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Assessment of the Crop Water Stress Index for Green Pepper Cultivation Under Different Irrigation Levels

Sedat Boyacı [1], Joanna Kocięcka [2,*], Barbara Kęsicka [2], Atılgan Atılgan [3] and Daniel Liberacki [2]

1 Department of Biosystems Engineering, Faculty of Agriculture, Kırşehir Ahi Evran University, 40100 Kırşehir, Türkiye; sedat.boyaci@ahievran.edu.tr
2 Department of Land Improvement, Environmental Development and Spatial Management, Poznan University of Life Sciences, 60-649 Poznań, Poland; barbara.kesicka@up.poznan.pl (B.K.); daniel.liberacki@up.poznan.pl (D.L.)
3 Department of Biosystems Engineering, Faculty of Engineering, Alanya Alaaddin Keykubat University, 07425 Alanya, Türkiye; atilgan.atilgan@alanya.edu.tr
* Correspondence: joanna.kociecka@up.poznan.pl

Abstract

The objective of this study was to evaluate the effects of different water levels on yield, morphological, and quality parameters, as well as the crop water stress index (CWSI), for pepper plants under a high tunnel greenhouse in a semi-arid region. For this purpose, the irrigation schedule used in this study includes 120%, 100%, 80%, and 60% (I120, I100, I80, and I60) of evaporation monitored gravimetrically. In this study, increasing irrigation levels (I100 and I120) resulted in increased stem diameter, plant height, fruit number, leaf number, and leaf area values. However, these values decreased as the water level dropped (I60 and I80). At the same time, increased irrigation resulted in improvements in fruit width, length, and weight, as well as a decrease in TSS values. While total yield and marketable yield values increased at the I120 water level, TWUE and MWUE were the highest at the I100 water level. I80 and I120 water levels were statistically in the same group. It was found that the application of I100 water level in the high tunnel greenhouse is the appropriate irrigation level in terms of morphology and quality parameters. However, in places with water scarcity, a moderate water deficit (I80) can be adopted instead of full (I100) or excessive irrigation (I120) in pepper cultivation in terms of water conservation. The experimental results reveal significant correlations between the parameters of green pepper yield and the CWSI. Therefore, a mean CWSI of 0.16 is recommended for irrigation level I100 for higher-quality yields. A mean CWSI of 0.22 is recommended for irrigation level I80 in areas where water is scarce. While increasing the CWSI values decreased the values of crop water consumption, leaf area index, total yield, marketable yield, total water use efficiency, and marketable water use efficiency, decreasing the CWSI increased these values. This study concluded that the CWSI can be effectively utilised in irrigation time planning under semi-arid climate conditions. With the advancement of technology, determining the CWSI using remote sensing-based methods and integrating it into greenhouse automation systems will become increasingly important in determining irrigation times.

Keywords: pepper; irrigation scheduling; deficit irrigation; total and marketable yield; water use efficiency

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1. Introduction

The importance of irrigation water for agricultural production is increasing day by day in regions where rainfall is irregular, dry, or drought is expected. Extreme temperatures and prolonged droughts are gaining strategic importance due to the limitation of the availability of freshwater resources [1]. The recent report compiled by the Copernicus Climate Change Service (C3S) and the World Meteorological Organization (WMO) [2] shows that 2024 reached the highest average temperature for both the world and Europe. The report highlighted the marked climatic contrast between eastern and western Europe, which was reflected in river flows. Therefore, the issue of saving irrigation water has always been in the area of interest of water-related sectors. The reasons for these problems are that farmers do not know how much water, when, and which irrigation method to apply, and they use low-efficiency primitive irrigation methods [3]. Agriculture consumes 70% of total freshwater, and this scarcity is critical in arid and semi-arid regions of the world. The efficiency of irrigation water use can be increased through proper irrigation management. Therefore, effective irrigation water management is necessary in times of water shortage, and the aim is to save water and maximise its efficiency [4–6]. The key issue for crop production in water-scarce regions is to get the most out of a water unit. This can be achieved by improving water use efficiency (WUE) [7].

Greenhouses require irrigation to ensure stable and high-quality yields. The sustainable use of water in protected agriculture areas requires the development of product-specific and water-saving irrigation techniques that do not negatively affect product productivity [8–10]. Inappropriate irrigation practices can lead to wastage of water resources and reduced fruit quality [11,12]. Efficient and cost-effective solutions are being sought to reuse water in agricultural facilities, which will affect the quantity and quality aspect of the water discharged [13,14].

A major cause of declining crop productivity is water stress. Inadequate water supply to the plant during critical growth stages, such as vegetative, flowering, and fruit formation, results in significant yield losses [15,16]. Limited irrigation should be applied during the phenological stages that are the least sensitive to water deficit, avoiding water stress during flowering and fruit set in vegetable crops such as pepper. This is a difficult task considering the long duration of these processes in most pepper varieties [12]. Pepper (*Capsicum annuum* L.) is a high-value crop grown in many parts of the world and is widely used in human nutrition, fresh or processed [7,17]. In addition, it is one of the most important vegetables cultivated under greenhouse conditions in the Mediterranean region [18,19] and in Turkey [20]. Various researchers have reported that a reduction in water application throughout the growth of the pepper has a negative effect on the final total yield. Therefore, sufficient water supply throughout the crop growing cycle is necessary for higher yield [16,21]. Antony and Singandhupe [22] found that the total yield of pepper was less at lower irrigation levels. Kurunc et al. [23] and Ünlükara et al. [24] reported that limited irrigation at different irrigation levels resulted in reduced water consumption, productivity, and vegetative development of pepper plants. Costa and Gianquinto [25] reported that continuous water stress considerably reduced the total fresh weight of the bell pepper fruit.

Irrigation is an essential input in arid and semi-arid climates, and its main purpose is to artificially store adequate water in the root zone of plants [26,27]. Otherwise, the crops will experience water stress and productivity will decrease significantly. In order to provide plants with optimum water supply, the first step is to select the proper method. Then, an irrigation programme should be established that specifies the timing of irrigation and the amount of water to be applied at each irrigation [28]. A good irrigation program depends significantly on a good understanding of irrigation principles and the correct application of these principles [29]. Plant water requirement is the main component in irrigation planning and improving the water use efficiency of cultivated crops [30]. Irrigation planning often depends on measuring meteorological parameters to model or calculate soil water content or evapotranspiration. Since plants respond to both the soil and air environments, irrigation scheduling based on crop water status should be more advantageous [31]. Researchers have worked on many methods to assess water stress in plants. Among these methods, the crop water stress index (CWSI), which is developed by utilising the difference between the crop surface temperature and the air temperature and the vapour pressure deficit, has been reported to be effectively applied in irrigation scheduling [32–34]. Infrared thermometers used to measure canopy temperatures for irrigation design have been successfully used in arid environments [35].

The CWSI is a complex tool to effectively monitor the degree of crop water stress and provide guidance for timely irrigation [36]. The CWSI is a simple and rapid method for assessing water stress, as reported by [37]. To assess the application of the CWSI in irrigation scheduling for several crops in different locations, Duran et al. [38] conducted research on chili pepper, Aladenola, and Madramootoo [39] bell pepper. Research was conducted on red pepper by Sezen et al. [34] and green pepper by Bo et al. [36]. Moreover, based on the existing findings of many researchers, it was concluded that the CWSI can be used reliably as a good indicator of irrigation timing and can be employed as a criterion to improve water conservation, yield estimation, and management of irrigation programs [34,38,40–42]. It is necessary to optimise water use, especially in semi-arid regions, due to the restricted availability of water resources. Therefore, accurately measuring crop water use in irrigated agriculture is becoming increasingly important [43]. In order to determine the applicability of the different methods and models proposed for crop irrigation, they should be researched and improved in different regions and crop types [32]. It has been stated by researchers that the CWSI has been used successfully in irrigation planning in open field conditions [34–39]. However, it seems that studies on the use of the CWSI in irrigation planning in greenhouse pepper cultivation are limited. Especially in semi-arid regions where water resources are limited, such as the Central Anatolian region of Turkey, the application and improvement of the more appropriate irrigation methods and programmes are important for the conservation of water resources in order to maximise the benefits from unit water use.

Research on the effect of the CWSI on bell pepper yield in Turkey remains under-researched. The relationship between the CWSI and bell pepper yield has not been quantified, in contrast to tomato studies, in which a significant correlation was found [8]. Current research does not adequately address how environmental factors such as temperature, humidity and soil moisture interact with the CWSI to affect bell pepper yield [44]. Therefore, one of this study's objectives is to determine the effects of different irrigation levels on morphological and quality parameters, water use efficiency, and the yield response factor of green pepper grown in high tunnel greenhouses. In addition, by recommending the application of the CWSI to determine relationships between water consumption, leaf area index, total and marketable yield, and total and marketable water use efficiency parameters, this study will help growers in irrigation planning.

2. Materials and Methods

2.1. Experimental Area Characteristics

This experiment was conducted in a polyethylene-covered high tunnel greenhouse with a fan pad system, located at the University of Kırşehir Ahi Evran (39°08′02″ N, 34°07′08″ E, 1082 m above sea level), Kırşehir, Türkiye. Kırşehir presents a continental semi-arid climate, with an average annual rainfall of 382 mm and a wide dry period during summer [45]. Temperature and relative humidity data were recorded by a data logger

(Onset HOBO U12), installed inside the greenhouse for the May to August growing season. The long-term mean monthly (1930–2022) and the 2022 growing season inside and outside climatic data of the experimental months are shown in Figure 1.

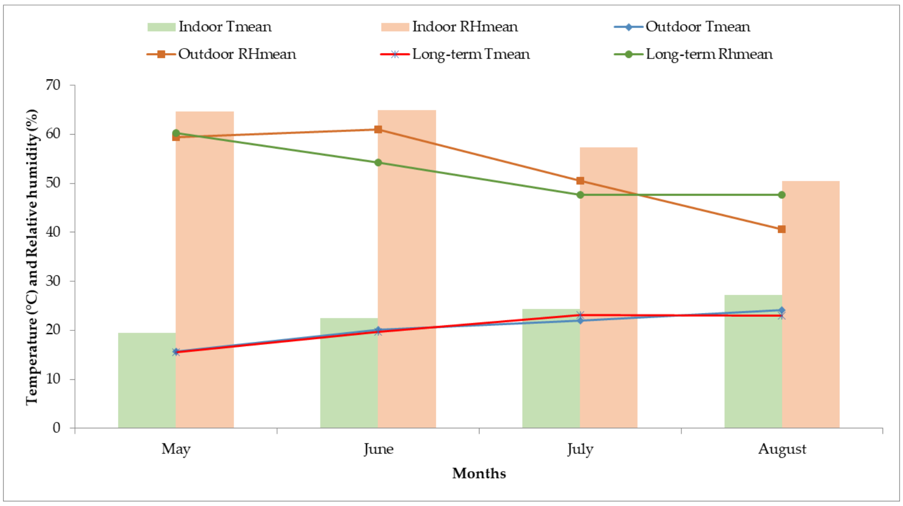

Figure 1. Climate parameters of the experimental area.

It was found that the mean outdoor and long-term temperatures were higher than the long-term climate data in the months when this study was conducted (Figure 1). The average temperature, relative humidity, and VPD measured with natural ventilation in the high tunnel greenhouse in Kırşehir province were determined as 36.1 °C, 27.9%, and 4.5 kPa, respectively [46,47]. A fan and pad system was used to reduce indoor temperatures in the high tunnel greenhouses. Thus, the indoor temperature decreased and the relative humidity increased slightly. The increasing relative humidity values decreased the VPD values.

In this study, each pot was filled with 4.1 L (20 × 18 cm) of air-dried soil and the water used for irrigation was taken from the tap. The class of irrigation water used in this study was determined by USSL [48] as C2-S1. The soil's physical properties and the irrigation water analysis are given in Tables 1 and 2.

Table 1. Physical properties of the experimental soil.

pH	EC ($dS\ m^{-1}$)	Particle Size Distribution (%)			Texture Class	Bulk Density ($g\ cm^{-3}$)	Field Capacity (%)	Wilting Point (%)
		Sand	Clay	Silt				
7.38	0.14	71.0	9.0	20.0	Sandy loam	1.29	20.5%	5.1%

Table 2. Analysis of the irrigation water.

pH	EC, $dS\ m^{-1}$	Cations, $meq\ L^{-1}$				Anions, $meq\ L^{-1}$				Sodium Adsorption Ratio (SAR)
		Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	$CO_3{}^{2-}$	$HCO_3{}^{-}$	Cl^{-}	$SO_4{}^{2-}$	
7.68	0.65	2.9	1.23	0.06	1.6	0	4.9	0.3	0.4	1.11

2.2. *Experimental Design, Irrigation Treatments, and Crop Management*

In this study, pepper seedlings were planted in pots on 10 May 2022 and equal irrigation was applied. Irrigation applications were started 1 week later. The pots were brought to the pot capacity before starting the experiment and applying the treatments. The experiment was terminated on 15 August 2022.

The irrigation water given to the pots was monitored gravimetrically daily during the experiment. The experiment design was arranged according to the randomised blocks trial design in random plots with three repetitions in 60 pots. The experimental applications consisted of four different irrigation levels and the irrigation level amounts were 120%, 100% (full irrigation), 80%, and 60% (I120, I100, I80, and I60, respectively) of the water depleted from the pot capacity.

The pepper plants (*C. annuum*, cv. Mostar F1) were transplanted on May 10 and the last harvest was on August 15. During the experiment, the total time from planting the seedlings in the high tunnel greenhouse to the last harvest was 98 days. In the experiment, planting was carried out on 10 May, the flowering was on 29 May, the fruit setting was on 8 June, the first harvest was on 29 June, and the last harvest was on 15 August.

The amount of fertiliser applied to each pot was calculated by considering 135 kg ha^{-1} for N, 37.5 kg ha^{-1} for P, and 75 kg ha^{-1} for K [18,24]. All P as diammonium phosphate and K as potassium sulphate were applied as half of the N in each treatment before transplanting, while the other half of the N was applied 20 days from the beginning of the experiments. Part of the N requirement came from DAP and the rest from ammonium nitrate fertiliser [24].

2.3. Measurements and Observations

In the presented study, the quantity of irrigation water to be applied to the pots was weighed and the soil moisture content was monitored gravimetrically, and irrigation was carried out daily. Accordingly, the quantity of irrigation water to be applied for each irrigation level was determined using Equations (1) and (2) [23,24].

$$\mathrm{IRW} = (\mathrm{IRW_{PFC}} - \mathrm{IRW_P}) \times \mathrm{C_{IR}} \quad (1)$$

$$\mathrm{ET} = (\mathrm{IRW_n} - \mathrm{IRW_{n+1}})(\mathrm{IRW} - \mathrm{R}) \quad (2)$$

In these equations, IRW = irrigation water amount (L), IRW_{PFC} = pot weight (kg) at the field capacity, IR_P = pot weight just before irrigation (kg), C_{IR} = irrigation level coefficient, ET = crop water consumption (L pot^{-1}), IRW_n and IRW_{n+1} = pot weights before the nth and (n + 1)th irrigation (kg), and R = applied water amounts (L).

In this study, total and marketable water use efficiency was determined with Equations (3) and (4) [49].

$$\mathrm{TWUE} = (\mathrm{YT}/\mathrm{ET}) \quad (3)$$

$$\mathrm{MWUE} = (\mathrm{YM}/\mathrm{ET}) \quad (4)$$

In these equations, TWUE and MWUE are the total and marketable water use efficiency (g L^{-1}) and YT and YM are the total and marketable yield (g pot^{-1}).

The relationships between ET and harvested yield were determined with Equation (5) [18].

$$\left(1 - \frac{Y_a}{Y_m}\right) = k_y\left(\frac{ET_a}{ET_m}\right) \quad (5)$$

In this equation, Y_a is the actual harvested yield (g pot^{-1}), Y_m is the maximum harvested yield (g pot^{-1}), ET_a is the actual evapotranspiration (L pot^{-1}), ET_m is the maximum evapotranspiration (L pot^{-1}), and k_y is the yield response factor.

The experiment's canopy temperature (Tc) was measured using a hand-held infrared thermometer (Santech ST-550, İstanbul, Türkiye). Canopy temperatures were measured from different directions (east, west, north, and south) in each plot between 12:00 and 14:00 under clear skies when the sun was directly on the plants, and the averages were taken to determine the canopy temperature. The crop water stress index (CWSI) was calculated based on Equation (6) [50]. Lower limits $(Tc - Ta)_{LL}$ versus the vapour pressure deficit relationship was determined using data collected only from the unstressed treatments and upper limits $(Tc - Ta)_{UL}$ were determined from fully stressed plants. In order to obtain a condition where evaporation does not occur, a bunch of pepper plants, cut with their roots, were hung in the greenhouse to dry and used in the measurements.

$$CWSI = \frac{(T_c - T_a) - (T_c - T_a)_{LL}}{(T_c - T_a)_{UL} - (T_c - T_a)_{LL}} \quad (6)$$

In this equation, T_c = plant canopy temperature (°C), T_a = air temperature in the high tunnel greenhouse (°C), and $(T_c - T_a)_{UL}$ and $(T_c - T_a)_{LL}$ = upper and lower baselines of the plant (°C).

2.4. Morphologic and Quality Measurements and Analyses of the Plants and Fruits

During the crop cycle, the first harvest began 42 days after planting and extended to 98 days after planting. Harvests were made when the fruits reached a certain size and colour. Accordingly, yield values per plant (g pot^{-1}) were determined by summing the yield values obtained in each picking period. Peppers were classified into two classes. Peppers that were firm, crisp, smooth, and free from various injuries were considered marketable, while peppers that were too small, misshapen and cracked were considered unmarketable [51]. In the experiment, morphological and quality measurements of the harvested fruits were carried out.

Morphological characteristics were measured at the end of the harvest by taking 3 randomly selected plants from each replicate. In the measurements, stem diameter was measured from 3 different points of the plant with a digital calliper (mm). Plant height was measured from the root collar to the growth tip with a meter (cm). The number of leaves was counted on each plant (by counting). Root and stem fresh and dry weights were weighed with an electronic scale (g). The plants were dried in an oven set at 65 °C.

For the quality analyses, a total of 15 fully ripe fruits were harvested, 5 from each replicate, and a mixture of these fruits was used in the analyses. The following quality characteristics were also measured and analysed: pepper width and length were measured by digital calliper, weight per fruit (gr) (with an electronic scale), pH (with Hanna, HI 9321, Woonsocket, RI, USA), firmness (kg m^{-2}), titratable acid (TA) (with the titration method 0.1 N NaOH up to an endpoint of pH 8.1), and total soluble solid (TSS) (°Brix) (with Hanna HI 96801, Woonsocket, RI, USA).

2.5. Statistical Analysis

In the study conducted with 3 replications according to the randomised plots experimental design, the SPSS 15.0 statistical program was used to evaluate the effects of irrigation levels on the properties of green pepper. The effects of irrigation levels on the morphological, quality, and yield parameters of green pepper, as well as other parameters, were evaluated by variance analysis (ANOVA). The means of the characteristics were compared using Duncan's multiple range test when the differences between the means were statistically significant ($p < 0.05$).

3. Results and Discussion

3.1. Determination of the Morphological Characters of the Pepper

Since pepper is sensitive to both soil water deficits and surpluses, water management strategies are commonly aimed at supplying the evapotranspiration demands of the crop [52]. The relationships between different irrigation water levels (I60, I80, I100, and I120) and morphological characteristics of the pepper plant are given in Figure 2.

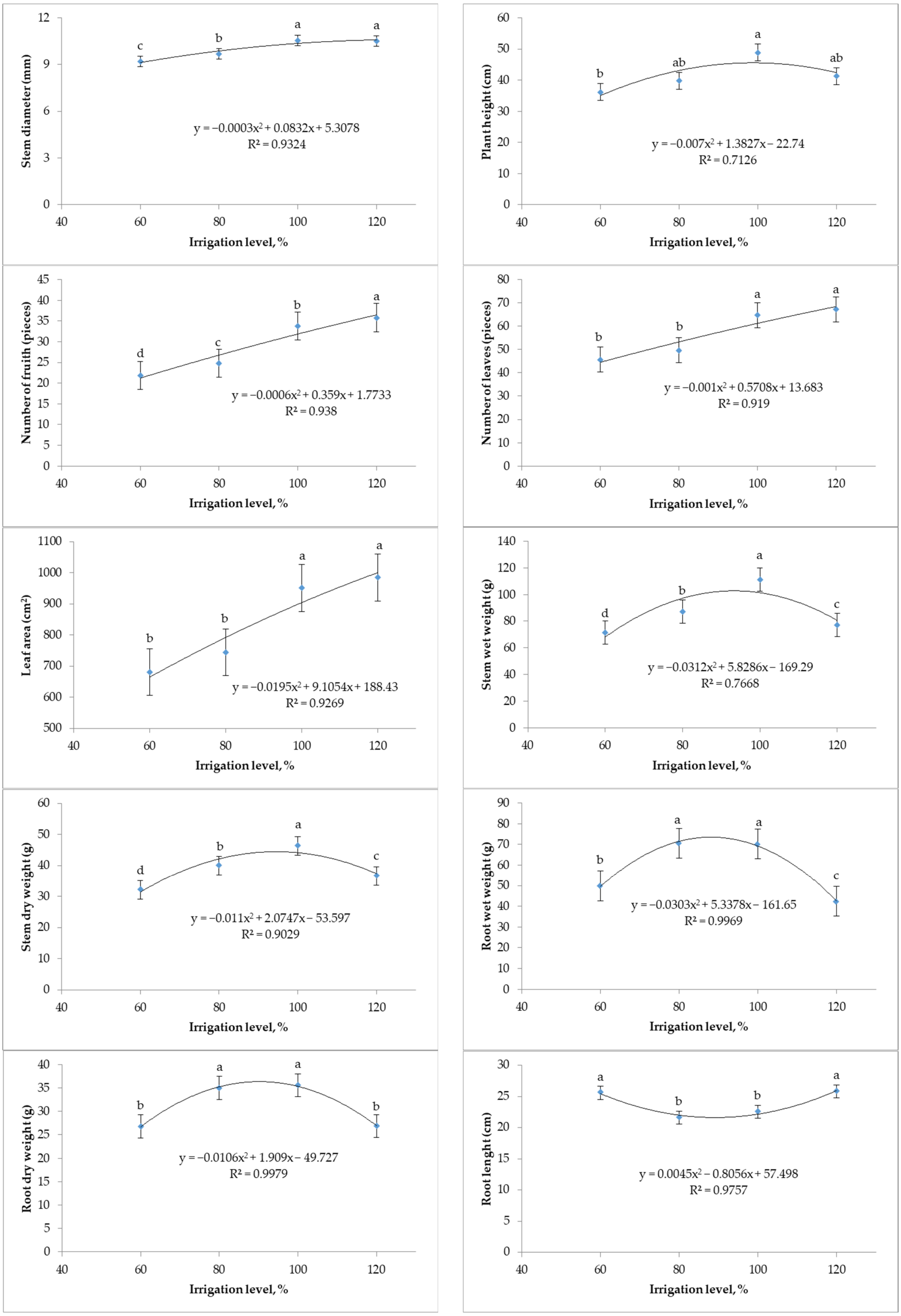

Figure 2. Morphological characteristics of green pepper under different irrigation levels. The error bars represent mean ± SE and different letters indicate significant differences between the treatments.

In this study, increases and decreases in irrigation levels caused increases and decreases in the morphological characteristics of pepper, resulting in second-degree polynomial equations. These results are consistent with the studies of Yamin Kabir et al. [53]. Irrigation treatments showed that the highest stem diameter was achieved for the I100 treatment (10.6 mm), but the difference between the I120 and I100 treatments was in the same group ($p > 0.05$). The lowest value of stem diameter was obtained for the I60 treatment (9.2 mm). According to the irrigation levels, the highest plant height was measured in the I100 treatment (48.9 cm) and the lowest in the I60 treatment (36.1 cm). The effect of irrigation level treatments on the stem diameter and plant height values was statistically significant ($p < 0.01$). Aladenola and Madramootoo [39] and Yamin Kabir et al. [53] stated that plant height and stem diameter increased with increasing irrigation levels. Similarly, in this study, it is shown in Figure 2 that stem diameter values increase with increasing irrigation levels.

The highest number of fruits was obtained in the I120 treatment (35.8 cm) and the lowest was obtained in the I60 (21.9 cm) treatment according to irrigation levels. The effect of different irrigation level treatments on the number of fruit values was statistically significant ($p < 0.01$). Hsiao [54] reported that water stress often reduces the number of fruits. In our study, limited water application led to a decrease in the number of fruits harvested. Researchers also stated that these stresses have similar effects on pepper fruits under different water deficit strategies [21,24]. The highest stem wet and dry weight was achieved in the I100 treatment in the experiment, according to different irrigation levels. Similarly, the highest root wet and dry weight was obtained in the I100 treatments. The lowest value of these parameters was measured at I60 irrigation levels. When the measured plant root length values were examined, the I60 and I120 treatments were statistically in the same group, while the I80 and I100 treatments were in the same group. The effects of irrigation level treatments on stem wet and dry weights, root wet and dry weights, and root length values were statistically significant ($p < 0.01$). According to the results of our study, it was found that the insufficient irrigation level (60%) applied to pepper plants grown under high tunnel greenhouse harmed the development of pepper. Yamin Kabir et al. [53] and Ünlükara et al. [24] found that the highest wet and dry matter amount for different irrigation levels was in the full irrigation application (100%). Similarly, this study determined that the wet and dry weights of the stem and roots increased at the I100 irrigation level. The increase in root length in the I60 treatments was due to water deficit, and in the I120 application, it was due to excess water applied.

Hsiao [54] reported that leaf growth is sensitive to water stress and that mild water stress slows leaf growth and results in less photosynthesis in crop canopy-deficient plants, decreasing biomass accumulation over time. The highest leaf number and leaf area index were obtained among the irrigation levels at the I120 level. The effects of irrigation level treatments on the leaf number and leaf area index values were statistically significant ($p < 0.01$). Sezen et al. [34] and Yıldırım [55] reported that leaf area values in pepper increased as the irrigation water level increased. Moreno et al. [56] determined the leaf area indexes for pepper plants according to four different irrigation water conditions (125%, 100%, 75%, and 50%); the leaf area index was the lowest in the limited water application and the highest in the 100% irrigation application. Yamin Kabir et al. [53] found that increased irrigation enhanced the vegetative growth characteristics of pepper. In our study, similarly, it was determined that leaf area increased with increasing irrigation levels.

3.2. Determination of the Quality Parameters of the Pepper

At present, there is an increasing demand for high-quality agricultural products [57,58]. For the pepper plant, sufficient irrigation water should be given to the plant during the growing season to achieve the best fruit growth and high-quality fruit yield from the crop [16,53]. The relationships between different irrigation water levels (I60, I80, I100, and I120) and quality parameters of the green pepper plant are given in Figure 3.

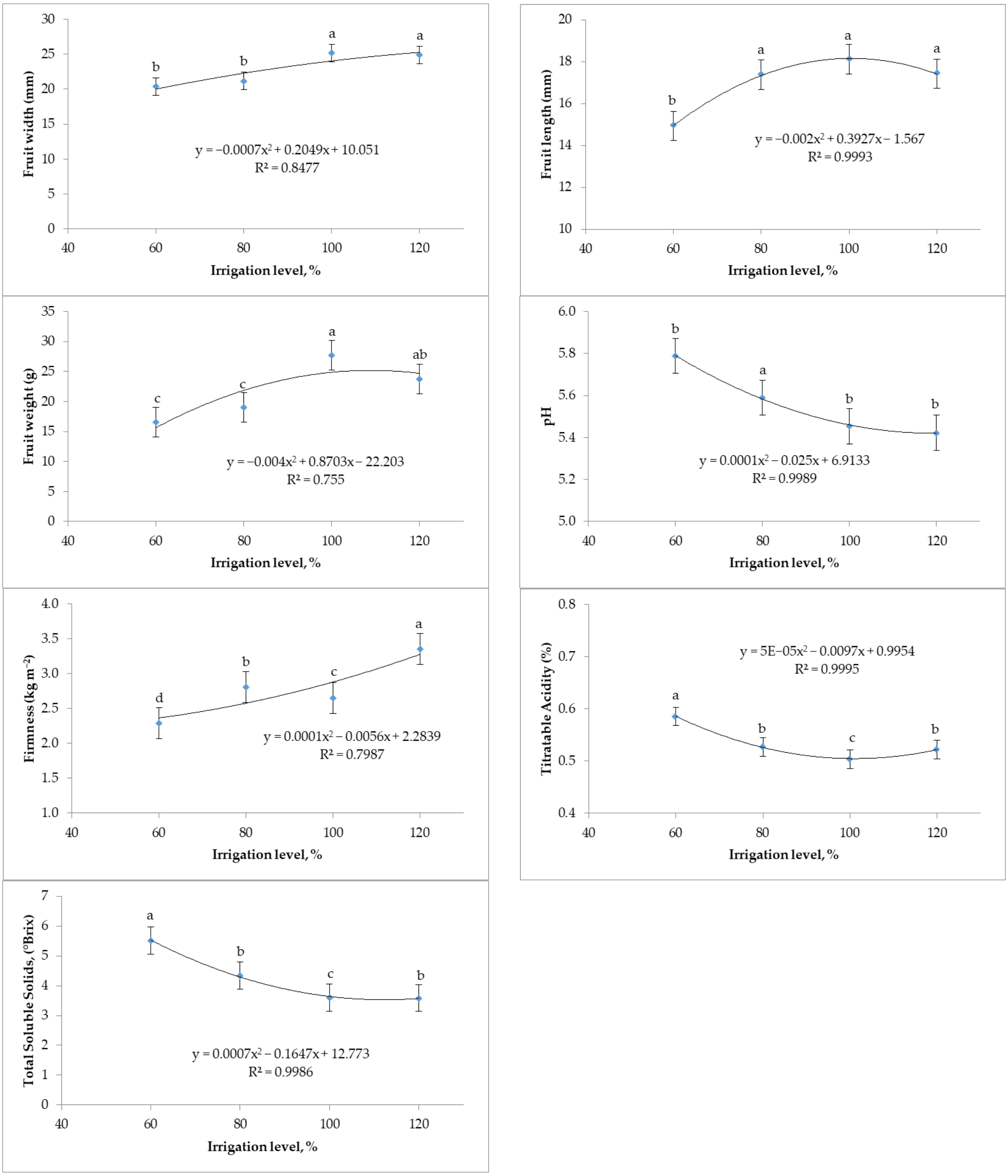

Figure 3. Quality parameters of the pepper at different irrigation regimes. The error bars represent mean ± SE and different letters indicate significant differences between treatments.

In this study, fruit width, length, and weight increased quadratically with increasing irrigation levels. Regarding parameters, I100 and I120 were the highest and in the same group. The I60 irrigation treatment was the lowest. Accordingly, it was found that both over-irrigation and deficit irrigation had an adverse effect on the weight of the fruit. In this study, the effects of the irrigation level treatments on the values of fruit width, fruit length, and fruit weight were statistically significant ($p < 0.01$). Irrigation levels considerably affect sweet peppers' quality [59]. This study determined that increasing irrigation water levels contributed to the increase in fruit quality parameters. These results showed similar characteristics to the researchers' relationships between irrigation levels and fruit width, fruit length, and fruit weight [39,53,60,61].

When the firmness values of pepper fruits were examined, the highest firmness value was measured at the I120 irrigation level, while the lowest was measured at the I60 irrigation level. While the fruit flesh thickness value was measured as 3.4 mm in the I120 treatment, it was measured as 2.3 mm in the I60 treatment. The effect of the irrigation level treatments on the firmness values was statistically significant ($p < 0.01$). Batu [62] stated that fruit firmness is an important harvesting criterion against mechanical damage. The results obtained in this study showed that a lack of water reduces the firmness of the fruit's flesh and that increasing the irrigation level improves the hardness values of the pepper.

Previous studies show that peppers grow and yield best in fertile, well-structured, warm soils with a pH of 5.5–6.5. In soils with a pH lower than 5.5, there may be problems with the availability of certain nutrients, especially P, K, Ca, B, and Mo [63]. The highest pH value was obtained at the I_{60} treatment (pH: 5.8); the I100 and I120 treatments were statically the same group ($p > 0.05$). It was found that the effect of the irrigation level treatments on the pH values was statistically significant ($p < 0.01$).

TSS values increased at decreasing irrigation levels (I60) and decreased at increasing irrigation levels (I100 and I120). Moreover, I100 and I120 were the highest in the statistically same group. The effect of the irrigation level treatments on the TSS values was statistically significant ($p < 0.01$). Demirel et al. [64] reported that TSS values increased with decreasing irrigation at four different irrigation levels (0%, 33%, 66%, and 100%). Also, Abdelkhalik et al. [6] reported that TSS increased with the decrease in irrigation dose (100, 75, and 50%). Similarly, Bozkut Çolak et al. [65] reported that TSS and fruit size of pepper fruits are important parameters to evaluate fruit quality and that higher TSS values were obtained under 50% water restriction irrigation regimes. In this study, TSS values increased with the decrease in irrigation level. The results obtained in this study are similar to previous studies in this respect.

Titiratable acidity values increased at I60 and decreased at the I100 irrigation level. The effect of the irrigation level treatments on the TA values was statistically significant ($p < 0.01$). In the study conducted by Turhan et al. [66], it was reported that the titratable acid values of pepper fruits increased with increasing water stress. The findings of this research are similar to those of previous studies in this respect. In this study, increases and decreases in irrigation levels caused increases and decreases in the quality parameters of pepper, resulting in second-degree polynomial equations. These results are consistent with the studies of Yamin Kabir et al. [53] and Bozkut Çolak et al. [67].

3.3. Determination of the Water Consumption, Crop Yield, and Water Use Efficiency

Although decreasing irrigation quantity affects the morphological and quality parameters of the pepper plant, determining WUE may become more important for cultivation in regions where water is limited, in order to provide information on the pepper yield obtained per unit of Et. The effects of the different irrigation levels on the yield and the efficiency of water use in this study are shown in Table 3.

Table 3. The effects of the different irrigation levels on the yield and water use efficiency.

Parameters	I_{60}	I_{80}	I_{100}	I_{120}	Imean
ET (L)	14.9 d	18.8 c	21.0 b	24.8 a	19.8
TY (g pot^{-1})	272.4 c	386.1 b	516.2 a	539.5 a	428.5
MY (g pot^{-1})	227.9 c	347.1 b	484.0 a	504.1 a	390.8
TWUE (g L^{-1})	18.2 c	20.6 b c	24.7 a	21.8 b	21.3
MWUE (g L^{-1})	15.3 c	18.6 b	23.1 a	20.3 b	19.3

ET—crop water consumption, TY—total yield, MY—marketable yield, TWUE—total water use efficiency, and MWUE—marketable water use efficiency. a–d: Means followed by the different letters within the same rows are significantly different from each other ($p < 0.05$) according to Duncan's multiple range test.

Due to the deficiency of water application at different irrigation levels, evapotranspiration decreased, thus the highest ET was obtained from the I120 treatment and the lowest from the I60 treatment. For I100, I80, and I60, ET reductions compared to I120 were 14.8%, 24.8%, and 39.6%, respectively.

When the total yield values in our study are examined, the highest TY was obtained from the I120 treatment (539.5 g pot^{-1}) where the plants were over-irrigated, while the lowest TY (272.4 g pot^{-1}) was obtained from the I60 irrigation level. According to the I120 irrigation level, TY reductions in the I100, I80, and I60 treatments were 14.8%, 28.4%, and 49.5%, respectively. However, the yield increase in I100 was 34% compared to I80, while the yield increase in I120 was 4% compared to I100. Accordingly, this study determined that the yield increase obtained with over-irrigation decreased after I100. When marketable yield values are considered, the highest MY was obtained from the over-irrigated I120 treatment (504.1 g pot^{-1}) and the lowest MY (227.9 g pot^{-1}) was obtained from the I60 irrigation level. Accordingly, in peppers harvested according to the water level treatments, the yield at the I120 irrigation level was 4.0%, 31.1%, and 54.8%, respectively, compared to the I100, I80, and I60 irrigation levels. In addition, according to total yield, the MY decrease in I60 was 16.3%, the MY decrease in I80 was 10.1%, the MY decrease in I100 was 6.2%, and the MY decrease in I120 was 6.6%. Accordingly, the lowest decrease was in the I100 irrigation level.

Among the irrigation levels, the highest TWUE and MWUE values were found at the I100 irrigation level (24.7 g L^{-1} and 23.1 g L^{-1}). The lowest TWUE and MWUE values were found at the I60 irrigation level (18.2 g L^{-1} and 15.3 g L^{-1}) where water restriction was highest. The effect of irrigation level treatments on the ET, TY, MY, TWUE, and MWUE values was statistically significant ($p < 0.01$).

In our study, similar to the study conducted by Ayas [61], the pepper plant's water use (ET) increased with the amount of water. In addition, Ünlükara et al. [24] found in an irrigation regime experiment (IR1 = 143%, IR2 = 100%, IR3 = 75%, and IR4 = 50%) that the highest pepper yields were obtained from the 100% (502.4 g pot^{-1}) and 143% (471.5 g pot^{-1}) irrigation levels, while the lowest yield (229 g pot^{-1}) was obtained for the 50% irrigation level. Compared to 100% irrigation, the yield reductions for the 75% and 50% irrigation levels were 18.9% and 54.4%, respectively. And the water stress caused yield loss because as the soil becomes drier, the soil water is strongly held by the soil matrix and the concentration of soil water increases. In the study conducted by Aladenola and Madramootoo [39], in the first year, the response of pepper yield to applied water was found to be 23% higher in marketable yield at 120% Etc than at 100% Etc, while total yield at 120% Etc was 4% higher than at 100% Etc. In the second year, it was reported that total and marketable yields at 120% Etc and 100% Etc were not significantly different, but both were significantly higher than 40% Etc. Yamin Kabir et al. [53] reported that irrigation levels between 67% and 100% Etc are acceptable to obtain adequate yields of bell pepper fruit. Mardani et al. [68] found that for regions with restricted water resources, a

20% reduction in water application compared to 100% Etc is appropriate for bell pepper production. Moreover, increasing the irrigation deficit resulted in a decrease in WUE. The highest WUE values were found in the 100% irrigation and deficit irrigation level DI80 treatments, while the lowest WUE values were found in the DI60 and DI40 irrigation levels. The study conducted by Díaz-Pèrez and Hook [69] found that irrigation level at 130% Etc reduced marketable yield by 24% compared to 100% Etc and that over-irrigation harmed yield. Abdelkhalik et al. [6] found that deficit irrigation reduces pepper yield; therefore, in places where water is easily available, it is more appropriate to apply full irrigation (100%) as it leads to higher gross income. Sezen et al. [70] reported that full irrigation should be applied for higher fruit yield in pepper. At the same time, researchers reported that moderate deficit irrigation provides an acceptable strategy for higher fruit yield in the case of water scarcity [71–75]. Yao et al. [76] reported that accurately determining Etc and its components is crucial to achieving efficient irrigation scheduling and improving water use efficiency. Ozbahce and Tari [77] stated that irrigation scheduling can improve water use efficiency. This study obtained the highest total and marketable yields at I100 and I120 irrigation levels. However, when total WUE and marketable WUE are taken into account, the I80 irrigation level can be an alternative irrigation level for pepper irrigation since it provides positive results in providing water and productivity balance in places where water is scarce.

3.4. Determination of the Yield Response Factor of Pepper

Optimal irrigation management is essential to maximise pepper production and profitability. Therefore, comprehensive information on the crop water use of pepper grown in the horticultural system is needed [78]. In this study, the yield response factor (ky), which is an important parameter for establishing a correct irrigation plan and evaluating the effect of water deficit on yield, was calculated to evaluate the tolerance of green pepper to water stress. The relationship between relative yield reduction and relative evapotranspiration deficit in pepper is shown in Figure 4.

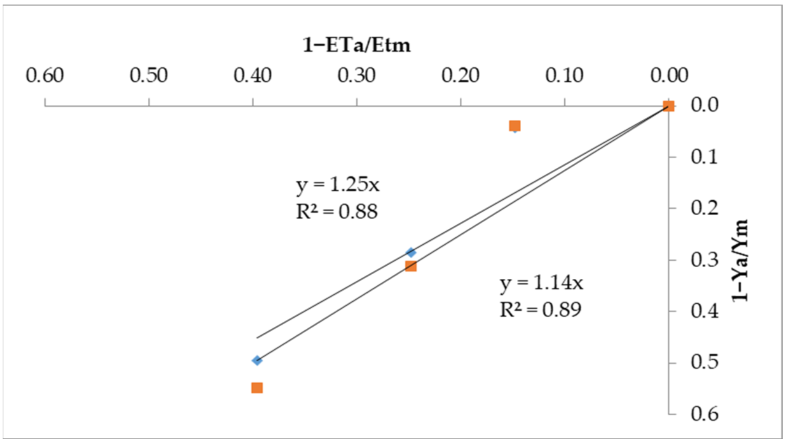

Figure 4. Determination of the yield response factor for green pepper.

The Ky value of the pepper TY was obtained in this study at 1.14 and the Ky value of the pepper MY was 1.25. Doorenbos and Kassam [18] stated that under limited water conditions, evenly distributed over the entire growing season, the crop with (ky > 1) would lose more yield than the crop with (ky < 1). According to this determined value of ky (1.14–1.25), which is bigger than 1.00, this result shows that pepper is responsive to water. The Ky value reported by Ünlükara et al. [24] was 1.66, Ayas [61] reported values of 1.29 in the first year and 1.24 in the second year, and Yılmaz and Kuşçu [60] reported a value of 1.12. The yield response factor obtained in this study was found among the results obtained by the researchers. Gençoğlan et al. [79] stated that ky is an important parameter for irrigation planning as it allows quantitative determination of water use regarding crop yield and production. Similar to previous studies, the ky value obtained in this study can be used to optimise the water use efficiency of pepper plants cultivated in a high tunnel greenhouse in semi-arid climate conditions.

3.5. Determination of the Upper and Lower Limit Equations and Crop Water Stress Index

The key to constructing the CWSI model is to determine the model's upper and lower limit baselines [34,36,80]. The lower baseline in the graph is calculated based on the energy balance. The upper baseline is determined by considering the measured Tc−Ta and the calculated VPD in the treatment where the evaporation was minimal during the experiment. The basic graph used in calculating the CWSI for pepper plants is given in Figure 5.

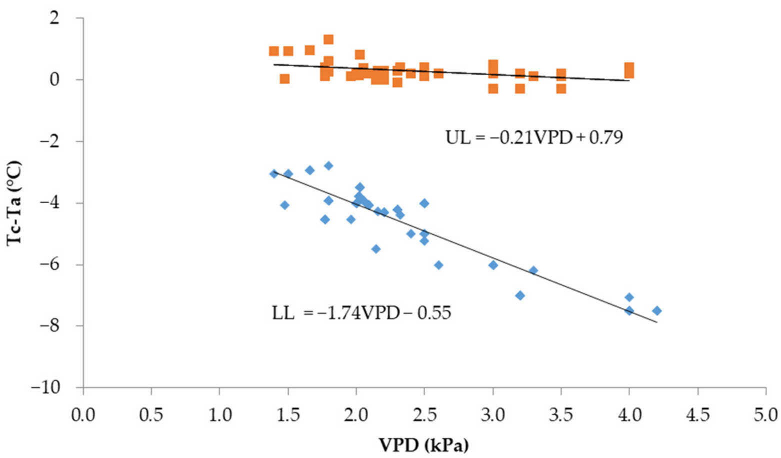

Figure 5. The lower and upper limits for green pepper crops for determining the CWSI.

This study found upper and lower limit equations as $T_c - T_a = -0.21$ VPD + 0.79 and $T_c - T_a = -1.74$ VPD − 0.55. For the lower limit in pepper crops, researchers reported the following relationship: Yıldırım [55] $T_c - T_a = -1.6153$ VPD − 1.6314 and Bo et al. [36] $T_c - T_a = -6.4217$ VPD − 0.1334. In the high tunnel greenhouse, the combination of high temperatures and low relative humidity increased VPD values. In this case, plants slow down photosynthesis by closing their stomata to minimise water loss and prevent critical water tension in the xylem, causing stress [24]. The results of this study align with previous findings by researchers, and it was observed that T_a, VPD, and irrigation practices measured during the experiment in the high tunnel greenhouse affected the $T_c - T_a$ difference. In addition, the fan pad cooling system used to reduce high temperatures in the greenhouse in our study contributed to reducing VPD values by increasing the relative humidity value while reducing indoor temperatures.

The variation in the CWSI at different irrigation levels during the growing season is shown in Figure 6.

This study shows that the CWSI values at different irrigation levels were ranked according to available water in the soil profiles. In the different irrigation level treatments, the CWSI values ranged between −0.27 and 0.61 in the growing season (Figure 6). In this study, total and marketable yield in the I100 and I120 treatments were statistically in the same group, while I100 was the best irrigation treatment in terms of total and marketable water use efficiency (Table 3). In order to obtain a high yield in pepper and to provide savings in places where water is limited, an average CWSI value of 0.1 can be used for the I100 treatment in irrigation planning and, as an alternative to the I100 treatment, a CWSI of 0.21 can be used for the I80 treatment. Researchers have suggested that the

CWSI values for high yields of pepper should be kept around 0.15 for full irrigation in greenhouses by Yıldırım [55], 0.09 for maximum pepper yields in greenhouses by Aladenola and Madramootoo [39], and around 0.3 to 0.65 for the limit value and 0.26 for drip irrigation and 0.38 for furrow irrigation for red pepper in Mediterranean climate conditions by Sezen et al. [34]. When a pepper variety is grown, greenhouse climate and seasonal factors are considered, and the results obtained in this study are similar to those of previous researchers. Moreover, Mashonjowa et al. [80] stated that in a greenhouse study, the VPD change in the greenhouse increased from morning to noon hours and decreased from noon to evening hours. Accordingly, in this study, depending on the increasing temperature values during the day, giving the water required by the plant with more than one irrigation during the day instead of a single irrigation will reduce plant stress.

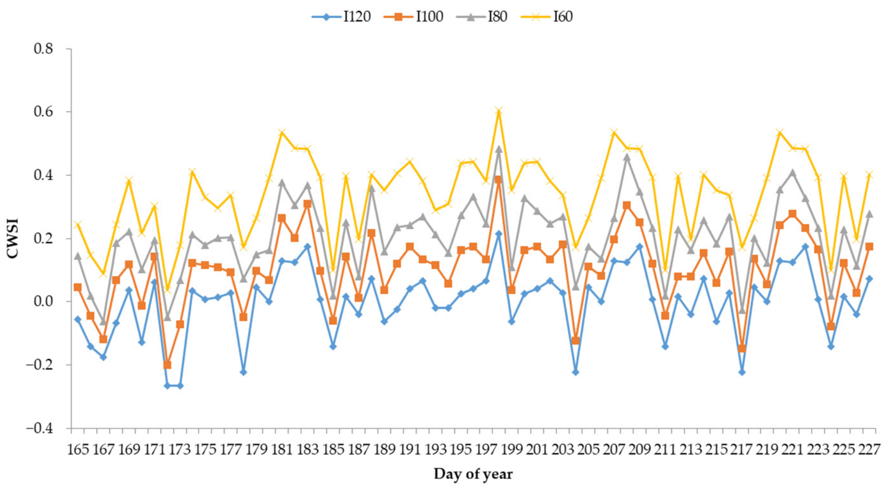

Figure 6. The variation in the CWSI according to different irrigation levels during the growing season.

3.6. Determination of the Relations Between the CWSI and Some Plant Parameters

The relationship between the CWSI and leaf area index, as well as total and marketable yield values, is given in Figure 7.

In this study, increasing irrigation levels decreased the CWSI values, and the relationship between the CWSI and ET was explained using a second-order polynomial equation. Similarly, the relationship between the CWSI and ET Bozkurt Çolak et al. [65] reported that 100% irrigation level (I100) resulted in the lowest CWSI values, and 50% irrigation level (I50 and PRD50 treatment) resulted in the highest CWSI values in the experimental years and, in general, as the irrigation water applied increased, the CWSI values decreased. The leaf area index (LAI) is an important parameter to characterise photosynthesis and can reflect the effect of the CWSI values of greenhouse-grown peppers on photosynthetic physiology [81]. In our study, the relationship between the CWSI and LAI indicated that the LAI values increased with increasing irrigation water quantity, and thus decreased with increasing CWSI values, resulting in a decrease in pepper yield. The pepper plant is considered sensitive to water stress, which can lead to a large reduction in yield [82]. In the present study, the reduction in the amount of irrigation water applied to the pepper plant caused the plant's transpiration rate to decrease. As a result, the plant's canopy temperature increased, resulting in losses in yield and growth. Our findings were similar to those of other researchers [34,39,53]. The decline in the LAI of green pepper due to the increase in leaf surface temperature and transpiration decreased in a similar pattern to the total yield, marketable yield, total water use efficiency, and marketable water use efficiency values [34,80]. In this study, second-degree polynomial equations were obtained between the CWSI values and ET, LAI, total–marketable yield, and total–marketable WUE because the yield values increasing up to I100 decreased relatively at I120. In other words, the excess irrigation water applied did not increase the yield linearly by negatively affecting the plant yield. This situation caused the formation of quadratic equations. The strong relationships between the CWSI values and ET, leaf area index, TY, MY, TWUE, and MWUE indicate its potential suitability for irrigation timing. These findings align with several previous studies on pepper and other crops [34,39].

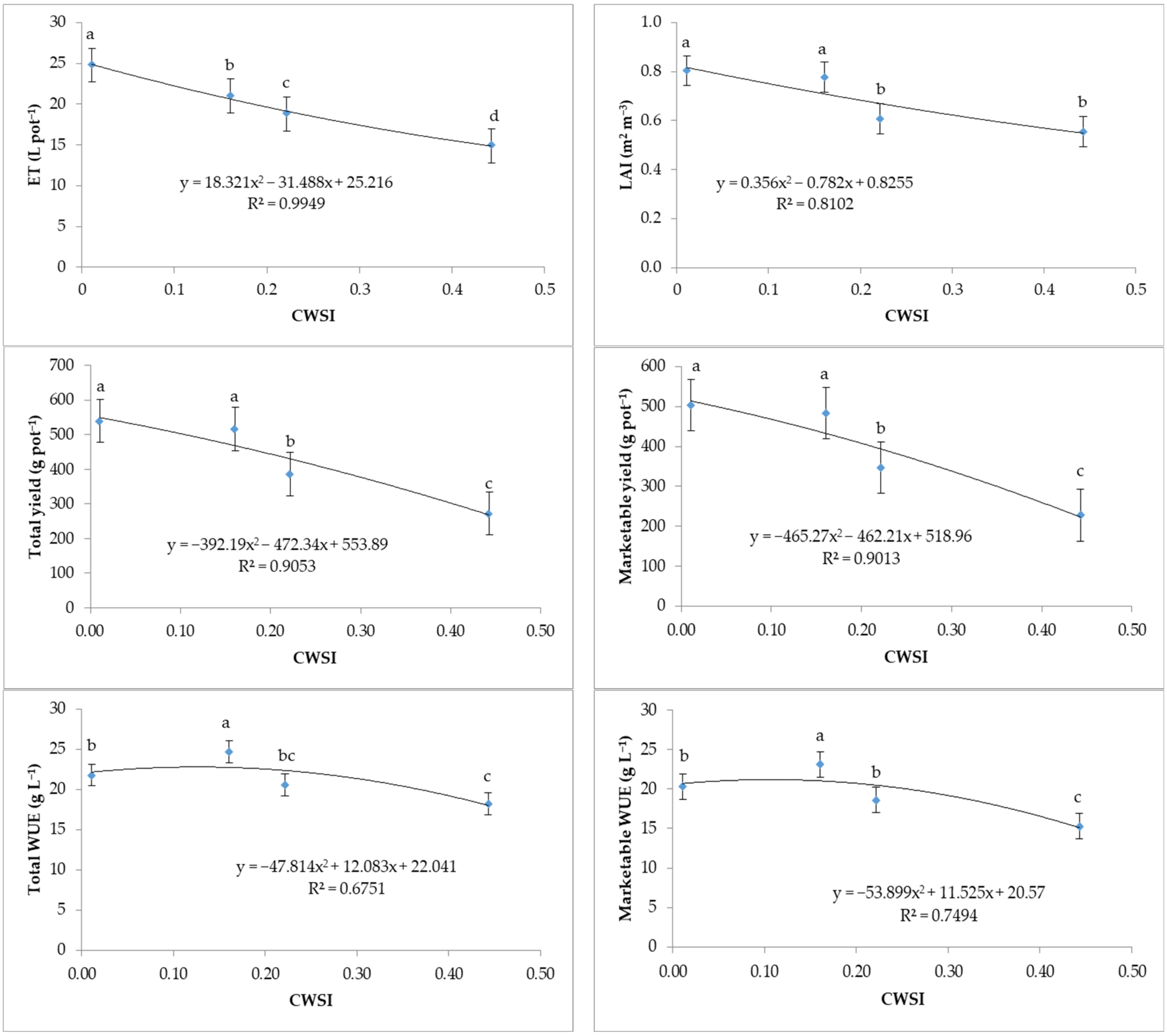

Figure 7. Relationship between the CWSI and some plant parameters. The error bars represent mean ± SE and different letters indicate significant differences between treatments.

4. Conclusions

This study demonstrates that in semi-arid climate conditions with limited water resources, accurate and timely assessment of water stress is important to assist water conservation and sustainable production practices, especially in water-limited regions. The highest total yield was obtained in the I120 treatment (539.5 g pot^{-1}), which had the highest evapotranspiration and I100 irrigation level (516.2 g pot^{-1}). Also, the highest total marketable yield was obtained in the I120 treatment (504.1 g pot^{-1}), which had the highest evapotranspiration and I100 irrigation level (484.4 g pot^{-1}). However, the difference between the I120 and I100 treatments was found to be statistically insignificant. In addition, total and marketable WUE were higher at the I100 (24.7 g L^{-1} and 23.1 g L^{-1}) level, while the lowest values were obtained at I60 (18.2 g L^{-1} and 15.3 g L^{-1}). Therefore, the use of low irrigation levels during pepper production in high tunnel greenhouses, especially in summer months, is not recommended due to its negative effects on plant parameters and yield.

The results obtained show that there are significant relationships between pepper yield and the CWSI. Accordingly, it is concluded that the CWSI can be used to measure the water status of the crop and improve irrigation planning for green pepper. In this context, for higher yields, an average of 0.16 CWSI values can be recommended for the I100 irrigation level and an average of 0.22 CWSI values can be recommended for the I80 irrigation level in regions where water is scarce. As a result of this study, it was determined that the CWSI can be used in irrigation time planning in semi-arid climate conditions. In addition, important relationships between the CWSI and LAI were determined. Therefore, integrating remote sensing-based methods in determining the leaf area index into greenhouse automation systems and using these methods in determining the irrigation time of pepper and similar plants should form the basis of future studies.

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