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# Evaluation of Crop Water Stress Index (CWSI) for High Tunnel Greenhouse Tomatoes under Different Irrigation Levels

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**Abstract:** An experiment was conducted to determine the effect of water stress on yield and various physiological parameters, including the crop water stress index for tomatoes in the Central Anatolian region of Turkey. For this purpose, the irrigation schedule used in this study includes 120%, 100%, 80%, and 60% ($I_{120}$, $I_{100}$, $I_{80}$, $I_{60}$) of evaporation from the gravimetrically. Water deficit was found to cause a stress effect in tomato plants, which was reflected in changes in plants' morphological and pomological function (such as stem diameter, fruit weight, pH, titratable acidity, and total soluble solids). Irrigation levels had a significant effect on the total yield of tomatoes. The lowest water use efficiency (WUE) was obtained from the $I_{60,}$ while the highest WUE was found in the $I_{100}$ irrigation level. The CWSI was calculated using an empirical approach from measurements of infrared canopy temperatures, ambient air temperatures, and vapor pressure deficit values for four irrigation levels. The crop water stress index (CWSI) values ranged from −0.63 to a maximum value of 0.53 in $I_{120}$, from −0.27 to 0.63 in $I_{100}$, from 0.06 to 0.80 in $I_{80}$, and from 0.37 to 0.97 in $I_{60}$. There was a significant relation between yield and CWSI. The yield was correlated with mean CWSI values, and the linear equation Total yield = −2398.9CWSI + 1240.4 can be used for yield prediction. The results revealed that the CWSI value was useful for evaluating crop water stress in tomatoes and predicting yield.

**Keywords:** tomatoes; water use efficiency; irrigation scheduling; deficit irrigation

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## 1. Introduction

The rapid increase in the world's population, pollution of natural resources, global warming, and climate change increase the pressure on limited water resources. Food and water demand also increase in parallel to the world's population increase [1]. Tomato (*Solanum lycopersicum* L.) is one of the major horticultural crops consumed [2,3] and cultivated worldwide [4]. This species is considered one of the world's most widely produced agricultural products in terms of weight [5,6]. In Turkey, tomatoes are grown in greenhouses and open fields, especially in the Mediterranean region. China is the world leader in fresh tomato production, with an annual production of 62.8 million tons. India ranks second, with a production of 19 million tons. Turkey is third, producing 13 million tons; the United States is fourth, producing 10.9 million tons [7].

Water stress is one of the most influential factors contributing to crop yield loss. Insufficient water supplied to a crop during critical stages of growth, such as vegetative, flowering, or fruit settings, causes substantial yield loss [8,9]. Many studies confirmed that reductions in water supply during tomato growth harm final yield. An adequate water supply is required during the crop cycle for high yields [10–12]. Costa and Gianquinto [13] reported that continuous water stress significantly reduced the total fresh weight of fruits. Sivakumar and Srividhya [14] and Lovelli et al. [10] stated that 50% deficit irrigation significantly reduced the number of fruits, fruit diameter, fruit weight, and tomato yield. Kırda et al. [15] concluded that fruit yield and quality can be investigated before adopting deficit irrigation practices as a management tool.

Predicting yield response to crop water stress is essential in developing strategies and decision-making concerning irrigation management under limited water conditions by farmers, their advisors, and researchers [16]. Irrigation scheduling is generally based on measuring soil water content or meteorological parameters for modelling or computing evapotranspiration [17–19]. Irrigation scheduling based on crop water status can be more advantageous since crops respond to the soil and aerial environment (evaporative demand) [20]. Developing deficit irrigation practices as a tomato production management tool can be very effective in water scarcity conditions and reduce wastewater pollution. This is important because tomato is a popular vegetable grown worldwide. The main factors limiting crop production worldwide are water deficits and insufficient water supply. Water-saving practices can reduce production costs, conserve water, and prevent nutrients and pesticides from leaching into groundwater [21]. Accurate measurements of the crop water status are becoming essential in irrigated agriculture, as water resources are limited, and its use must be optimised, especially in semi-arid conditions [22].

Increasing irrigation efficiency requires consistent monitoring of crop water status from field to regional scale [23]. Productivity response to water stress differs for each crop and is expected to vary with the climate. Many factors must be accounted for to measure stress levels, but leaf temperature is the most important factor [24,25]. Critical crop water stress index (CWSI) values should be determined for a particular crop in different climates and soils for yield prediction and irrigation management [16]. To calculate the CWSI, two input parameters must be known that relate plant temperature under and without maximum water stress to the water vapor pressure deficit [26]. The crop water stress index is the most frequently used index to quantify crop water stress based on canopy surface temperature [27]. The behaviour of plant canopy temperature (Tc) under stress and non-stress conditions shows crop water status and yield performance during drought conditions. This is based on the fact that transpirational cooling reduces leaf temperature relative to air temperature, which is greater at relatively high vapor pressure deficit (VPD) values compared to low VPD values. Leaf temperature increases when water supply to a plant limits transpiration and when radiant energy is not dissipated via evaporation [28,29].

Research has been conducted to evaluate the application of the CWSI in irrigation scheduling for different crops in different places: Sezen et al. [25] red pepper, Çolak et al. [1] eggplant, Kovalenko and Zuhuravlov [26] tomatoes, López-López et al. [30] husk tomatoes, Bartzanas et al. [31] tomatoes, Erdem et al. [16] bean, and Erdem et al. [32] broccoli. However, little research has been carried out to evaluate the CWSI for greenhouse crops in Turkey, especially the Central Anatolian part, where crop water stress is frequent and pervasive. The dependence of crop yield on water supply is a critical issue due to increasingly limited water resources for irrigation.

The objectives of this study were to (i) evaluate CWSI for differentially irrigated tomatoes grown in the Central Anatolia region of Turkey; (ii) determine the effect of water stress occurring during the growing season on yield and water use efficiency of greenhouse tomatoes irrigated; and (iii) compare deficit irrigation (DI) for their effects on water relations, growth, and yield of tomatoes. The results of this study provide a guideline to regional growers and irrigation agencies for water-saving irrigation and optimum water management programs for greenhouses in the Central Anatolia region.

## 2. Materials and Methods

### 2.1. Experimental Site Description

The study was carried out in a high tunnel greenhouse at Kırşehir Ahi Evran University in Turkey (latitude 39°08′02″ N, longitude 34°07′08″ E, 1082 m above sea level). The experiment lasted from early May to mid-August 2021 (2021–2022 spring–summer season). Typical continental climate conditions prevail in the study area. The average annual rainfall is 383.2 mm, and more than half of the rainfall is received between November and May. Class A pan annual average evaporation is 1368.9 mm, average annual temperature is 11.5 °C, and average humidity is 63.0% [33]. Long-term mean climate data for the study area are given in Table 1.

**Table 1.** Long term and 2021 growing season some outdoor climatic data of the experimental area [33].

| Year | Climatic Parameters | May | June | July | August |
|---|---|---|---|---|---|
| 2021 | $T_{max}$, °C | 31.6 | 33.0 | 35.0 | 29.2 |
| | $T_{min}$, °C | 3.9 | 10.6 | 11.6 | 12.1 |
| | $T_{mean}$, °C | 16.0 | 20.2 | 22.0 | 20.3 |
| | $RH_{mean}$, % | 59.0 | 60.5 | 50.9 | 52.9 |
| Long-term (1930–2021) | $T_{max}$, °C | 22.1 | 26.3 | 29.9 | 30.0 |
| | $T_{min}$, °C | 8.6 | 12.4 | 15.6 | 15.6 |
| | $T_{mean}$, °C | 15.5 | 19.7 | 23.1 | 23.0 |
| | $RH_{mean}$, % | 60.2 | 54.2 | 47.6 | 47.6 |
| | Rainfall, mm | 44.3 | 34.6 | 8.3 | 7.9 |
| | Evaporation, mm | 159.7 | 218.0 | 299.3 | 287.6 |

$T_{max}$: maximum air temperature; $T_{min}$: minimum air temperature; $T_{mean}$: mean air temperature; $RH_{mean}$: relative humidity.

It was observed that the temperature value in the experiment area was higher in the months during which the experiment was carried out compared to the long-term. A direct evaporative cooler (fan pad system) was used to reduce the increasing temperature values in the high tunnel greenhouse. With the help of evaporative cooling, indoor temperature values were reduced, and relative humidity values were increased slightly.

Air-dried soil was used to fill each pot with 6.4 L in volume. Some physical and chemical properties of the experimental soil are presented in Table 2. The soil is classified as sandy loam textured, with 15.5% clay, 28.5% silt, and 56% sand. A bulk density of 1.51 g cm$^{-3}$ was used in experiments. Soil pH 7.38 and EC 0.72 dS m$^{-1}$. The gravimetric soil water contents at the field capacity and wilting point were 18.6% and 5.8%, respectively.

**Table 2.** Irrigation water analysis.

| pH | EC, dS m$^{-1}$ | Anions, meq L$^{-1}$ | | | | Cations, meq L$^{-1}$ | | | | SAR |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Ca | Mg | K | Na | $CO_3$ | $HCO_3$ | Cl | $SO_4$ | |
| 7.70 | 0.62 | 2.8 | 1.20 | 0.05 | 1.40 | 0 | 5 | 0.3 | 0.3 | 1.40 |

pH: Water reaction, EC: Irrigation water electrical conductivity, SAR: Sodium Adsorption Ratio.

Water was obtained from the tap; the irrigation water quality class is C2-S1 [34]. The results of the irrigation water analysis are provided in Table 2.

### 2.2. Experimental Design

The experiment brought pots to field capacity on 11 May 2021 before starting the irrigation subjects. Then, irrigation practices started and were terminated on 6 August 2021. The pots were weighed daily to determine the amount of irrigation water applied to the treatments, and soil moisture levels were monitored gravimetrically. Accordingly, irrigation practices were carried out as follows: $I_{120}$ irrigation (20% water excess), using the total amount of water to be given to increase the missing soil moisture to the pot capacity;

$I_{100}$ irrigation (full irrigation), where 100% of the water amount was used; $I_{80}$ irrigation (with 20% water deficit), where 80% of the water amount was used; and $I_{60}$ irrigation (with a 40% water deficit), where 60% of the water supply was used. The experiment was carried out with four irrigation levels and three replications (in each replication 5 pots), totalling 60 pots according to the factorial arrangement trial design in random plots.

### 2.3. Crop Water Requirement and Water Use Efficiency

The field capacity weight of each pot was determined before the experiments started. First, pots were saturated with tap water, and the tops of the pots were covered to prevent evaporation. After the drainage ceased, the weight of each pot was assumed as the pot's field capacity weight ($W_{FC}$). In order to determine the amount of water that should be applied to each pot in each watering, pots were weighed just before irrigation. The amount of applied irrigation water (IW) was calculated by using Equation (1) [35,36].

$$IW = ((W_{FC} - W)/\rho w) \times C_{AW} \quad (1)$$

where IW is the amount of irrigation water application (L), WFC is the mass of the pot at field capacity, i.e., the weight of the pot just before irrigation (kg), ρw is the unit mass of water (1 kg $L^{-1}$), and $C_{AW}$ is the water application coefficient.

Plants were irrigated at daily intervals, considering the soil water content of the control treatments. Evapotranspiration between two consecutive irrigations was calculated by using the water balance equation (Equation (2)).

$$ET = (W_n - W_{n+1})(IW - R) \quad (2)$$

where $W_n$ and $W_{n+1}$, are the pot weights before the nth and (n + 1)th irrigation (kg), and R is the amounts of applied and drainage water (L).

A drain pan was placed underneath each pot to collect leachate. To check and adjust leaching fractions to a 0.30 value, the amount of collected drainage water volume for each pot was measured after the drainage ceased. This adjustment also helped to compensate for the effect of plant growth on the field capacity value of each pot in Equation (1) throughout the experiment.

### 2.4. Water Use Efficiency

WUE was estimated as Total WUE (g $kg^{-1}$) and Marketable WUE (g $kg^{-1}$) as reported by [10]. The Total WUE was calculated as the ratio of total yield (g $pot^{-1}$) and total water applied to the plant (L). The Marketable WUE was determined as the ratio of marketable yield (g $pot^{-1}$) and total water applied to the plant (L). WUE values were determined with the help of Equation (3), considering the ET and yield of the treatments in the study [12].

$$WUE = (EY/ET) \quad (3)$$

where WUE is the water use efficiency (g $kg^{-1}$), EY is the economic yield (g $pot^{-1}$), and ET is the plant water consumption (L).

### 2.5. Crop Water Stress Index

Canopy temperatures (Tc) were measured with a hand-held infrared thermometer (IRT) (Santech ST-550). IRT readings were taken at a horizontal angle of 30–40° to have only crop canopy in the view area. Tc data collection was initiated in the middle of June in the experimental year when the plant cover percentage was nearly 85–90%. Tc measurements were taken between 12:00 and 14:00 h (local standard time) under clear skies when clouds unobscured the sun. The mean VPD was computed as the average of the calculated instantaneous wet and dry bulb temperatures and the standard psychrometer equation List [37] with a mean barometric pressure of 101.25 kPa.

The CWSI was calculated based on the empirical equation suggested by Idso et al. [38] (Equation (4)):

$$\mathrm{CWSI} = \frac{(\mathrm{T_c} - \mathrm{T_a}) - (\mathrm{T_c} - \mathrm{T_a})_{\mathrm{UL}}}{(\mathrm{T_c} - \mathrm{T_a}) - (\mathrm{T_c} - \mathrm{T_a})_{\mathrm{LL}}} \tag{4}$$

where LL represents the non-water-stressed baseline (lower baseline), and UL represents the non-transpiring upper baseline; $\mathrm{T_c}$: canopy temperature (°C); $\mathrm{T_a}$: air temperature (°C). The LL for the canopy–air temperature difference ($\mathrm{T_c} - \mathrm{T_a}$) versus the vapor pressure deficit (VPD) relationship was determined using data from the unstressed treatments. UL was computed according to the procedures explained by Idso et al. [38]. To verify the upper baseline, canopy temperatures of the stressed plants were determined several times during the tomato growing season.

### *2.6. Crop Management*

In the study, TYBİF F1 tomato variety was used as the plant material. The distribution of the water and nutrient solution required for the plants to the plant root area was provided by a measuring container. The nutrient solution used in the study was provided by the "Hoagland nutrient solution" modified as a complete nutrient solution by adding the nutrients needed by tomato plants to the irrigation water. Accordingly, N: 242 mg $\mathrm{L^{-1}}$, P: 31–54 mg $\mathrm{L^{-1}}$, K: 234–263 mg $\mathrm{L^{-1}}$, Ca: 160 mg $\mathrm{L^{-1}}$, Mg: 48 mg $\mathrm{L^{-1}}$, Fe: 2.5 mg $\mathrm{L^{-1}}$, Mn: 0.5 mg $\mathrm{L^{-1}}$, Zn: 0.5 mg $\mathrm{L^{-1}}$, Cu: 0.02 mg $\mathrm{L^{-1}}$, B: 0.05 mg $\mathrm{L^{-1}}$, Mo: 0.01 mg $\mathrm{L^{-1}}$ [39]. In the study, the nutrient solution applied in tomato cultivation was prepared in two different concentrations: from seedling planting to fruit set and from fruit set to harvest. Before applying the nutrient solution to the plants, pH and EC measurements were taken in the nutrient solution, and with the addition of nitric acid, the pH value was kept in the range of 6.0–6.5 and the EC value was kept in the range of 2.0–2.5 dS $\mathrm{m^{-1}}$.

### *2.7. Measurements and Analyses of the Plants and Fruits*

#### 2.7.1. Morphological Measurements

The selected agronomic variables are plant height, stem diameter, number of leaves, and yield. In the study, plant height (cm) was measured in meters from the root neck of the plant to the growth tip. Stem diameters (mm) were measured from 3 different plant points with the help of a digital calliper, and their averages were recorded. The number of leaves (number $\mathrm{plant^{-1}}$) and the number of leaves on the plant were recorded. At the end of the experiment, the tomato plants were cut from the root collar, the stem and root parts of the plants were weighed, and their fresh weight (g) was determined, and the dry weight (g) of the same samples was determined after they were dried in an oven set to 65 °C.

#### 2.7.2. Pomological Measurement and Analysis

To determine the pomological characteristics, fruits of similar size and maturity and without external defects were collected for each sample. The water of the sample was obtained using an extractor. Fruit width (mm) and fruit length (mm) were determined with a digital calliper with a sensitivity of ±0.1 mm, and fruit weight (g) was determined with an electronic scale with a sensitivity of ±0.005 g. Soluble solids content, pH, and titratable acidity (TA) values were determined in fruit juice extracts. TSS (%) (°Brix) was measured with a digital refractometer (Hanna HI 96801, Woonsocket, RI, USA), and the pH value was measured with a digital pH meter (Hanna, HI 9321). Titratable acidity was determined via titration with 0.1 N NaOH up to an endpoint of pH 8.1 and given as a percentage of citric acid in 100 mL of juice. Colour measurement of fruits picked up randomly from each replication was carried out using a colourimeter (Konica-Minolta CR-410, Tokyo, Japan). The L*, a*, and b* values for colour measurement were determined after the calibration process based on a white plate. After the calibration, the Chroma and Hue angles were calculated [40].

Yield values per plant (g/pot): Harvest was made when the fruits acquired the specific size and colour of the variety. At the end of the treatment, the end-harvest yield values were combined to find the total yield value. Determining the marketable fruit yield (g/pot) and the classification of marketable fruit weight were performed according to [41,42]. Accordingly, fruit width in classification is larger than 5.5 cm (class I), between 4.5 and 5.5 cm (class II), between 3.5 and 4.5 cm (class III), and below 3.5 cm (class IV). Fruits that were too small, misshapen, and cracked were deemed unmarketable.

### *2.8. Greenhouse Weather Data Measurements*

Indoor and outdoor air temperatures were measured with Onset HOBO U12 data loggers, which record temperature and relative humidity values. These devices can measure temperature in the range of −20/+70 °C with an accuracy of ±0.35 °C, and relative humidity measurements between 5% and 95% with an accuracy of 2.5%. The indoor and outdoor greenhouse environment measurements were recorded at 1 h intervals.

### Statistical Analysis

The experiment was conducted in 3 replications according to the randomised plot design. The differences in tomato properties between the irrigation regimes were analysed using SPSS 15.0. The Kruskall–Wallis (K-W) test, a non-parametric test, was used for the difference between group averages. According to the results of this test, the comparison between the groups showing the statistically significant difference was carried out using Post-Hoc Tamhane's T2 pairwise comparison test [43].

## 3. Results and Discussion

### *3.1. Morphological Properties of Tomatoes*

The morphological properties of the tomato samples are given in Table 3.

**Table 3.** Morphological properties of tomatoes at different irrigation regimes.

| **Measurement** | **Treatment** | | | | |
|---|---|---|---|---|---|
| | $I_{120}$ | $I_{100}$ | $I_{80}$ | $I_{60}$ | $I_{mean}$ |
| Stem diameter (mm) | $11.2^{b}$ | $13.1^{a}$ | $12.7^{a}$ | $11.1^{b}$ | 12.0 |
| Plant height (cm) | $92.6^{b}$ | $104.7^{a}$ | $87.0^{bc}$ | $81.1^{c}$ | 91.3 |
| Number of leaves (pieces) | $20.1^{a}$ | $18.6^{b}$ | $18.2^{b}$ | $18.1^{b}$ | 18.8 |
| Stem wet weight (g) | $204.1^{c}$ | $232.7^{a}$ | $208.0^{b}$ | $102.1^{d}$ | 186.7 |
| Stem dry weight (g) | $65.6^{b}$ | $70.6^{a}$ | $65.2^{b}$ | $40.3^{c}$ | 60.4 |
| Root wet weight (g) | $115.2^{b}$ | $136.1^{a}$ | $65.2^{c}$ | $42.5^{d}$ | 89.7 |
| Root dry weight (g) | $55.6^{b}$ | $80.5^{a}$ | $35.1^{c}$ | $30.3^{d}$ | 50.4 |
| Root lenght (cm) | $34.0^{a}$ | $33.6^{a}$ | $29.3^{b}$ | $29.0^{b}$ | 31.5 |

Irrigation level, $I_{120}$: 120% ET; $I_{100}$: 100% ET; $I_{80}$: 80% ET; $I_{60}$: 60% ET; $I_{mean}$: Mean values of the treatments, $^{a\text{–}d}$: Different letters within the same rows show significant differences at $p < 0.05$ significance level.

Although the highest stem diameter was obtained in the $I_{100}$ subject (13.1 mm) according to the irrigation treatments, the difference between the $I_{100}$ and $I_{80}$ subjects was statistically insignificant. The lowest stem diameter was determined for $I_{60}$ (11.1 mm). The study found the difference in stem diameter values between irrigation levels was statistically significant ($p < 0.01$). Colimba-Limaico et al. [12] stated that increasing irrigation doses (80%, 100%, 120%, and 140%) increased stem diameter values. In the study, stem diameter values were lower in $I_{120}$ than in $I_{100}$.

The highest plant height was obtained in the I100 subject according to irrigation levels. The lowest plant height was determined at $I_{60}$ (81.1 cm). The difference between $I_{60}$ and $I_{80}$ subjects was statistically insignificant. In the study, the difference in plant height values between irrigation levels was found to be statistically significant ($p < 0.01$). Researchers determined the plant height for different irrigation treatments as Nangare et al. [44] and Atilgan et al. [7] as higher tomato plant height in full irrigation (100%) than in incomplete irrigation. Colimba-Limaico et al. [12] stated that increasing irrigation doses (80%, 100%, 120%, and 140%) increased plant height values. In the study, plant height was found to be lower at irrigation level $I_{120}$ than at irrigation level $I_{100}$.

According to irrigation levels, the highest number of leaves was obtained at the $I_{120}$ level. In the study, the difference in leaf number values between irrigation levels was found to be statistically significant ($p < 0.01$). Atilgan et al. [7] reported that the difference between the number of leaves for different irrigation doses (100%, 90%, 80%, and 70%) was insignificant. Similarly, in the study, while the difference between the number of leaves in irrigation levels $I_{60}$, $I_{80}$, and $I_{100}$ was insignificant, the number of leaves in irrigation level $I_{120}$ had the highest value.

The highest stem and root wet weight was obtained in $I_{100}$ according to irrigation levels. According to the wet weights obtained, the dry weights of the stem and roots also increased at $I_{100}$. The lowest stem and root wet and stem and root dry weights were determined for $I_{60}$. Regarding plant root length, $I_{120}$ and $I_{100}$ were in the same group, while $I_{80}$ and $I_{60}$ were in the same group. Considering the results obtained, it was determined that the deficit irrigation water for $I_{60}$ negatively affected plant development. In the study, the difference in plant wet and dry weight values between irrigation levels was statistically significant ($p < 0.01$). Researchers determined the highest dry matter amount for different irrigation levels in Lovelli et al. [10] and Tarı and Sapmaz [11] at full irrigation (100%). Accordingly, in the conducted study, it was similarly determined that stem and root wet and stem and root dry weights increased at an irrigation level of $I_{100}$.

### *3.2. Pomological Properties of the Tomatoes*

The pomological properties of the tomato samples are given in Table 4.

**Table 4.** Pomological properties of tomatoes at different irrigation regimes.

| **Measurement** | **Treatment** | | | | |
|---|---|---|---|---|---|
| | $\mathbf{I_{120}}$ | $\mathbf{I_{100}}$ | $\mathbf{I_{80}}$ | $\mathbf{I_{60}}$ | $\mathbf{I_{mean}}$ |
| Fruit width (mm) | $59.4^{a}$ | $61.6^{a}$ | $59.6^{a}$ | $51.8^{b}$ | 58.1 |
| Fruit length (mm) | $50.2^{ab}$ | $51.7^{a}$ | $52.0^{a}$ | $44.7^{b}$ | 49.7 |
| Fruit weight (g) | $97.1^{a}$ | $97.8^{a}$ | $82.1^{b}$ | $73.6^{c}$ | 87.7 |
| pH | $4.1^{c}$ | $4.2^{b}$ | $4.3^{a}$ | $4.2^{b}$ | 4.2 |
| Firmness (kg $m^{-2}$) | $2.6^{a}$ | $2.5^{a}$ | $1.82^{b}$ | $1.5^{c}$ | 2.1 |
| Titratable Acidity (%) | $0.38^{ab}$ | $0.31^{c}$ | $0.37^{b}$ | $0.39^{a}$ | 0.4 |
| Total Soluble Solids, (°Brix) | $5.3^{c}$ | $5.0^{d}$ | $5.6^{b}$ | $6.0^{a}$ | 5.5 |
| Hue° | $24.2^{b}$ | $23.7^{c}$ | $25.6^{a}$ | $23.9^{bc}$ | 24.3 |
| Crome | $48.4^{c}$ | $66.0^{a}$ | $44.6^{c}$ | $63.2^{b}$ | 45.8 |

Irrigation level, $I_{120}$: 120% ET; $I_{100}$: 100% ET; $I_{80}$: 80% ET; $I_{60}$: 60% ET; $I_{mean}$: Mean values of the treatments, $^{a–d}$: Different letters within the same rows show significant differences at $p < 0.05$ significance level.

Compared to the $I_{100}$ level, fruit width decreased by 3.6% in $I_{120}$, 3.2% in $I_{80}$, and 15.9% in $I_{60}$. Compared to the $I_{100}$ level, fruit width decreased by 2.9% in $I_{120}$, increased by 0.6% in $I_{80}$, and decreased by 13.5% in $I_{60}$. Although there were differences between irrigation levels in terms of fruit width and length, $I_{120}$, $I_{100}$, and $I_{80}$ were statistically insignificant. However, in $I_{60}$, fruit width and length decreased significantly. In the study, the difference in fruit width and length values between irrigation levels was statistically significant ($p < 0.01$).

The highest fruit weight was obtained at the $I_{100}$ level (97.8 g) according to irrigation levels. The lowest fruit weight was determined in $I_{60}$ (73.6 g). Compared to the $I_{100}$ application, fruit weight decreased by 1.6% for $I_{120}$, 16.1% for $I_{80}$ and 24.7% for $I_{60}$. In the study, the difference in fruit weight values between irrigation levels was statistically significant ($p < 0.01$). Accordingly, it was determined that over-irrigation, as well as deficit irrigation, had a negative effect on fruit weight.

In tomatoes, fruit flesh hardness and skin resistance vary during product storage, distribution, and maturity and are important harvest criteria against mechanical damage [45]. When the hardness values were examined, it was determined that the hardness values increased for $I_{120}$ and decreased for the $I_{60}$ level. In the study, the difference in flesh hardness values between irrigation levels was statistically significant ($p < 0.01$). Accordingly, it was determined that water stress reduced fruit flesh firmness, which was statistically significant.

The pH in tomato juice is a critical quality parameter determining the taste. In general, in quality analysis, a low pH value (around 2.0) indicates sour fruits [46]. pH values caused differences between irrigation levels. The highest pH value was obtained at $I_{80}$ (pH: 4.3). In the study, the difference in pH values between irrigation levels was found to be statistically significant ($p < 0.01$). Researchers determined fruit pH values between 4.20 and 4.34 for different irrigation levels. Lovelli et al. [10] found that the difference between pH values was significant. Colimba-Limaico et al. [12] reported an insignificant difference between pH values between 4.30–4.35 and irrigation levels. Accordingly, in the study, pH values varied between 4.1 and 4.3, and the differences between irrigation levels were found to be significant.

When TA values were examined, it was determined that TA acidity decreased at $I_{100}$. In general, a low acidity value in quality analysis indicates sweet fruits [46]. In the study, the difference in TA values between irrigation levels was statistically significant ($p < 0.01$). Lovelli et al. [10] determined fruit TA values between 0.26 and 0.40 for different irrigation levels and reported that the difference between TA values was insignificant. Hong et al. [47] reported that for different irrigation levels (60%, 80%, 100%, 120%, and 140%) the tomato fruit TA in the two seasons (Autumn–Winter and Winter–Spring) between 0.41 and 0.56. In the study, TA content increased at first and then decreased with the increase in irrigation. The lower the TA content, the sweeter the tomato tastes, indicating that the irrigation amount affected the taste of the tomato fruit. Also, that the difference between TA values for different irrigation levels was significant. Accordingly, in the conducted study, TA values varied between 0.31–0.39 and the differences between irrigations were significant. The total soluble solids in tomato fruits represent one of the most important fruit quality components that create fruit flavour [48]. In the study, when TSS values were examined, it was determined that TSS increased for $I_{60}$. In the study, the difference in TSS values between irrigation levels was statistically significant ($p < 0.01$). Researchers found fruit TSS values for different irrigation levels Lovelli et al. [10] 5.57–7.03 in tomato, Colimba-Limaico et al. [12] 3.71–4.32 in tomato, Tarı and Sapmaz [11] 4.53–5.53 in tomato, Hong et al. [47] 4.21–6.10 in tomato, Ünlükara et al. [36] determined it to be 5.04–6.55 in pepper, and Çolak et al. [1] determined it to be 4.38–4.68 in eggplant. They also reported that the difference between TA values was significant. Additionally, researchers determined the highest TSS in the levels with the highest water deficit. Accordingly, in the study conducted similarly, TSS values varied between 5 and 6, and it was found that water deficit increased TSS and the difference between irrigation levels was significant.

In tomatoes, fruit colour hue° angle values express the tone of the colour. A lower hue° colour angle causes the colour red to appear better (Özkaplan and Balkaya [39]). The study determined the lowest hue° values at $I_{100}$ and $I_{60}$ irrigation levels. In the study, the difference in hue values between irrigation levels was found to be statistically significant ($p < 0.01$). In tomato fruits, fruit skin colour and chroma values express the saturation and vividness of the colour [49]. When looking at the chroma values, it was determined that chroma was the highest for the $I_{100}$ level. In the study, the difference in chroma values between irrigation levels was statistically significant ($p < 0.01$). Accordingly, it was determined that irrigation levels statistically affected tomatoes' hue and chroma values.

### 3.3. Water Consumption and Water Use Efficiency (WUE)

Water management in tomatoes is extremely important at all stages of plant development due to its impact on fruit set and quality. The water consumption and water use efficiency at different irrigation levels are given in Table 5.

**Table 5.** Water consumption and water use efficiency at different irrigation levels.

| **Treatment** | $\mathbf{I_{60}}$ | $\mathbf{I_{80}}$ | $\mathbf{I_{100}}$ | $\mathbf{I_{120}}$ |
|---|---|---|---|---|
| ET (L) | 17.2 $^{d}$ | 21.6 $^{c}$ | 24.3 $^{b}$ | 28.7 $^{a}$ |
| Total Yield (g pot$^{-1}$) | 663.0 $^{d}$ | 853.4 $^{c}$ | 1075.2 $^{b}$ | 1184.8 $^{a}$ |
| Marketable Yield (g pot$^{-1}$) | 603.0 $^{d}$ | 783.4 $^{c}$ | 1002.0 $^{b}$ | 1112.8 $^{a}$ |
| Total WUE (g L$^{-1}$) | 38.5 $^{b}$ | 39.5 $^{b}$ | 44.2 $^{a}$ | 41.3 $^{ab}$ |
| Marketable WUE (g L$^{-1}$) | 35.0 $^{c}$ | 36.2 $^{c}$ | 41.2 $^{a}$ | 38.8 $^{b}$ |

Irrigation level, $I_{120}$: 120% ET; $I_{100}$: 100% ET; $I_{80}$: 80% ET; $I_{60}$: 60% ET; $I_{mean}$: Mean values of the treatments, $^{a–d}$: Different letters within the same rows show significant differences at $p < 0.05$ significance level.

Evapotranspiration was reduced due to deficit water application in irrigation levels; thus, a lower evapotranspiration amount was obtained in $I_{80}$ and $I_{60}$ applications. The highest ET was determined for $I_{120}$. The ET reduction relative to $I_{120}$ for $I_{100}$, $I_{80}$, and $I_{60}$ was 15.3%, 24.6%, and 40.0%, respectively. In the study, the difference in ET values between irrigation levels was found to be statistically significant ($p < 0.01$). Moreover, the highest total yield was obtained from the $I_{120}$ (1184.8 g), and the lowest total yield (663.0 g) was obtained from the $I_{60}$ application. Compared to the $I_{120}$ treatment, the total yield reductions in the $I_{100}$, $I_{80}$, and $I_{60}$ treatments were 9.2%, 28%, and 44.0%, respectively. The difference in total yield values between irrigation levels was statistically significant ($p < 0.01$). The experiment obtained the highest marketable yield from $I_{120}$ (1112.8 g) and the lowest total yield (603.0 g) from the $I_{60}$ application. Compared to the $I_{120}$ treatment, the total efficiency reductions in the $I_{100}$, $I_{80}$, and $I_{60}$ treatments were 10.1%, 29.6%, and 45.8%, respectively. Furthermore, the difference in marketable yield values between irrigation levels was statistically significant ($p < 0.01$). Yao et al. [50] reported that it is crucial to accurately determine ETc and its components for attaining efficient irrigation scheduling and enhancing water use efficiency. Water stress causes yield loss because as the soil dries, the soil matrix strongly retains soil water, and the soil water concentration increases [36]. In the irrigation levels, the highest total WUE $I_{100}$ (44.2 g L$^{-1}$) and the lowest total WUE (38.5 g L$^{-1}$) were obtained from the $I_{60}$ application. Additionally, the highest marketable WUE $I_{100}$ (41.2 g L$^{-1}$) and the lowest total WUE (35.0 g L$^{-1}$) were obtained from the $I_{60}$ application. In the study, the difference in total and marketable WUE values between irrigation levels was statistically significant ($p < 0.01$).

Patane et al. [51] reported in their study that full irrigation (100% ETc restoration throughout the entire growing season) is necessary to maximise marketable yield in the processing of tomatoes grown in arid climate conditions. However, especially in regions where water resources are gradually decreasing, such as the Mediterranean basin, they have suggested adopting deficit irrigation strategies in which a 50% reduction in the ETc recovered during the entire growing season, or part of it (i.e., from flowering), is applied. Similarly, Lovelli et al. [10] stated that both total and marketable yields were greatly reduced by cutting ETc restoration by 50% compared to full irrigation control (100% ETc). Tarı and Sapmaz [11] reported that for different irrigation conditions (60%, 80%, 100%, and 120%) in tomatoes, WUE values increased up to 100% irrigation and decreased at 120%. Hong et al. [47] reported that for different irrigation levels (60%, 80%, 100%, 120%, and 140%) in tomatoes, the tomato fruit yields in the two seasons (Autumn–Winter and Winter–Spring Season) increased at first and then decreased as ETc increased and reached its maximum value in the 120% treatment. The fruit yield in the two seasons varied within the range of 58.50–91.10 t·ha$^{-1}$. The order of tomato fruit yield order was 120 > 140 > 100 > 80 > 60, and tomato WUE varied within the range of 15.68–26.15 kg·m$^{-3}$. The WUE order for the five treatments was 60% > 100% > 80%> 120% > 140%. Except for 100% treatment, the WUE in the two seasons gradually decreased as ETc increased and reached a maximum value under 60% treatment. Xu et al. [52] conducted an experiment for small-scale water saving with the conventional irrigation amount (4500 m$^{3}$/ha) as the basis, decreasing by 7%, 14%, 21%, and 28% successively. Overall, it was reported that marketable yield and irrigation water productivity tended to increase and then decrease with decreasing irrigation levels. However, it was reported that moderately lowering the regular irrigation was favourable for more satisfactory yields and quality of processing tomatoes, whereas excessively lowering the water supply reduced the yield and quality of processing tomatoes.

Colimba-Limaico et al. [12] found the total WUE for different irrigation conditions (80%, 100%, 120%, and 140%) in tomatoes as 58.32, 54.26, 49.89, and 45.97, respectively. Marketable WUE was determined as 52.68, 49.92, 46.56 and 42.81. Accordingly, it was determined that total WUE and marketable WUE decreased with increasing irrigation doses. However, as a result of the study, they reported that the highest efficiency increase was between 80% ETc and 100 ETc doses. Local tomato growers are recommended a daily dose of water that covers 100% crop evaporation. This recommendation considers the balance between crop production, fruit quality, and water use efficiency. Therefore, the grower's income will not be affected. Pereira et al. [53] stated that in particular in areas of water scarcity, such as those of the Mediterranean basin, maximising water productivity may be more profitable to the farmer than maximising crop yield. Similarly, as seen in the study, although the highest total WUE and marketable WUE were found for $I_{100}$, it was determined that the $I_{80}$ application gave positive results in maintaining the balance between water and efficiency in places with water constraints.

### *3.4. Crop Water Stress Index (CWSI) and Baseline Equations*

As in open field conditions, researchers have successfully used CWSI for different plants in greenhouse environments: Bartzanas et al. [31] tomatoes, Roh et al. [54] cucumber, Langton et al. [55] pot chrysanthemum and dieffenbachia, Ru et al. [56] grapevine, and Bo et al. [57] green pepper. However, the key to building the CWSI model was to determine the model's upper and lower limit baseline [1,27,57].

The baseline for $T_c - T_a$ versus VPD for tomatoes is illustrated in Figure 1. The upper limit ($I_{120}$) and ($I_{60}$) equations were developed as follows: $T_c - T_a = -2.51$ VPD + 1.04 and $T_c - T_a = -0.08$ VPD + 4.26. The upper limits of $T_c - T_a$ were found to be using the procedure given by [38].

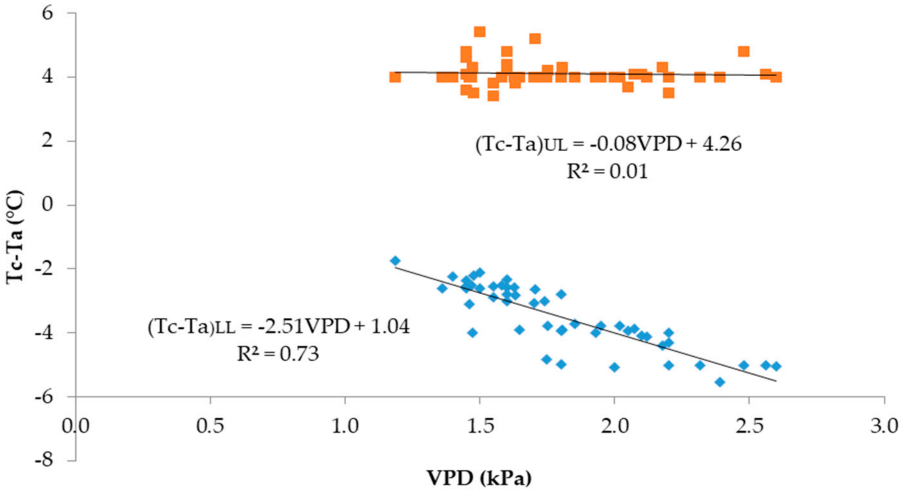


**Figure 1.** The temperature difference between canopy–air temperature depending on the deficit of water vapor pressure.

Researchers reported the following relation for the lower limit in tomato crops: $T_c - T_a = 2.86–1.96$ VPD [29], $T_c - T_a = 1.21–1.31$ VPD [30], $T_c - T_a = -0.842–2.591$ VPD [26]. In the study conducted by the researchers, if the VPD increased by 1 kPa, the $T_c - T_a$ value decreased by 1.96 °C [29], 1.31 °C [30], and 2.59 °C [26]. In the study, the decrease was determined as 2.51 °C. High VPD causes plants to close their stomata to minimise water loss and prevent critical water tension in the xylem, resulting in reduced photosynthesis in the plant. This situation causes increased plant water stress. The CWSI values increased with increasing water stress. There were day-to-day variations of CWSI in all treatments. Deficit irrigation level ($I_{60}$) had the highest CWSI among the treatments. The CWSI values for full irrigation treatments ($I_{100}$ and $I_{120}$) decreased compared to deficit irrigation treatments. It can be observed that all relations are different, which agrees with the results obtained by [58], who point out that the intercept and slope values vary depending on the climate, type of soil, and crop being cultivated. Erdem et al. [16] found that several factors, such as errors in determining relative humidity, IRT calibration, IRT aiming or field of view, and microclimate factors (such as clouds or wind), can affect the baseline relationship.

Figure 2 shows the course of the CWSI on a time scale from day of the year (DOY) 168 to 216 for each irrigation level. Irrigations occurred early every day in the morning. Moreover, Figure 2 shows that CWSI values were ranked according to available water in the soil profiles.

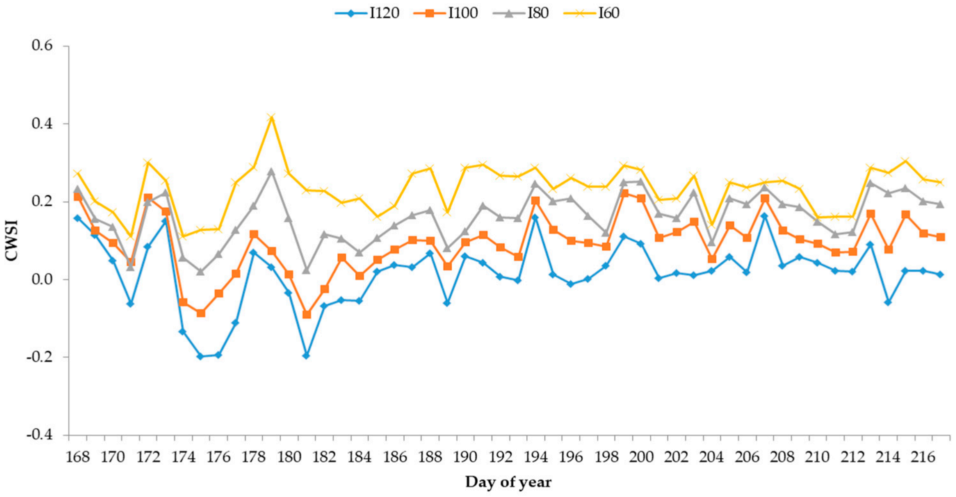


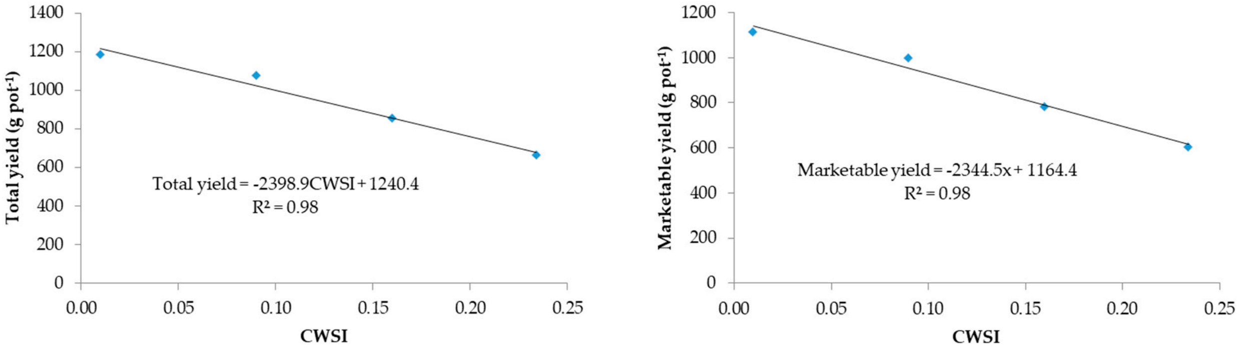
**Figure 2.** The variation of CWSI with time for each treatment.

The CWSI values ranged from −0.2 to a maximum value of 0.16 in $I_{120}$, from −0.09 to 0.22 in $I_{100}$, from 0.02 to 0.28 in $I_{80}$, and from 0.11 to 0.42 in $I_{60}$. The CWSI values for each irrigation level calculated as the average for the entire measurement period were 0.01 in $I_{120}$, 0.09 in $I_{100}$, 0.16 in $I_{80}$, and 0.23 in $I_{60}$. High temperature and low relative humidity values in the high tunnel greenhouse, which was irrigated once a day, increased the plants' irrigation needs. Although evaporative cooling helps increase the indoor environment's relative humidity values, it was challenging to provide the optimum relative humidity values required for the plants during the experiment months. However, it was effective in reducing plant leaf temperatures to some extent.

### *3.5. Relations between CWSI and Yield*

The relationship between yield and CWSI values was primarily linear, within the range of mean CWSI (Figure 3).

Alordzinu et al. [59] stated that at a high soil water deficit, crop water uptakes are reduced, reducing transpiration rates and increasing the crop canopy temperatures, leading to yield reduction and economic loss. As shown in Figure 3, the linear equation total yield = −2398.9 CWSI + 1240.4 and marketable yield = −2344.5 CWSI + 1164.4 can be used to predict the yield potential of tomatoes. Predicting yield response to crop water stress is essential to farmers and researchers for developing strategies and decision-making concerning irrigation management under limited water conditions [16]. Bo et al. [57] reported that if off-season greenhouse peppers are irrigated when the average CWSI lies in the 0.2–0.4 range, the water use efficiency will be at its maximum. Erdem et al. [32] reported that for broccoli an average threshold CWSI value of about 0.51 before irrigation produced the maximum yield. Sezen et al. [27] reported that the CWSI values proved to be a good indicator of plant-to-available water for red pepper and it may be used to predict yield where the CWSI is known. In our study, the equation given above to predict the yield as a function of CWSI can be a useful tool for such goals. Also, this result agrees with many other studies of different crops [26,30,59,60]



(**a**) (**b**)

**Figure 3.** (**a**) Relationship between total yield and CWSI values (**b**) relationship between marketable yield and CWSI values.

## 4. Conclusions

The results of the current study demonstrate that the effects of irrigation water amount and water use are significantly important to obtain higher yields of greenhouse tomatoes under the Central Anatolia climatic conditions in Turkey. Irrigation levels had a significant effect on the total yield of tomatoes. The maximum yield of 1184.8 (g pot$^{-1}$) was obtained from the $I_{120}$ treatment, which had the highest evapotranspiration. Moreover, the results showed that total WUE and marketable WUE values were higher at $I_{100}$ and $I_{80}$ than at the $I_{120}$ irrigation level. However, the lowest irrigation levels ($I_{60}$) resulted in the lowest total yield of tomatoes and quality. Thus, using low irrigation levels for greenhouse tomato production in the region is not recommended. In addition, it is essential to use evaporative cooling methods due to the high temperature and low relative humidity values that occur in the high tunnel greenhouse. Experimental results show that the CWSI could be used to measure crop water status and improve tomato irrigation scheduling. Significant linear relations were found between the tomato yield and CWSI. Predicting the yield response to crop water stress is important in developing strategies and decision-making for farmers, their advisors, and researchers for irrigation management under limited water conditions. The results of this study will help producers optimise water application in protected agriculture and also provide guidelines for other similar regions. Additionally, with developing technology, determining and disseminating CWSI in the greenhouse by remote sensing-based methods and determining irrigation time will be extremely important in reducing efficiency and economic losses while saving time and labour.

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