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Crop water stress index assessment of safflower (*Carthamus tinctorius* L.) under limited water conditions

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ABSTRACT: To ensure the sustainability of agriculture and the production of safe food, supplementary irrigation is required for crops that are primarily rainfed, particularly in arid conditions. This study aimed to determine the water stress response of safflower (*Carthamus tinctorius* L.) under limited water conditions and to establish the crop water stress index (CWSI) as a basis for crop-based irrigation scheduling. Irrigation applications were conducted using the line-source sprinkler irrigation method to create three constraints (35, 75, and 100 % of the water requirement) and a rainfed condition (control plot) under different crop growth periods. The main plots consisted of three growth periods of safflower and only one supplementary irrigation during the vegetative, flowering, and ripening periods. The highest yield was obtained at 3.06 and 3.42 t ha^{-1} for 2019 and 2021, respectively, in the plot that was irrigated in each period during the growing season. The irrigation water (I) and water use efficiency (WUE) were 0.42 and 0.51 kg m^{-3} in the first year, and 0.47 and 0.59 kg m^{-3} in the second year, respectively, for the subject fully irrigated throughout the season. The upper base value, which can be utilized in calculations of the CWSI, was determined to be approximately 14.50. The lower base equation was obtained as Y = −4.9428 (VPD) + 19.121 at a statistical significance level of 1 % where Y is yield and VPD is vapor pressure deficit. The CWSI values calculated for each treatment ranged between –0.25 and 1.45. The threshold value at which irrigation should commence was determined to be 0.63, and it will serve as a valuable reference data source for irrigation scheduling.

Keywords: abiotic stress, canopy-air temperature, evapotranspiration, vapor pressure deficit, yield

Introduction

Globally, approximately 2.3 billion people lack access to adequate and appropriate food. Of these, approximately 828 million are malnourished and face hunger, as reported by the United Nations Food and Agriculture Organization (UN-FAO) and the World Food Programme (WFP). Furthermore, only one percent of the world's freshwater is utilized as a freshwater source (FAO, 2021). According to the intercontinental sectoral water uses, agriculture accounts for roughly 70 % of the freshwater use, which is by far the highest share. However, in recent years, the decrease in the share of usable freshwater resources allocated to agriculture has been exacerbated by many factors, such as the reduction and pollution of water resources due to human activities and climate change. Despite the reduction in water and soil resources, providing food for a rapidly increasing population and meeting the supply of raw materials for industry, which ensures the safe food, remains critical. Consequently, research focuses on the effective use and development of water resources, increasing agricultural water use efficiency, and maximizing the yield and quality obtained per unit area.

In a scenario of drought conditions caused by climate change, sustainable food production, and deficit in water resources, the objective of this research was to determine the yield response of the safflower crop to water with supplementary irrigation in the study site, which is located in the semi-arid climate zone. Additionally, the study aimed to develop an appropriate crop-based irrigation scheduling program. The safflower crop, which contributes significantly to oil production due to its high seed oil content, is also utilized as a source of dyestuffs in industrial crops and as a medicinal-aromatic crop due to its distinctive flower characteristics in the food and textile sectors (Singh and Nimbkar, 2016).

Approximately 590,869 tons of safflower are produced in an area of 652,780 ha globally, with South Asia accounting for the majority of production. Turkey, in particular, produces roughly 21,883 tons over an area of 15,860 ha (FAO, 2022; TSI, 2022). In irrigation scheduling, it is of paramount importance to employ crop-based observation and measurement techniques and to collectively evaluate the soil water, plant physiology, and climate. To this end, the objective was to determine the safflower's lower and upper base limits, which had not been previously determined in the region, and to establish a foundation for subsequent crop water stress studies. The crop water stress index (CWSI) was calculated empirically using the base values, and its relationship with irrigation water use efficiency (IWUE) and yield was evaluated.

Materials and Methods

Study site and experimental features

The study, which investigated the crop-water relations of the safflower crop, was carried out in the field of application and research area of the Faculty of Agriculture and Natural Sciences in Bilecik in the Marmara Region of Turkey in 2019 and 2021. The research activities were suspended for a year due to the Covid-19 pandemic. The site is located at 40°06′44″ N, 30°00′04″ E, with an altitude of 205 m. The temperature, precipitation, relative humidity, evaporation, sunshine duration, and wind speed data for the research area were obtained from the Bilecik Meteorology Provincial Directorate. These data are presented as long-term averages in Figure 1, with a temperature value of 12.9 °C, an annual precipitation total of 482 mm, and an average relative humidity of 62 % (Table 1; TSMS, 2021).

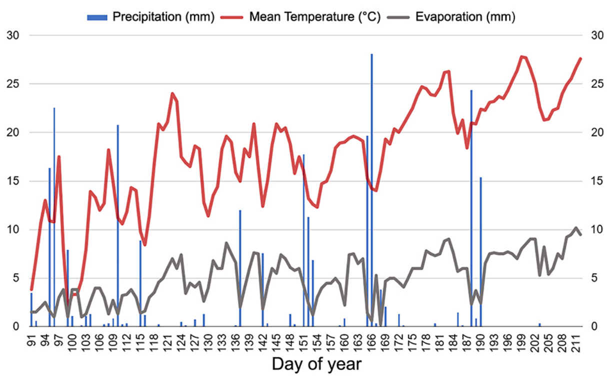

Figure 1 – Change of meteorological parameters based on long-term averages.

Table 1 – Climate data of the experimental site (TSMS, 2021).

		Climate data*					
Period	Month	T	RH	W	N	E	P
		°C	%	m s^{-1}	h	------- mm --------	
2019	Apr	11.0	64.8	1.7	5.8	3.1	31.3
	May	17.9	59.9	1.6	7.9	5.5	32.4
	June	21.3	66.7	1.5	8.3	5.1	163.4
	July	21.7	61.4	1.6	9.9	6.1	30.9
	Aug	22.6	55.6	1.7	11.2	9.0	9.9
2021	Apr	12.5	66.0	1.1	5.3	2.9	77.0
	May	17.6	59.0	1.3	9.7	5.6	40.0
	June	18.9	69.0	1.2	7.7	4.8	68.4
	July	23.7	61.0	1.5	10.7	7.2	42.4
	Aug	23.1	60.0	1.3	10.5	6.9	17.1
Long Term (1939-2021)	Apr	11.5	64.0	2.6	6.3	3.2	42.1
	May	16.2	64.0	2.5	8.0	4.5	47.5
	June	19.9	62.0	2.6	9.6	5.8	42.3
	July	22.1	60.0	2.8	10.4	6.7	19.3
	Aug	22.1	60.6	2.8	9.9	6.3	13.8

*T = average temperature; RH = average relative humidity; W = average wind speed at 2 m; N = sunshine duration; E = Class-A pan evaporation; P = precipitation.

The region exhibits characteristics of the Continental and Mediterranean climate regions. The soils in the experimental site have a 90 cm profile, with a sand ratio of 38.66 %, a silt ratio of 32.81 %, and a clay ratio of 28.53 %. These soils are classified as clay-loam structure. Upon evaluating the soil in the trial area about other properties, it exhibits slightly alkaline (pH = 7.8), reduced calcareousness, an absence of salt, a moderate level of organic matter, and a sufficient phosphorus content. The irrigation water's electrical conductivity value is determined to be 0.5 dS m^{-1}, while the sodium adsorption rate is found to be 0.6.

In the study, the safflower crop was planted on 10 Apr 2019 day of the year (DOY 100) and 15 Apr 2021 (DOY 105). After reaching sufficient harvest maturity, it was harvested on 8 Aug 2019 (DOY 220) and 15 Aug 2021 (DOY 227). The experiment was initiated by sowing the safflower seeds with a planter at a spacing of 10-15 cm above the rows and 45 cm between the rows. Agricultural processes, including the application of fertilizers and pesticides, were implemented as needed based on the monitoring of the safflower crop's development status and physiological conditions.

Irrigation water management and evapotranspiration

The single lateral sprinkler irrigation method was employed in plots that were formed as supplemented irrigation in all three growth periods (III), solely in the vegetative growth period (I00), solely in the flowering growth period (0I0), and solely in the early ripening growth period (00I), according to the growth stages (Figure 2). Additionally, the water constraint issues planned for the study were based on the principle of decreasing water as it moves away from the sprinkler head. The sprinkler heads utilized in the study have a wetted diameter of 30 m and are positioned at 5 m intervals, in accordance with the methodology of a linear source sprinkler irrigation system (Hanks et al., 1976). In order to ensure reliable uniform water distribution in the method, a range of 10-25 % of the wetted diameter is recommended as the spacing between the heads.

The experiment was carried out in accordance with the methodology proposed by Hanks et al. (1980), employing a split-plot design with four replications. Each plot encompassed an area of 25 m^2. Three irrigation scenarios were chosen: a full irrigation treatment (I1) (closest to the lateral, 100 %), two limited irrigations (I2 and I3) (with the application of 35 and 75 % of irrigation water), and a rainfed control treatment (I0), which was created outside the wetting area. Irrigation was terminated when the volume of accumulated water (mL) in the collection container closest to the lateral equaled the irrigation water Eq. (1) to be applied. The application rate regarding the constraint issue was determined using collection containers placed in the second half of the area after the lateral. The volume of water collected in

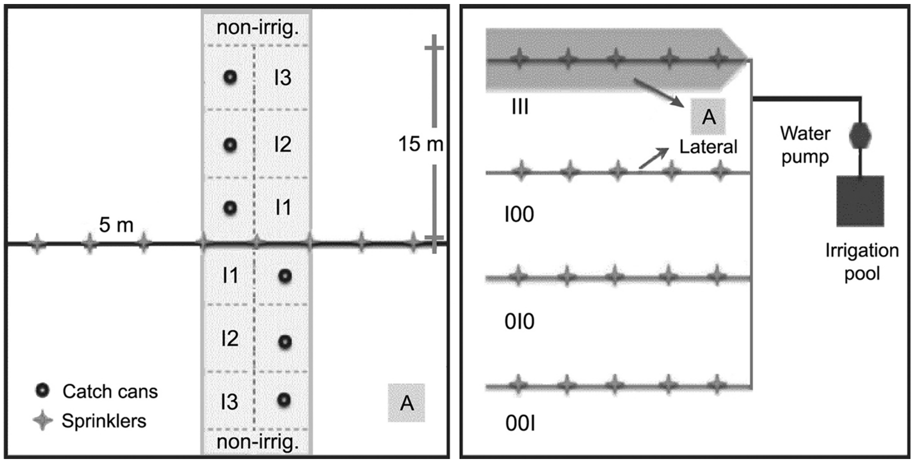

Figure 2 – Details of the line-source sprinkler irrigation system. A = the lateral pipe shown in detail; III = full irrigation in all three growth periods; I00 = irrigation during the vegetative growth period; 0I0 = irrigation during the flowering period; 00I = irrigation during the early ripening period. Irrigation at 100, 75, 35, and 0 % of water requirement designated as I1, I2, I3, and non-irrigated (non-irrig.), respectively.

the containers was calculated. Two repetitions occurred in the north and south of the lateral in a singular lateral arrangement.

$$NIR = \frac{FC - Sa}{100} \gamma t \ D \quad (1)$$

where: *NIR* is the net irrigation requirement (mm), *FC* is soil moisture at the field capacity (% weight), *Sa* is the actual soil moisture (% weight), γt is the soil bulk density (g cm^{-3}), and *D* is the effective root depth (mm).

The amount of applied irrigation water (I, mm) was calculated on the basis of the effective root depth of 90 cm, and seasonal evapotranspiration (ET) was calculated in accordance with the water budget approach proposed by Allen et al. (1998), taking into account the change in soil water storage (ΔSW, mm) in the 120 cm soil profile in order to monitor the potential for deep percolation. Given that the amount of irrigation water was regulated, it was assumed that runoff (mm) would be negligible.

The irrigation water use efficiency (IWUE) and water use efficiency (WUE) were calculated using Eq. (2) and (3), respectively, with the harvested grain yields obtained from each treatment plot (Zhang et al., 1999).

$$IWUE = (Y_I - Y_0) / I \quad (2)$$

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

where: Y_I is the yield (t ha^{-1}), Y_0 is the yield of the non-irrigated plots (t ha^{-1}), *I* is the irrigation water (mm), and *ET* is the evapotranspiration (mm).

Crop water stress measurement

An experimental approach, the Idso model, was employed to determine the degree of crop water stress (Idso et al., 1981; Gardner et al., 1992). The model is based on the theoretical calculation of the CWSI according to the atmospheric vapor pressure deficit (VPD) and crop surface temperatures. To this end, the lower baseline was established through infrared thermometer (IRT) measurements taken during the experiment, wherein 100 % (I1) of the water deficit in the soil was applied, which was not subjected to water stress, and the upper baseline was obtained from the never-irrigated anhydrous subject. Basic graphics were subsequently generated. The lower baseline is plotted based on the difference between leaf temperature (T_c), air temperature (T_a), and vapor pressure deficit (VPD). The CWSI values were determined using Eq. (4), with the aforementioned graphs serving as the bases for this calculation (Idso et al., 1981).

$$CWSI = \frac{\left[(T_c - T_a) - (T_c - T_a)_{UL}\right]}{\left[(T_c - T_a)_{LL} - (T_c - T_a)_{UL}\right]} \quad (4)$$

where: T_c is the leaf temperature (°C), T_a is the air temperature (°C), *LL* is the non-water stressed baseline (lower baseline), and *UL* is the non-transpiring upper baseline.

Infrared thermometer measurements were conducted exclusively in 2021 during the late vegetative and flowering period, when the crop had completed its vegetative development. Measurements were taken at noon (12h00), when the sun rays were the most intense. The measurements commenced on 10 July 2021 (DOY 191) and concluded on 22 July 2021 (DOY 203). During the measurements, an IRT (Raynger ST8 model) with filters that detect rays with a wavelength of 7-18 mm was employed with the emissivity coefficient set at 0.98. The angle of view of the instrument was 3°. During the T_c measurements, the vehicle was positioned at an angle of 20-30° with the horizontal plane to ensure only the leaf was within the field of view. In accordance with the trial subjects in the IRT measurements across each plot, the upper portions of two distinct crops were considered, with measurements obtained from four directions for each leaf exposed to full sunlight. The mean of eight measurements taken in each plot was used to calculate the average leaf temperature for that plot. Prior to each measurement, the wet and dry thermometer readings were obtained using a hygro-thermometer (Extech RH390 model), and the VPD was calculated in accordance with the principles specified in List (1951). In these calculations, the barometric pressure of the trial area was taken as 101.25 kPa, and in addition to this, the relationship between CWSI and yield was determined.

Statistical analyses

The experimental analyses were performed using MSTAT statistical software with a split-block design, which is a variation of the time modification of the split-plot design for the line source irrigation method based on Hanks et al. (1980) and Sezen and Yazar (2006).

Results

Interaction between irrigation water, crop water consumption, and crop yield

The study revealed that the amount of applied I in each growth period, as well as the amount of supplementary irrigation, seasonal water consumption calculated due to precipitation and soil moisture change, varied significantly over the years. The variations are depicted in Figures 3 and 4. In 2019, 268 mm of total precipitation fell during the growing period, while the total precipitation in 2021 was 245 mm. The amount of irrigation water applied varied considerably between subjects in the first year, with values ranging from 14 to 155 mm. The amount of water consumed by the crops was calculated to be between 392 and 595 mm. In the second year, these values exhibited a slight degree of variation, with values ranging from 17 to 153 mm and 388 to 582 mm, respectively.

The lateral line in treatment (I1) received the greatest amount of water (100 %). The amount of water (100 %) applied decreased with distance from the lateral line, with 35 % for the furthest lateral line in treatment (I3).

The average yields obtained from each experimental plot and their statistical results based on a split-plot design are presented in Table 2. The data also includes the values of WUE and IWUE calculated using the values of yield, I, and ET and their statistics (Table 2). The highest yield for the safflower crop was observed in subject III-I1, which received 100 % of the I and received one irrigation in all growth periods. This subject yielded 3.06 t ha^{-1} in 2019 and 3.42 t ha^{-1} in 2021. The lowest yields were 2.41 t ha^{-1} and 2.70 t ha^{-1}, respectively, in the I0 subject, which was not irrigated. Upon estimation of the yield values, it was found that the subject (III), which was irrigated throughout the season, and the subject

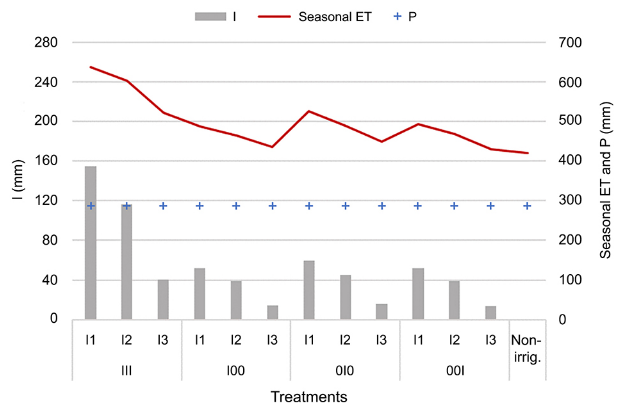

Figure 3 – Water parameter variations based on irrigation treatment for the year 2019. I = irrigation water; ET = evapotranspiration; P = precipitation; III = full irrigation in all three growth periods; I00 = irrigation during the vegetative growth period; 0I0 = irrigation during the flowering period; 00I = irrigation during the early ripening period. Irrigation at 100, 75, 35, and 0 % of water requirement designated as I1, I2, I3, and non-irrigated, respectively.

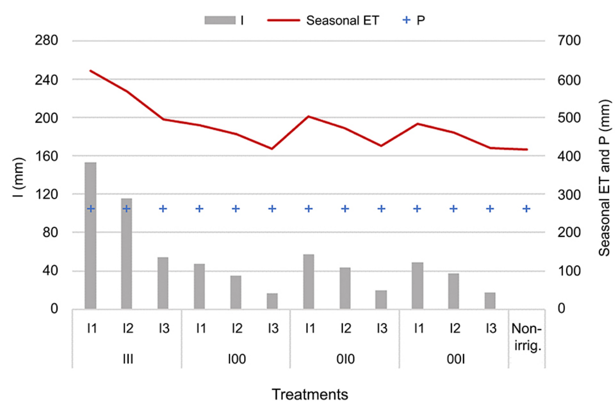

Figure 4 – Water parameter variations based on irrigation treatment for the year 2021. ET = Evapotranspiration; P = Precipitation; III = full irrigation in all three growth periods; I00 = irrigation during the vegetative growth period; 0I0 = irrigation during the flowering period; 00I = irrigation during the early ripening period. Irrigation at 100, 75, 35, and 0 % of water requirement designated as I1, I2, I3, and non-irrigated, respectively.

(I1), which received the optimum water level, were the two most yielding groups. In other words, there was a statistically significant difference between the subjects at a 1 % significance level based on the variance analysis results. According to the least significant difference grouping, these subjects formed the initial and transition groups. In all subjects where single-period irrigation was applied, subject I1 demonstrated the highest efficiency. This indicates that in cases where water resources are sufficient, restrictions on irrigation support for the safflower plant are not recommended. The yield values of the proposed treatment (III-I1) demonstrated a robust correlation with I and ET at the $p < 0.01$ significance level, as illustrated in Figure 5.

Table 2 – Crop yield and water parameters of safflower for all treatments per year.

Irrigation time[a]	Irrigation level[b]	2019			2021		
		Y	IWUE	WUE	Y	IWUE	WUE
		t ha^{-1}	kg m^{-3}		t ha^{-1}	kg m^{-3}	
III	I1	3.06 a***	0.42 e	0.51	3.42 a	0.47 e	0.59
	I2	2.99 ab	0.50 d	0.53	3.36 ab	0.56 d	0.63
	I3	2.51 ef	0.25 f	0.52	2.71 h	0.02 h	0.59
I00	I1	2.68 cde	0.52 cd	0.59	3.01 cde	0.64 c	0.67
	I2	2.61 def	0.52 cd	0.60	2.92 efg	0.63 c	0.69
	I3	2.48 ef	0.49 d	0.59	2.71 h	0.12 g	0.69
0I0	I1	2.78 bcd	0.62 b	0.57	3.10 cd	0.72 b	0.66
	I2	2.70 cde	0.64 b	0.59	3.03 cde	0.73 b	0.68
	I3	2.55 def	0.89 a	0.61	2.80 fgh	0.50 e	0.70
00I	I1	2.88 abc	0.90 a	0.63	3.18 bc	1.01 a	0.71
	I2	2.66 cde	0.64 b	0.61	2.94 def	0.65 c	0.68
	I3	2.49 ef	0.59 bc	0.62	2.74 gh	0.28 f	0.70
LSD		0.243**	0.076*	ns	0.185**	0.054*	ns
III		2.85 a	0.39 c	0.52 b	3.16 a	0.35 c	0.61 b
I00		2.59 c	0.52 b	0.59 a	2.88 b	0.46 b	0.69 a
0I0		2.67 b	0.72 a	0.59 a	2.98 b	0.65 a	0.68 a
00I		2.68 b	0.71 a	0.62 a	2.96 b	0.65 a	0.70 a
LSD		0.034*	0.060*	0.034*	0.134**	0.049*	0.034*
	I1	2.76 a	0.49 a	0.46	3.09 a	0.57 a	0.53
	I2	2.67 a	0.46 ab	0.47	2.99 b	0.52 b	0.54
	I3	2.49 b	0.45 b	0.47	2.73 c	0.19 c	0.54
	I0	2.41 d		0.61	2.70 c		0.70
LSD		0.110**	0.034*	ns	0.061*	0.024*	ns

[a]III = full irrigation in all three growth periods; I00 = irrigation during the vegetative growth period; 0I0 = irrigation during the flowering period; 00I = irrigation during the early ripening period. [b]Irrigation at 100, 75, 35, and 0 % of water requirement designated as I1, I2, I3, and I0, respectively. *Significant at the 0.05 probability level. **Significant at the 0.01 probability level. *** Letters indicate different groups based on LSD analysis. LSD = least significant difference; ns = non-significant. Y = yield; IWUE = irrigation water use efficiency; WUE = water use efficiency.

Given the substantial precipitation throughout the cultivation period in both years of the experiment, the non-irrigated plot achieved a notable level of productivity. However, it formed the last group. In both years, the total precipitation during the cultivation period was approximately 100 mm more than the long-term average. Consequently, the difference between all treatments with respect to precipitation and WUE values was found to be insignificant, with values fluctuating between 0.46 and 0.63 kg m^{-3} for 2019 and 0.53 and 0.71 kg m^{-3} for 2021. The IWUE values exhibited significant differences at the 1 % level, contingent upon the difference in I amounts. Statistical analysis of the IWUE revealed that the safflower crop irrigated once during the flowering (0I0) and ripening (00I) periods exhibited higher efficiency, with values of 0.72 and 0.71 kg m^{-3} in the first year and 0.65 and 0.65 kg m^{-3} in the second year, respectively.

Crop water stress index and baseline equations

The response of the safflower plant to the water constraint issues caused by the amounts of applied I in different development stages and the characteristics of the irrigation method was evaluated using the CWSI, which was calculated based on theoretical calculations. In the second year of the research, the differences between the T_c and the T_a measured in the trial plots, which were irrigated with supplementary irrigation throughout the season and where 100 % of the water need was met, and in the unirrigated plots, were associated with the VPD. Thus, the lower and upper base equations required for the calculation of CWSI were obtained and presented in Figure 6. The upper base value obtained from the unirrigated field was 14.5 °C, while the lower base equation derived from the fully irrigated field was $T_c - T_a = -4.9428$ VPD + 19.121 (Figure 6). The lower base equation exhibited a high predictive ability with a statistical significance level of $p < 0.01$ (determination coefficient, $R^2 = 0.70$**) and a low standard error (standard error of estimates, S_{yx} = 1.39 °C). The CWSI chart calculated for each subject using the base equations is presented in Figure 7. Leaf temperature measurements were taken after irrigation during the flowering period (DOY 184), but readings could not be taken between DOY 185 and 190 due to cloudiness and rainfall. A total of 34 mm of rainfall occurred during this period, which resulted in an initial underestimation of CWSI values. The CWSI values exhibited a tendency to increase before irrigation and decrease with irrigation.

The mean CWSI value was calculated based on the I1, I2, and I3 irrigation levels and three developmental

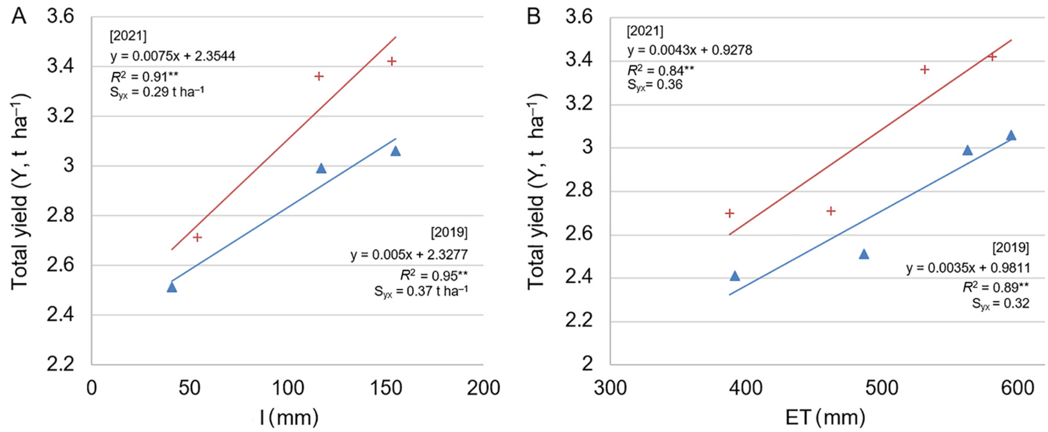

Figure 5 – A) Relationship between yield (Y) and seasonal applied irrigation water (I) and B) seasonal evapotranspiration (ET) for the proposed treatment. R^2 = determination coefficient; S_{yx} = standard deviation; **Significant at the 0.01 probability level.

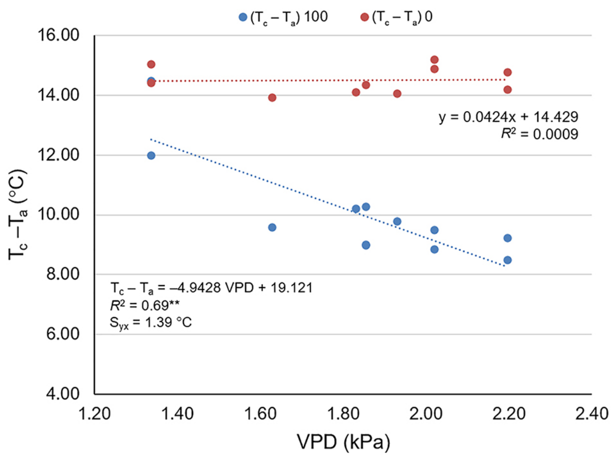

Figure 6 – Leaf and air temperature differential ($T_c - T_a$) vs air vapor pressure deficit (VPD) for well-watered and maximally stressed safflower in 2021. R^2 = determination coefficient; S_{yx} = standard deviation. **p < 0.01, significant differences at the 1 % significance level.

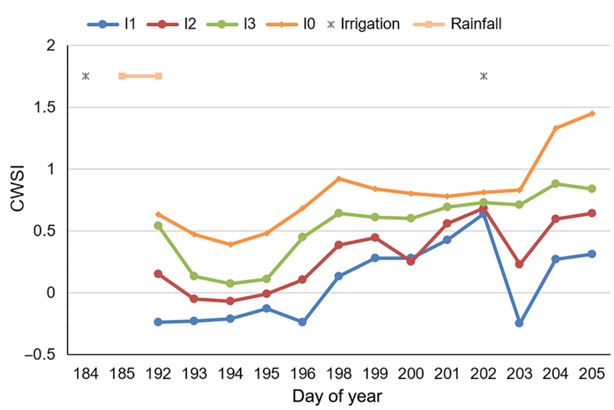

Figure 7 – Crop water stress index (CWSI) variations for all irrigation levels of the irrigated treatment over the growing season. Irrigation at 100, 75, 35, and 0 % of water requirement designated as I1, I2, I3, and I0, respectively.

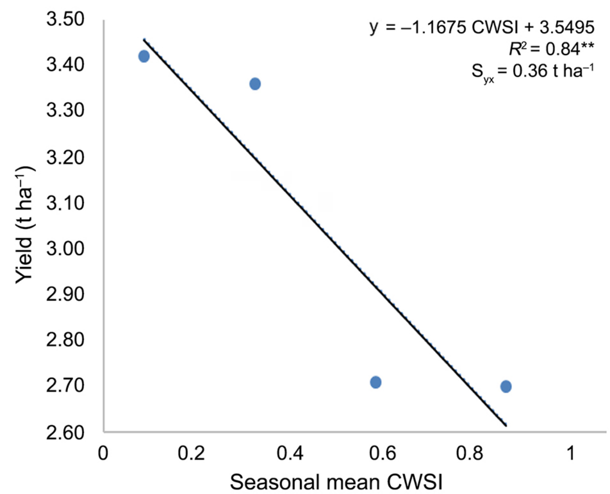

Figure 8 – Yield (Y) as related to seasonal mean crop water stress index (CWSI). R^2 = determination coefficient; S_{yx} = standard deviation; **p < 0.01, significant differences at the 1 % significance level.

periods (III) of the subjects irrigated during the vegetative, flowering, and ripening periods. In the non-irrigated treatment, the mean CWSI values were 0.08, 0.30, 0.54, and 0.80, respectively. The mean CWSI values just before irrigation were calculated as 0.63, 0.68, and 0.73 for the same subjects. Based on the yield and IWUE statistics, the stress value for initiating irrigation in the III-I1 interaction, identified as the optimal practice, was determined to be 0.63.

The yield values increased in direct proportion to the increase in the amount of irrigation water, while the mean CWSI values decreased in parallel. A significant linear relationship was obtained between yield and CWSI at the $p < 0.01$ level, with the equation $Y = -1.1675\ CWSI + 3.5495$, $R^2 = 0.84$, $S_{yx} = 0.36$ t ha^{-1}. This relationship can be used for yield estimation, as demonstrated in Figure 8.

Discussion

Despite the assertion that the safflower crop is drought-resistant due to its origin and other intrinsic characteristics, a literature review reveals studies that demonstrate the plant's response to irrigation practices and its sensitivity to water and temperature stress (Nabipour et al., 2007; Ferreira-Santos et al., 2018; Mohtashami et al., 2018; Pabuayon et al., 2019).

Safflower is a robust plant that can thrive in nutrient- and water-scare environments. However, in the context of global climate change, where irregularities in precipitation and temperature are becoming increasingly prevalent, ensuring sufficient water availability is crucial, particularly during periods of high water demand. For this reason, the sustainability of agriculture and the economy requires the implementation of supplementary irrigation during the periods when the crop is most sensitive to water deficiency, as opposed to the current practice of irrigating throughout the entire season (Gültaş and Ahi, 2020; Karaş, 2020; Wang, 2017; Karrou and Oweis, 2012; Kiani and Mirlatifi, 2012; Bélanger et al., 2000).

The contribution of supplementary irrigation practices to crop yield in semi-arid regions where water resources are limited is evident. Several studies have reported and corroborated this hypothesis, such as the studies conducted by Ghamarnia and Sepehri (2010). Under three different irrigation methods, supplementary irrigation and rainfed were tested with varying constraints, and yield values ranged from 0.55 (rainfed) to 3.9 t ha^{-1}. The amount of applied I under supplemental irrigation was 111 mm, with a yield of 0.9 t ha^{-1} and a WUE of 0.32 kg m^{-3}, comparable to the results of our research. In both years of our study, the treatment nearest the lateral received the highest water amount, as expected. The deficit irrigation treatments received less water. The non-irrigated treatment exhibited relatively high water consumption values, which can be attributed to precipitation that deviated from the meteorological data of many years. The increase in soil water due to precipitation and irrigation increases evapotranspiration, as evidenced by the result graphs. These results have been corroborated in various regions under different climatic conditions.

In this study, which partially reflects the semi-arid climate conditions in which the research was conducted, full and limited irrigation applications were carried out during different growth periods of safflower. The seasonal crop water consumption ranged between 234 and 591 mm, while the yield values ranged between 2.48 t ha^{-1} and 5.10 t ha^{-1}. The values were comparable in the non-irrigated treatment, but the yield values were slightly higher in the optimum treatment since the amount of applied I was higher (428 mm). The irrigation method, irrigation schedule, quality and quantity of water, and climatic conditions significantly impact safflower yield. In a study in which the surface irrigation method was employed in summer safflower, the applied I was 441 mm, the crop water consumption was 673 mm, and the yield was 3.74 t ha^{-1} in irrigated at the optimum level throughout the season. The applied I and ET were higher than in our study, in which the single lateral sprinkler irrigation method was used. The differences observed in these studies can also be attributed to the variability in the amount and distribution of precipitation throughout the year (Bassil and Kaffka, 2002; Istanbulluoglu, 2009, Karaş, 2020).

In their study of safflower, researchers observed that while irrigation increased yield in summer safflower, limited water applications and non-irrigated issues resulted in yield losses. In these studies, ET values ranged between 239 and 575 mm, while WUE values ranged from 0.14 to 0.69 kg m^{-3}. The results of water restriction-based research conducted to improve the ability of the CROPGRO model to predict water consumption, WUE, and yield of summer safflower indicate that higher ET (approximately 500 mm on average) and yield (2.5 t ha^{-1}) were obtained for three different cultivars in the fully irrigated treatment compared to the non-irrigated and restricted treatments during the growing periods. The WUE value was found to be relatively consistent between the treatments, with an average of approximately 0.54 kg m^{-3} (Singh et al., 2016; 2017).

Limited water applications in semi-arid conditions saved I without causing a significant reduction in yield, as revealed by a study conducted in the Texas state (USA) on oilseed crops. The study applied water at four levels: extreme (51 mm), severe (127 mm), moderate (203 mm), and mild (279 mm), and the yield ranged from 1.37 t ha^{-1} to 1.68 t ha^{-1}. The average rainfall during the season was 267 mm. Drought stress and different nitrogen doses were observed to be effective in altering yield and yield components. Safflower suffers significant yield loss if the crop undergoes water stress conditions during the late vegetative period. The effects of drought-resistant growth periods and the water restraint levels on yield applied in each of them were investigated. The differences in the physiological behaviors of the cultivars, in addition to water stress, also had an effect (Istanbulluoglu, 2009; Sabbagh et al., 2012; Singh et al., 2016; Pabuayon et al., 2019; Emongor and Emongor, 2023; Salehi et al., 2023; Ghiyasi et al., 2023).

Crop yield in semi-arid regions is threatened by high temperatures, low humidity, and a lack of rainfall during the growth period, which causes a significant change in the physiological and biochemical properties (Salehi et al., 2023). In terms of adaptation to climate change, it is essential to determine the responses to stress conditions and develop measures for practices that will increase the tolerance of oilseed crops. The most effective method for determining the stress conditions is to monitor the physiological properties of the plant, including leaf temperature, leaf water potential, and leaf pore resistance, among others. This allows for the identification of reliable indices that can be evaluated (Tuccio et al., 2019; Ru et al., 2020; Seleiman et al., 2021). To this end, numerous studies have been conducted under a range of crop, climate, water, and soil conditions.

To accurately identify the plant's stress level, an IRT is an effective and inexpensive technology. Furthermore, plant-based irrigation scheduling can enhance water, food, and energy efficiency, while also increasing sustainability. Despite numerous studies conducted under diverse climatic, plant, water, and soil conditions, there is a paucity of research on the CWSI of safflower Kirnak et al., 2019 (seed pumpkin); Yetik and Candoğan, 2023 (sugar beet); Bijanzadeh et al., 2022 (safflower); Katimbo et al., 2022 (soil water dynamics relation); Irmak et al., 2000 (corn); Erdem et al., 2010 (broccoli).

The literature identifies a single study on the safflower water stress index, the study of Bijanzadeh et al. (2022), which addresses our findings. The study revealed that the upper base value obtained in safflower from the non-irrigated treatment for 2017 and 2018 were 7.8 and 8.9 for the Goldasht variety and 10.8 and 11.5 for the Isfahan variety, respectively. Furthermore, the lower base equations were obtained with high correlation. The values obtained in our study were relatively similar to that reported in the article, which was 14.5. However, the VPD values observed in the study of Bijanzadeh et al. (2022) ranged between 0 and 8.5 kPa, whereas in our study, they were calculated in a narrower range. This difference can be attributed to varying climatic conditions and the use of different varieties. The CWSI values were found to range from 0.18 to 0.23 in the well-watered treatment (100 % FC), and from 0.28 to 0.33, from 0.57 to 0.66, from 0.57 to 0.66, and from 0.62 to 0.77 for the 75 %, 50 %, and 25 % treatments, respectively. These values are in parallel with the CWSI values obtained in our study: 0.08 in I1, 0.30 in I2 constraint, 0.54 in I3 constraint, and 0.80 in non-irrigated subject. The research recommends 75 % FC with a CWSI of 0.28-0.33, demonstrating lower stress levels. In other words, the results indicate that CWSI values within this range can be utilized for irrigation scheduling. Conversely, in both studies, strong linear relationships were observed between yield and CWSI, which can be employed in yield estimation.

A review was conducted of studies based on the CWSI for plants in the oilseed cereal groups. The results of these studies were then discussed. With regard to irrigation scheduling, a CWSI value of 0.60 in sunflower was recommended by Erdem et al. (2006), a value of 0.21 in canola was proposed by Gültaşand Ahi (2020), a value of 0.22 in soybean was recommended by Candogan et al. (2013), a value of 0.22 in maize was proposed by Irmak et al. (2000). A value of 0.40 in cotton was recommended by O'Shaughnessy et al. (2011). As plants become increasingly sensitive to water deficit, the CWSI threshold value is typically reduced. The aforementioned threshold values can be effectively utilized to ensure the optimal use of water resources, particularly when integrated with new irrigation automation and systems.

The results of this research indicate that the yield of safflower can be increased, and the sustainability of water resources and food production can be ensured through supplementary irrigation in all development periods in dry years when rainfall is low. Using the water stress index threshold values obtained for the crop's water stress management will result in water savings and increased water use efficiency. This study recommends a threshold value for starting irrigation of 0.63. The results will serve as an important data source for researchers, decision-makers, and end-users in ensuring the sustainability of agriculture and water resources by developing measures to mitigate the impacts of drought on production.

Conflict of interest

The author declares that there is no conflict of interest.

Data availability statement

The author does not have permission to share data.

Declaration of use of AI Technologies

AI technologies or supported applications and programs were not used in the creation of the text and the calculations made.

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