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RESEARCH ARTICLE

Evaluation of irrigation strategies and crop water stress index in maize under Mediterranean conditions

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ABSTRACT

As water resources become increasingly constrained, irrigation strategies that reduce water use are essential for sustaining crop production in water-limited regions. A two-year field experiment (2020-2021) under Mediterranean climatic conditions evaluated 'Pioneer P1574' hybrid maize (*Zea mays* L.) yield responses to deficit irrigation and examined the crop water stress index (CWSI) as an irrigation-scheduling indicator. The trial followed a randomized complete block design with three replicates. Five irrigation strategies were compared: Full irrigation (FI), where the measured soil water deficit in the 0-60 cm profile was refilled to field capacity at 7 d intervals; DI_{75}, DI_{50} and DI_{25}, receiving 75%, 50% and 25% of the irrigation water applied in FI; and rainfed (RF) without irrigation. Canopy temperature was monitored throughout the growing season using an infrared thermometer, and CWSI was calculated using the air vapor pressure deficit (VPD) to represent atmospheric demand. Grain yield was highest under FI (17 370 kg ha^{-1}) and lowest under RF (7460 kg ha^{-1}). Although yield decreased with increasing water restriction, water productivity (WP) and irrigation water productivity (IWP) improved as irrigation inputs declined, with maximum WP and IWP obtained in DI_{25}. Seasonal mean CWSI values decreased as applied water increased, ranging overall from 0.21 to 0.66. Across both years, yield, thousand-grain weight, plant height, WP and IWP showed significant second-order polynomial relationships with CWSI. Based on these relationships, the approximately 0.23 threshold value for mean CWSI was identified as a practical threshold for achieving high maize yields while promoting efficient water use under Mediterranean conditions. This approach supports climate-smart management.

Key words: Crop water stress index, deficit irrigation, irrigation scheduling, maize, *Zea mays*.

INTRODUCTION

Maize (*Zea mays* L.), the world's third most widely grown cereal crop, annually produces over 1.1 billion tons worldwide. Maize is considered a primary crop due to its uses in both food and animal feed and as a base material in many industrial products (Mueller et al., 2012). The areas with the lowest precipitation levels in semi-arid and Mediterranean climates are being increasingly impacted by droughts, and as such irrigation practices need to be optimized to ensure that maize productivity is maintained at levels that support food security (Zou et al., 2021; Igwe et al., 2025). Due to projected decreases in available water for agriculture in semi-arid and Mediterranean climates it is expected that there will be even greater need for development of water efficient crop production systems (Bo et al., 2023). In Türkiye, particularly in the Çukurova region, maize is an important crop grown as both a main and second crop; however, increasing irrigation demand and pressure on water resources require more efficient water management in maize production (Koç et al., 2022; Şen, 2023).

Strategies utilizing deficit irrigation (DI) are being recognized as viable options to increase water productivity (WP) while maintaining or improving yields in water limiting environments (Comas et al., 2019; Allakonon et al., 2022). A global meta-analysis of maize response to DI indicated that applying water strategically can increase WP by 15%-40% compared to full irrigation, depending on the level of stress applied to plants during the different growth stages and the frequency of water applications (Allakonon et al., 2022). Specifically, multi-stage regulated DI has been identified as a promising strategy, with several studies indicating that up to 25%-50% of water savings may be possible while still achieving 85%-95% of yields obtained with full irrigation (Jiao et al., 2024; Zhang et al., 2025). To successfully implement DI, it is necessary to monitor crop water status with precision to provide guidance for determining the optimal time and quantity of irrigation to apply to prevent excessive stress that could result in permanent yield reductions (Wang et al., 2023; Melkie et al., 2024).

Crop water stress index (CWSI) provides a quantitative method to assess plant water status and optimize irrigation scheduling (Gu et al., 2021). Initially developed by Idso et al. (1981) and Jackson et al. (1981), CWSI compares the actual canopy temperature of a crop to the theoretical non-stressed and fully stressed baseline temperatures of a crop under prevailing environmental conditions to quantify the level of crop water stress. Studies have demonstrated strong relationships between CWSI and maize yields, evapotranspiration rates, and soil moisture content under a variety of irrigation management strategies (Liao et al., 2024). However, CWSI threshold values for initiating irrigation varied greatly among studies conducted in different environments and during different growth stages of the crop, ranging from 0.15 to 0.40 (Qin et al., 2021). Therefore, establishing specific threshold values of CWSI based upon location and growth stage is necessary to optimize irrigation scheduling and maximize both yield and water use productivity (Bo et al., 2023; Liao et al., 2024).

While research on deficit irrigation and CWSI in maize production has been extensive, relatively few studies have identified optimal irrigation strategies and CWSI threshold values under Mediterranean climate conditions in southern Türkiye. Although CWSI-based irrigation scheduling and yield-CWSI relationships for maize have previously been investigated under Çukurova conditions (Gençoğlan and Yazar, 1999), further evaluation of multiple deficit irrigation levels under Mediterranean conditions remains necessary. Additionally, the relationship between CWSI and yield response under Mediterranean conditions, which present unique stress dynamics due to high temperatures and vapor pressure deficits, requires additional evaluation. Thus, the objectives of this study were to: (1) Evaluate the effects of five irrigation management strategies (i.e., full irrigation, three deficit irrigation levels, and rainfed) on maize grain yield, water productivity, and irrigation water productivity; (2) evaluate the relationship between CWSI and grain yield under Mediterranean conditions; and (3) develop a recommended CWSI threshold value for irrigation scheduling to maximize both productivity and water productivity in the study region.

MATERIALS AND METHODS

Experimental site and soil and irrigation water

This study was conducted at the Soil and Water Resources Unit of Alata Horticultural Research Institute (36°53’ N, 34°57’ E; 30 m a.s.l.), in Tarsus in the Mediterranean region of Türkiye during 2020 and 2021 growing seasons. Climate data for the research years and the long-term (1952-2019) period are presented in Table 1. The study area has a typical Mediterranean climate. According to data from the Alata Horticultural Research Institute, Tarsus Soil and Water Resources location, the long-term average rainfall for the region is 616 mm. The wettest months are November, December, January, and February, while the driest months are June, July, August, and September. The 54% of the total rainfall occurs during the winter months. The majority of the precipitation is in the form of rain. The long-term average temperature in the region is 18.2°C. The warmest month average is August with 27.2°C, and the coldest month average is January with 8.9°C. According to long-term measurements, the average relative humidity is 70.2%. The annual evaporation rate, according to long-term averages, is 1478 mm. The highest evaporation rate is in July with 216 mm (MGM, 2021).

The soils of the experimental site have a high water-holding capacity and a relatively high lime content, with a pronounced increase in lime concentration toward the deeper layers. Selected physical and chemical properties of the site soils are presented in Table 2. As shown in the table, soil pH ranges from 8.0 to 8.1 across the profile; electrical conductivity of the saturated soil extract (ECe) varies between 0.85 and 0.88 dS m^{-1}; bulk density ranges from 1.30 to 1.40 g cm^{-3}; gravimetric water content at field capacity is 28.1%-29.1%; and gravimetric water content at the permanent wilting point ranges from 20.5% to 21.9%. The soil texture class was determined as silty clay loam (SiCL) at 0-30 and 60-90 cm, and as silty clay (SiC) at 30-60 cm.

The irrigation water used in the study was obtained from the irrigation canal. Samples of irrigation water taken from the irrigation canal were analyzed in the Soil and Water Resources Laboratory. According to the analysis results, the electrical conductivity of the irrigation water (ECw) was determined to be 0.464 dS m^{-1} and the pH value was 8.04.

Table 1. Historical monthly mean and 2020-2021 growing seasons climatic data of the experimental area. Tmax: Maximum air temperature; Tmin: minimum air temperature; Tmean: mean air temperature.

Experimental years	Climatic parameters	March	April	May	June	July	August
2020	Tmax (°C)	20	23	29	30	34	35
	Tmin (°C)	9	11	15	18	23	23
	Tmean (°C)	14	17	22	24	28	28
	Rainfall (mm)	22.6	14.2	12.6	8	0	0
2021	Tmax (°C)	24	34	32	35	36	37
	Tmin (°C)	7.6	11	16	19	24	23
	Tmean (°C)	13	17	22	24	28	29
	Rainfall (mm)	45	26	3	0	0	0
Long-term (1950-2019)	Tmax (°C)	20	24	28	31	33	33
	Tmin (°C)	7	11	15	19	21	21
	Tmean (°C)	13	17	21	25	27	27
	Rainfall (mm)	60	40	30	11	4	2

Table 2. Physical and chemical properties of different soil layers of the experimental field. FC: Field capacity; WP: permanent wilting point; BD: bulk density; ECe: electrical conductivity of the saturated soil extract; SiCL: silty-clay-loam; SiC: silty-clay.

Soil depth	Sand	Silt	Clay	Texture class	FC	WP	BD	ECe	pH	$CaCO_3$
cm		——— % ———			—— % ——		g cm^{-3}	dS m^{-1}		%
0-30	17.5	44.1	38	SiCL	29.1	21.6	1.30	0.874	8.0	29.41
30-60	13.7	42.8	43	SiC	28.8	20.5	1.38	0.851	8.0	28.62
60-90	17.3	44.2	39	SiCL	28.1	21.9	1.40	0.866	8.1	30.37

Experimental design and irrigation treatments and drip irrigation systems

The study was conducted using a randomized block design with three replicates. Five irrigation strategies were compared: Full irrigation (FI), where the measured soil water deficit in the 0-60 cm profile was refilled to field capacity at 7 d intervals; DI_{75}: 75% of full irrigation; DI_{50}: 50% of full irrigation; DI_{25}: 25% of full irrigation and a rainfed (RF) without irrigation. Each plot contained 10 rows of plants. The plot length was 25 m and the width was 6.3 m. Ten rows of lateral lines were placed in each experimental plot.

A surface drip irrigation system was used in the experiment. The drip irrigation system control unit includes a sand-gravel filter, disc filter, pressure gauge, water meter, valves and fittings; fertilizer tank and fertilizer injection system. In the surface drip system, a main line, manifold and laterals made of PE pipes were used in the transmission system. The laterals are 20 mm in diameter and have in-line drippers at 40 cm intervals. The dripper flow rate was selected as 1.8 L h^{-1} at an operating pressure of 100 kPa. The laterals were placed in the middle of each plant row.

Agronomic practices

The 'Pioneer P1574' hybrid corn (*Zea mays* L.) was used as the component plant material. 'Pioneer P1574' is a hybrid with high yield potential, strong ear development ability, a strong stem and root system, lodging tolerance, and significant grain drying speed and green retention characteristics. This cultivar can reach harvest maturity in approximately 120-135 d under the conditions of the study area.

The experimental field was sown in 10 rows using a planter with 70 cm row spacing, and 'Pioneer P1574' hybrid maize was planted on 11 March 2020 and 1st March 2021, respectively. Fertilization practices were carried out as basal and top dressing based on the nutrient requirements of the crop. Diammonium phosphate (DAP) was applied as basal fertilizer at a rate of 450 kg ha^{-1} at sowing, whereas ammonium sulfate was applied as top dressing through the irrigation system at a rate of 450 kg ha^{-1} on 16 May 2020 and 1st May 2021, respectively.

Throughout the experimental period, necessary crop protection practices including the timely application of herbicides, insecticides, and weed control measures were meticulously implemented as required.

Measurements and observations

During the experimental period, daily meteorological data including precipitation and minimum, maximum, and mean air temperatures were obtained from an automated meteorological station located at the research site and summarized for each growing season. Additionally, long-term (1950-2019) climatic data for the region are presented in Table 1.

Soil water content (SWC) was measured at three depths (30, 60, and 90 cm) in increments of 0.3 m, using a neutron probe (Model 503 DR, Campbell Pacific Nuclear, Martinez, California, USA) before each irrigation event throughout the growing season. Aluminium access tubes were installed at the center of the experimental sub-plots, extending to a depth of 1.5 m. The surface soil layer (0-30 cm) was sampled gravimetrically on a weekly basis. Calibration of the neutron probe was performed on-site, with the calibration equation for the probe given as follows: Pv = 57.43 × CR - 0.10 (R^2 = 0.98), where Pv represents the volumetric soil water content and CR is the count ratio.

The amount of irrigation water applied in the drip irrigation treatments was calculated using the following equation:

$$I = A \times \Delta s \times P \qquad (1)$$

where I is the amount of irrigation water applied (L), A is the plot area (m^2), Δs is the lack of soil moisture at a soil depth of 60 cm, and P represents the percentage of the irrigated area. The percentage of wetted area was monitored throughout the experimental period by tracking the canopy cover percentage; accordingly, the wetted percentage was determined prior to each irrigation event.

Actual seasonal evapotranspiration (ETa) values for maize were estimated based on the water balance equation:

$$ETa = R + I - Dp - Roff + \Delta SW \qquad (2)$$

where ETa is crop evapotranspiration (mm), R is precipitation (mm), I is the amount of irrigation water applied (mm); ΔSW is the change in soil water storage in the 120 cm soil profile between sowing and harvest (mm), Dp is deep percolation losses below the root zone (mm), and Roff is surface runoff from the experimental plots (mm).

Harvesting for each treatment and replicate was carried out mechanically over an area of 157.5 m^2 (25 m × 6.3 m). The grain yield data obtained were calculated on a plot basis, converted to a per-hectare basis, and expressed as kg ha^{-1} at 15% grain moisture content.

Grain yield and yield components of maize thousand grain weight and plant height were determined in the experimental years. Plant height measurements were taken by marking 3 plants in each plot and measuring their height every 7 d throughout the experiment, and the averages were calculated.

Water productivity (WP) of maize crop was determined on the basis of the yield and crop evapotranspiration for the growing period. Following equations were used for determination of WP (Howell et al., 1990):

$$WP = Y/ETa \qquad (3)$$

where WP in maize was determined by dividing the grain yield (Y, kg m^{-3}) by the actual ETa (mm) recorded during the growing season, while irrigation water productivity (IWP) reflected the ratio of yield to the total amount of irrigation water applied:

$$IWP = (Y - Yo)/I \qquad (4)$$

where IWP is the irrigation water productivity based on the seasonal irrigation water amount applied to any treatment (kg m^{-3}), Y is the grain yield of the treatment (kg ha^{-1}), Yo is the grain yield of the rainfed treatment (kg ha^{-1}), I is seasonal irrigation water applied to a certain treatment (mm) during the growing season.

Canopy temperature (Tc) measurements began during the second week of May, when approximately 70% canopy closure was reached, and continued until plants reached physiological maturity. Canopy temperature was recorded at four corners of each plot, at about 1 m above the canopy, and the mean value was used to represent each plot. All measurements were conducted under open-sky conditions between 12:00 and 14:00 h, when solar radiation was at its peak. During the same period, dry-bulb and wet-bulb air temperatures were monitored near the experimental area at a height of 1.5 m using an aspirated Assmann psychrometer (Sato Keiryoki MFG, Tokyo, Japan). The mean atmospheric pressure was assumed as 101.25 kPa, and the mean vapor pressure deficit (VPD) was calculated from psychrometric readings using the standard formula.

The crop water stress index (CWSI) was calculated based on the linear relationship between VPD and the canopy-air temperature difference (Tc - Ta) for a fully transpiring crop, as described by Idso et al. (1981), considering the defined upper and lower baselines:

$$CWSI = [(Tc - Ta) - LL)/(UL - LL)] \quad (5)$$

where Tc is the canopy temperature (°C), Ta is the air temperature (°C), LL is the non-water-stressed baseline (lower baseline) and UL is the non-transpiring upper baseline. The upper baseline calculated under water stress conditions was determined using values from RF treatment.

Statistical analysis

Data were analysed statistically using JMP Statistical software version 8.0 developed by SAS (SAS Institute, Cary, North Carolina, USA). Significant differences among treatment means were determined using the least significant difference (LSD) test (Steel and Torrie, 1980).

RESULTS AND DISCUSSION

Applied irrigation water amount and crop evapotranspiration

Climate data from the research years, when compared to long-term averages, showed that drier conditions prevailed during the growing season. While average temperatures generally remained close to long-term values, the maximum temperature in July reached 34 °C in 2020 and 36 °C in 2021, exceeding the long-term average of 33 °C. There was also a significant decrease in precipitation. While the long-term average total precipitation for the March-May period is 130 mm, precipitation was 49.4 mm in 2020 and 74 mm in 2021. Furthermore, it was determined that precipitation was very low after June in both years, and no precipitation was observed in July and August. This indicates that the plant's water requirements were largely met by irrigation during the research period, and that dry climate conditions were dominant during the experimental years.

The data on applied irrigation water amount, relative irrigation, crop evapotranspiration (ETa) and relative ETa for the different treatments in the experimental years are given in Table 3. Although some rainfall events occurred during the early part of the growing season, no irrigation was initially required. However, in order to ensure equal fertilizer application to all treatments, equal irrigation was applied on 6 May 2020 in the first year and on 10 May 2021 in the second year. Irrigation for each treatment was started on 28 May 2020 in the first year and 24 May 2021 in the second year, when the maize plant reached 40-45 cm in height and had 7-8 leaves, and when 50% of the available water in the 0-60 cm soil profile was depleted. During irrigation, the moisture deficit in the 0-60 cm soil profile was replenished weekly to field capacity, and irrigation was stopped approximately 1 mo before harvest after the milk ripening stage. In the first year, 586 mm of irrigation water was applied for full irrigation (FI), 445 mm for 75% deficit irrigation (DI_{75}), 303 mm for 50% deficit irrigation (DI_{50}), 162 mm for 25% deficit irrigation (DI_{25}), and 20 mm for rainfed (RF). In the second year, these values were 576, 437, 298, 159, and 20 mm, respectively. The similarity of climatic conditions during the research years resulted in the total amount of irrigation water applied being close to each other. Relative irrigation values clearly reflected the applied irrigation levels. In both experimental years, treatment FI had a relative irrigation value of 100%, while treatments DI_{75}, DI_{50}, and DI_{25} had relative irrigation rates of approximately 75.9%, 51.7%, and 27.6%, respectively. In treatment RF, the relative irrigation value remained at approximately 3%-4% in both years (Table 3).

Table 3. Seasonal irrigation, relative irrigation, actual crop evapotranspiration (Eta), relative ETa, total yield, yield reduction, water productivity (WP) and irrigation water productivity (IWP) values for the different treatments in the experimental years. FI: Full irrigation; DI_{75}: 75% of full irrigation; DI_{50}: 50% of full irrigation; DI_{25}: 25% of full irrigation; RF: rainfed.

Irrigation systems	Irrigation regimes	Seasonal irrigation	Relative irrigation	ETa	Relative ETa	Yield	Yield reduction	WP	IWP
		mm	%	mm	%	kg ha^{-1}	%	kg m^{-3}	
2020	FI	586	100.0	725	100.0	16020	0.0	2.2	1.3
	DI_{75}	445	75.9	604	83.3	15120	5.6	2.5	1.5
	DI_{50}	303	51.7	465	64.1	14770	7.8	3.2	2.2
	DI_{25}	162	27.6	333	45.9	13290	17.0	4.0	3.1
	RF	20	3.4	202	27.9	8240	48.6	4.1	0.0
2021	FI	576	100.0	734	100.0	18720	0.0	2.6	2.1
	DI_{75}	437	75.9	609	83.0	15030	19.8	2.5	1.9
	DI_{50}	298	51.7	473	64.4	14120	24.6	3.0	2.5
	DI_{25}	159	27.6	343	46.7	12540	33.0	3.7	3.7
	RF	20	3.5	215	29.3	6680	64.3	3.1	0.0

Actual ETa values of maize crops varied considerably depending on climate, volume of irrigation water applied, precipitation amounts during the growing season and the volume of stored water in the soil. It was also found that an increase in irrigation levels paralleled an increase in ETa values. The total seasonal ETa values were 725 mm and 604, 465 and 333 mm in FI, DI_{75}, DI_{50} and DI_{25} in 2020, respectively, while ETa was 202 mm in the RF treatment, which represented rainfed conditions. Similar trends occurred in 2021. The total seasonal ETa values were 734 mm and 609, 473 and 343 mm in FI, DI_{75}, DI_{50} and DI_{25}, respectively, while ETa was 215 mm in the RF treatment. These results demonstrate that increased irrigation water application directly corresponds to an increase in crop water use, and that water restriction resulted in a significant decrease in ETa. When relative ETa values were compared, it was observed that crop water use decreased significantly depending on the level of irrigation. Relative ETa values were 100% for treatment FI, and 83.3%, 64.1% and 45.9% for treatments DI_{75}, DI_{50}, and DI_{25}, respectively in 2020. The relative ETa value was 27.9% for the RF treatment. A similar trend was observed in 2021, with relative ETa values of 83.0%, 64.4% and 46.7% for treatments DI_{75}, DI_{50}, and DI_{25}, respectively (Table 3).

A clear relationship existed between the irrigation water applied and ETa, demonstrating a direct link between water availability and crop water use under Mediterranean environmental conditions. The results from this study support previous research conducted in semi-arid and Mediterranean climates, where water availability is the main limiting factor for ETa (Comas et al., 2019; Zou et al., 2021). As irrigation levels decreased, the reduction in ETa corresponded with the plant's adaptive response to water limitation via stomatal closure and reduced transpiration, as previously documented in maize subjected to water stress (Allakonon et al., 2022). The large reduction in ETa between full irrigation and rainfed treatments emphasizes the importance of supplemental irrigation for maize production under Mediterranean conditions, where summer rainfall is insufficient to meet crop water requirements and irrigation demand is high (Şen, 2023).

The ETa values expressed on a relative scale helped provide insight into how much water maize used based on how much water was available for it to be irrigated with.

A key finding of the study was that DI_{75} received approximately 76% of the irrigation water applied under FI, while maintaining about 83% of the ETa recorded under full irrigation across the two growing seasons. One reason for this is because drought stress caused by DI_{75} resulted in less water being lost as non-productive evaporative losses, e.g., through soil evaporation or drainage below root zone, as shown in earlier research studies like those conducted by Jiao et al. (2024). The similarity in relative ETa values between each year, regardless of differing weather conditions in each season, also demonstrates that maize water use varied little during the years studied as a result of the amount of irrigation applied to it.

Variation of soil water content

Figure 1 shows the changes in soil water content (SWC) before irrigation at an effective root zone depth of 60 cm under different irrigation treatments in the 2020 and 2021 experimental years. During the research years, SWC was measured from maize planting to harvest. In all treatments, SWC remained above 50% available moisture until the start of the irrigation treatments. After the start of irrigation treatments, SWC generally remained around 50% available moisture in the FI treatment, while in the DI_{75}, DI_{50}, and DI_{25} treatments, this value mostly remained below this level. In the RF treatment, SWC decreased over time and fell below the wilting point towards harvest.

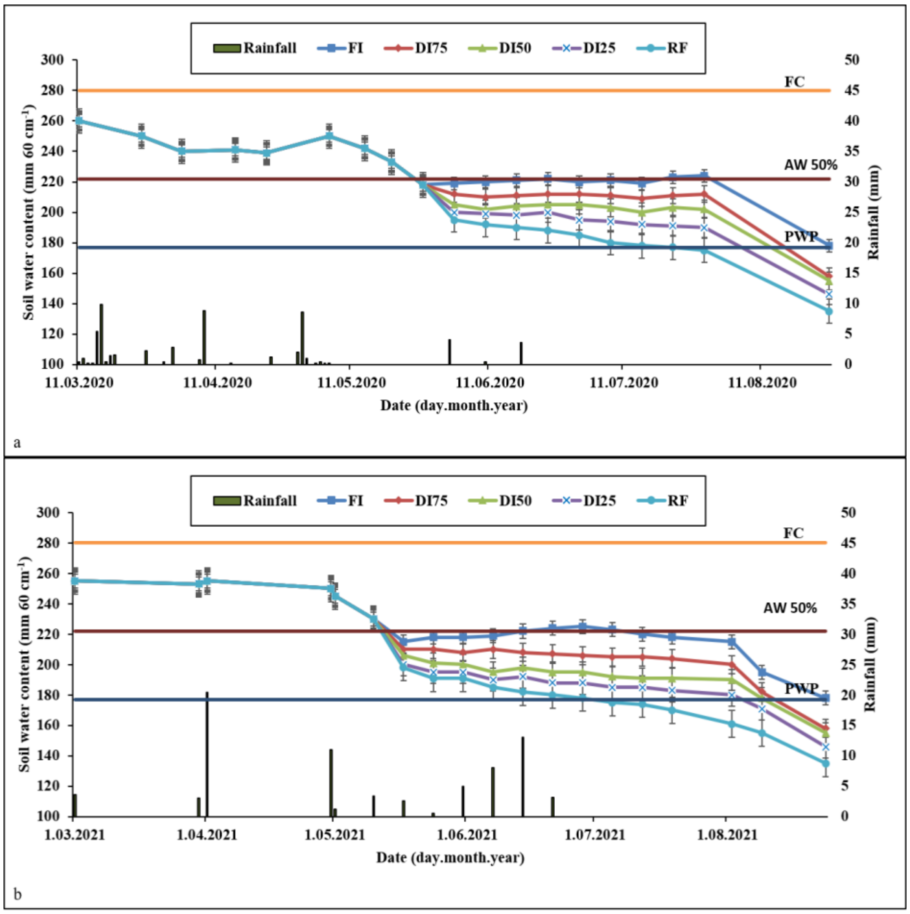

Figure 1. Soil water content variation prior to irrigations in maize for the experimental treatments during the study years, 2020 (a) and 2021 (b). Vertical bars represent the standard error of the mean ± SE (*n* = 14). FC: Field capacity; PWP: permanent wilting point; AW: available water; FI: full irrigation; DI_{75}: 75% of full irrigation; DI_{50}: 50% of full irrigation; DI_{25}: 25% of full irrigation; RF: rainfed.

The SWC dynamics observed in this study illustrate the effectiveness of the irrigation scheduling approach based on soil moisture depletion. Maintaining irrigation in the FI treatment at a maximum allowable depletion of approximately 50% of available soil water represents a practical balance between adequate water supply and efficient irrigation management in maize production (Attia et al., 2021). The progressive decline in soil moisture under deficit irrigation treatments demonstrates the intended water stress gradients, with each treatment experiencing distinct levels of water availability throughout the growing season. The fact that SWC in the RF treatment fell below the wilting point toward harvest highlights the severe water limitation under rainfed conditions in this semi-arid environment, a condition commonly associated with reduced maize productivity under erratic rainfall regimes (Madamombe et al., 2025).

Grain yield

The grain yields obtained during the experimental years are given in Table 3, and the ANOVA results and least significant difference (LSD) groupings are given in Table 4. In both years, the effect of irrigation treatments on grain yield was significant at the 1% ($P < 0.01$) level. In the first experimental year, the highest grain yield was obtained with 16 020 kg ha^{-1} in treatment FI, followed by treatments DI_{75}, DI_{50}, and DI_{25}, with yield values of 15 120, 14 770, and 13 290 kg ha^{-1}, respectively. The lowest yield was observed in treatment RF with 8240 kg ha^{-1}. A similar trend was observed in the second experimental year, with the highest yield of 18 720 kg ha^{-1} in treatment FI, followed by treatments DI_{75}, DI_{50}, and DI_{25} with yields of 15 030, 14 120, and 12 540 kg ha^{-1}, respectively. The RF treatment again yielded the lowest yield value with 6680 kg ha^{-1}. Yield reduction values increased in parallel with the decrease in irrigation level; in 2020, they were 5.6%, 7.8% and 17.0% in treatments DI_{75}, DI_{50} and DI_{25} respectively, and 48.6% in the RF treatment. In 2021, the yield reduction in the same treatments was 19.8%, 24.6% and 33.0% respectively, while the highest reduction was determined in the RF treatment with 64.3%. These findings show that the decrease in irrigation water level significantly limits grain yield and that yield losses increase significantly, especially with the intensification of water restriction.

Table 4. Maize yield, thousand grain weight, plant height and crop water stress index (CWSI) values under different treatments in the experimental years. Means followed by the same lowercase letter within each year and column are not significantly different at $P > 0.05$ according to the LSD test. **Significance at $P < 0.01$. FI: Full irrigation; DI_{75}: 75% of full irrigation; DI_{50}: 50% of full irrigation; DI_{25}: 25% of full irrigation; RF: rainfed.

Experimental years	Irrigation regimes	Yield	Thousand grain weight	Plant height	CWSI
		kg ha^{-1}	g	cm	
2020	FI	16 020^{a}	364.8^{a}	316.0^{a}	0.25^{e}
	DI_{75}	15 120^{b}	341.7^{b}	309.7^{b}	0.35^{d}
	DI_{50}	14 770^{c}	324.7^{c}	306.7^{b}	0.48^{c}
	DI_{25}	13 290^{d}	302.6^{d}	298.3^{c}	0.57^{b}
	RF	8 240^{e}	281.0^{e}	270.0^{d}	0.66^{a}
Statistical analysis	LSD (0.05)	156	10.71	4.09	0.07
	Probability	0.0001**	0.0001**	0.0001**	0.0001**
	CV, %	0.6	1.8	0.7	8.0
2021	FI	18 720^{a}	335.0^{a}	311.7^{a}	0.21^{e}
	DI_{75}	15 030^{b}	313.0^{b}	302.7^{ab}	0.31^{d}
	DI_{50}	14 120^{c}	284.0^{c}	295.3^{bc}	0.43^{c}
	DI_{25}	12 540^{d}	265.0^{d}	290.3^{c}	0.52^{b}
	RF	6 680^{e}	236.0^{e}	274.0^{d}	0.61^{a}
Statistical analysis	LSD (0.05)	143	5.21	10.21	0.06
	Probability	0.0001**	0.0001**	0.0003**	0.0001**
	CV, %	1.57	1.97	1.84	7.6

The grain yield responses to deficit irrigation observed in this study are consistent with previous findings in semi-arid and Mediterranean environments. The relatively modest yield reductions under DI_{75} (5.6% in 2020 and 19.8% in 2021) align with the findings of Jiao et al. (2024), who reported that mild deficit irrigation can maintain relatively high maize yield while improving water productivity. This suggests that moderate water restrictions, particularly when severe stress is avoided during sensitive growth stages, can achieve substantial water savings with acceptable yield penalties.

The progressive increase in yield reduction with decreasing irrigation levels indicates that maize productivity declined as water stress became more severe, a pattern well documented in maize under strategic deficit irrigation (Comas et al., 2019; Wang et al., 2023).

The yield reduction of approximately 8% under DI_{50} in 2020 and 25% in 2021 falls within the range reported in the global meta-analysis by Allakonon et al. (2022), who showed that maize yield losses under deficit irrigation increase with stress severity and depend strongly on environmental conditions. The year-to-year variability in yield responses also highlights the importance of seasonal weather patterns in modulating the effects of deficit irrigation (Simić et al., 2023). The more severe yield penalties observed in 2021 may therefore be associated with greater water limitation during reproductive development, particularly around flowering and grain filling, because drought stress at these stages has been shown to reduce grain biomass and yield formation in maize (Salgado-Aguilar et al., 2020).

The substantial yield reductions under DI_{25} (17% in 2020 and 33% in 2021) and RF (49% in 2020 and 64% in 2021) indicate that severe water stress results in disproportionately large yield losses. This non-linear response suggests a threshold effect, beyond which the plant's adaptive mechanisms are insufficient to maintain productivity. Similar threshold responses have been documented by Wang et al. (2023), who emphasized that there is a critical water deficit level beyond which yield losses accelerate rapidly due to irreversible damage to reproductive processes. These findings underscore the importance of maintaining adequate irrigation, particularly during critical growth stages, to avoid catastrophic yield losses in water-limited environments.

Thousand grain weight

The thousand-grain weight values obtained in the experiment, along with the results of ANOVA and LSD groupings, are presented in Table 4. According to ANOVA results, the effect of irrigation treatments on thousand-grain weight was significant at the 1% ($P < 0.01$) level in both experimental years. Thousand-grain weight values showed a regular decrease depending on the decrease in irrigation level, and all treatments were found to be different from each other according to the LSD grouping. Indeed, in 2020, the highest thousand-grain weight was determined in the FI treatment with 364.8 g, while this value was determined as 341.7, 324.7 and 302.6 g in the DI_{75}, DI_{50} and DI_{25} treatments, respectively, and the lowest value was obtained in the RF treatment with 281.0 g. Similarly, in 2021, the highest thousand-grain weight was determined in the FI treatment with 335 g, this value decreased to 313, 284, and 265 g in the DI_{75}, DI_{50}, and DI_{25} categories respectively, and reached its lowest level in the RF treatment with 236 g. These results show that water restriction negatively affects the grain filling process, causing significant reductions in thousand-grain weight.

The progressive reduction in thousand-grain weight with increasing water stress reflects the sensitivity of the grain filling process to water availability. During grain filling, water stress limits photosynthetic capacity and reduces the translocation of assimilates to developing kernels, resulting in lighter grains with reduced starch accumulation. This physiological interpretation is supported by Yang et al. (2019), who showed in maize that water-deficit conditions impair photosynthetic performance and leaf water relations, thereby contributing to poorer grain formation under stress. The 23% reduction in thousand-grain weight under rainfed conditions in 2020 and 30% reduction in 2021 demonstrate the severe impact of prolonged water stress on kernel development. Similar effects have been reported in maize under deficit irrigation, where reduced irrigation significantly decreased thousand-grain weight and adversely affected grain quality traits (Özdemir and Sade, 2024).

The consistent ranking of treatments across both years, with clear differentiation among irrigation levels, indicates that thousand-grain weight is a reliable indicator of water stress severity. The strong response of this parameter to irrigation treatments suggests that it integrates the cumulative effects of water stress throughout the grain filling period. This sensitivity makes thousand-grain weight a useful indicator for assessing the adequacy of irrigation management, particularly in retrospective evaluations of crop performance under varying water availability conditions.

Plant height

Plant height values from the experiment, along with ANOVA and LSD grouping results, can be seen in Table 4. Based on the ANOVA results, there were highly significant ($p < 0.01$) effects for the irrigation treatments on plant height in each year of the experiment. In 2020, the tallest plants were grown in the FI treatment with a mean height of 316.0 cm, followed by the DI_{75} treatment with a mean height of 309.7 cm and the DI_{50} treatment with a mean height of 306.7 cm. As the amount of irrigation applied decreased, the average plant heights also decreased: 298.3 cm in the DI_{25} treatment and 270.0 cm in the RF treatment. Similar trends were observed in 2021. The largest plant heights were achieved in the FI treatment (311.7 cm), while the average heights in the DI_{75} (302.7 cm), DI_{50} (295.3 cm), and DI_{25} (290.3 cm) treatments were all lower than those of the FI treatment. The smallest plant heights were achieved in the RF treatment (274.0 cm). The LSD groupings indicated that there were highly significant differences among all treatments except for DI_{25} and DI_{50}, and further indicated that there were large differences between the fully irrigated treatments and the RF treatment, which suggests that the imposition of water restrictions has a significant impact on the vegetative development of maize.

Under water-stressed conditions, the decrease in plant height is indicative of a morphological response, where cell expansion is restricted and overall vegetative growth is adversely affected. The approximately 15% decrease in plant height under rainfed conditions relative to full irrigation in this study is consistent with previous findings showing that water deficit reduces plant height and limits vegetative growth in maize (Huang et al., 2023). Although plant height does not always have a direct relationship with grain yield, it is generally an indicator of overall plant vigor and developmental status. The relatively small decreases in plant height under the moderately deficit-irrigated treatments (DI_{75} and DI_{50}) suggest that these treatments still allowed sufficient vegetative growth to support reasonable productivity, whereas the larger decreases observed under DI_{25} and RF indicate that plant development was more severely constrained by water limitation.

Water productivity and irrigation water productivity

Water productivity (WP) and irrigation water productivity (IWP) values for all applications throughout the study years are presented in Table 3. Water productivity and IWP values showed significant variations depending on the irrigation level. When WP values were examined, it was observed that the productivity obtained from unit water consumption generally increased as the amount of irrigation water decreased. Indeed, while the WP value was determined as 2.2 kg m^{-3} in the FI treatment in 2020, this value increased to 2.5, 3.2 and 4.0 kg m^{-3} in the DI_{75}, DI_{50} and DI_{25} treatments, respectively. The highest WP value was obtained in the RF treatment with 4.1 kg m^{-3}. A similar trend was observed in 2021 as well; the WP values were calculated as 2.44, 2.34, 2.77, and 3.57 kg m^{-3} for treatments FI, DI_{75}, DI_{50}, and DI_{25}, respectively, and 3.14 kg m^{-3} for the RF treatment.

When evaluated in terms of IWP, it was determined that the yield obtained per unit of irrigation water increased depending on the decrease in the amount of irrigation water. Accordingly, in 2020, the IWP value was 1.3 kg m^{-3} for treatment FI, while it was calculated as 1.6, 2.2, and 3.1 kg m^{-3} for treatments DI_{75}, DI_{50}, and DI_{25}, respectively. In 2021, the IWP values for the same treatments were 1.91, 1.72, 2.14, and 3.46 kg m^{-3}, respectively. Since no irrigation was applied to the RF treatment, the IWP value was not calculated. These results show that WP increased as irrigation water levels decreased, although maximum productivity did not coincide with maximum grain yield. Thus, full irrigation was more effective for achieving the highest yield, whereas lower irrigation levels provided an advantage in terms of WP under limited water conditions.

The substantial increase in WP under deficit irrigation, particularly under DI_{25}, demonstrates one of the main advantages of strategic water management in water-scarce regions. This finding is consistent with the global meta-analysis of Allakonon et al. (2022), who showed that deficit irrigation can improve WP while limiting yield losses depending on stress severity and environmental conditions. The marked improvements in IWP observed under DI_{25} further highlight the efficiency gains achievable when irrigation water is applied strategically to maximize returns per unit of applied water. Similar improvements in maize WP under optimized deficit irrigation have also been reported by Wang et al. (2023) and Jiao et al. (2024).

The relatively stable ranking of WP and IWP across treatments in both years suggests that the response of maize water-use efficiency to irrigation level was consistent under the climatic conditions of the study. These findings indicate that moderate to severe reductions in irrigation can substantially improve WP, although such gains should be interpreted together with the accompanying reductions in grain yield.

Crop water stress index

The time-dependent variation of pre-irrigation crop water stress index (CWSI) values for different irrigation treatments during the 2020 and 2021 growing seasons is presented in Figures 2a-2b. Psychrometric measurements were used to determine the air vapor pressure deficit (VPD) in CWSI calculations, and empirical lower and upper baseline equations were used to establish the relationship between canopy temperature (Tc) - air temperature (Ta) and CWSI. In this context, the lower baseline (LL) and upper baseline (UL) equations were determined separately for each growing season. For 2020, the lower and upper baseline equations were LL: Tc − Ta = -3.10 VPD + 1.35 and UL: Tc − Ta = 0.0017 VPD + 4.15, respectively. For 2021, the corresponding equations were LL: Tc − Ta = -2.75 VPD + 1.08 and UL: Tc − Ta = 0.0025 VPD + 4.06, respectively.

In this study, CWSI measurements were initiated on 26 May and concluded on 28 July in 2020 and started on 9 May and completed on 18 July in 2021. It was determined that CWSI values varied depending on weather conditions and SWC throughout the measurement periods. Examination of the figures shows that CWSI values were lower in the FI and DI_{75} treatments, where water stress was limited, and higher in the DI_{50}, DI_{25}, and RF treatments, where water constraint was more pronounced.

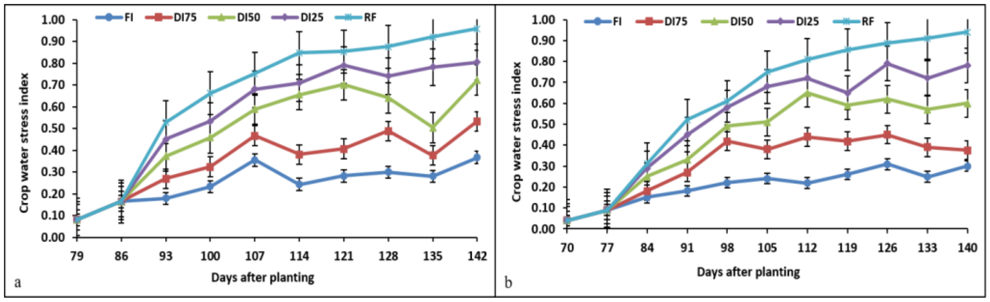

Figure 2. Crop water stress index (CWSI) variation in maize for the experimental treatments during the study years, 2020 (a) and 2021 (b). Vertical bars represent the standard error of the mean ± S.E. (n = 14). FI: full irrigation; DI_{75}: 75% of full irrigation; DI_{50}: 50% of full irrigation; DI_{25}: 25% of full irrigation; RF: rainfed.

The CWSI values, their ANOVA results, and LSD groupings are given in Table 4. According to ANOVA, the effect of irrigation treatments on CWSI was found significant at the 1% ($P < 0.01$) level in both years. Indeed, in 2020, the lowest CWSI value was determined in the FI treatment at 0.25, while this value was calculated as 0.35, 0.48, and 0.57 in the DI_{75}, DI_{50}, and DI_{25} treatments, respectively, and the highest value was obtained in the RF treatment at 0.66. Similarly, in 2021, the lowest CWSI value was detected in the FI treatment at 0.21, while values of 0.31, 0.43, and 0.52 were determined in the DI_{75}, DI_{50}, and DI_{25} treatments, respectively, and the highest stress level was observed in the RF treatment at 0.61. The LSD groupings revealed significant differences in CWSI among irrigation treatments. These results clearly demonstrate that a decrease in irrigation water quantity regularly increases water stress in the plant and that CWSI is a reliable stress indicator sensitive to irrigation levels.

The CWSI threshold of approximately 0.23 was determined under the Mediterranean conditions of the study area. Notably, this value was calculated as the average of 0.25 in 2020 and 0.21 in 2021 under full irrigation. This value is close to recently reported threshold values for maize under different environmental and irrigation conditions, including 0.299 for summer maize and 0.31 under subsurface drip irrigation conditions (Qin et al., 2021; Das et al., 2024). Moreover, Liao et al. (2024) emphasized the importance of growth stage-specific baselines for accurate CWSI interpretation. Therefore, the CWSI value obtained under full irrigation under the same field conditions, i.e., approximately 0.23, can serve as a practical reference threshold for irrigation scheduling in similar Mediterranean environments.

As indicated above, the increase in CWSI values with decreasing irrigation levels illustrates the sensitivity of this thermal-based indicator to variations in water stress. Additionally, the lack of overlap among LSD groups across all irrigation treatments demonstrates that CWSI can differentiate among varying degrees of water stress, making it a valuable tool for real-time irrigation management based on crop water status. This utility also stems from the fact that CWSI provides immediate information on plant water status, which can support decisions regarding irrigation timing and stress-based crop monitoring (Bo et al., 2023). Furthermore, the consistent ranking of CWSI across two separate growing seasons, despite differing weather conditions, suggests that CWSI provides reliable assessments of crop water status under Mediterranean conditions.

The CWSI-based irrigation scheduling provides several advantages over soil- or weather-based methods. First, as a plant-based indicator, CWSI integrates the combined effects of available soil water, atmospheric evaporative demand, and crop physiological responses, thereby providing a comprehensive assessment of crop water status (Pradawet et al., 2023). Second, because temperature measurement is non-invasive and thermal cameras and infrared thermometers are becoming increasingly available, CWSI is becoming more accessible for practical irrigation management (Mangus et al., 2016). Finally, CWSI can be integrated into variable-rate irrigation systems to optimize water application across spatially variable fields in the context of precision agriculture and site-specific irrigation management.

Relationships between CWSI, grain yield, thousand grain weight, plant height, WP and IWP

The relationships between CWSI and five main maize traits, namely grain yield, thousand-grain weight, plant height, WP, and IWP, were investigated over 2 yr. As depicted in Figures 3a-3e, CWSI was associated with the above-mentioned traits. It was found that there were significant second-order relationships between CWSI and the examined yield, growth, and WP traits. More specifically, there was a clear decreasing trend in grain yield, thousand-grain weight, and plant height as CWSI increased, indicating that water stress negatively affected both generative and vegetative development in maize. Additionally, the explanatory power of the relationships between CWSI and grain yield was found to be quite high; the coefficients of determination (R^2) were calculated as R^2 = 0.94 in the first year and R^2 = 0.92 in the second year. Likewise, the explanatory power of the relationships between CWSI and thousand-grain weight was also found to be very high in both years, expressed through significant second-order equations with R^2 = 0.99 and R^2 = 0.99 values, respectively. Moreover, the explanatory power of the relationships between CWSI and plant height was also very high; these values were calculated as R^2 = 0.94 and R^2 = 0.97, respectively. Significant relationships were also identified between CWSI and WP indicators. Specifically, the relationship between CWSI and WP was calculated as R^2 = 0.96 in the first year and R^2 = 0.62 in the second year, whereas the relationship between CWSI and IWP had very high coefficients of determination in both years, i.e., R^2 = 0.99 and R^2 = 0.99, respectively. Thus, the findings of the present study show that changes in water stress levels are important not only for the yield and growth characteristics of maize, but also for its water use performance. In conclusion, the strong relationship established between yield and CWSI shows that CWSI may be used to estimate yield-related performance in maize. Furthermore, this index demonstrates that, in addition to being a reliable measure for assessing water stress in plants, it is also a useful indicator of yield, growth, and water use efficiency.

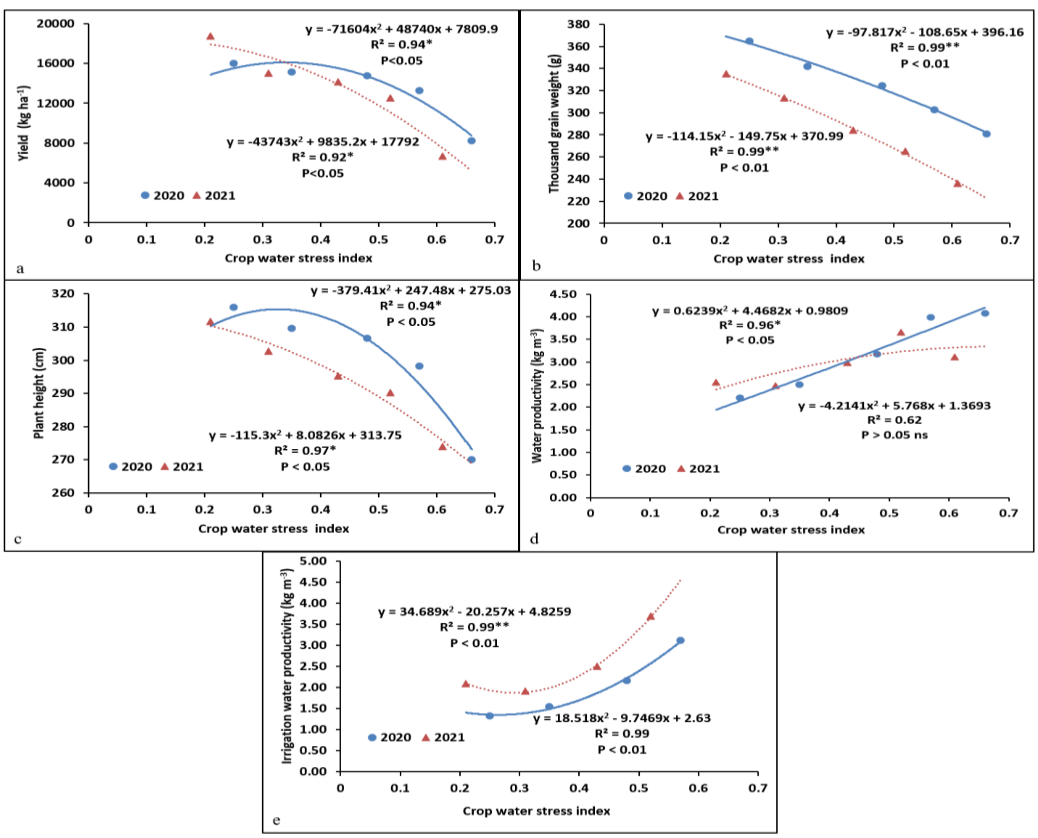

Figure 3. Relationships between crop water stress index and yield (a), thousand grain weight (b), plant height (c), water productivity (d), and irrigation water productivity (e) for maize in two growing seasons. *, **Significant differences at 0.05 and 0.01 probability levels, respectively, according to LSD.

The second-order polynomial relationships between CWSI and crop performance parameters found in this study are in agreement with recent findings by Liao et al. (2024), who showed that CWSI can effectively characterize maize productivity across different growth stages. The high coefficients of determination (R^2 values ranging from 0.92 to 0.99) show that CWSI explains most of the variation in yield, growth, and WP parameters and thus can serve as a powerful tool for irrigation management. The second-order nature of the established relationships indicates that the effects of water stress become increasingly severe as CWSI values exceed the optimal threshold, while also reflecting the nonlinear physiological responses of maize to progressive water deficits. The particularly strong relationships between CWSI and thousand-grain weight (R^2 = 0.99 in both years) and between CWSI and IWP (R^2 = 0.99 in both years) highlight the high sensitivity of these parameters to water stress. The close association between CWSI and thousand-grain weight likely reflects the critical importance of water availability during grain filling, since water deficit can disrupt kernel development, shorten kernel-filling duration, and reduce final kernel weight in maize (Alam et al., 2021). The strong relationship between CWSI and IWP shows that water stress levels, as reflected by canopy temperature, are effective indicators of irrigation water use efficiency, providing a mechanistic link between plant physiological status and agronomic WP.

The robust associations between CWSI and the studied parameters support the application of CWSI as a practical tool for irrigation scheduling and crop performance assessment in Mediterranean maize production systems. By monitoring CWSI throughout the growing season and keeping CWSI values below critical thresholds during sensitive growth stages, farmers can apply precision irrigation strategies that improve the balance between yield and water conservation goals (Nakabuye et al., 2022; Das et al., 2024). The combination of CWSI-based irrigation scheduling with deficit irrigation strategies represents a promising approach for sustainable maize production in water-limited Mediterranean regions, where adaptive irrigation strategies are necessary to maintain agricultural productivity under increasing water scarcity and climatic variability (Igwe et al., 2025). Based on the findings of the current study, it can be concluded that strategic deficit irrigation using CWSI can allow substantial water savings while maintaining satisfactory productivity levels in Mediterranean maize production systems. The CWSI threshold of approximately 0.23 represents a practical reference for irrigation scheduling under Mediterranean conditions. The demonstrated trade-offs between yield and WP can help farmers and water managers make appropriate decisions depending on local water availability. These results contribute to the growing body of evidence supporting the adoption of precision irrigation technologies for sustainable agricultural intensification in water-scarce regions.

CONCLUSIONS

The results showed that crop water stress index (CWSI) can be used as a practical indicator for assessing maize water status and supporting irrigation scheduling under Mediterranean conditions. The mean CWSI values under full irrigation were 0.25 in 2020 and 0.21 in 2021, resulting in an average threshold value of approximately 0.23. Strong second-order polynomial relationships were also obtained between CWSI and grain yield, thousand-grain weight, plant height, water productivity, and irrigation water productivity, indicating that CWSI can effectively reflect both crop performance and water stress severity.

Full irrigation produced the highest grain yield, averaging 17 370 kg ha^{-1} across the two growing seasons. However, deficit irrigation (DI) improved water productivity as irrigation water decreased. Among the deficit irrigation treatments, 75% irrigation water (DI_{75}) provided a relatively balanced response by maintaining comparatively high yield while reducing irrigation water use, whereas 25% (DI_{25}) produced the highest water productivity and irrigation water productivity but with greater yield reduction. Overall, the findings indicate that CWSI-based monitoring combined with DI can support more efficient irrigation management for maize production under water-limited Mediterranean conditions.

Author contribution

Conceptualization: E.G., Y.B.Ç. Methodology: E.G., Y.B.Ç., M.Ö., A.B. Formal analysis: E.G., Y.B.Ç., M.Ö., A.B., B.D. References: E.G., Y.B.Ç. Data collection: E.G., Y.B.Ç., M.Ö., A.B., B.D. Drafting the original manuscript: E.G., Y.B.Ç., M.Ö., A.B., B.D. Review and editing: A.B., Y.B.Ç., B.D. Supervision: E.G., Y.B.Ç., M.Ö., A.B., B.D. All authors have read and accepted the published version of the article.

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