temperature (T), and relative humidity (RH), and (**b**) total radiation (Rs), during whole tomato growth period from 2019 to 2020.

2.5.3. Soil Moisture

Soil moisture was manually measured by a Frequency Domain Reflector (FDR) (Diviner2000 Sentek Pty Ltd., Stepney, Australia). Three access tubes were buried in each plot, one was under the lateral region (an access tubes that was buried under the drip line beside it), another one was in the middle of the ridge, and the third one was in the middle of the ridge slope, with 20 cm horizontal spacing between access tubes. The measurement depth was 120 cm and there was a reading taken every 10 cm interval. Soil moisture was measured one day before and one day after irrigation.

2.5.4. Fruit Yield

When the tomato had matured, three rows of tomato plants that showed uniform growth and no obvious pests and diseases were detected in each plot. The tomato fruits were harvested and weighed, and their average values were taken as the yield for each treatment.

2.5.5. Fruit Quality

At the end of the fruiting stage, fruits with uniform maturity and color were randomly selected for quality determination. The single fruit weight (SFW) was measured using an electronic scale with sensitivity of 0.01 g; total soluble solids (TSS) were measured using a handheld sugar meter; vitamin C (V_c) was measured by the molybdenum blue colorimetry [25,26]; and total titratable acids (TTA) was determined by the titration method [27].

2.6. Parameter Calculation

2.6.1. Reference Crop Evapotranspiration

Solar greenhouses are relatively closed, with poor air mobility. To avoid the effect of zero aerodynamics, the Penman–Monteith equation with correction for the aerodynamic terms related to wind was used to calculate the reference crop evapotranspiration in the solar greenhouse [28,29], and the equation is as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{1694}{T+273}(e_s - e_a)}{\Delta + 1.64\gamma} \quad (2)$$

where ET_0 is the reference crop ET, mm·d^{-1}; R_n is the net radiation, MJ·m^{-2}·d^{-1}; G is the soil heat flux at the soil surface, MJ·m^{-2}·d^{-1}; Δ is the slope of the saturation vapor pressure versus temperature curve, kPa·°C^{-1}; γ is the psychrometer constant kPa·K^{-1}; T is the mean daily air temperature measured at a height of 1.5 to 2.5 m, °C; e_s is the saturation vapor pressure of air, kPa; and e_a is the actual vapor pressure of air, kPa.

2.6.2. Evapotranspiration

The evapotranspiration of tomatoes was calculated according to the water balance method using Equation (3) [30].

$$ET_c = P + I + K - D - R \pm \Delta S \quad (3)$$

where ET_c is the evapotranspiration from tomato plants over a certain period of time, mm; p is the precipitation, mm; I is the irrigation amount, mm; K is the root zone water supplied by groundwater, mm; D is the deep percolation below the root zone, mm; R is the surface runoff, mm; and $\pm\Delta S$ is the change in soil moisture contents between two samplings, mm.

The solar greenhouse was covered with plastic film, which meant that precipitation could be ignored in Equation (3) ($p = 0$). Water provided to the root zone by groundwater was ignored when the water table was greater than 6 m ($K = 0$). Tomato plant roots are mainly distributed in the 40 cm soil layer [28] and the measurement depth was 120 cm. The maximum irrigation quota in the experiment was 24.9 mm, so there was no deep seepage ($D = 0$). The tomato plants were irrigated by drip irrigation, so there was no surface runoff ($R = 0$).

When the water balance method is used to calculate ET_c, it is necessary to accurately obtain the soil moisture variation within the scheming wetted soil layer depth. The following factors can affect the accurate acquisition of soil water content:

(1) The instrument measurement error. Since the Diniver2000 was used for soil moisture monitoring in this study, in order to reduce the measurement error, the instrument was calibrated before the experiment started;
(2) The layout of the access tubes: different from flood irrigation, drip irrigation is a localized irrigation technology, the layout of the access tubes will directly affect the accurate acquisition of soil moisture. A total of three access tubes were installed in the experiment (see Section 2.5.3), and the average value of soil moisture measurements of three access tubes at a certain depth were used as the soil water content at that depth;
(3) Installation of the access tube: when the Diniver2000 is used to measure soil moisture, the contact between the side wall of an access tube and the soil will greatly affect the measurement results (when there are pores, the measured value is higher than the actual value). Therefore, after an access tube is buried, the gap between the side wall of the access tube and the soil is filled with mud to secure a close contact and then ensure the accuracy of soil moisture data;
(4) The measurement of soil water content: due to the redistribution process of soil water after irrigation, it is important to measure the soil water content at an adequate time. If the measurement is carried out too early, the measured soil moisture change will be larger than the actual result because the soil water in the scheming wetted soil layer is still draining from the soil after the measurement, and. In this study, the soil moisture is usually measured 12 h after irrigation to ensure that the gravity water in the scheming wetted soil layer depth has been completely drained.

2.6.3. Crop Coefficient

The crop coefficient (K_c) was obtained by dividing the ET_c by the reference crop evapotranspiration (ET_0) for each growth period [29]. It was calculated using the following equation:

$$K_{ci} = \frac{ET_{ci}}{ET_{0i}} \quad (4)$$

where K_{ci} is the crop coefficient for stage i; ET_{ci} is the crop evapotranspiration during stage i, mm; and ET_{0i} is the ET_0 of the crop in stage i, mm.

2.6.4. Water Use Efficiency

Water use efficiency (*WUE*) reflects the water absorption and utilization efficiency of crops during the growth process. It is defined as the total amount of economic products divided by the total amount of water consumed and can be calculated as follows:

$$WUE = \frac{Y}{ET_c} \tag{5}$$

where *WUE* is water use efficiency, kg·m^{-3}; Y is the tomato fruit yield, kg·ha^{-1}; and ET_c is the actual evapotranspiration by tomatoes, m^3·ha^{-1}.

2.7. Comprehensive Evaluation

The technique for order preference by similarity to an Ideal Solution (TOPSIS) method was used to comprehensively evaluate and analyze the results of the experiments in order to determine the optimal irrigation amount [31,32].

2.7.1. Indicator Weight

The indicator weight was determined by the coefficient of variation method of objective weighting. Due to the different dimensions of each indicator, it was difficult to directly compare the degree of variation. Therefore, the coefficient of variation of each indicator was used to compare the degree of variation. The indicator weight was calculated as following:

$$V_j = \frac{\sigma_j}{X_j} \tag{6}$$

$$W_j = \frac{V_j}{\sum_{j=1}^{n} V_j} \tag{7}$$

where V_j is the coefficient of variation of indicator j, also known as the standard deviation coefficient; σ_j is the standard deviation of indicator j; X_j is the average value of indicator j; and W_j is the weight of indicator j.

2.7.2. Normalization of Evaluation Indicators

Five treatments were set as evaluation objects, with six evaluation indicators including fruit yield, WUE, SWF, TSS, TTA and V_c, among which the TTA indicator was converted to a positive indicator using reciprocal transformation. The evaluation indicators were normalized to establish a normalized matrix.

$$Z_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \tag{8}$$

where, z_{ij} is the j index normalized value in i treatment; x_{ij} is the j index value in the i treatment. i = 1, 2, . . . , n; j = 1, 2, . . . , m.

2.7.3. Ideal Solution ($Z_{ij}{}^{+}$) and Negative Solution ($Z_{ij}{}^{-}$)

The ideal solution ($Z_{ij}{}^{+}$) and the negative solution ($Z_{ij}{}^{-}$) were determined to form the ideal solution vector Z^{+} and the negative solution vector Z^{-}, respectively.

$$Z_{ij}{}^{+} = \left(z_{i1}{}^{+}, z_{i2}{}^{+}, z_{i3}{}^{+} \cdots\cdots z_{ij}{}^{+}\right) \tag{9}$$

$$Z_{ij}{}^{-} = \left(z_{i1}{}^{-}, z_{i2}{}^{-}, z_{i3}{}^{-} \cdots\cdots z_{ij}{}^{-}\right) \tag{10}$$

where, $Z_{ij}{}^{+}$ and $Z_{ij}{}^{-}$ represent the maximum and minimum values of the evaluation object in the j-th index, respectively.

2.7.4. Euclidean Distances (D_i^+ and D_i^-)

The Euclidean distances (D_i^+ and D_i^-) were determined as follow:

$$D_i^+ = \sqrt{\sum_{j=1}^{m}\left[w_j \times \left(z_{ij} - Z_{ij}^+\right)\right]^2} \tag{11}$$

$$D_i^- = \sqrt{\sum_{j=1}^{m}\left[w_j \times \left(z_{ij} - Z_{ij}^-\right)\right]^2} \tag{12}$$

where, D_i^+ and D_i^- represent the Euclidean distance from each evaluation object to the positive and negative ideal solution; w_j is the weight of indicator j.

2.7.5. Relative Proximity Coefficient R_i

The relative proximity coefficient R_i of each treatment was calculated; that is, the proximity between the evaluation object and the optimal scheme was calculated as follows:

$$R_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{13}$$

where, R_i is the relative proximity coefficient of each treatment.

2.8. Statistical Analysis

Statistical analysis of the data was carried out using SPSS Version 19.0, (IBM Corp., Armonk, NY, USA). Variance analysis (PROC ANOVA) was used to determine whether differences between data groups were significant. Before performing ANOVA, we checked if the data was normally distributed and homogenous. We checked for residual normality and homogeneity using the check_normality function and check_homogeneity function of the Performance package in R statistical software, respectively. When the difference was significant, Duncan's test was used to establish the groups that were different. A value of $p \leq 0.05$ was considered statistically significant.

3. Results

3.1. ET_0 Variations in the Solar Greenhouse over the Two Seasons

The ET_0 in the solar greenhouse varied within the range of 1.19~5.99 mm·d^{-1} in 2019 and varied within the range of 1.62~6.57 mm·d^{-1} in 2020 (Figure 4). The average ET_0 for the two seasons was 3.70 and 3.88 mm·d^{-1}, and the cumulative ET_0 for each season was 439.92- and 537.32-mm d^{-1}, respectively. The ET_0 in the winter–spring season was greater than that in the autumn–winter season. The ET_0 in the autumn–winter season gradually decreased with time, while the ET_0 in the winter–spring season gradually increased with time. It can also be seen from the figure that there were several extremely low ET_0 values in the greenhouse over the two seasons.

3.2. Water Requirement

The daily ET_c values of tomatoes in the two seasons all increased at first and then decreased over the whole growth period (Figure 5a,d). The daily ET_c in the autumn–winter season reached its maximum value between 25 September and 10 October, and ET_c in the winter–spring season reached its maximum value between 10 April and 17 April. A difference could be seen in the changes in tomato daily average ET_c during the growth period in the two seasons, where in the daily average ET_c of each treatment during the maturation period increased by 0.45~0.64 mm·d^{-1} in the winter–spring season compared with that in the autumn–winter season.

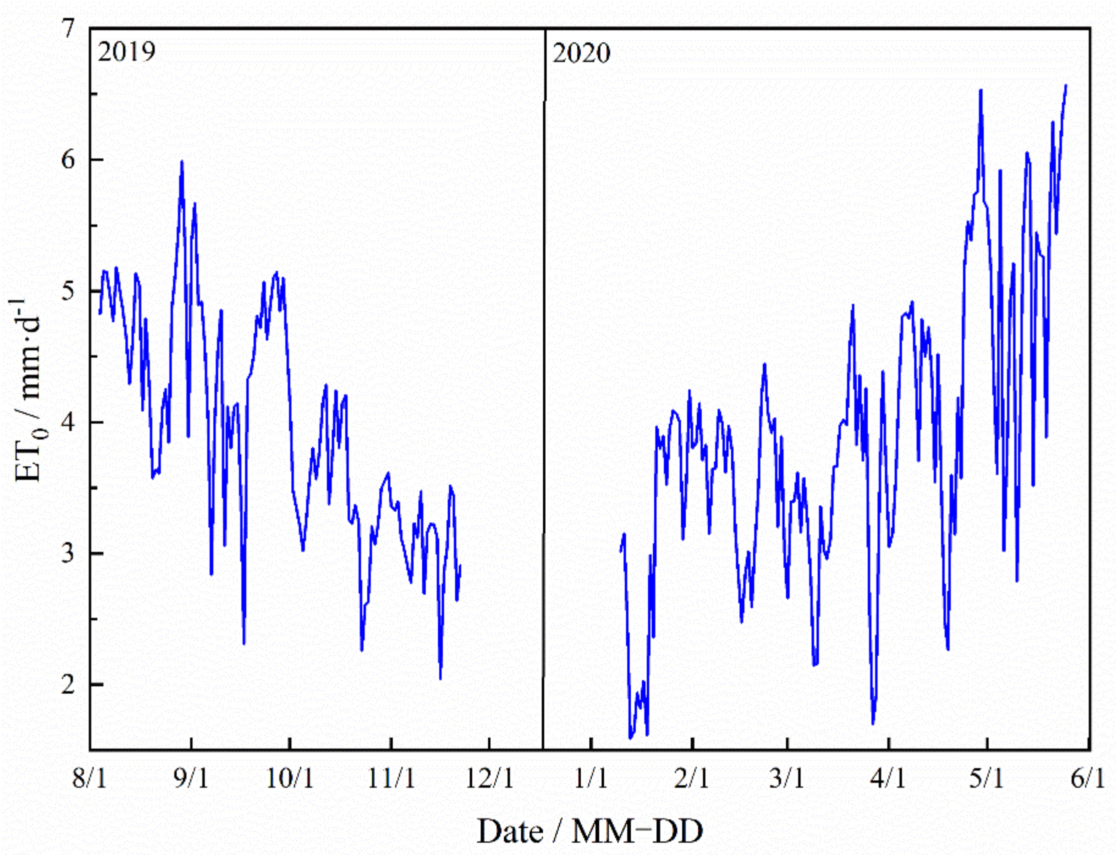

Figure 4. Variation in the reference crop evapotranspiration (ET_0) in the solar greenhouse from 2019 to 2020.

The average daily ET_c values of tomatoes for each treatment in the three main growth periods are shown in Figure 5b,e. The average daily ET_c of each growth period in the two seasons increased with the increase in irrigation amount. In terms of the average daily ET_c in the whole growth period, in the autumn–winter season, the irrigation amount of T1 and T2 decreased by 40% and 20%, respectively, compared with that of T3. However, the ET_c only decreased by 25.31% and 12.16%. Compared with T3, the irrigation amount of T4 and T5 increased by 20% and 40%, respectively, but the average daily ET_c only increased by 11.4% and 23.43%. The variations in the average daily ET_c in the whole growth period for each treatment in the winter–spring season were basically the same as those in the autumn–winter season. With the increase or decrease in irrigation amount, the ET_c of each treatment did not change in the same amount, and the change in the ET_c of tomato in each treatment was approximately 60% for each irrigation amount change.

The order of accumulated ET_c for each treatment was T5 > T4 > T3 > T2 > T1 in the two seasons (Figure 5c,f). Since the growth period of tomatoes in the winter–spring season is 26 days longer than that in the autumn–winter season, the cumulative ET_c in the whole growth period of each treatment in the winter–spring season increased, varying between 46.1 and 117.3 mm compared with that in the autumn–winter season. The changes in the cumulative ET_c with the irrigation amount in the whole growth period of each treatment were similar to the changes in the average daily ET_c with the irrigation amount.

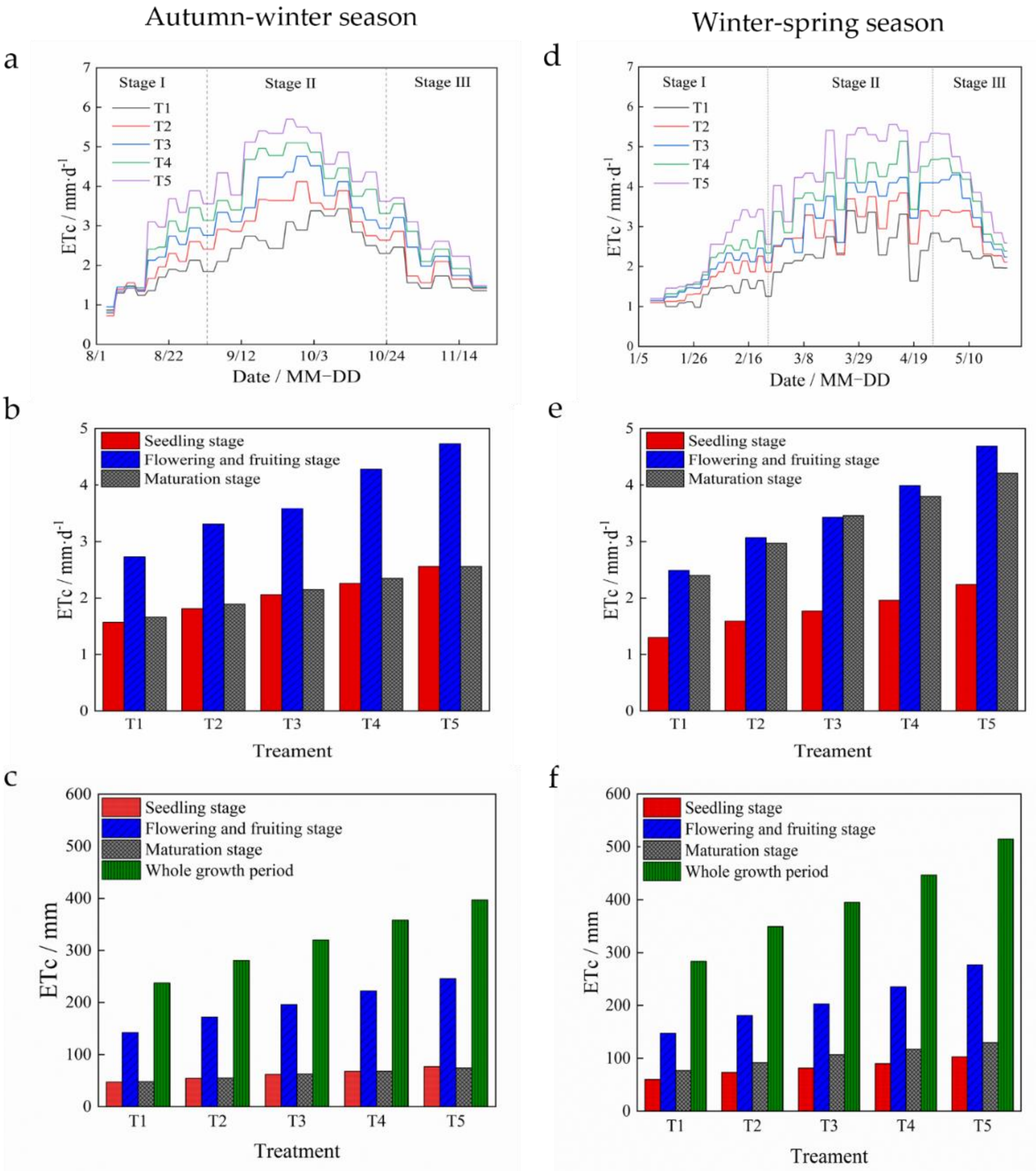

Figure 5. Variation in the tomato's daily ET_c for each treatment during the whole growth period (**a**,**d**). Average daily ET_c (**b**,**e**) and, cumulative ET_c (**c**,**f**) for tomatoes under the different treatments during three growth periods. Stages I, II and III in figures represent seedling, flowering and fruiting, and maturation stage, respectively.

3.3. Crop Coefficient

Figure 6 shows the variation in the tomato crop coefficient (K_c) over the whole growth period. It can be seen that the K_c of tomato grown in the solar greenhouse in the two seasons presented a three-stage change throughout the growth period. At the early stage after transplantation, the tomato plants were short, the water requirement was small, and the K_c was relatively small, within the range of 0.25~0.57. As the growth process advanced, the tomato plants grew rapidly, the water requirement rose, and the K_c increased rapidly. When the tomato leaves completely shaded the ground at the flowering and fruiting stage, the K_c reached its maximum, within the range of 0.71~1.34. After entering the maturation stage, the plant leaves began to turn yellow and fall off, the tomato plant transpiration gradually decreased, the water requirement intensity declined correspondingly, and K_c

also decreased, within the range of 0.49~0.86. The K_c over the whole growth period for each treatment ranged from 0.55 to 0.99, and the values in each growth period for each treatment followed the order T5 > T4 > T3 > T2 > T1. For treatments with a smaller irrigation quota, the K_c in each growth period was relatively small, because, when ET_0 was constant, reducing the irrigation amount often reduced the actual water requirement of the crops, resulting in a smaller K_c.

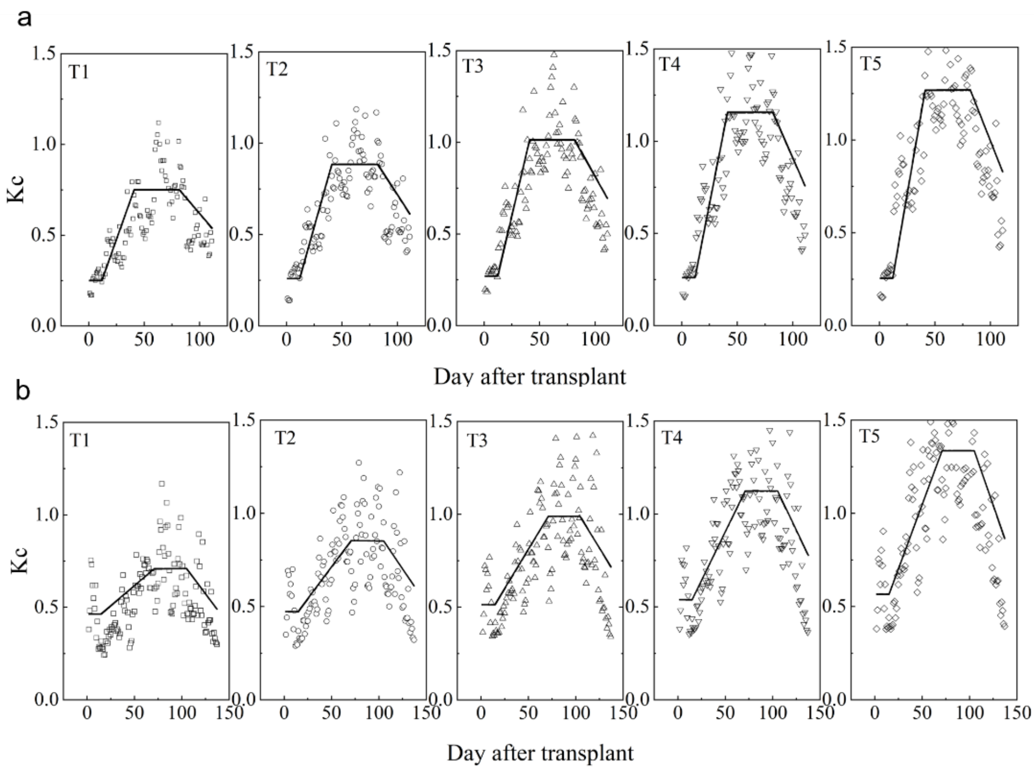

Figure 6. Variation trend for the tomato crop coefficient (K_c) in the autumn–winter season (**a**) and winter–spring season (**b**).

3.4. Fruit Yield and WUE

Table 4 shows the tomato fruit yield and WUE under the different treatments. It can be seen that the fruit yield in the two seasons varied within the range of 58.50~91.10 $t \cdot ha^{-1}$. The tomato fruit yields in the two seasons increased at first and then decreased as ET_c increased and reached its maximum value in the T4 treatment. The order of tomato fruit yield order was T4 > T5 > T3 > T2 > T1, and T4 was significantly different from other treatments ($p < 0.05$). In the autumn–winter season, there were no significant differences between T2, T3, and T5 ($p > 0.05$), but T1 was significantly different from the other treatments ($p < 0.05$). In the winter–spring season, there was no significant difference between T3 and T5 treatments, but there was a significant difference between them and T1, T2 treatments ($p < 0.05$), and between T2 and T1 ($p < 0.05$). Tomato WUE varied within the range of 15.68~26.15 $kg \cdot m^{-3}$. With the exception of treatment T3, the WUE in the two seasons gradually decreased as ET_c increased and reached a maximum value under T1 treatment. The WUE order for the five treatments was T1 > T3 > T2 > T4 > T5, in which T5 was significantly different from other treatments ($p < 0.05$). There was no significant difference among T1~T4 treatments ($p < 0.05$).

Table 4. Tomato fruit yield and water use efficiency (WUE) of each treatment in a solar greenhouse.

Treatment	Autumn–Winter Season			Winter–Spring Season		
	ET_c/mm	Yield/t·ha^{-1}	WUE/kg·m^{-3}	ET_c/mm	Yield/t·ha^{-1}	WUE/kg·m^{-3}
T1	237.49	62.10d	26.15a	283.58	58.50d	20.63a
T2	280.98	71.84c	25.57a	349.23	67.20c	19.24a
T3	320.19	82.18bc	25.67a	395.06	77.38b	19.59a
T4	358.29	91.10a	25.43a	446.71	85.91a	19.23a
T5	397.12	86.28bc	21.73b	514.40	80.64b	15.68b

Note: Different letters in the same row indicate differences between treatments ($p < 0.05$). Residuals appear as normally distributed. Variances in each of the groups are the same (Bartlett Test).

3.5. Fruit Quality

The effects of irrigation amount on the tomato fruit quality were evaluated by analyzing SFW, TSS, TTA, and V_c of the tomato fruits in each treatment. The mean values of the above indexes for tomato fruits grown in the two seasons are shown in Table 5. The results show that irrigation had a considerable impact on tomato fruit quality, and that the SFWs of the fruits from the T4 and T5 treatments were significantly higher than those under the other treatments ($p < 0.05$). The TSS and V_c contents in T1 and T2 treatments were significantly higher than those of other treatments ($p < 0.05$); and moreover, in contrast to T2, the TTA content in T3 treatment was significantly higher than that in other treatments ($p < 0.05$). SFW increased gradually with increase in irrigation amount, indicating that increasing the irrigation amount could significantly increases the SFW. The TSS and V_c contents significantly decreased with the increase in irrigation amount, indicating that reducing the irrigation amount improved fruit quality. The TTA content increased at first and then decreased with the increase in irrigation. The lower the TTA content, the sweeter the tomato tastes, indicating that the irrigation amount affected the taste of the tomato fruit. The highest SFW was seen in treatments T4 and T5, the highest TSS and V_c content was seen in treatments T1 and T2, the lowest TTA content was seen in treatments T1 and T5.

Table 5. Quality of the tomato fruits produced by each treatment in a solar greenhouse.

Season	Treatment	SFW /g	TSS /%	TTA /%	V_c /mg·(100 gFW)$^{-1}$
Autumn–winter season	T1	165.2c	5.70a	0.41c	5.32a
	T2	171.5c	5.30a	0.49ab	5.01a
	T3	193.5b	4.80b	0.52a	4.57b
	T4	204.8a	4.77b	0.46b	4.46bc
	T5	208.0a	4.21b	0.42c	4.31c
Winter–spring season	T1	159.4c	6.10a	0.43c	4.93a
	T2	165.5c	5.80a	0.51ab	4.76a
	T3	187.5b	5.31b	0.56a	4.32b
	T4	197.6a	4.76bc	0.48b	4.26b
	T5	204.0a	4.51c	0.45c	4.21b

SFW: single fruit weight; TSS: total soluble solids; TTA: total titratable acids; V_c: vitamin C. Different letters in the same row indicate differences between treatments ($p < 0.05$). Residuals ap-pear as normally distributed. Variances in each of the groups are the same (Bartlett Test).

3.6. Comprehensive Evaluation Based on TOPSIS Method

Taking the fruit yield, WUE, SFW, TSS, TTA, and V_c as evaluation indicators, the TOPSIS method was used to comprehensively determine the optimal irrigation amount (Table 6). The ranking for the different irrigation treatments was T4, T3, T5, T2, T1 in the two tomato growth seasons. The TOPSIS analysis showed that T4 was the optimal irrigation treatment for the tomato with high quality, high yield, and high WUE.

Table 6. TOPSIS-based comprehensive evaluation of irrigation amount effects on the tomato quality, yield, and WUE.

Season	Treatment/ Weighting	Normalized Decision Matrix						Euclidean Distance		Relative Proximity Coefficient	Rank
		Yield	WUE	SFW	TSS	TTA	V_c	D_i^+	D_i^-		
Autumn–winter season	T1	0.35	0.469	0.39	0.512	0.496	0.501	0.04	0.158	0.799	5
	T2	0.405	0.458	0.405	0.476	0.415	0.472	0.031	0.159	0.836	4
	T3	0.463	0.460	0.457	0.431	0.391	0.430	0.025	0.159	0.865	2
	T4	0.513	0.456	0.484	0.428	0.442	0.42	0.019	0.159	0.895	1
	T5	0.486	0.389	0.491	0.378	0.484	0.406	0.027	0.159	0.853	3
	Weighting efficient	0.233	0.189	0.161	0.114	0.146	0.167				
Winter–spring season	T1	0.351	0.487	0.388	0.512	0.499	0.489	0.039	0.157	0.799	5
	T2	0.403	0.454	0.403	0.487	0.421	0.472	0.032	0.157	0.833	4
	T3	0.464	0.462	0.457	0.446	0.383	0.429	0.025	0.157	0.862	2
	T4	0.515	0.454	0.481	0.399	0.447	0.423	0.02	0.157	0.887	1
	T5	0.484	0.37	0.497	0.378	0.477	0.418	0.031	0.157	0.836	3
	Weighting efficient	0.215	0.193	0.163	0.116	0.145	0.168				

Note: WUE, water use efficiency; SFW, single fruit weight; TSS, total soluble solids; TTA, total titratable acid; V_c, vitamin C; D_i^+, Euclidean distance of ideal solutions; D_i^-, Euclidean distance of negative ideal solutions.

4. Discussion

In this study, the tomato water requirement and crop coefficient were obtained under the membrane drip irrigation. An increasing number of farmers are not only concerned about the tomato fruit yield but also about the nutritional quality and appearance, seeking to increase their economic profits. The TOPSIS analysis showed that T4 (120% Ia) was the optimal irrigation treatment for tomatoes with high quality, high yield, and high WUE. Therefore, T4 was the optimal treatment. The tomato water requirement (ET_c) and the crop coefficient (K_c) of T4 can be applied to the tomato production in solar greenhouses in Hetian, southwest of the Taklimakan Desert.

The daily ET_c of tomatoes increased with increase in the irrigation amount (Figure 5 b,e). Similar results were also found by Liu [15] and Kong [33]. In this study the recommended daily ET_c of tomatoes at the seedling, flowering and fruiting, and maturation stages in the autumn–winter and winter–spring seasons were 2.26, 4.28, and 2.35 mm·d^{-1} and 1.96, 3.99, and 3.80 mm·d^{-1}, respectively, in our research experiments. The results are different from those of previous studies; for example, a study on the water requirements of summer tomato in a solar greenhouse on the North China Plain showed that the ET_c values for the three growth stages were 2.2, 3.34, and 2.86 mm·d^{-1}, respectively [34]. The daily ET_c values of tomatoes in the summer solar greenhouse in Xinxiang, Henan, located in the warm temperate climate, were 1.15~2.44, 3.24~4.21, and 2.86~3.86 mm·d^{-1} in the three growth periods, respectively [15,18]. Another study on the water requirements of tomatoes under drip irrigation with mulching in the winter–spring season in central and eastern Ningxia showed that the daily ET_c values for tomatoes at the three growth stages in a solar greenhouse were 3.04, 3.92, and 2.22 mm·d^{-1}, respectively [33]. The daily ET_c range was 5~6 mm·d^{-1} at the main growth stage of tomatoes in a tropical solar greenhouse [13]. The above comparison showed that the daily ET_c of solar greenhouse tomatoes differed significantly in different regions and seasons, which could be attributed to ET_c being affected by a variety of factors, such as crop variety, soil, weather, and cultivation practices. It further illustrated that existing research results on the daily ET_c of tomatoes grown in solar greenhouses cannot be directly used in the southwestern area of the Taklimakan Desert.

The total ET_c of tomatoes increased with the increase in the irrigation amount (Figure 5c,f) which was consistent with previous research [33,35–37]. The suitable total ET_c of tomatoes in a solar greenhouse in the southwest of the Taklimakan Desert was 358.29 and 446.71 mm in the autumn–winter and winter–spring seasons, respectively. The optimal total ET_c for tomatoes over the whole growth period in a solar greenhouse in the winter–spring season in the arid region of central and eastern Ningxia was 517.70 mm [33]. The variation in total ET_c was between 249.1 and 388.0 mm during the summer season in a solar greenhouse on the North China Plain [15]. Gong et al. found that the total ET_c for tomatoes in a solar greenhouse over the whole growth period during the spring–summer season varied between 315.1 and 348.8 mm in the Yellow River Basin under a full irrigation in a three-year irrigation experiment [18]. Xu et al. found that the total ET_c for tomatoes in a solar greenhouse in Eastern China during the spring–summer season was approximately 123.6 mm [38]. Zhang et al. reported that the total ET_c for tomatoes in a solar greenhouse in the winter–spring season in Southwest China was approximately 386.1 mm [35]. The ET_c of tomatoes obtained in this study were higher than those for Eastern and Southern China because the rainfall is less, the air is drier, and accumulated temperature is higher in the Hetian area than that in Central and Eastern China. On the other hand, the tomato's growing period studied by Kong et al. [33] was nearly one month longer than that in this study, which explains why the ET_c of tomatoes obtained in this study are lower than the total ET_c for solar greenhouse tomatoes in the Ningxia region.

The average K_c values for tomatoes at the seedling, flowering and fruiting, and maturation stages in the autumn–winter and winter–spring seasons were 0.49, 1.10, and 0.76 and 0.61, 1.09, and 0.78, respectively. The FAO recommends that the tomato K_c should be 0.6, 1.15, and 0.70 for each growth stage, respectively [39]. Zhao et al. reported tomato K_c values of 0.59, 1.01, and 0.61 for each growth period, respectively [34]. Gong et al. obtained tomato K_c values of 0.60, 1.09, and 0.71, respectively [18]. The tomato K_c values obtained by Qiu et al. varied within 0.51~0.63, 0.77~0.97, and 0.50~0.79, respectively [40]. In the western San Joaquin Valley, USA, the maximum mean K_c measured by a lysimeter was 1.05 [41], and in the Mediterranean region, K_c ranged from 1.0 to 1.4 in the middle and late growth periods of greenhouse tomatoes [42]. Hanson and May reported that the average K_c for tomato in the mid-growth period varied between 0.96 and 1.09 [43]. Stanghellini et al. found that under field conditions, the wind forced water vapor away from the leaf blade surface, so the canopy resistance largely depended on the wind speed. In the greenhouse, the wind speed is very low (5–50 $cm \cdot s^{-1}$) [44]. The solar greenhouse in this study had no forced ventilation equipment, and the wind speed in the greenhouse was far lower than that in the field. Liu's [45] research results showed that the solar radiation obtained in the greenhouse decreased by approximately 40% outdoors, but the humidity and temperature increased by 39.50% and 32.22%, respectively. Compared with outdoors, high temperatures in the greenhouse will increase the soil evaporation and crop transpiration, while the high humidity in turn reduces the soil evaporation and crop transpiration [46,47]. The combined effect of high temperature, high humidity and low wind speed results in a lower K_c value. A study showed that plastic mulching could reduce the K_c by 10–35% in the middle growth stage [39,48]. The small fluctuations in air flow in the greenhouse could ensure the relatively constant boundary layer resistance, and the crop transpiration rate in the greenhouse was not sensitive to the boundary layer resistance [49]. The K_c values obtained for tomatoes in a solar greenhouse in this study were slightly lower than those recommended by the FAO and closer to the K_c values for tomatoes in solar greenhouses in other areas.

The TSS and V_c contents of tomato decreased gradually with the increase in irrigation amount, which was consistent with prior conclusions [37,50–52]. On one hand, a moderate water deficit increased the activities of sucrose acid invertase and synthase in tomato fruits and promoted the conversion of more sucrose to fructose and glucose [53,54]. On the other hand, water had a dilutive effect on nutrients in tomato fruits, so the soluble solid content and vitamin C content decreased with the increase in irrigation amount [55]. In this study, SFW gradually increased with the increase in irrigation amount. Wang et al. found that the SFW, diameter, and length of tomatoes were mainly determined by the variety and were also affected by the irrigation treatment because the water content of ripe tomatoes accounted for more than 90% of its total weight [56]. Studies have shown that a larger irrigation amount increases the fruit weight and diameter [51,57–59]. The TTA content increased at first and then decreased with the increase in irrigation amount, which was consistent with the conclusions reported by Feng et al. [51,60] and Tang et al. [61]. The analysis suggested that this might be caused by the metabolic key enzymes used to regulate the accumulation of TTA, which need a suitable water environment. If the irrigation amount is too low, it is difficult for plants to absorb water, which is not conducive to the accumulation of titratable acid. When the water supply is sufficient, it tends to increase the water content of the fruit, which leads to the dilution of titratable acids. In general, decreasing the irrigation amount can increase the TSS and V_c contents of tomatoes, and conversely, increase the SFW of tomato fruits. Moreover, changes in the irrigation amount can change the flavor of tomato fruits.

In this study, optimal irrigation treatment was obtained in the current fertilization management level in the Hetian area. The result of this study filled the gap of irrigation research in the extremely arid desert areas and provided a theoretical basis for the development of scientific irrigation schedules in desert agriculture. The ET_c is closely related to irrigation and fertilization measures. Additional studies are highly recommended to advance our understanding of the effects of fertigation on the tomato growth and yield as well as irrigation requirements in a solar greenhouse, and to improve the water and fertilizer management in local protected agriculture, and to eventually realize the efficient utilization of limited water and soil resources in local areas.

5. Conclusions

The present result indicated that the crop evapotranspiration (ET_c) of tomatoes is closely related to the irrigation amount in a solar greenhouse, varying with the growth stage. The TOPSIS analysis showed that T4 (120% I_a) was the optimal irrigation treatment for tomatoes with high quality, high yield, and high WUE. The average daily ET_c values in three tomato growth stages in the autumn–winter and winter–spring seasons were determined as approximately 2.26, 4.28, and 2.35 $mm \cdot d^{-1}$ and 1.96, 3.99, and 3.80 $mm \cdot d^{-1}$ with membrane under drip irrigation. The average crop coefficients (K_c) were 0.49, 1.10, and 0.76 in the autumn–winter season, and 0.61, 1.09, and 0.78 in the winter–spring season.

The determination of tomato's water requirements at various growth stages is of significant importance in developing protected agriculture in the southwest region of the Taklimakan Desert, Xinjiang, China. This study will help producers to optimize the application of water and fertilizer in local protected agriculture and also provide guidelines for other similar regions.

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Abbreviations

D	Deep percolation below the root zone
ET_0	Reference crop evapotranspiration
ET_c	Crop evapotranspiration
E_s	Saturation vapor pressure of air
e_a	Actual vapor pressure of air
FC	Field capacity
G	Soil heat flux at the soil surface
H	Root depth
I	Irrigation amount
I_a	Medium irrigation quota
K	Root zone water supplied by groundwater
K_c	Crop coefficient
p	In Equation (1) is the wetted percentage and in Equation (2) is precipitation
R	Surface runoff
R_n	Net radiation
R_s	Average daily total radiation
RH	Relative humidity
SFW	Single fruit weight
T	Air temperature
TSS	Total soluble solids
TTA	Total titratable acid
WUE	Water use efficiency
V_c	Vitamin C
γ	Psychrometer constant
Δ	Slope of the saturation vapor pressure versus temperature curve

References

1. Oliveira, M.; Calado, A.; Portas, C. Tomato root distribution under drip irrigation. *J. Am. Soc. Hortic.* **1996**, *121*, 644–648. [CrossRef]
2. Gao, L.; Qu, M.; Ren, H.; Sui, X.; Chen, Q.; Zhang, Z. Structure, function, application, and ecological benefit of a single-slope, energy-efficient solar greenhouse in China. *Hort. Technol.* **2010**, *20*, 626–634. [CrossRef]
3. Esmaeli, H.; Roshandel, R. Optimal design for solar greenhouses based on climate conditions. *Renew Energ.* **2020**, *145*, 1255–1265. [CrossRef]
4. Mazzeo, D.; Baglivo, C.; Panico, S.; Gonedo, P.M. Solar greenhouses: Climates, glass selection, and plant well-being. *Sol. Energy* **2021**, *230*, 222–241. [CrossRef]
5. Wang, Y.; Jia, X.; Olasupo, I.O.; Feng, Q.; Wang, L. Effects of biodegradablefilms on melon quality and substrate environment insolar greenhouse. *Sci. Total Environ.* **2022**, *829*, 154527. [CrossRef]
6. Zhao, Y.; Hong, M.; Qu, J.; Xie, X.; Ma, X. Effects of irrigation quota on growth, yield and quality of greenhouse capsicums under drip irrigation in Hetian. *J. Water Res. Water Eng.* **2021**, *32*, 222–228, 235.
7. Li, X. Water resources problems in the process of poverty alleviation and development in Hetian Xinjiang. *Water Res. Develop. Res.* **2017**, *17*, 4–8+14.
8. Xu, H.; Li, Y.; Cui, Y.; Jiang, W.; Zou, Z. Thermal performance test and analysis of solar greenhouse in hinterland of Hetian desert, Xinjiang. *Trans. Chin. Soc. Agric. Eng.* **2018**, *34*, 6.
9. Wang, Y.; Zhang, H.; Xu, X. Study on the wetting front of water infiltration and soil water redistribution in aeolian sandy soil. *J. Arid. Environ.* **2009**, *23*, 190–194.
10. Xuan, C.; Ding, R.; Shao, J.; Liu, Y. Evapotranspiration and quantitative partitioning of spring maize with drip irrigation under mulch in an arid region of northwestern China. *Water* **2021**, *13*, 3169. [CrossRef]
11. Yaghia, T.; Arslana, A.; Naoum, F. Cucumber (*Cucumis sativus*, L.) water use efficiency (WUE) under plastic mulch and drip irrigation. *Agric. Water Manag.* **2013**, *128*, 149–157. [CrossRef]
12. Adekaldu, E.; Amponsah, W.; Tuffour, H.O.; Adu, M.O.; Agyar, W.A. Response of chilli pepper to different irrigation schedules and mulching technologies in semi-arid environments. *J. Agric. Food Chem.* **2021**, *6*, 100222. [CrossRef]
13. Harmanto; Salokhe, V.M.; Babel, M.S.; Tantau, H.J. Water requirement of drip irrigated tomatoes grown in greenhouse in tropical environment. *Agric. Water Manag.* **2005**, *71*, 225–242. [CrossRef]
14. Guo, Z.; Liu, H.; Wu, W.; Yang, S. Water consumption of cherry tomato with mulched drip irrigation in solar greenhouse. *Trans. Chin. Soc. Agric. Eng.* **2010**, *26*, 53–58.

15. Liu, H.; Duan, A.; Li, F.; Sun, J. Drip irrigation scheduling for tomato grown in solar greenhouse based on pan evaporation in North China Plain. *J. Integ. Agric.* **2013**, *12*, 520–531. [CrossRef]
16. Mohmed, A.M.A.; Cheng, J.; Feng, S.; Liu, W.; Xia, X. Response of greenhouse tomato growth, yield and quality to drip irrigation. *J. Irrig. Drain.* **2016**, *35*, 36–41.
17. Li, Y.; Chen, Z.; Zhang, D.; Yang, F.; Li, Y.; Wei, M. Study on water requirement characteristics of tomato grown in different seasons in solar greenhouse. *J. Irrig. Drain.* **2019**, *38*, 1–6.
18. Gong, X.; Qiu, R.; Sun, J.; Li, Y.; Wang, s. Evapotranspiration and crop coefficient of tomato grown in a solar greenhouse under full and deficit irrigation. *Agric. Water Manag.* **2020**, *235*, 106154. [CrossRef]
19. Saadon, T.; Lazarovitch, N.; Jerszurki, D.; Tas, E. Predicting net radiation in naturally ventilated greenhouses based on outside global solar radiation for reference evapotranspiration estimation. *Agric. Water Manag.* **2021**, *257*, 107102. [CrossRef]
20. Bao, C. *Water Consumption and Irrigation System of Tomato with Drip Irrigation in Solar Greenhouse under Wind-Sand Soil Conditions*; Xinjiang Agricultural University: Urumqi, China, 2021.
21. Zhang, Z. *Planning and Design Principle and Application of Drip Irrigation Engineering*; China WaterPower Press: Beijing, China, 2007.
22. Marino, S.; Aria, M.; Basso, B.; Leone, A.P.; Alvino, A. Use of soil and vegetation spectroradiometry to investigate crop water use efficiency of a drip irrigated tomato. *Eur. J. Agron.* **2014**, *59*, 67–77. [CrossRef]
23. Wang, J.; Niu, W.; Li, Y.; Lv, W. Subsurface drip irrigation enhances soil nitrogen and phosphorus metabolism in tomato root zones and promotes tomato growth. *Appl. Soil Ecol.* **2018**, *124*, 240–251. [CrossRef]
24. Yang, Z.; Deng, S. The design of drip irrigation system. *J. Agril. Mech. Res.* **2012**, *34*, 96–98+102.
25. Lu, S.; Zhang, X.; Liang, P. Influence of drip irrigation by reclaimed water on the dynamic change of the nitrogen element in soil and tomato yield and quality. *J. Clean. Prod.* **2016**, *139*, 561–566. [CrossRef]
26. Liu, T.; Cheng, Z.; Meng, H.; Ahmad, I.; Zhao, H. Growth, yield and quality of spring tomato and physicochemical properties of medium in a tomato/garlic intercropping system under plastic tunnel organic medium cultivation. *Sci. Hortic.* **2014**, *170*, 159–168. [CrossRef]
27. Zheng, J.; Huang, G.; Jia, D.; Wang, J.; Mota, M.; Pereira, L.S.; Huang, Q.; Xu, X.; Liu, H. Responses of drip irrigated tomato (*Solanum lycopersicum* L.) yield, quality and water productivity to various soil matric potential thresholds in an arid region of Northwest China. *Agric. Water Manag.* **2013**, *129*, 181–193. [CrossRef]
28. Chen, X.; Cai, H.; Li, H.; Wang, J. Calculation and verification of crop evapotranspiration in greenhouse. *Adv. Water Sci.* **2007**, *18*, 812–815.
29. Liu, H.; Sun, J.; Liang, Y.; Wang, C.; Duan, A. Estimation model for water requirement of greenhouse tomato under drip irrigation. *Chin. J. Appl. Ecol.* **2011**, *22*, 1201–1206.
30. Yang, H.; Du, T.; Qiu, R.; Chen, J.; Wang, F.; Li, Y.; Wang, C.; Gao, L.; Kang, S. Improved water use efficiency and fruit quality of greenhouse crops under regulated deficit irrigation in northwest China. *Agric. Water Manag.* **2017**, *179*, 193–204. [CrossRef]
31. Sun, G.; Hu, T.; Liu, X. Optimizing irrigation and fertilization at various growth stages to improve mango yield, fruit quality and water-fertilizer use efficiency in xerothermic regions. *Agric. Water Manag.* **2022**, *260*, 107296. [CrossRef]
32. Luo, H.; Li, F. Tomato yield, quality and water use efficiency under different drip fertigation strategies. *Sci. Hortic.* **2018**, *235*, 181–188. [CrossRef]
33. Kong, D.; Zheng, G.; Zhang, Y.; Zhu, J. Research of water consumption regularity with drip irrigation under mulch of greenhouse tomato in Ningxia. *Acta. Agric. Boreali-Occident. Sin.* **2011**, *20*, 119–123.
34. Weixia, Z.; Jiusheng, L.; Zhen, W.; Yanfeng, L. Developing crop coefficients and pan coefficient for greenhouse-grown tomato under drip irrigation. 2013 ASABE Annual International Meeting. In Proceedings of the 2013 Kansas City, Kansas City, MI, USA, 21–24 July 2013.
35. Zhang, Y.; Feng, C.; Fang, X.; Li, C. Study on water requirement of tomato under drip irrigation in solar greenhouse. *Water Sav. Irri.* **2014**, *8*, 16–18.
36. Liu, H.; Ning, H. Optimizing irrigation frequency and amount to balance yield, fruit quality and water use efficiency of greenhouse tomato. *Agric. Water Manag.* **2019**, *226*, 105787. [CrossRef]
37. Wu, Y.; Yan, S.; Fan, J.; Zhang, F.; Xiang, Y. Responses of growth, fruit yield, quality and water productivity of greenhouse tomato to deficit drip irrigation. *Sci. Hortic.* **2021**, *275*, 109710. [CrossRef]
38. Xu, J.; Peng, S.; Luo, Y. Tomato and cowpea crop evapotranspiration in an unheated greenhouse. *Water Sci. Eng.* **2008**, *1*, 112–120.
39. Allen, G.R.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper 56*; FAO: Rome, Italy, 1998.
40. Qiu, R.; Song, J.; Du, T.; Kang, S.; Tong, L. Response of evapotranspiration and yield to planting density of solar greenhouse grown tomato in northwest China. *Agric. Water Manag.* **2013**, *130*, 44–51. [CrossRef]
41. Phene, C.J.; Mccormick, R.L.; Miyamoto, J.M. Evapotranspiration and crop coefficient of trickle-irrigated tomatoes. Third International Drip/Trickle Irrigation Congress. In Proceedings of the ASAE, Fresno, CA, USA, 18–21 November 1985.
42. Santiago Bonachela, A.M.G.; María, D.F. Irrigation scheduling of plastic greenhouse vegetable crops based on historical weather data. *Irrig. Sci.* **2006**, *25*, 53–62. [CrossRef]
43. Hanson, B.R.; May, D.M. Crop evapotranspiration of processing tomato in the San Joaquin Valley of California, USA. *Irrig. Sci.* **2006**, *24*, 211–221. [CrossRef]

44. Stanghellini, C. *Transpiration of Greenhouse Crops: An Aid to Climate Management*; Wageningen University: Wageningen, The Netherlands, 1987.
45. Liu, H. *Water Requirement and Optimal Irrigation Index for Effective Water Use and High-Quality of Tomato in Greenhouse*; Chinese Academy of Agricultural Sciences: Xinxiang, China, 2010.
46. Chen, J.; Kang, S.; Du, T.; Qiu, R.; Guo, P.; Chen, R. Quantitative response of greenhouse tomato yield and quality to water deficit at different growth stages. *Agric. Water Manag.* **2013**, *129*, 152–162. [CrossRef]
47. Gong, X.; Liu, H.; Sun, J.; Gao, Y.; Zhang, H. Comparison of Shuttleworth-Wallace model and dual crop coefficient method for estimating evapotranspiration of tomato cultivated in a solar greenhouse. *Agric. Water Manag.* **2019**, *217*, 141–153. [CrossRef]
48. Amayreh, J.; Al-Abed, N. Developing crop coefficients for field-grown tomato (*Lycopersicon esculentum* Mill.) under drip irrigation with black plastic mulch. *Agric. Water Manag.* **2005**, *73*, 247–254. [CrossRef]
49. Stanghellini, C.; Ooster, B.; Heuvelink, E. *Greenhouse Horticulture*; Wageningen Academic Publishers: Wageningen, The Netherlands, 2019.
50. Patanè, C.; Tringali, S.; Sortino, O. Effects of deficit irrigation on biomass, yield, water productivity and fruit quality of processing tomato under semi-arid Mediterranean climate conditions. *Sci. Hortic.* **2011**, *129*, 590–596. [CrossRef]
51. Feng, T.; Zhou, X.; Yu, Y. Influence of irrigation amount on yield and quality of tomato in greenhouse. *North. Hortic.* **2016**, *10*, 54–58.
52. Lu, J.; Shao, G.; Cui, J.; Wang, X.; Keabetswe, L. Yield, fruit quality and water use efficiency of tomato for processing under regulated deficit irrigation: A meta-analysis. *Agric. Water Manag.* **2019**, *222*, 301–312. [CrossRef]
53. Ho, L.C. Metabolism and Compartmentation of Imported Sugars in Sink Organs in Relation to Sink Strength. *Ann. Rev. Plant Physiol. Plant Mol. Bio.* **1988**, *39*, 355–378. [CrossRef]
54. Qi, H.; Li, T.; Zhang, J. Effects of Irrigation on Sucrose Metabolism, Dry Matter Distribution and Fruit Quality of Tomato Under Water Deficit. *Tran. CSAE* **2004**, *37*, 1045–1049.
55. May, D.M. Irrigation and nitrogen management as they affect fruit quality and yield of processing tomatoes. *Acta Hort.* **1994**, *376*, 227–234. [CrossRef]
56. Wang, Z.; Liu, Z.; Zhang, Z.; Liu, X. Subsurfacedrip irrigation scheduling for cucumber (*Cucumis sativus* L.) grown in solar greenhouse based on 20 cm standard pan evaporation in Northeast China. *Sci. Hortic.* **2009**, *123*, 51–57. [CrossRef]
57. Sanders, D.C.; Howell, T.A.; Hile, M.M.S.; Hodges, L.; Meek, D.; Phene, C.J. Yield and quality of processing tomatoes in response to irrigation rate and schedule. *J. Am. Soc. Hortic. Sci.* **1989**, *114*, 904–908. [CrossRef]
58. Zhou, J.; Wang, F.; Yao, M.; Zhang, Z. Effects of water and nitrogen on yield and fruit quality of tomato under furrow irrigation and plastic film mulching cultivation. *Agric. Res. Arid. Areas* **2013**, *31*, 43–49.
59. Du, Y.; Cao, H.; Liu, S.; Gu, X.; Cao, Y. Response of yield, quality, water and nitrogen use efficiency of tomato to different levels of water and nitrogen under drip irrigation in Northwestern China. *J. Integ. Agric.* **2017**, *16*, 1153–1161. [CrossRef]
60. Feng, P.; Chen, S.; Zhou, Z.; Hu, T. Effect of soil water content on titratable acid content in tomato fruits based on rotatable design. *J. Northwest A F Univ.-Nat. Sci. Ed.* **2017**, *45*, 67–75+84.
61. Tang, X.; Liu, M.; Wang, W. Influences of regulated deficit irrigation on sensory quality and flavor components of tomato. *J. Plant Nutr. Ferti.* **2010**, *165*, 970–977.