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RESEARCH ARTICLE

Optimizing water use in aerobic rice: Evaluating drip irrigation strategies and crop water stress index under Mediterranean conditions

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ABSTRACT

Increased limited water resources coupled with the increasing effect of climate change calls for more efficient use of water in plant production in the Mediterranean region. Therefore, assessment of threshold level of crop water stress index (CWSI) is of paramount importance for precision irrigation scheduling for rice in 2019 and 2020 under the Mediterranean environmental conditions. The experimental treatments consisted of two irrigation methods namely surface drip (DI) and subsurface drip systems (SDI), three irrigation levels designated as plant pan coefficients ($I_{1.00}$: Class A-pan (Ep) × 1.00; $I_{1.25}$: Class A-pan Ep × 1.25 and $I_{1.50}$: Class A-pan Ep × 1.50) and conventional flooding (CF) method as control plot. Canopy temperatures were measured throughout the growing season with an infrared thermometer and depending on the plant canopy temperature (Tc) and air temperature (Ta) difference (Tc - Ta) and air vapor pressure deficit (VPD), the equation of the lower baseline without water stress was determined as Tc - Ta = -2.2069VPD + 0.8263, and the upper baseline calculated under water stress conditions using values obtained from plants cut on different days was determined as 5.08 °C. Two years seasonal average CWSI values ranged from 0.09 in CF to 0.34 in SDI-$I_{1.00}$. According to the obtained results, it was determined that the infrared thermometer technique could be used in the irrigation programming of rice. It has been determined that if this technique is used in Mediterranean conditions, irrigation scheduling can be done in such a way that the average CWSI value is kept around 0.15 for drip irrigation, which provides water savings throughout the season.

Key words: Aerobic rice cultivation, crop water stress index, irrigation scheduling, paddy.

INTRODUCTION

Rice (*Oryza sativa* L.) is one of the most critical food crops globally due to its central role in the diets of more than half of the world's population. While traditional paddy systems in Asia benefit from naturally flooded conditions, water-scarce regions face challenges in maintaining such water-intensive practices. The conventional method of continuous flooding is not sustainable under Mediterranean and semi-arid climates, prompting a shift towards more efficient irrigation strategies (Gao et al., 2015). Among these, drip irrigation—including both surface and subsurface systems—has gained attention for its capacity to enhance water use efficiency (WUE), nutrient uptake, and crop yield, particularly when combined with proper fertigation practices.

With increasing water scarcity, the role of scientific irrigation scheduling has become vital, especially in high water-consuming crops such as rice. Subsurface drip irrigation has demonstrated promising results in conserving water and improving productivity across diverse cropping systems (Li et al., 2021). Accurate irrigation management depends on timely and reliable evaluation of crop water status and demand at different growth stages. In this context, plant-based indicators are often more sensitive than soil-based methods for early detection of stress. The crop water stress index (CWSI), calculated based on the difference between canopy and air temperatures along with vapor pressure deficit, has been widely validated across crops as a reliable metric for quantifying plant water stress and guiding irrigation scheduling (Yadav et al., 2024).

Monitoring canopy temperature a key input for CWSI offers a non-invasive and scalable means to assess water deficit. Under drought conditions, stomatal closure leads to reduced transpiration and photosynthesis, resulting in elevated canopy temperature. This physiological response has been consistently observed in crops such as wheat, maize, and rice (Mahmoodi et al., 2021). Thus, CWSI has evolved from a research metric to a practical decision-support tool in irrigation management, helping to reduce water loss, maintain yield, and optimize irrigation timing (Godson Amamoo et al., 2022).

Many researchers have addressed the impact of water stress on crop physiological activity and growth. The CWSI has been applied in many different crops, such as wheat (Kumari et al., 2024; Yadav et al., 2024), cotton (Li et al., 2021), rice (Gao et al., 2015; Xu et al., 2016; Godson Amamoo et al., 2022; Ramos-Fernández et al., 2024), soybean (Karaca et al., 2018), maize (Bai et al., 2022), black cumin (Irik et al., 2024) and black gram (Mahmoodi et al., 2021). These research results indicate that CWSI can serve as a reliable tool for both irrigation scheduling and yield estimation in rice production systems.

The declining availability of freshwater resources for agricultural irrigation has highlighted the need to improve water productivity in paddy rice, which is among the most water-demanding crops. Accordingly, this study aims to evaluate water stress levels in rice cultivated under surface and subsurface drip irrigation systems in comparison to conventional flooding, within the context of Mediterranean climatic conditions. Additionally, the study seeks to assess the applicability of the crop water stress index (CWSI) in irrigation scheduling and to determine a threshold CWSI value suitable for guiding irrigation decisions.

MATERIALS AND METHODS

Experimental site and soil

The field trials took place in 2019 and 2020 at the experimental plots of the Alata Horticultural Research Institute in Tarsus, southern Turkey. Positioned at 60 m elevation (36°53′ N, 34°57′ E), the site experiences a typical Mediterranean climate: Winters are usually mild and rainy, while summers can be both hot and dry. Over nearly seven decades (1950-2019), regional records indicate an average of 616 mm precipitation each year, with July marking the peak of monthly evaporation 212.1 mm while annual evaporation totals reach 1478 mm (MGM, 2020). Average temperatures hover around 18.2 °C, but can swing from a low of 3.9 °C in January to a high of 27.2 °C in August. Relative humidity averages just above 70% through most of the year.

As a result of the analysis of disturbed and undisturbed soil samples taken from different points of the experimental area, some properties of the soil were determined (Table 1). According to the layers, soil pH varied between 7.8-8.0, salt content was 0.4-0.5 dS m^{-1}, bulk density was 1.34-1.43 g cm^{-3}, field capacity was 29.75-31.15 g g^{-1} and wilting point was 20.11-22.36 g g^{-1}. It was observed that the soils of the experimental area had a clay texture at 0-30 cm soil depth, silty clay at 30-90 cm depth and silty clay loam at 90-120 cm. The usable water amount at 90 cm profile depth was 111 mm. Field capacity and wilting point water contents were determined as 384 and 273 mm in depth.

Table 1. Physical and chemical properties of different soil layers of the experimental field. FC: Field capacity; WP: permanent wilting point; BD: bulk density; OM: organic matter; SiC: silty clay; SiCL: silty clay loam.

Soil depth	Sand	Silt	Clay	Texture class	FC	WP	BD	EC	pH	$CaCO_3$	P_2O_5	K_2O	OM
cm	%	%	%		— g g^{-1} —		g cm^{-3}	dS m^{-1}		%	— kg ha^{-1} —		%
0-30	15.9	39.8	44.3	C	31.14	21.65	1.34	0.5	7.8	27.78	3.8	105.6	1.46
30-60	13.6	44.1	42.3	SiC	30.79	21.98	1.39	0.5	7.8	28.80	1.1	74.18	1.03
60-90	10.0	48.0	42.0	SiC	31.15	22.36	1.40	0.4	8.0	32.80	0.6	43.01	0.66
90-120	10.3	52.0	37.8	SiCL	29.75	20.11	1.43	0.5	8.1	35.31	0.2	30.11	0.44

Experimental design and irrigation treatments

The study was carried out according to the randomized block split plot design with three replicates. The experiment was created as main plots with two different irrigation methods (subsurface and surface), subplots with three irrigation levels according to plant pan coefficient values (I_1: Class A-pan (Ep) × 1.00; I_2: Ep × 1.25 and I_3: Ep × 1.50) and the control plot was created as conventional flooding (CF) method.

Class A evaporation pan

To determine the amount of irrigation water to apply, a Class A evaporation pan galvanized, 121 cm in diameter and 25.5 cm deep was set up on a wooden platform about 15 cm above ground within the trial area. During measurements, the water level in the pan was generally maintained 5.0-7.5 cm below the rim.

Irrigation water characteristics

Irrigation for the experimental plots was drawn from the State Hydraulic Works (DSI) canal, which supplies water via the Institute's Soil and Water Resources Center. The chemical characteristics of the irrigation water were determined following Richards (1954), and are provided in Table 2. Based on electrical conductivity (EC) and sodium adsorption ratio (SAR) values, the water fell into the C_2S_1 classification (Richards, 1954).

Table 2. Some chemical properties of irrigation water used in the current research. EC: Electrical conductivity; SAR: sodium adsorption ratio.

		Cations					Anions					
EC	pH	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	Total	CO_3	HCO_3^-	Cl^-	SO_4	Total	SAR
dS m^{-1}		——— meq L^{-1} ———					——— meq L^{-1} ———					
0.464	8.04	1.80	3.11	0.36	0.03	5.30	0.77	3.26	0.98	0.29	5.30	0.23

Drip irrigation systems

For both surface (DI) and subsurface drip irrigation (SDI) treatments, lateral pipes with a diameter of 20 mm were used. Pressure-regulated emitters, spaced 40 cm apart, were installed along these pipes. Each emitter had a discharge rate of 2 L h^{-1}, selected in consideration of the soil's infiltration capacity (Geoflow Corte Madera, California, USA). In the SDI system, specialized lateral pipes were used to prevent roots from reaching the emitters. These pipes were buried at a depth of 25 cm below the soil surface, and both the main and manifold pipes were also placed underground. A totalizing flow meter (Green-Gutentop water meter, Taizhou Green Valves, Yuhuan City, Taizhou, Zhejiang Province, China) was installed at the control unit to measure total flow distributed to all replications in each treatment. In the subsurface drip irrigation system, air-release valves have been installed at the manifold outlets. The subsurface laterals are equipped with anti-siphon features. The spacing between laterals was set at 60 cm.

In the conventional flooding method, the experimental plots were first leveled and then surrounded by bunds 30 cm in height. During irrigation, water was distributed across the field via the main pipeline, delivered to manifolds, and the volume applied was accurately monitored using a water meter.

Plant material, sowing, fertilization, and crop management practices

In this study, the imazamox (IMI)-group 'Rekor CL' rice (*Oryza sativa* L.), developed by the Trakya Agricultural Research Institute (Edirne, Türkiye), was selected due to its resistance to both red rice and conventional rice herbicides, thus providing effective control of herbicide-resistant weeds. Sowing was performed with a row spacing of 20 cm, on 24 May 2019 in the first year and 2 June 2020 in the second year. The experimental plots were designed to be 20 m in length and 5 m in width. Harvesting was carried out on 1st October 2019 and 13 October 2020 for the first and second years, respectively.

For basal fertilization, 250 kg ha^{-1} diammonium phosphate (DAP) (18-46-0) fertilizer was applied at sowing. For topdressing, ammonium sulfate (21% N) was divided into three equal portions and applied at a rate of 170 kg ha^{-1} during stem elongation, tillering, and grain filling stages, resulting in a total application of 500 kg ha^{-1}. Additionally, foliar fertilization was conducted to mitigate any potential adverse effects of the herbicide on the rice plants. 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 (1952-2020) climatic data for the region are presented in Figure 1.

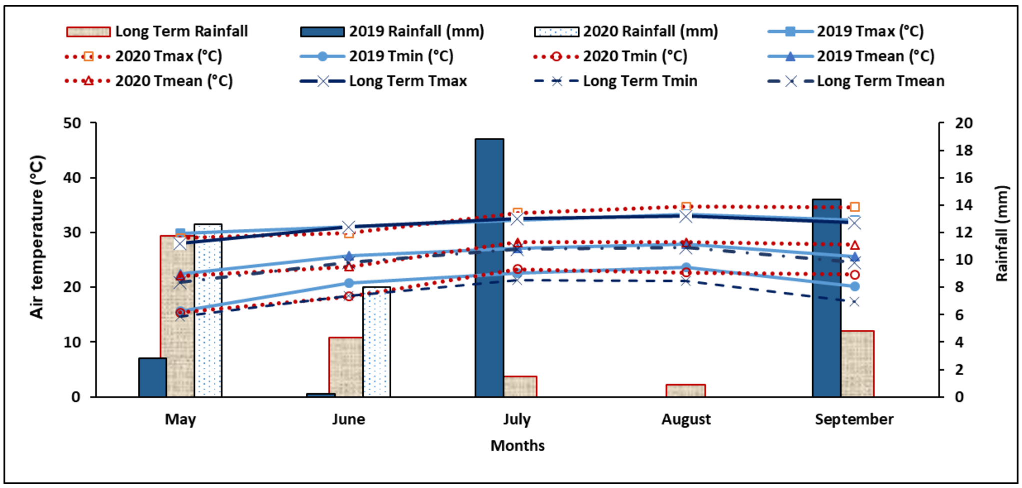


Figure 1. Mean monthly weather data in the experimental years along with long-term historical means (1952-2020).

Soil water content (SWC) was measured at four depths in increments of 0.3 m (30, 60, 90, and 120 cm), using a neutron probe (Model 503 DR, Campbell Pacific Nuclear, Martinez, California, USA) before each irrigation event throughout the growing season. Aluminum 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 = 58.52 × CR - 0.12 (R^2 = 0.96), 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. Cumulative evaporation values and sub-application coefficients (1.00, 1.25, and 1.50) were determined according to the method described by Doorenbos and Pruitt (1977):

$$I = A \times Epan \times kp \times P \quad (1)$$

where I is the amount of irrigation water applied (L), A is the plot area (m^2), Epan is the cumulative evaporation from the pan (mm), kp is the pan coefficient used in the experiment, and P represents the percentage of the irrigated area. In these applications, the total plot area was accepted as the irrigated area, and this value remained constant throughout the growing season.

In the drip irrigation treatments, actual seasonal evapotranspiration (ETa) values for rice were estimated based on the water balance equation:

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

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).

The water balance equation was used to estimate seasonal actual yield evaporation (ETa) of rice in drip irrigation experimental applications.

In the conventional flooding method, the 0-30 cm soil layer was maintained near field saturation, and this condition was preserved until crop emergence (approximately 15-20 d). Following emergence, the paddies were filled with water in a controlled manner to prevent crop damage, and water depth was maintained at 10 cm until the end of the growth period. To meet the oxygen demand of the plants, the paddies were completely drained once per week and refilled with fresh, oxygen-rich water. In the drip irrigation treatments, irrigation events were scheduled three times per week on Mondays, Wednesdays, and Fridays.

Harvesting for each treatment and replicate was conducted manually over a 30 m^2 area (3 m × 10 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 14% grain moisture content.

To determine milling efficiency, a 100 g rice sample was collected from each plot and processed using a laboratory-type rice milling machine to produce brown rice (cargo rice), with only the outer husk removed. The weight of the resulting brown rice was measured with a precision of 0.01 g, and milling efficiency was calculated as a percentage of the initial sample weight. To evaluate fracture-free efficiency (FFE), the proportion of whole, unbroken grains obtained after milling was measured and results were expressed as percentages for each treatment.

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

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

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

$$IWUE = Y/I \qquad (4)$$

where IWUE is the irrigation WUE 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}), I is seasonal irrigation water applied to a certain treatment, mm during the growing season.

Throughout the growing season, leaf area index (LAI) was monitored every 2 wk using a LAI-2000 plant canopy analyzer (LI-COR, Lincoln, Nebraska, USA). Considering the potential local differences in LAI caused by the proximity of plants to the drip lines, LAI measurements were taken from the three rows of plants located between two laterals (60 cm apart) at the center of each plot (with 20 cm spacing between rows). For each sampling event, readings were taken from four spots beneath the canopy and one spot above, helping to accurately estimate the fraction of incoming light captured by leaves and stems. These data were then interpreted using a radiative transfer model to derive LAI values.

Canopy temperature (Tc) measurements began during the first week of July, 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:

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

where Tc is the canopy temperature (°C), Ta is the air temperature (°C), LL is the non-water-stressed baseline (lower baseline-line) and UL is the non-transpiring upper baseline. The upper baseline calculated under water stress conditions was determined using values obtained from plants cut on different days.

Statistical analysis

All data obtained in this study were analyzed using the JMP statistical software (SAS Institute, Cary, North Carolina, USA). The ANOVA was employed as the primary method for evaluating the data. Student's t-test was used to compare differences between the control group and the highest-performing drip irrigation treatments. 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

In the research in 2019, the highest temperature value was measured as 33.3 °C in August, and the lowest temperature value was 15.6 °C in May. The average temperatures during the paddy growing period ranged between 22.5 and 27.9 °C. When we look at the precipitation, the highest precipitation was 61.6 mm in October. The total amount of precipitation during the paddy growing period was 36.2 mm. In the research in 2020, the highest temperature value was measured as 34.7 °C in August, and the lowest temperature value was measured as 15.4 °C in May. The average temperatures during the paddy growing period ranged between 22.1 and 28.2 °C. When we look at the precipitation, the highest precipitation was 12.6 mm in May. The total amount of precipitation during the paddy growing period was 8.0 mm. The quantities of irrigation water applied to the experimental treatments during the study years are shown in Figure 2. In the first year of the investigation (2019), irrigation commenced on 25 May, with a total of 305 mm water applied through nine uniform irrigation events. Subsequently, irrigation applications were initiated on 26 June, during which 34 irrigation applications were conducted. Irrigation applications were concluded on 13 September, 18 d prior to harvest. Following the onset of irrigation applications, cumulative evaporation measured using the Class A evaporation pan was determined to be 490 mm. Accordingly, total irrigation water applied, including both uniform and irrigation applications, amounted to 795, 918, and 1041 mm for treatments $I_{1.00}$, $I_{1.25}$, and $I_{1.50}$, respectively. In contrast, the treatment irrigated with the conventional basin irrigation method (conventional flooding, CF) received 1800 mm water. Water savings and yield reduction for experimental treatments during the study years are shown in Figure 3. Compared to CF, the use of drip irrigation systems resulted in 56% water savings under the $I_{1.00}$ Class A pan evaporation coefficient, 49% under the $I_{1.25}$ coefficient, and 42% under the $I_{1.50}$ coefficient. In the second year of the research (2020), irrigation operations commenced on 2 June, and 285 mm irrigation water was applied over 11 uniform irrigation events. Irrigation applications began on 13 July 2020, comprising 32 individual applications. Irrigation was terminated on 23 September, 20 d prior to harvest. The cumulative evaporation recorded from the Class A evaporation pan after the initiation of irrigation applications were measured at 508 mm. Consequently, the total irrigation water applied to treatments $I_{1.00}$, $I_{1.25}$, and $I_{1.50}$ was 793, 920, and 1047 mm, respectively. The treatment managed with the CF method received 2350 mm irrigation water throughout the season. Relative to CF, drip irrigation systems achieved water savings of 66%, 61%, and 55% under the $I_{1.00}$, $I_{1.25}$, and $I_{1.50}$ irrigation coefficients, respectively (Figure 3). Higher uniform watering was applied in the first year of the study than in the second year, primarily because soil moisture levels were significantly lower after planting and air temperatures were higher. The variation in irrigation strategies implemented across the 2 yr exerted measurable effects on both water use and yield performance. Drip irrigation not only minimized water input compared to the CF method but also achieved reductions between 42%-56% in 2019 and 55%-66% in 2020, aligning with regional assessments in Turkey that reported savings in the range of 60%-70% (Çebi et al., 2023). Incremental increases in irrigation aligned with the $I_{1.00}$, $I_{1.25}$, and $I_{1.50}$ pan coefficients led to corresponding rises in actual evapotranspiration (ETa), reaffirming the proportional relationship between irrigation volume and crop water uptake observed in other agroclimatic zones, such as India (Sarkar et al., 2018). Among the tested treatments, $I_{1.50}$ emerged as a threshold where water input efficiency was maintained without compromising yield, consistent with studies from Indonesia showing that drip systems can halve water consumption while sustaining productivity (Sasmita et al., 2022).

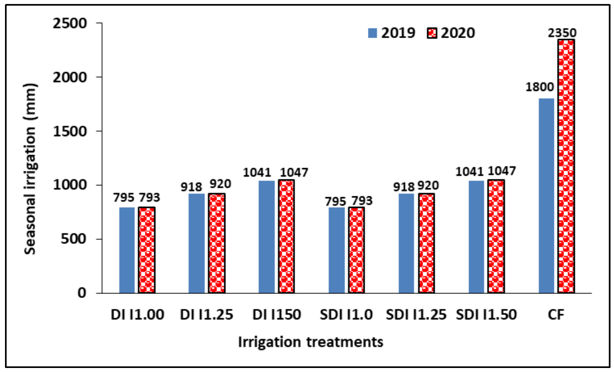


Figure 2. Seasonal irrigation for the experimental treatments during the study years. DI: Drip irrigation; SDI: subsurface drip irrigation; CF: conventional flooding; $I_{1.00}$: Class A-pan (Ep) × 1.00; $I_{1.25}$: Class A-pan Ep × 1.25; $I_{1.50}$: Class A-pan Ep × 1.

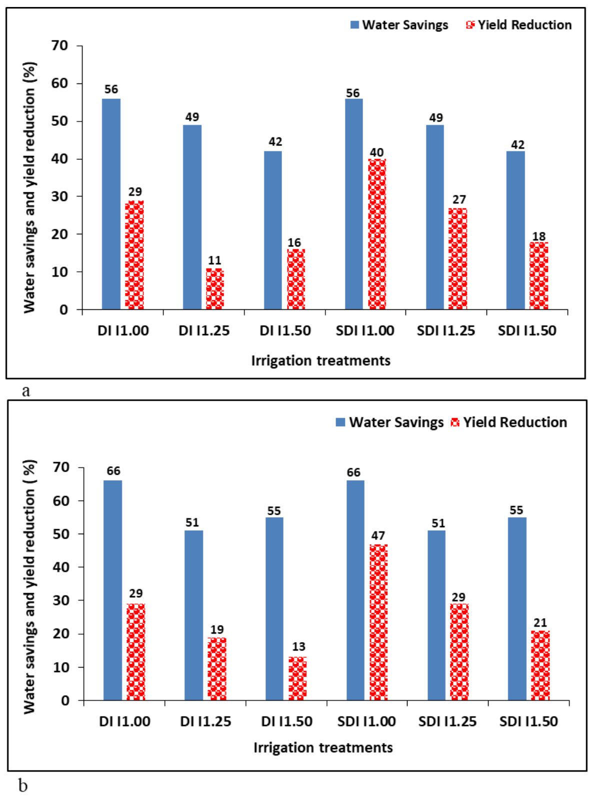


Figure 3. Water saving and efficiency yield reduction of different plant pan coefficients in surface (DI) and subsurface drip irrigation (SDI) systems compared to conventional flooding system in 2019 (a) and in 2020(b).

Crop evapotranspiration in drip irrigation treatments

Crop evapotranspiration (ETa) in drip irrigation treatments for the experimental treatments during the study years are shown in Figure 4. In the first year of the study, a total of 36.2 mm precipitation fell from planting to harvest. In the plots irrigated with drip irrigation, ETa values varied between 904 and 1145 mm depending on the irrigation conditions. The lowest ETa was 904 mm in subsurface drip (SDI)-$I_{1.00}$ irrigation and the highest ETa was 1145 mm in surface drip (DI)-$I_{1.50}$ irrigation. In the second year of the study, a total of 8.0 mm precipitation fell from planting to harvest. The ETa values varied between 852 and 1097 mm depending on drip irrigation conditions. In both years of the study, the highest ETa occurred in August in all treatments. Water consumption values increased as the amount of applied irrigation water increased. The observed pattern corresponds with studies conducted under the auspices of the International Rice Research Institute (IRRI), where subsurface drip irrigation (SDI) achieved greater water efficiency by reducing ETa while supporting biomass and yield gains compared to surface systems (Chandana et al., 2024). In line with this, research in Türkiye also documented elevated ETa values in surface drip irrigation, while SDI demonstrated improved water use efficiency (WUE) (Çebi et al., 2023). The increased evaporation loss from the exposed soil surface in DI systems explains the higher ETa values, whereas SDI minimizes such losses by concentrating water delivery directly in the root zone. The progressive rise in ETa with increasing irrigation levels in this experiment, particularly under $I_{1.50}$, indicates intensified water uptake during key phenological phases, echoing results from Sharma (2017), who found that while irrigation increases ETa, it may not proportionally improve water productivity. The interplay between system configuration and irrigation intensity thus emerges as a central factor in optimizing crop evapotranspiration and irrigation efficiency.

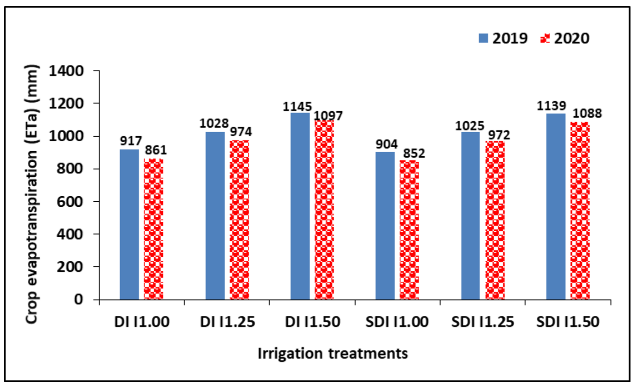


Figure 4. Crop evapotranspiration (ETa) for the experimental treatments during the study years. DI: Drip irrigation; SDI: subsurface drip irrigation; $I_{1.00}$: Class A-pan (Ep) × 1.00; $I_{1.25}$: Class A-pan Ep × 1.25; $I_{1.50}$: Class A-pan Ep × 1.50.

Variation of soil water content

Variations of soil water content (SWC) in the effective root-zone depth of 90 cm in the different irrigation treatments under surface and SDI systems are shown for 2019 and 2020 experimental years (Figure 5). The soil water content (30 cm) was kept at values close to saturation level from the planting of the paddy plant until it germinated and became approximately 10 cm. Since we started the irrigation applications on 26 June (34 d after planting, DAP), the soil water content values showed differences depending on the amounts of irrigation water applied to the subjects. While in the DI-$I_{1.50}$, SDI-$I_{1.50}$, SDI-$I_{1.25}$ irrigation treatments remained above 60% available water during the irrigation period, the DI-$I_{1.25}$ irrigation treatment remained at 60% available water level throughout the season. The DI-$I_{1.00}$ and SDI-$I_{1.00}$ irrigation treatments remained below 60% available water throughout the season. The soil water content dropped below the wilting point at the end of the season. In the second year (2020) of the research, the soil water content values showed differences depending on the amounts of irrigation water applied to the treatments since 10 July (DAP-39), when we started the treatment. Similar results were obtained with the first year in terms of the change in soil water content in terms of irrigation treatments. These observations indicate that DI and SDI systems influence the distribution and persistence of moisture in the root zone differently. Treatments such as SDI-$I_{1.50}$, SDI-$I_{1.25}$, and DI-$I_{1.50}$ maintained more than 60% of available water throughout the season, while lower irrigation levels (DI-$I_{1.00}$ and SDI-$I_{1.00}$) frequently dropped below the wilting point. Supporting this, a study from Iraq (Ati et al., 2023) found that SDI could sustain adequate soil moisture and enhance rice yield even under water stress, with more effective performance at lower depletion levels. Surface systems, on the other hand, were more prone to rapid moisture loss during hot periods, potentially intensifying plant water stress.

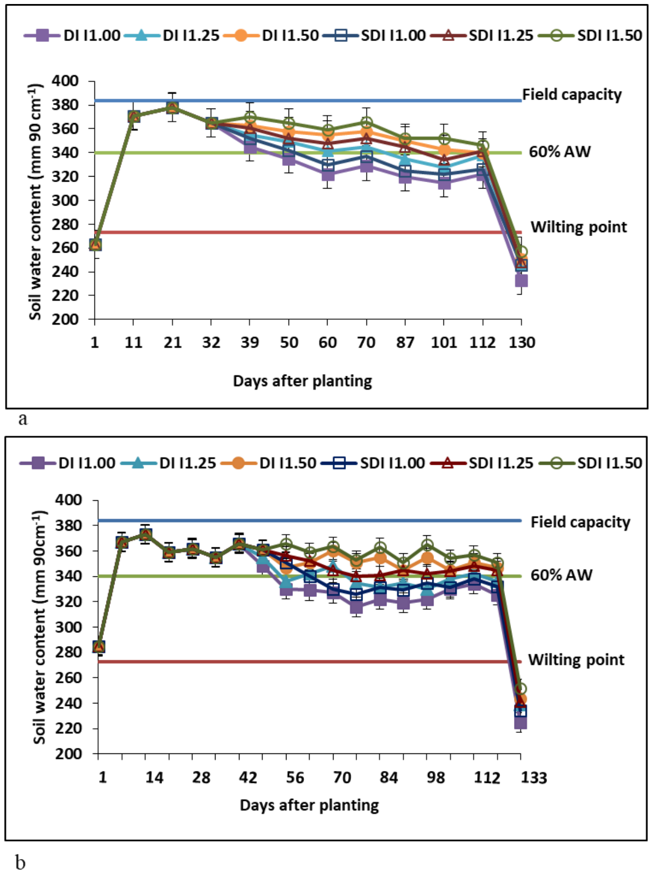


Figure 5. Soil water content variation prior to irrigations for the different plant pan coefficients under surface (DI) and subsurface drip irrigation (SDI) systems in 2019 (a) and 2020 (b). Vertical bars represent standard errors the mean ± SE (n = 17). AW: Available water; $I_{1.00}$: Class A-pan (Ep) × 1.00; $I_{1.25}$: Class A-pan Ep × 1.25; $I_{1.50}$: Class A-pan Ep × 1.50.

Grain yield

The grain yield data and corresponding statistical analysis results are presented in Figure 6, Tables 3 and 4. Evaluation of yield and yield components over the 2-yr trial period revealed that year-specific climatic conditions played a dominant role in determining rice yield. Therefore, yield and quality parameters for 2019 and 2020 were evaluated separately. In the first year, irrigation systems, irrigation coefficients, and their interactions had significant effects on grain yield ($P < 0.01$). In both years, the highest grain yields were obtained with the conventional flooding (CF) method 9580 kg ha^{-1} in 2019 and 8250 kg ha^{-1} in 2020. In the first year, the lowest yield was recorded for the SDI-$I_{1.00}$ treatment (5730 kg ha^{-1}), whereas the highest yield among drip irrigation treatments was observed with DI-$I_{1.50}$ (8056 kg ha^{-1}). A similar trend was found in the second year: The lowest yield was recorded in SDI-$I_{1.00}$ (4360 kg ha^{-1}), while the highest yield among drip irrigation treatments was obtained with DI-$I_{1.50}$ (7150 kg ha^{-1}). Overall, surface drip irrigation treatments produced higher yields compared to subsurface drip irrigation. In both years, the DI-$I_{1.50}$ treatment showed the best performance among drip irrigation systems. Moreover, the difference in yield between CF and DI-$I_{1.50}$ was significant in both years ($P < 0.01$). Comparable findings were reported in Türkiye by Çebi et al. (2023), who observed that while CF produced the highest absolute yields, drip irrigation systems enabled 60%-70% water savings with only a 20%-25% yield reduction—consistent with the 42%-66% savings found in this study. Additionally, Chandana et al. (2024) documented yield increases of 6.52% and 18.82% under SDI in 2020 and 2021, respectively, attributed to increases in filled grain number and panicle count. However, other studies have reported potential drawbacks of SDI; Demirel et al. (2020) found that although SDI with a moisture barrier saved up to 69% water, it led to yield reductions as high as 40%, likely due to insufficient moisture in the root zone under low irrigation levels. In this context, DI-$I_{1.50}$ emerges as an optimal surface drip treatment, balancing yield with water efficiency. The SDI's yield limitations may stem from deeper or uneven water distribution, emphasizing the need to tailor irrigation strategies to field conditions, plant density, and irrigation frequency.

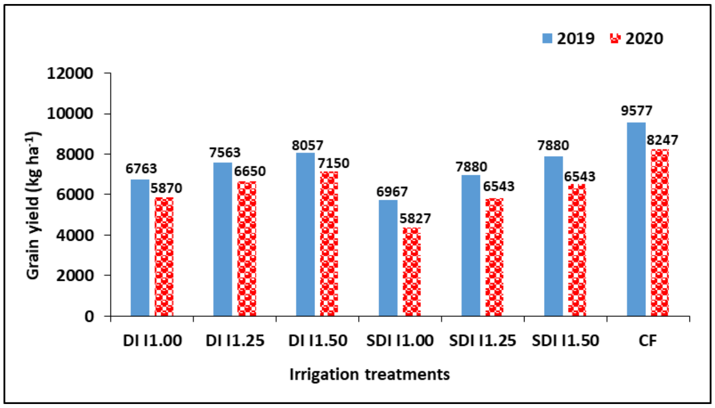


Figure 6. Grain yield for the experimental treatments during the study years. DI: Drip irrigation; SDI: subsurface drip irrigation; $I_{1.00}$: Class A-pan (Ep) × 1.00; $I_{1.25}$: Class A-pan Ep × 1.25; $I_{1.50}$: Class A-pan Ep × 1.50; CF: Conventional flooding.

Table 3. Statistical analysis results on grain yield, leaf area index (LAI) and crop water stress index (CWSI) of rice under different treatments in the 2019 experimental year. CV: Coefficient variation; LSD: least significant difference; DI: drip irrigation; SDI: subsurface drip irrigation; CF: conventional flooding; $I_{1.00}$: Class A-pan (Ep) × 1.00; $I_{1.25}$: Class A-pan Ep × 1.25; $I_{1.50}$: Class A-pan Ep × 1.50. Values followed by different small letters indicate significant differences at $^{*}P < 0.05$; $^{**}P < 0.01$; ^{ns}nonsignificant.

Irrigation treatments	Irrigation treatments and statistical analysis	Grain yield	Milling efficiency	Fracture-free efficiency	Maximum LAI	Mean CWSI
		kg ha^{-1}	——————— %	———————	m^2 m^{-2}	
Irrigation systems (IS)	DI	7461^a	65.7	55.0	6.04^a	0.22^a
	SDI	6859^b	65.1	54.1	5.67^b	0.26^b
	LSD (0.05)	261.1	-	-	1.44	0.027
	P (Probability)	0.0100**	^{ns}	^{ns}	0.0080**	0.0179*
Irrigation coefficients (IC)	$I_{1.00}$	6247^c	64.2^b	52.9^b	5.15^c	0.31^a
	$I_{1.25}$	7265^b	65.6^a	53.9^b	5.99^b	0.25^b
	$I_{1.50}$	7968^a	66.4^a	56.8^a	6.43^a	0.17^c
	LSD (0.05)	158.4	0.84	1.14	0.11	0.30
	P (Probability)	0.0001**	0.0011**	0.0001**	0.0001**	0.0001**
IS × IC	DI-$I_{1.00}$	6763^c	64.8	53.1	5.45^e	0.28
	DI-$I_{1.25}$	7563^b	65.9	54.6	6.10^c	0.22
	DI-$I_{1.50}$	8057^a	66.4	57.4	6.58^a	0.15
	SDI-$I_{1.00}$	5730^d	63.6	52.7	4.85^f	0.33
	SDI-$I_{1.25}$	6967^c	65.3	53.4	5.88^d	0.26
	SDI-$I_{1.50}$	7880^a	66.3	56.3	6.28^b	0.18
	LSD (0.05)	224.0	-	-	0.15	-
	P (Probability)	0.0008**	^{ns}	^{ns}	0.0075**	^{ns}
	CV, %	1.7	1.0	1.6	1.4	12.6
CF	CF	9577	66.5	56.8	7.2	0.08
	Best drip irrigation treatment	8057 (DI-$I_{1.50}$)	66.4 (DI-$I_{1.50}$)	57.4 (DI-$I_{1.50}$)	6.58 (DI-$I_{1.50}$)	0.15 (DI-$I_{1.50}$)
	Probability (t)	0.0087**	^{ns}	^{ns}	0.0082**	0.034*

Table 4. Statistical analysis results on grain yield, leaf area index (LAI) and crop water stress index (CWSI) of rice under different treatments in the 2020 experimental year. IS: Irrigation systems; IC: irrigation coefficients; CV: coefficient variation; LSD: least significant difference; DI: drip irrigation; SDI: subsurface drip irrigation; CF: conventional flooding; $I_{1.00}$: Class A-pan (Ep) × 1.00; $I_{1.25}$: Class A-pan Ep × 1.25; $I_{1.50}$: Class A-pan Ep × 1.50. Values followed by different small letters indicate significant differences at $^{*}P < 0.05$; $^{**}P < 0.01$; ^{ns}nonsignificant.

Irrigation treatments	Irrigation treatments and statistical analysis	Grain yield	Milling efficiency	Fracture-Free efficiency	Maximum LAI	Mean CWSI
Irrigation Systems (IS)		kg ha^{-1}	——— % ———		m^2 m^{-2}	
	DI	6557^a	66.7^a	52.6^a	5.63^a	0.24
	SDI	5577^b	64.9^b	49.8^b	5.14^b	0.28
	LSD (0.05)	97.6	1.46	0.88	0.096	-
	P (Probability)	0.0005**	0.0306**	0.0052**	0.0021**	^{ns}
Irrigation Coefficients (IC)	$I_{1.00}$	5115^c	64.7	52.6^a	4.94^c	0.33^a
	$I_{1.25}$	6238^b	66.2	49.8^b	5.32^b	0.26^b
	$I_{1.50}$	6847^a	66.4	53.5^a	6.89^a	0.18^c
	LSD (0.05)	134.8	-	1.39	0.079	0.034
	P (Probability)	0.0001**	^{ns}	0.0005**	0.0001**	0.0001**
IS × IC	DI-$I_{1.00}$	5870^c	65.0	51.1	5.25^d	0.31
	DI-$I_{1.25}$	6650^b	67.4	51.3	5.59^c	0.24
	DI-$I_{1.50}$	7150^a	67.9	55.5	6.03^a	0.16
	SDI-$I_{1.00}$	4360^d	64.5	48.1	4.63^f	0.35
	SDI-$I_{1.25}$	5827^c	65.1	49.8	5.05^e	0.28
	SDI-$I_{1.50}$	6543^b	65.0	51.5	5.75^b	0.20
	LSD (0.05)	190.7	-	-	0.112	-
	P (Probability)	0.0001**	^{ns}	^{ns}	0.0029**	^{ns}
	CV, %	1.6	1.8	2.0	1.1	9.9
CF	CF	8247	68	60.1	6.91	0.09
	Best drip irrigation treatment	715.0 (DI-$I_{1.50}$)	67.9 (DI-$I_{1.50}$)	55.5 (DI-$I_{1.50}$)	6.03 (DI-$I_{1.50}$)	0.16 (DI-$I_{1.50}$)
	Probability (t)	0.0100**	^{ns}	0.0024**	0.0041**	0.0131*

Milling efficiency and fracture-free efficiency

The milling efficiency results and corresponding statistical analyses for each study year are summarized in Tables 3 and 4. In the first year, irrigation coefficients had a significant effect on milling efficiency, while in the second year, the irrigation systems were the primary factor influencing this parameter ($P < 0.01$). In both years, the highest milling efficiency was obtained with CF, measured as 66.5% and 68% for 2019 and 2020, respectively. In 2019, milling efficiency increased from 63.6% under SDI-$I_{1.00}$ to 66.4% under DI-$I_{1.50}$; similarly, in 2020, it increased from 64.5% (SDI-$I_{1.00}$) to 67.9% (DI-$I_{1.50}$). Overall, values obtained under DI were higher than those recorded for SDI. In both years, the DI-$I_{1.50}$ treatment achieved the highest milling efficiency among drip irrigation treatments; however, the difference between CF and DI-$I_{1.50}$ was nonsignificant. The fracture-free efficiency (FFE) results and their statistical analyses are also presented in Tables 2 and 3. In the first year, irrigation coefficients, and in the second year, both irrigation system and coefficients, had significant effects on FFE ($P < 0.01$). The highest FFE in both years was recorded under CF 56.8% in 2019 and 60.1% in 2020. In 2019, FFE increased from 52.7% (SDI-$I_{1.00}$) to 57.4% (DI-$I_{1.50}$), while in 2020, it rose from 48.1% (SDI-$I_{1.00}$) to 55.5% (DI-$I_{1.50}$). Values obtained under DI were generally higher than those under SDI. In both years, DI-$I_{1.50}$ yielded the best results among the drip irrigation treatments; however, the difference between CF and DI-$I_{1.50}$ was nonsignificant in 2019 but became significant in 2020 ($P < 0.01$). These findings align with recent studies on grain quality under different irrigation systems. Sasmita et al. (2022) observed that drip irrigation improved the proportion of whole kernels and reduced broken grains, enhancing milling efficiency. Bhardwaj et al. (2018)

also reported optimal rice yield and quality at 100%-125% cumulative evaporation from the pan (Epan) in drip-irrigated treatments, suggesting that sufficient water supply mitigates stress effects. Although the CF method traditionally ensures the highest milling efficiency, DI, particularly at $I_{1.50}$ level, can closely match these results under well-managed conditions, indicating the strategic applicability of drip systems not only for water savings but also for maintaining grain quality. Regarding FFE, the study demonstrated that both irrigation method and level significantly influence the physical integrity of rice grains. The CF consistently delivered the highest FFE values in both years, with DI-$I_{1.50}$ closely following. The lowest FFE values were observed in SDI-$I_{1.00}$ treatments. Hou et al. (2023) found similar outcomes in their comparison of irrigation regimes, where CF maintained the highest "perfect kernel" ratios, while alternate wetting and moderate soil drying irrigation (AWD) and dry-direct seeding systems increased the rate of broken grains due to post-anthesis stress-induced starch degradation. Maalik et al. (2020) further highlighted that water stress during flowering and grain filling stages can compromise cellular development and grain fullness, increasing fracture susceptibility. These observations substantiate the current study's findings that lower-level SDI treatments underperform in FFE due to insufficient moisture support. Nonetheless, DI-$I_{1.50}$ treatment demonstrated competitive quality preservation, reinforcing that high-level drip irrigation strategies can be both yield- and quality-effective under proper management.

Leaf area index

The maximum leaf area index (LAI) values and their statistical analyses with respect to rice yield are summarized in Tables 3 and 4. In 2019, the maximum LAI values across different irrigation treatments ranged from 4.85 under SDI-$I_{1.50}$ to 7.20 under CF. In the first year, irrigation system, irrigation coefficients, and their interaction all had significant effects on maximum LAI (P < 0.01). In both experimental years, the highest maximum LAI values were recorded under conventional flooding (CF), with 7.20 $m^2 m^{-2}$ in 2019 and 6.91 $m^2 m^{-2}$ in 2020. The lowest maximum LAI for the first season appeared in the SDI-$I_{1.00}$ plots, with values down to 4.85 $m^2 m^{-2}$. By contrast, among the drip treatments, DI-$I_{1.50}$ achieved the highest LAI, reaching 6.58 $m^2 m^{-2}$. This pattern was largely repeated in the second year as well: SDI-$I_{1.00}$ once again had the lowest LAI (4.63 $m^2 m^{-2}$), while DI-$I_{1.50}$ stood out with the highest value (6.03 $m^2 m^{-2}$) among drip-irrigated plots. Surface drip treatments, as a group, consistently produced higher LAI values compared to SDI. Notably, DI-$I_{1.50}$ outperformed all other drip strategies in both study years. The distinction between CF and DI-$I_{1.50}$ was also found to be significant (P < 0.01). These outcomes are broadly consistent with the recent literature. Chandana et al. (2024) observed that DI systems outperformed SDI ones in terms of LAI, tillering, and plant height in intensive rice systems. Similarly, Umilsingh et al. (2024) reported the highest LAI (5.95) under 200% pan evaporation (PE) irrigation and 125% three fertigation levels (RDF) fertilization, suggesting LAI development is influenced not only by irrigation methods but also nutrient and water levels. Additionally, Maftukhah et al. (2019) highlighted that while LAI responses were comparable under shallow and continuous irrigation, varietal differences were significant. Taken together, these findings support that DI-$I_{1.50}$, particularly under optimal water conditions, can enhance LAI and contribute to yield, potentially rivaling CF systems in performance while offering water savings.

Irrigation water amount-yield relations

The relationships between irrigation water amount and grain yield (Y) during the experimental years are presented in Figure 7. The findings demonstrated that, in both years, significant second-degree (polynomial) relationships were observed between irrigation water and grain yield under surface drip irrigation (DI), whereas significant linear relationships were identified under subsurface drip irrigation (SDI). In the first experimental year, R^2 values of 0.96 for DI and 0.98 for SDI were obtained, indicating highly significant relationships (P = 0.0001**; P < 0.01). In the second year, R^2 values were 0.98 for DI and 0.96 for SDI, again confirming highly significant associations between irrigation water and grain yield (P = 0.0001**; P < 0.01). These findings align well with research in water-scarce regions. For example, Jajere et al. (2024) reported from Nigeria that irrigation scenarios meeting 100% and 85% of crop evapotranspiration (ETc) resulted in the highest yields (6485 kg ha^{-1}), while excessive irrigation limited further yield improvements. Furthermore, applying 85% ETc achieved the most efficient irrigation water use (IWUE). These results highlight the need to balance maximum yield with optimal water use. In this context, DI-$I_{1.50}$ serves as a practical example of achieving competitive yields with reduced water compared to CF. The ability to conserve water while maintaining yield stability and grain quality underscores the strategic importance of modern irrigation technologies.

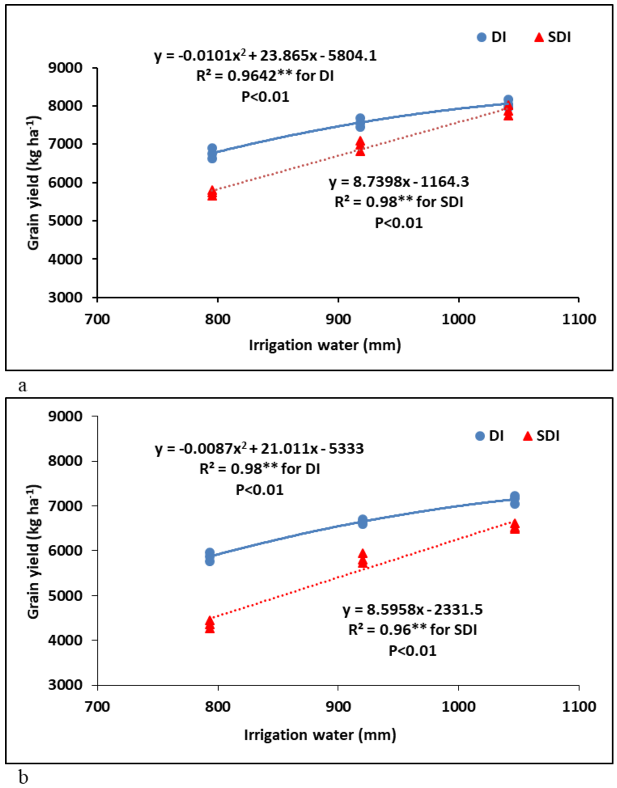
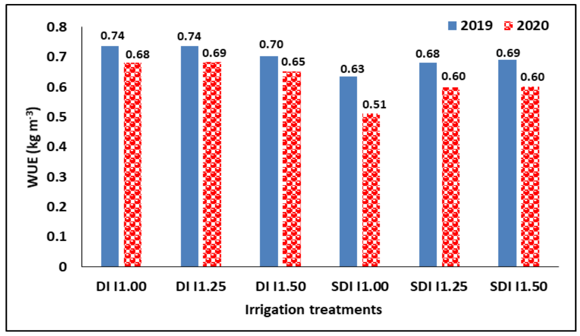


Figure 7. Seasonal irrigation water amount yield relationship under surface (DI) and subsurface drip irrigation (SDI) systems in 2019 (a) and 2020 (b). *, **Significant differences at 0.05 and 0.01 probability levels, respectively, according to LSD.

Water use efficiency and irrigation water use efficiency

The values of water use efficiency (WUE) and irrigation water use efficiency (IWUE) for all treatments across the study years are presented in Figure 8. In the first year, the highest WUE among drip irrigation treatments was observed in DI-$I_{1.00}$ and DI-$I_{1.25}$, both at 0.737 kg m^{-3}, while the lowest value was recorded in SDI-$I_{1.00}$ at 0.634 kg m^{-3}. A similar trend was observed in the second year, with the highest WUE again in DI-$I_{1.00}$ and DI-$I_{1.25}$ (0.683 kg m^{-3}), and the lowest in SDI-$I_{1.00}$ (0.512 kg m^{-3}). The IWUE also emerged as a key parameter for comparing different irrigation strategies. In the first year, the highest IWUE was obtained in DI-$I_{1.00}$ (0.850 kg m^{-3}), and the lowest in SDI-$I_{1.00}$ (0.721 kg m^{-3}). The IWUE value under the CF method was calculated as relatively low (0.532 kg m^{-3}). Similarly, in the second year, the highest IWUE was again observed in DI-$I_{1.00}$ (0.740 kg m^{-3}), the lowest in SDI-$I_{1.00}$ (0.550 kg m^{-3}), and CF recorded a value of 0.351 kg m^{-3}.

Drip irrigation systems have consistently demonstrated higher IWUE values compared to CF, highlighting their effectiveness in water-saving strategies. Numerous studies conducted both regionally and internationally support this finding. For instance, Sharda et al. (2017), Demirel et al. (2020), and Çebi et al. (2023) all reported superior IWUE under drip irrigation. Nabipour et al. (2024) found IWUE values between 0.44 and 0.68 kg m^{-3} in drip tape systems, with increases up to 22% over intermittent irrigation. Similarly, Fukai and Mitchell (2022) observed IWUE ranging from 0.36 to 1.17 kg m^{-3} in aerobic rice, reflecting a 9%-150% increase compared to CF. Other studies, including those by Samoy-Pascual et al. (2021), Panigrahi et al. (2021) and Sharda et al. (2017), recorded gains from 22% up to 1.8-fold improvements in IWUE with drip irrigation.



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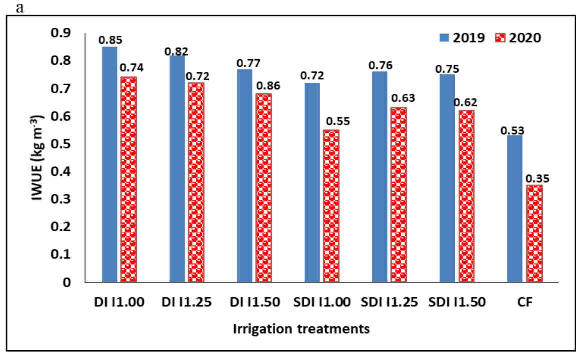

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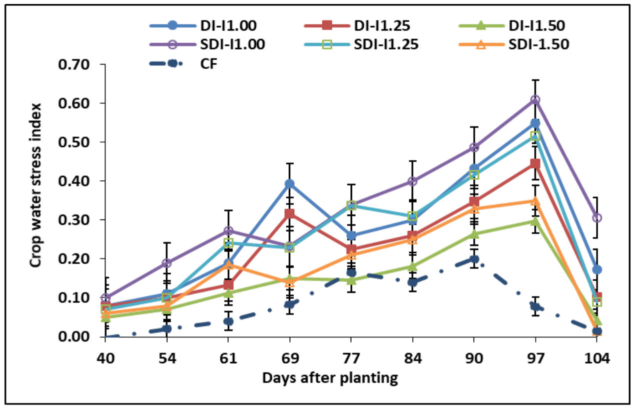
Figure 8. Water use efficiency (WUE) (a) and irrigation WUE (IWUE) (b) for the experimental treatments during the study years. DI: Drip irrigation; SDI: subsurface drip irrigation; $I_{1.00}$: Class A-pan (Ep) × 1.00; $I_{1.25}$: Class A-pan Ep × 1.25; $I_{1.50}$: Class A-pan Ep × 1.50.

Crop water stress index

The fluctuations in crop water stress index (CWSI) values prior to irrigations for different irrigation treatments with time during the 2019 and 2020 growing seasons are shown in Figures 9a-9b. Psychrometric measurements were used to determine vapor pressure deficit (VPD) of the air and the empirical technique was used to calculate the relationship between Tc − Ta and the CWSI. Using the empirical equations from Idso et al. (1981), the upper limit (UL) and lower limit (LL) for rice were established as follows: LL = -2.2069 VPD + 0.8263 and UL = -0.01009 VPD + 5.0848. However, since the intercept value in the UL calculation is modest, the UL is assumed to be 5.08 °C. The changes in CWSI before irrigation for the different treatments during the growing seasons were studied. The mean crop water stress index values and statistical analysis results related to CWSI during the research years are given in Tables 3 and 4. In the first year of the study, irrigation systems and in the second-year irrigation coefficients on CWSI were found to be significant at $P < 0.05$ and $P < 0.01$, respectively. The two seasons' mean CWSI values for CF, DI-$I_{1.00}$, DI-$I_{1.25}$, DI-$I_{1.50}$, SDI-$I_{1.00}$, SDI-$I_{1.25}$, SDI-$I_{1.50}$ were 0.09, 0.29, 0.23, 0.15, 0.34, 0.27 and 0.19 respectively. As the irrigation water applied increased, CWSI decreased. The -CF treatment resulted in lowest CWSI, SDI-$I_{1.00}$ resulted in the highest CWSI. The soil water content was consistent with the CWSI values in SDI-$I_{1.00}$, which had the largest soil water depletion levels and greater CWSI values, while the highest irrigation level was CF and drip irrigation was DI-$I_{1.50}$ and had the smallest soil water depletion levels and lower CWSI values. These findings align with the study by Ramos-Fernández et al. (2024) in Peru, where CWSI values under water-restrictive irrigation strategies such as alternating wetting and drying (AWD) ranged from 0.4 to 1.0, yet yield reductions were nonsignificant. A strong negative correlation (R = -0.91) was also observed between CWSI and stomatal conductance (g_s), reinforcing the physiological validity of the index. Similarly, Visitacion et al. (2022) in the Philippines demonstrated a high negative correlation (r > -0.78) between CWSI and yield during the flowering stage of rainfed rice. The current study also revealed significant ($P < 0.01$) and negative linear correlations between CWSI and yield (R^2 = 0.97 and 0.92), milling efficiency, FFE, and LAI, supporting CWSI's multidimensional utility for irrigation scheduling and yield prediction. The consistency between CWSI values and soil moisture further affirms the index's physical validity.



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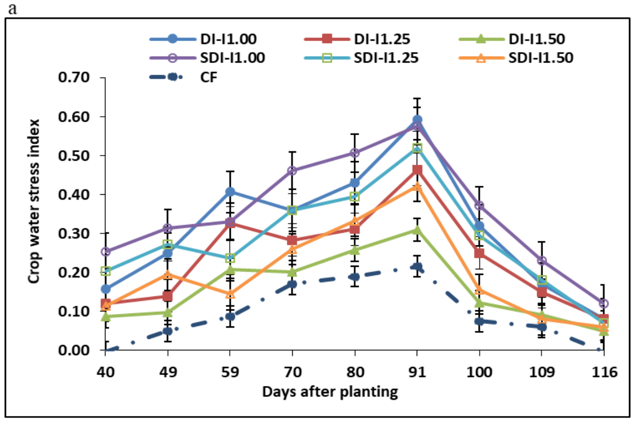

b

Figure 9. Crop water stress index (CWSI) variation in rice for the experimental treatments during the study years, 2019 (a) and 2020 (b). Vertical bars represent standard errors the mean ± SE (n = 20). DI: Drip irrigation; SDI: subsurface drip irrigation; CF: conventional flooding; $I_{1.00}$: Class A-pan (Ep) × 1.00; $I_{1.25}$: Class A-pan Ep × 1.25; $I_{1.50}$: Class A-pan Ep × 1.50.

Relationships between crop water stress index, grain yield, milling efficiency, FFE and LAI

During the experimental years, significant curvilinear relationships were identified between the crop water stress index (CWSI) and grain yield, milling efficiency, FFE, and maximum LAI. These relationships are detailed in Figures 10a-10d. Overall, there was a significant ($P < 0.01$) and negative correlation between CWSI and both yield and quality parameters as well as LAI. In other words, as CWSI values increased, grain yield and quality indicators in rice exhibited a decreasing trend. Analyses revealed that these relationships were best described by linear equations. In both the first and second growing seasons, the relationship between CWSI and grain yield showed a particularly high degree of explanatory power, with coefficients of determination (R^2) calculated as 0.97 and 0.92, respectively. For both years, the relationships between CWSI and milling efficiency, FFE, and LAI also exhibited coefficients of determination greater than 0.83, all significant ($P < 0.01$). However, the coefficient of determination for milling efficiency in the second year was slightly lower ($R^2 = 0.65$), though still significant ($P < 0.05$). These findings align with recent research emphasizing the relevance of CWSI and LAI as predictors of rice yield. For instance, Hashimoto et al. (2023) reported that LAI values measured within the 400-600 °Cd range significantly influenced components such as panicle number and 1000-grain weight, despite moderate correlation levels ($R = 0.18$-0.61). Ji et al. (2022) demonstrated that LAI could be accurately estimated through remote sensing using regression models with R^2 up to 0.878, highlighting its predictive utility. Together, these studies support the dual use of CWSI and LAI for early warning systems in rice yield forecasting. The high R^2 values observed in the current study for CWSI-yield relationships underline CWSI's strength as a decision-support tool not only for managing stress but also for maintaining grain quality under water-limited conditions.

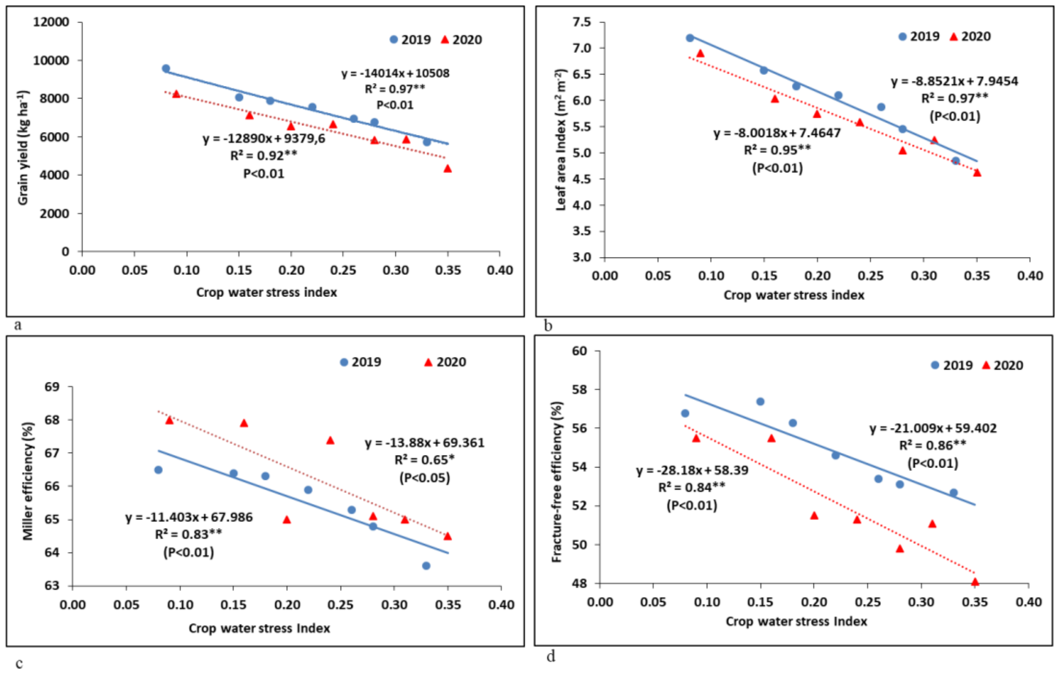

Figure 10. Relationships between crop water stress index and yield (a), maximum leaf area index (b), milling efficiency (c), and fracture-free efficiency (d) for rice in two growing seasons. *, **Significant differences at 0.05 and 0.01 probability levels, respectively, according to LSD.

CONCLUSIONS

This study demonstrated that the crop water stress index (CWSI) is a reliable and practical indicator for determining the water status and optimal irrigation scheduling of rice under Mediterranean conditions. The findings indicate that surface drip irrigation applied at class A-pan evapotranspiration × 1.50 ($I_{1.50}$) level provided significant water savings compared to conventional flooding and emerged as the most effective drip irrigation strategy, delivering high yield and quality. Although conventional flooding resulted in the highest absolute yields, it required substantially more water and proved to be environmentally unsustainable, especially under increasing water scarcity. The strong negative relationships identified between CWSI and grain yield, milling quality, fracture-free grain ratio, and leaf area index demonstrate that this index can be effectively utilized to optimize irrigation practices and enhance water use efficiency. Future research should prioritize the integration of CWSI-based thresholds into user-friendly decision support systems and the validation of these findings across different genotypes and soil types

Author contribution

Y.B.Ç. designed the study and wrote the manuscript.

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