



Evaluation of crop water stress index and leaf water potential for deficit irrigation management of sprinkler-irrigated wheat

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Abstract

This study evaluated crop water stress index (CWSI) and midday flag leaf water potential (ψ_l) on wheat (*Triticum aestivum* L. Adana 99) under the three different supplemental and conventional irrigation strategies using sprinkler line-source system during 2014 and 2015 in Adana, Turkey. The irrigation strategies were as follows: conventional irrigation (CI), supplemental irrigation (SI) during flowering (SIF), SI during grain filling (SIG), SI both during flowering and grain filling (SIFG). These strategies were tested under four irrigation levels 100, 75, 50, 25% and rain-fed. The CI₁₀₀ treatment achieved the highest grain yield in both seasons, followed by CI₇₅ and SIFG₁₀₀. The CI₇₅ had the greatest water use efficiency of 1.20 kg m⁻³, and SIF₂₅ resulted in the lowest WUE. Grain yield and available soil water correlated linearly to CWSI. These relations could be employed in predicting the yield response to water stress. A higher grain yield was obtained when irrigation was applied at CWSI values less than 0.26, suggesting CWSI as a good indicator to improve irrigation timing for wheat. Prolonged drought in early grain filling stage led to a decline in Ψ_l in the advanced growth stage which in turn reduced grain yield. Significant correlations between Ψ_l and grain yield and CWSI were obtained, which could be useful in improving wheat irrigation water management. CI₁₀₀ is recommended when there is no water shortage; however, under water scarcity conditions CI₇₅, SIFG₁₀₀ and SIFG₇₅, with higher WUE and relatively higher yields, are recommended.

Introduction

Wheat is an important staple food contributing about 29% of global food grain production and plays a vital role in the nutritional security of more than 35% of the world's population. Since it is mostly cultivated as a rain-fed crop, the productivity of wheat is limited by inadequate water supplies, especially in arid and semi-arid regions (Wakchaure et al. 2016). Farmers in the Mediterranean region usually do not irrigate wheat except during drought years in which they apply one or two supplemental irrigations by surface methods, and this region generally suffers from lack of rainfall from March until May during sensitive growth stages of wheat (flowering and grain filling stages). Supplemental irrigation can help to alleviate this problem. Adequate water on or after anthesis period not only allows the plant to increase

its photosynthesis rate but also gives extra time to translocate the carbohydrate to grains which improve grain size and thereby lead to increase grain yield (Zhang and Oweis 1998; Saint Pierre et al. 2012; Ayed et al. 2017).

The total bread wheat production in the Mediterranean region is 75.2 MT, which is about 12% of global production 644 MT and the total harvested area in the region is 18.1 Mha (9% of world harvested area). Turkey is the second biggest producer with 22% (after France 47%) during 2010–2013 (MED-Amin 2015).

The influence of irrigation management on crop water use is a practical consideration to improve yield and crop water productivity. Irrigation scheduling is generally based on measurement of soil water content or meteorological parameters for modeling or computing evapotranspiration. Irrigation scheduling based upon crop water status should be more advantageous since crops respond to both the soil and aerial environment (evaporative demand) (Yazar et al. 1999). Plant-based methods such as leaf water potential and crop water stress index are considered to have great potential for irrigation control although, in some cases, there are issues in defining reference or threshold values (Jones 2004).

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Canopy surface temperature measured with infrared thermometers (IRT) or other remote infrared sensors provide an important tool to detect water stress in a crop, which has been in practice for some decades. The crop water stress index (CWSI) is the most frequently used method to quantify crop water stress based on canopy surface temperature for different crops and climatic conditions, for example, Yazar et al. (1999); Chen et al. (2010); Taghvaeian et al. (2012); DeJonge et al. (2015) for corn; Yuan et al. (2004); Gontia and Tiwari (2008) for wheat; Yazar et al. (2002); O'Shaughnessy et al. (2011); Argyrokastritis et al. (2015) for cotton. Alderfasi et al. (2000) developed lower baseline equation as $T_c - T_a = 0.4 - 1.5VPD$ for calculating CWSI of winter wheat. Gontia and Tiwari (2008) reported the wheat CWSI values ranged from zero to 0.96 using different irrigation levels (including rain-fed). Zia (2012) evaluated CWSI for different irrigation treatments and found seasonal mean CWSI 0.33 for farmer practice, 0.43 in full conventional irrigation CI_{100} , 0.56 in CI_{50} , 0.61 in CI_{16} and 0.65 in NI (no irrigation) of winter wheat. Orta et al. (2004) developed baseline equations, which can be used to quantify crop water stress index (CWSI) of winter wheat and to predict yield in Turkey. Mediterranean environment is characterized by a low vapor pressure deficit (VPD) during winter and in the spring (Zhang et al. 1998), and VPD increases sharply from 1 kPa to values of 2–3 kPa at the end of grain filling (Condon et al. 1992; Sato et al. 2006). As an index for irrigation scheduling, CWSI can predict when to irrigate (Irmak et al. 2000; Kacira et al. 2002), but it cannot indicate how much to irrigate.

Leaf water potential is considered as a reliable indicator of plant water status (Karamanos 2003). Jiang et al. (2013) showed that low leaf water potential corresponds to low soil water content. For most wheat plants, the immediate response to water deficit is the decline in the leaf water potential (Ψ_l), which leads to stomatal closure and reduced photosynthesis. Prolonged drought can limit plant growth and biomass production (Puri and Swamy 2001). There were significant differences in leaf water potential (Ψ_l) of wheat midday among the three water regimes CI_{100} , CI_{50} and Rain-fed (RF) and the differences become larger as the season developed and water stress increased with values of (Ψ_l) ranging for CI_{100} and R from -14.22 to -17.78 bar at flowering and from -18 to -24.03 bar at grain filling stage (Matić 2008). Waraich and Ahmad (2010) applied one to four irrigations during different growth stages (tillering, stem elongation, anthesis and grain filling) and found that increasing the number of irrigations significantly increased the values of water potential and osmotic potential. Xue et al. (2006) observed maximum water potential 10 days after anthesis and noticed progressive decreases until minimum values recorded 30 days after anthesis. Siddique et al. (2000) reported that the reason

for decreased photosynthetic rate may be the decreased Ψ_l under water stress due to limited irrigation and exposure of wheat to drought leading to a noticeable decrease in leaf water potential. Ali et al. (2014) observed that during crop growth seasons, the leaf water potential, osmotic potential, and relative water content dropped linearly with decreasing irrigation levels from 100% ET_0 to 60% ET_0 . This reduction in these attributes might have caused the partial closure of stomata that resulted in a significant decrease in stomatal conductance which limited the access of photosynthetic apparatus to CO_2 . Liang et al. (2002) reported that when the growth rates of wheat started to decrease sharply during the three drying spells, the leaf water potentials were -0.9 , -1.2 and -1.5 MPa, respectively, and it declined to -1.8 MPa at the end of the third drying spell.

Water use efficiency (WUE) is defined as the ratio of grain yield to evapotranspiration. Rao et al., (2012), observed the highest mean WUE of 1.28 kg m^{-3} in wheat in their ET_{75} irrigation treatment. However, the highest grain yield was under full irrigation in comparison to deficit irrigation levels. Several studies have reported WUE values that were higher under water deficit than high irrigation conditions, especially when irrigation was applied in critical stages of plant development (Mandal et al. 2005). However, Farre and Faci (2006), observed that water use efficiency decreased with decreasing irrigation. Water use efficiency of wheat grain yield was increased from 0.97 to 1.10 kg m^{-3} by supplemental irrigation, although WUE for dry matter was not affected by it (Zhang et al. 1998). One study (Li et al. 2001b) suggested that limited supplemental irrigation during the growth season can significantly increase WUE and wheat yield. Winter wheat water use (evapotranspiration) depends on variety, growth stage, canopy and leaf structure, climatic conditions, irrigation, soil, and crop management practices. Zhang et al. (2006) carried out a water-deficit study and observed biomass yields of wheat between 15 and 20 ton ha^{-1} depending on irrigation quantity and its application growth stage. However, Tari (2016) reported a range between 20.9 and 10.1 ton ha^{-1} for full irrigation and rain-fed and recommended that water deficit should be applied in milky grain stage of wheat to reduce the yield losses. Padhi et al. (2010) stated that grain yield, straw and leaf area index have significant differences among treatments where the full irrigation treatment resulted in greatest values and these features decreased with increasing stress levels. Rao et al. (2012) found the highest values of total biomass, grain yield and harvest index of wheat under full irrigation using a line source sprinkler irrigation in comparison to deficit irrigation levels. Sezen and Yazar (2006) observed the highest average wheat grain yield under full irrigation with a 7-day interval using sprinkler line source system as 8340 kg ha^{-1} , and the lowest yield was obtained from rain-fed treatment

with 2940 kg ha⁻¹. Huang et al. (2005) stated increasing grain yield was noted with increasing biomass yield.

The agricultural sector and water security in the Mediterranean region are facing many environmental challenges including climate change (increasing temperature and potential evapotranspiration, decreasing rainfall and increasing the drought spells), water scarcity, rapid population growth and urbanization (FAO 2016).

We hypothesized that use of CWSI and leaf water potential in monitoring irrigation scheduling under different supplemental and conventional irrigation strategies during different growth stages of crop would benefit water management and increase WUE and farmers profits. The objective of this research, therefore, was to evaluate crop water stress index and midday flag leaf water potential on wheat (*Triticum aestivum* L. Adana 99) under conventional and three different supplemental irrigation strategies at four irrigation levels using sprinkler line-source system under the Mediterranean climatic conditions of Turkey.

Materials and methods

Experimental site

The experiment was carried out in research field of the Irrigation and Agricultural Structures Department at Çukurova University (36°59'N latitude, 35°18'E longitude and altitude of 35 m above sea level), located in Adana, Turkey, during the 2014 and 2015 wheat growing seasons using a local wheat variety (*Triticum aestivum* L. Adana 99).

Soil and water

The soil of the experimental site is classified as the Mutlu soil series (*Palaxerollic Chromoxeret*) (FAO 2006), with a clay texture throughout the profile, and has a pH range 7.62–7.78, electrical conductivity of the saturation extract (EC_e) 0.12–0.19 dS m⁻¹, and average volumetric soil water content at field capacity and permanent wilting point of the root-zone 38% and 22%, respectively. Mean bulk density varies from 1.15 to 1.25 g cm⁻³. The available water-holding capacity of the soil is 198 mm in the 120 cm soil profile. Irrigation water is obtained from an open channel irrigation system in the experimental area, with quality classified as (C₂S₁) according to USSS (1954), pH of 7.8, and average electrical conductivity of 0.78 dS m⁻¹.

Climate

Çukurova is located in a semi-arid climate. Weather data were collected from an automatic recording meteorological station located about 60 m from the experimental site.

Precipitation, maximum and minimum air temperatures, air humidity, wind speed and solar radiation measured on a daily basis, and summarized for each growing season along with long-term climatic data from 1960 to 2015 are shown in Table 1.

Experimental design and treatments

In the experiment, line source sprinkler design was employed for studying the effect of supplemental, deficit irrigation strategies and irrigation levels on wheat yield. Separate sprinkler lines were employed for the main treatments and sprinkler lateral was laid out parallel to plant rows. The line source sprinkler system was used to assess crop yield response to different levels of deficit irrigation, where the applied irrigation water was uniformly distributed parallel to sprinkler lateral and water application gradually decreased with distance away from the line source. Double nozzle sprinkler heads (4.5 mm × 4.8 mm) placed at 6 m intervals on the laterals provided a linearly decreasing wetting pattern under an operating pressure of 300 kPa.

In this study, four irrigation strategies were considered, namely conventional irrigation (CI), irrigation at flowering and grain filling (SIFG), irrigation only at flowering stage (SIF) and irrigation only at grain filling stage (SIG). Four irrigation levels in each irrigation strategy, namely one full (I₁₀₀) and three deficit (I₂₅, I₅₀, I₇₅) irrigations and a rain-fed treatment were envisaged. Schematic field layout of the line-source sprinkler system, plot dimensions, the location of catch-cans and neutron access tubes is shown in Fig. 1.

The amount of irrigation water applied in conventional full irrigation next to the sprinkler lateral (I₁₀₀) was based on restoring root zone moisture deficit (when 50% of available water was depleted in effective root-zone depth of 90 cm) to near-field capacity. The other irrigation treatments automatically received approximately linearly decreasing proportions (0.75, 0.50 and 0.25) of the full irrigation amount. For supplemental irrigation strategies during the corresponding growth stage, soil water deficit in the top 90 cm of the soil profile was replenished to field capacity for full irrigation level plots next to the sprinkler lateral.

Measurements and observations

Soil water content

The soil water content was measured by gravimetric method (dry oven at 105 °C for 24 h) at planting and harvesting by using hand-auger at 30 cm depth increments down to 90 cm soil profile. During the wheat growing season, soil water content was monitored before irrigation at approximately 2-week intervals and prior to water application by a neutron probe (Hydroprobe Model 503, California, USA). Access

Table 1 Monthly maximum temperature (Tmax), minimum temperature (Tmin), total precipitations (P), maximum relative humidity (RHmax), minimum relative humidity (RHmin), wind speed (WS), solar radiation (SR), evaporation from Class A pan (E) of wheat growing seasons 2013/2014, 2014/2015 and long-term (1960–2015)

Climatic parameters	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Long-term average (1960–2015)								
T_{max} (°C)	22.5	16.8	15.0	16.2	19.6	23.7	28.2	31.7
T_{min} (°C)	10.9	7.2	5.5	6.2	8.6	12.3	16.1	20.2
P (mm)	76.7	129.0	106.2	87.2	67.6	55.8	46.6	20.1
RH_{avg} (%)	63.9	67.6	66.1	66.2	66.5	67.7	67.0	67.0
WS (m s ⁻¹)	1.2	1.4	1.5	1.5	1.6	1.6	1.7	1.8
SR (MJ m ⁻² d ⁻¹)	8.6	6.4	7.2	10.0	13.5	17.0	20.0	21.8
E (mm)	66.4	45.1	45.6	52.5	82.9	114.0	163.0	207.2
Growing season (2013/2014)								
T_{max} (°C)	24.5	16.1	17.6	18.7	20.9	30.7	27.9	–
T_{min} (°C)	10.7	3.9	5.7	5.2	8.1	11.3	14.8	–
P (mm)	26.0	17.0	48.0	41.0	54.5	33.6	30.5	–
RH_{max} (%)	83.5	78.4	87.4	94.4	89.9	92.5	90.8	–
RH_{min} (%)	33.2	25.0	43.2	36.1	39.4	45.7	38.4	–
WS (m s ⁻¹)	0.5	1.3	0.6	0.7	0.9	0.8	0.8	–
SR (MJ m ⁻² d ⁻¹)	10.2	9.2	8.7	13.5	16.4	19.5	22.2	–
Growing season (2014/2015)								
T_{max} (°C)	–	18.2	14.0	15.5	20.0	22.2	29.9	31.9
T_{min} (°C)	–	8.3	3.8	6.1	7.7	8.4	14.0	18.2
P (mm)	–	70.5	62.0	85.0	96.3	25.0	65.0	15.0
RH_{max} (%)	–	90.3	86.6	90.4	90.9	92.0	91.2	90.5
RH_{min} (%)	–	49.6	46.0	50.2	41.8	41.4	36.7	40.9
WS (m s ⁻¹)	–	0.7	0.8	0.9	0.8	0.8	0.7	1.0
SR (MJ m ⁻² d ⁻¹)	–	7.5	8.0	9.7	16.0	19.8	23.5	24.4

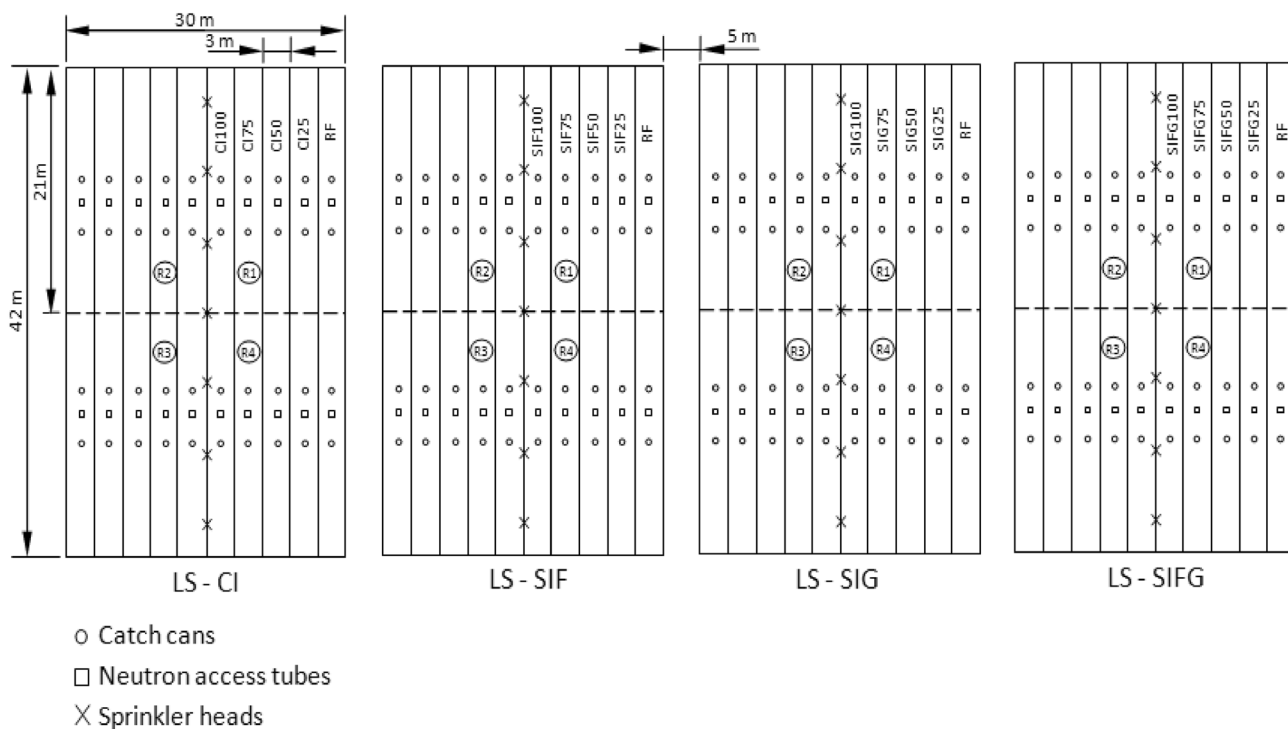


Fig. 1 Schematic field layout of the line-source sprinkler system, plot dimensions, location of catch-cans and neutron access tubes

tubes were installed to a depth of 120 cm in the middle of all plots (Fig. 1). The amount of available water in 90 cm soil depth was estimated as the difference in soil water content between field capacity (345 mm) and wilting point (201 mm) as presented in Figs. 2 and 3.

Evapotranspiration

The evapotranspiration of wheat (ET_a) for individual plots was determined for total seasons and between the growing stages by using the soil water balance equation (Allen et al. 1998) as follows:

$$ET_a = I + P \pm \Delta SW - D_p - R_o, \quad (1)$$

where I : The amount of applied water irrigation (mm) that is measured in the catch cans, P : The precipitation (mm) that is measured at the weather station on the site, $\pm \Delta SW$: is the change of soil water content (mm) between any consecutive irrigations in the 90-cm soil profile taken as effective root zone depth, D_p : the drainage from the bottom of the root zone below 90 cm depth, which is negligible since single

rainfall amount and distribution during the growing seasons did not exceed soil water storage capacity in the 90-cm soil depth; R_o : surface runoff occurring during the study seasons. R_o from the experimental plots was negligible as there was sufficient surface roughness (due to dry sowing) for water infiltration and also there were low ridges of sowing lines.

Water use efficiency

The water use efficiency for the different treatments was calculated as the ratio of grain yield (kg ha^{-1}) to evapotranspiration in mm (Kijine et al. 2002).

Crop water stress index

Canopy temperature (T_c) and air temperature (T_a) were recorded in $^{\circ}\text{C}$ using a portable infrared thermometer (IRT) (model RAYMX-4PTDG - Germany). The infrared thermometer had a field of view (FOV) of 3° , resolution of 0.25°C , operated with emissivity set at 0.98, and equipped with spectral band filter of a 9–14 μm and an air temperature

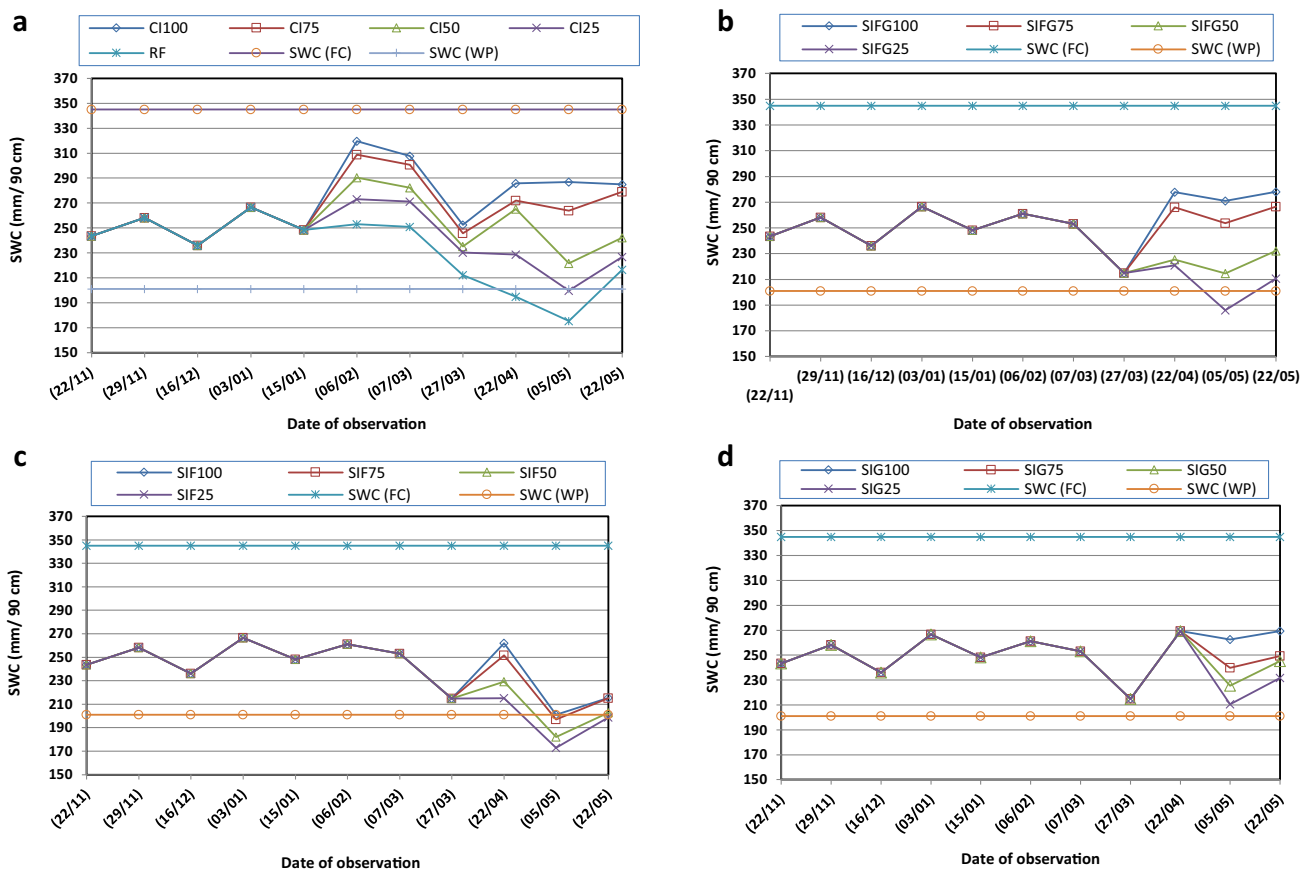


Fig. 2 The effect of different irrigation levels on root zone total soil water content (SWC) under **a** conventional irrigation (CI), **b** supplemental irrigation during flowering and grain filling (SIFG), **c** supple-

mental irrigation during flowering (SIF) and **d** irrigation during grain filling (SIG) in 2014 season

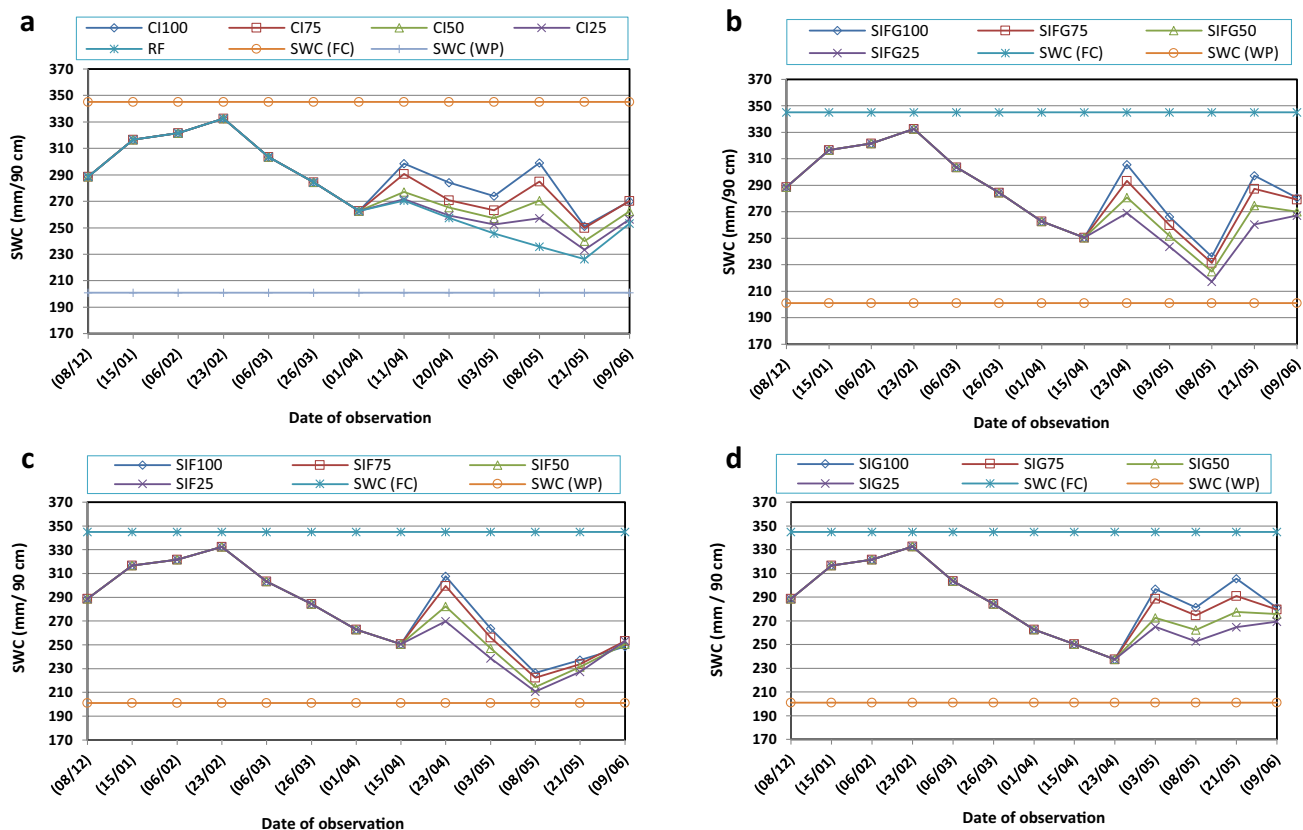


Fig. 3 The effect of different irrigation levels on root zone total soil water content (SWC) under **a** conventional irrigation (CI), **b** supplemental irrigation during flowering and grain filling (SIFG), **c** supple-

mental irrigation during flowering (SIF) and **d** irrigation during grain filling (SIG) in 2015 season

sensor. Canopy temperature and the corresponding air temperature measurements were taken from four directions (east, west, north, south) across the planted rows when the crop cover was greater than 70%. The IRT canopy temperature readings were taken with angle of 30–40° from horizontal line by targeting the upper side of the wheat canopy on clear sky conditions around solar noon time (12:00–14.00 h) at distance of 1.0 to 1.5 m from the canopy (crop), measurements were made on sunlit leaves, to assure that the measurements should be taken at maximum solar intensity. The mean canopy temperature for each plot was collected as the average of six readings. Dry and wet-bulb temperatures were measured with a psychrometer (Assmann Psychrometer, Sato Keiryoki MFG. Co., Ltd, Japan) at a height of 1.5 m in the open area adjacent to the experimental plots. Canopy air temperature difference ($T_c - T_a$) was calculated separately for both well-irrigated and non-irrigated treatments and plotted against vapor pressure deficit (VPD) of the corresponding day. The mean VPD was computed as the average of the calculated instantaneous wet and dry bulb temperatures and the standard psychrometer equations (Allen et al. 1998) with a mean barometric pressure of 101.2 kPa for the experimental site. CWSI was calculated separately for each treatment

depending on the following equation developed using the empirical approach of Idso et al. (1981):

$$CWSI = \frac{[(T_c - T_a) - (T_c - T_a)_{LL}]}{[(T_c - T_a)_{UL} - (T_c - T_a)_{LL}]}, \quad (2)$$

where $(T_c - T_a)$: is the difference in the canopy and air temperature (°C), LL represents the non-water-stressed baseline (lower baseline) and UL represents the non-transpiring upper baseline. LL for the canopy–air temperature difference ($T_c - T_a$) versus the VPD relationship was determined using data collected only from the unstressed treatments (full irrigation). UL was computed according to the procedures explained by Idso et al. (1981). To verify the upper baseline, canopy temperatures of the fully stressed plants were determined several times during the growing season of wheat.

Leaf water potential

Leaf water potential (ψ_l) was measured using a pressure chamber instrument (PMS Instrument Company, Model 615, Albany, USA). Measurements were taken at midday

with the sunny and clear sky on four healthy flag leaves of wheat plants per experimental unit. The sampled leaves were covered with a small plastic bag immediately after excision to avoid the water loss during the transfer of each leaf to chamber. The time between chamber pressurization and leaf excision was brief as possible and generally less than 15 s. The leaf petiole was cut with a sharp razor from the shoot and placed in chamber. The chamber was sealed and gradually and slowly pressurized with nitrogen gas. The pressure increases at some point which sap forces out of the xylem system and it is observed with a magnifying glass at the cut end of the leaf stem. The amount of pressure that it takes to cause water to appear at the cut surface determines how much tension the leaf is experiencing at this point (balance pressure) is recorded as leaf water potential (bar) (Scholander et al. 1965). The leaf water potential readings were made two times, namely in 139 and 157 DAP in the first season, whereas in the second year carried out on 142 and 158 DAP, respectively.

Grain, biomass yield

For grain yield the crop was harvested at full maturity on May 22, 2014 and June 9, 2015. At harvest, all plants in the 2-m long and 1.5-m wide area in the center of each plot were cut at ground level. Grain and straw were separated by threshing machine and weighed. All plant samples were dried for 48 h in an oven at 68 °C for determination of dry matter.

Statistical analysis

The experiment was carried out by using randomized complete block design. The experimental data were analyzed statistically using computer software program SAS (Statistical Analysis System—Version 9.00 TS level 00M0 XP_PRO platform). Comparisons between different treatment means were made through Duncan's Multiple Range Test at 5% probability level.

Results and discussion

Distribution of rainfall during the wheat growing seasons

The 2014 experimental year was a dry year, and the total precipitation during the season recorded was just 251 mm. However, the rainfall increased in the wet year of 2015 to 419 mm. The first and second seasons' rainfall amounts were lower than the long-term means by 49.1 and 14.9%, respectively. Hence the first wheat growing season (2014) was classified as a drought year. In dealing with distribution the

rainfall during both seasons, throughout the first 3 months of December, January and February the monthly precipitation in the 2014 season was 51.2% lower than the second season and 67.1% lower than the long-term average. Furthermore, the precipitation quantity in the 2014 season during the tillering stage was insufficient, as only 17 mm of rain fell in December and, therefore, the wheat was irrigated with equal quantity for all treatments to insure plant establishment. During the advanced growth stages (after the heading) the monthly precipitation in April for the first and second seasons was similar to one another.

Irrigation and crop water use (evapotranspiration)

The actual amount of irrigation water applied was determined by measuring the water collected in the catch cans located in the center of each plot during an irrigation event. The greatest seasonal irrigation water applied to 100% level was under the CI₁₀₀ treatment with values 276 and 188 mm in the first and second year, respectively. The amount of irrigation water applied to SIFG₁₀₀ varied between 246 and 163 mm in 2014 and 2015 growing seasons. The corresponding values for SIF₁₀₀ strategy were 149 and 73 mm; for SIG₁₀₀ 247 and 144 mm for the first and second growing seasons, respectively. The total irrigation water applied to the treatments during flowering growth stage SIF₁₀₀ saved 46–61% water as compared to CI₁₀₀ for the first and second growing season, respectively. The corresponding water savings were 11–13% when water was applied at flowering and grain filling stages SIFG₁₀₀.

Since the precipitation during the 2014 growing season from November to March was relatively scarce at the experimental site, ET_a was mainly from applied irrigation water. Therefore, the effect of supplemental irrigation on studied crop parameters of CW_{SI}₁ and grain yield appeared strongly. Seasonal ET_a in 2014 ranged from 462 mm for SIFG₁₀₀ to 428 mm for SIF₁₀₀; however, CI₁₀₀ resulted in the highest value of 485 mm and the lowest value was measured in RF treatment as 293 mm. ET_a values ranged from 645 mm for CI₁₀₀ to 474 mm under RF treatment in the wet year. The seasonal crop evapotranspiration of the CI₁₀₀ treatment was higher than full supplemental irrigation SIFG, SIF and SIG by 4.9, 13.3 and 2.9% in the 2014 growing season and the corresponding values in the above mentioned strategies in the second year recorded as 5.7, 16.9 and 9.1%, respectively.

Soil water content variation

During the drier season, 2014, the SWC was lower in the beginning of the season at planting until tillering growth stage owing to no rain. In relation to the wetter season, 2015, with more sufficient rainfall, the soil water content values were higher during the first growth stages of winter wheat. In

2015 SWC started increasing after planting to reach its maximum value in the season on 78 DAP (332.58 mm/90 cm), then decreased gradually to the lowest levels observed during heading, flowering and grain filling stages, which resulted in the gradual increase of water stress during these periods. Furthermore, SWC increased early in conventional strategy due to irrigation applied on 116 DAP at heading stage, while SWC decreased in SIFG and SIF irrigation strategies until flowering stage and then increased following an irrigation application on 130 DAP. In relation to grain filling strategy, the soil water content continued to decrease more than SIF and SIFG strategies due to a relatively late irrigation application on 138 DAP in grain filling stage. Generally, the highest soil water content during all the growth stages of wheat occurred in conventional strategy. Relative to the first-year data, SWC was found to be below wilting point at the end of the season for RF, CI₂₅ and SIFG₂₅; this also occurred with SIF strategy under 75, 50 and 25% levels during the grain filling stage. However, the soil water content fluctuated gradually between field capacity and wilting point until the end of the season for the rest of the treatments in the first and second season as shown in Figs. 2 and 3.

Crop water stress index (CWSI)

Evaluation of upper and lower CWSI baselines

Lower and upper baselines for CWSI were derived using the procedures of Idso et al. (1981). In the first year, these were expressed by the linear equations: $(T_c - T_a)_{ll} = -1.22 \text{ VPD} + 0.49$, and $(T_c - T_a)_{ul} = 0.04 \text{ VPD} + 2.13$. The VPD

values ranged from 1.65 to 2.12 kPa for upper baseline (maximum stress) of RF treatment. During the second season, the non-water-stressed baseline was represented by the following equation: $(T_c - T_a)_{ll} = -1.11 \text{ VPD} + 0.77$, and the fully stressed baseline was expressed by the equation: $(T_c - T_a)_{ul} = 0.02 \text{ VPD} + 2.08$. The VPD values varied from 1.9 to 2.3 kPa during the study periods. These results agree with studies reported in the Mediterranean environments where the VPD increases sharply from 1 to values of 2–3 kPa at the end of grain filling (Condon et al. 1992; Sato et al. 2006; Zhang et al. 1998). Howell et al. (1986) reported the maximum differences between T_c and T_a (upper limit), which is given as 2 °C for winter wheat under rain-fed treatment (RF) at Bushland, TX, and the same difference was observed by Gontia and Tiwari (2008) for fully stressed treatment in India; however, 2.7 °C difference was observed for winter wheat in Iran (Irandoust and Bijanzadeh 2017).

The intercept and slope of the lower baseline were 0.49 °C and -1.22 °C in the first season and 0.77 °C and -1.11 °C in the second season as presented in Fig. 4. The slope of lower baseline of winter wheat developed in India by Gontia and Tiwari (2008) was fairly close to our findings (-1.11), however, slightly different from published values for wheat by Alderfasi et al. (2000) who reported an intercept of approximately 0.41 and slope -1.50 for non-water stressed baseline. Irandoust and Bijanzadeh (2017) reported a slope value of -1.0 and an intercept value of 0.72 for winter wheat in Iran. The difference can be attributed to different climatic conditions and also wheat varieties between the Mediterranean region, India, Iran and Colorado in the United States.

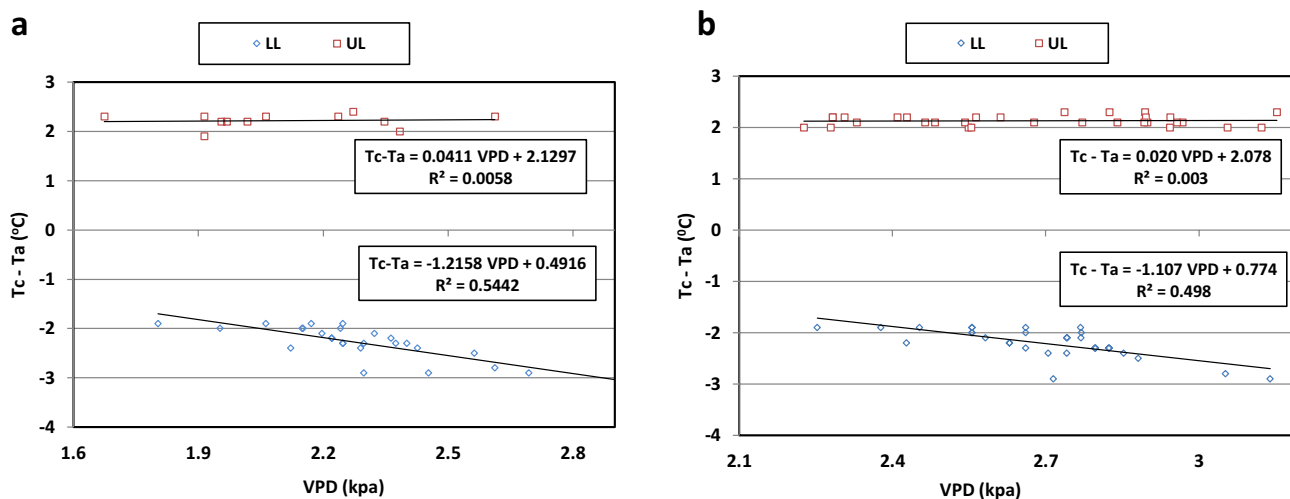


Fig. 4 Canopy-air temperature difference ($T_c - T_a$) versus air vapor pressure deficit (VPD) in well watered (LL) and maximally stressed (UL) wheat. R^2 : determination coefficient in 2014 (a) and 2015 (b)

CWSI and irrigation scheduling

Canopy and air temperature difference ($T_c - T_a$) and VPD measurements were initiated at tillering stage after 95 DAP under CI strategy in 2014 growing season where the highest CWSI value of 0.807 was recorded in the rain-fed treatment. The decreasing SWC due to rainless period and no irrigation led to increased CWSI values at heading stage (122 DAP) to 0.90 in rain-fed and 0.26 in CI_{100} (Fig. 5). The observations of ($T_c - T_a$) in CI during the 2015 season started a little late at the end of heading stage on 127 DAP due to rainfall. The range of CWSI values in the second year appeared to be lower compared to the dry year, and there was no significant difference between CI_{25} and RF treatments which had average CWSI values of 0.32 and 0.38, respectively. The fully irrigated treatment CI_{100} reflected no water stress with lowest CWSI values of 0.08 in both years.

In general, the CWSI of CI appeared relatively low in comparison with SIF and SIFG due to the extra irrigation applied at tillering stage (60 DAP), whereas irrigation under strategies SIF and SIFG commenced at flowering stage in

first season. The results obtained in second season were in contrast to the 2014 year as the CWSI in CI was relatively high compared to the supplemental irrigation strategies SIF and SIFG due to decreasing soil water content. This is likely due to the fact that the $T_c - T_a$ measurements were taken on 134 DAP, which corresponded to 4 days after irrigation in flowering stage on 130 DAP under SIF and SIFG strategies. However, $T_c - T_a$ was measured in CI 18 days later than irrigation application on 116 DAP during the heading stage.

In general, the CWSI value following an irrigation on 165 DAP in grain filling stage appeared relatively high as compared to the flowering stage after an irrigation on 136 DAP due to warmer weather conditions increased maximum air temperatures to 28.8, 31.2 and 34.6 °C for $T_c - T_a$ measurements taken on 136, 152 and 165 DAP, respectively. Even though the temperatures were high at the end of the second season which reached 30.8, 32.1 and 36.4 °C on 139, 149 and 156 DAP, the CWSI values were relatively lower compared to the first season due to higher soil water content because of rains at the beginning of the second growing season.

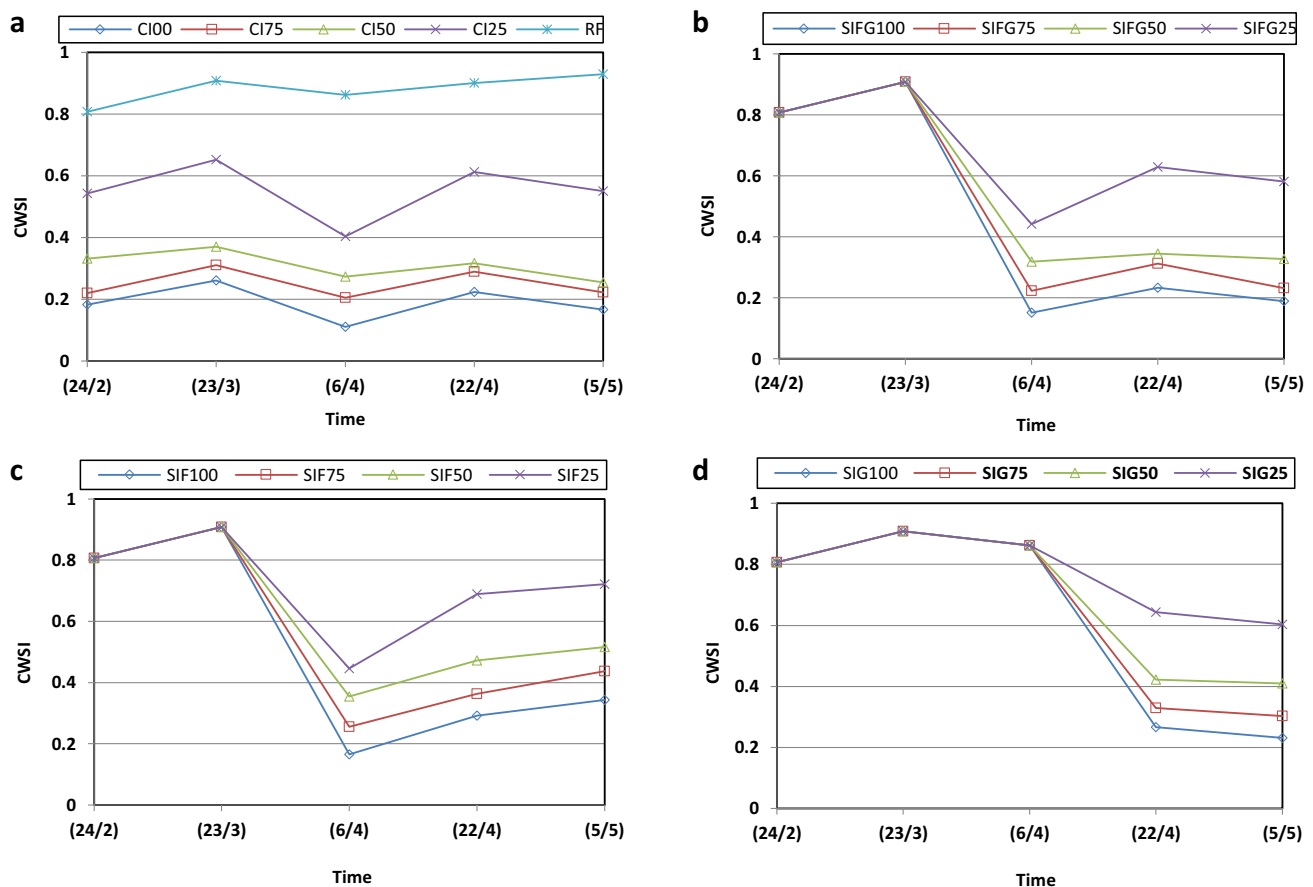


Fig. 5 Crop Water Stress Index (CWSI) in different irrigation strategies under different irrigation levels during 2014 season. *CI* conventional irrigation, *SIFG* supplemental irrigation during flowering and

grain filling, *SIF* supplemental irrigation during flowering, *SIG* irrigation during grain filling

The results indicated that CWSI values increased with declining soil water content on 152 DAP in 2014 season, then decreased on 165 DAP due to irrigation on 154 DAP at grain filling stage for all treatments (except SIF treatments and RF). CWSI values for CI₁₀₀, SIFG₁₀₀ and SIG₁₀₀ decreased from 0.22, 0.23 and 0.27 before irrigation to 0.17, 0.19 and 0.23, respectively. The data obtained in year 2015 (Fig. 6) were different than in the first year due to varying irrigation times. On 139 DAP (watery grain filling stage) the smallest range of CWSI was found in SIG, followed by CI. However, the CWSI range was slightly higher and close to each other under SIFG and SIF strategies. The reason for decreased CWSI values in SIG and CI might be the prevailing non-stress conditions since the crop was irrigated on 138 DAP in SIG strategy and on 135 DAP in CI. However, irrigation in SIF and SIFG was applied on 130 DAP. These results are in agreement with findings of Gontia and Tiwari (2008) who explained that CWSI values for wheat ranged from zero to 0.96 using different irrigation levels (including rain-fed), and Zia et al. (2012) indicated that the CWSI values were between 0.33 and 0.65 depending on irrigation quantity.

It was observed that the CWSI values of irrigation at grain filling stage (SIG) were higher in comparison to SIFG strategy in both years, due to the irrigation during flowering and grain filling stages in SIFG strategy but during only grain filling stage for SIG. Consequently the water stress occurring in SIG raised the canopy temperatures much higher than those in SIFG.

Data regarding SIF strategy indicated that the CWSI values increased steadily after flowering toward the end of the growing seasons in both years. The reasons for the increased CWSI values in SIF might be increased canopy temperatures at the end of the season and cutting irrigation early (130 DAP) in both growing seasons that led plant leaves more dried and senesced; consequently, canopy temperature became higher and resulted in increased CWSI values. Similar results were observed in the RF treatment in which the CWSI values were higher than all other treatments throughout the experiment. The observed increase of CWSI in 2014 was greater than 2015 season due to the effect of drought conditions (rain 251 mm) that prevailed from the tillering growth stage until the end of the first season.

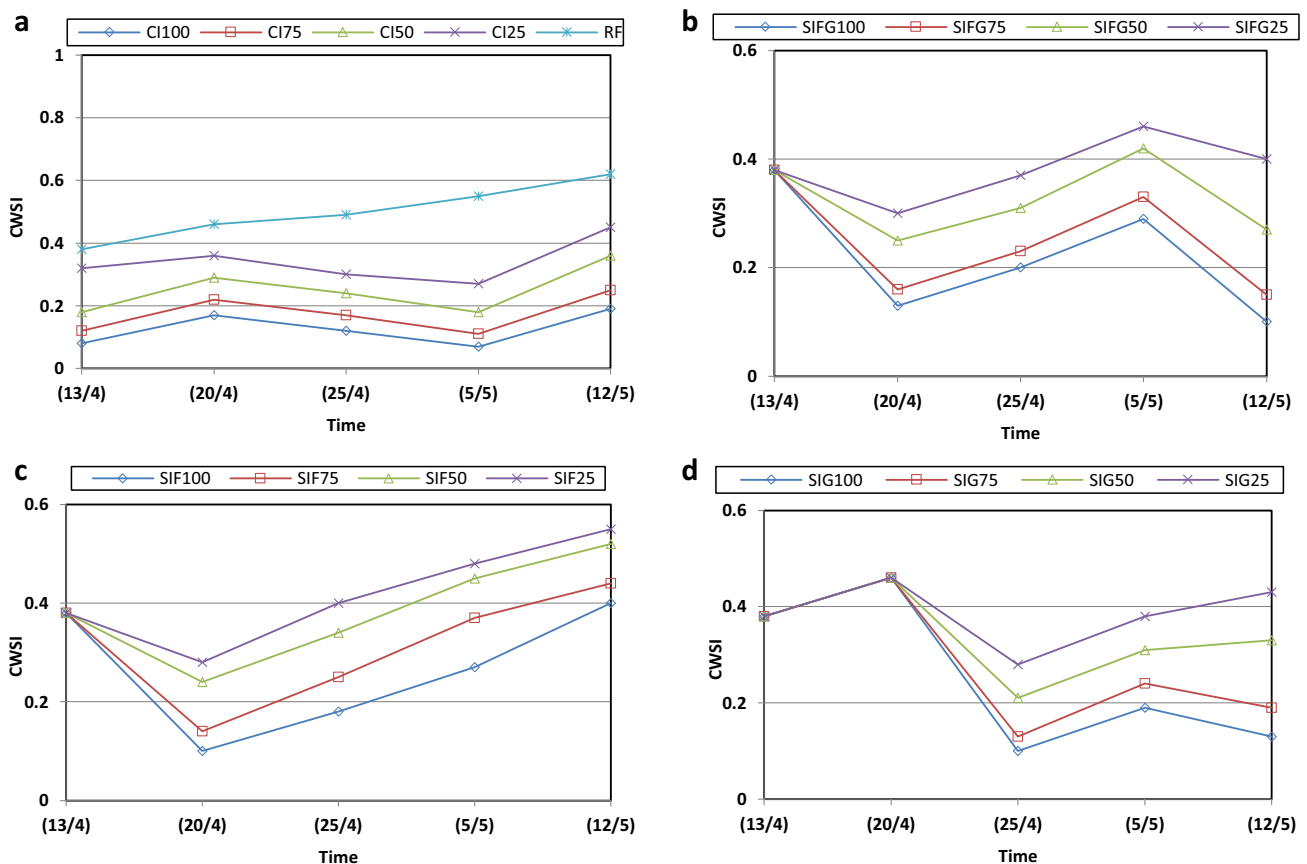


Fig. 6 Crop Water Stress Index (CWSI) in different irrigation strategies under different irrigation levels during 2015 season. CI conventional irrigation, SIFG supplemental irrigation during flowering and

grain filling, SIF supplemental irrigation during flowering, SIG irrigation during grain filling

Seasonal CWSI

The seasonal average of CWSI under non-water-stressed (well-irrigated) treatments were 0.18, 0.24, 0.19 and 0.26 for full irrigation strategies CI, SIG, SIFG and SIF in the drier season, and the corresponding CWSI values in the wetter season were 0.12, 0.22, 0.18 and 0.23, respectively. For moderately water-stressed treatments the seasonal mean CWSI amounted to 0.31, 0.35 and 0.41 for SIG₇₅, SIF₇₅ and SIG₅₀ treatments in the first growing season, the values became lower in the second year with an average of 0.25, 0.30 and 0.32, respectively. Under stressed treatments and non-irrigated treatment, the CWSI of wheat had a minimum value of 0.34 in CI₂₅ and maximum value of 0.88 in rain-fed, corresponding to the wet and dry seasons, respectively. Bijanzadeh and Emam (2012) reported that under well and excess watering conditions in Iran CWSI in wheat cultivars ranged from 0.31 to 0.36, and that decreasing water supply resulted in increasing CWSI.

Based on the previous seasonal average CWSI values that ranged from 0.12 to 0.26 for well-irrigated treatments, it is suggested that winter wheat should be irrigated when CWSI reaches between 0.18 and 0.26 and between 0.12 and 0.23 during dry and wet climatic conditions, respectively, in Mediterranean region. However, under water scarcity and high price of water, the moderately water-stressed range (0.31–0.41) in dry years and (0.25–0.32) in wet years of CWSI could be considered as limited irrigation scheduling strategies. Therefore, CWSI can be used to predict when to irrigate, but it cannot provide information how much to irrigate as the general case for plant-based irrigation scheduling methods (Irmak et al. 2000; Kacira et al. 2002).

Midday leaf water potential of wheat

The midday of leaf water potential (ψ_l) measurements were conducted in post-anthesis stage (watery grain filling stage) that occurred after 139 and 142 DAP in 2014 and 2015 growing seasons (Table 2). In the first season, CI₁₀₀ treatment resulted in significantly higher ψ_l than those in the three full supplemental irrigation treatments due to higher soil water content in the root zone. There was no significant difference between full supplemental irrigation treatments in the first year. The results showed that ψ_l was affected by the irrigation regime in the second season where ψ_l values in the full supplemental irrigation SIFG were lower as compared with full conventional and full grain filling treatments.

ψ_l values under moderate irrigation levels (75% and 50%) in SIG were higher in comparison with other supplemental irrigation treatments SIF and SIFG with average -20.9 and -21.72 bar in 2014 season and achieved -17.85 and -20.25 bar in second year, respectively. The reduction in ψ_l values under SIG was due to the measurements made

Table 2 The effect of interaction between the irrigation strategies and irrigation levels on leaf water potential (ψ_l) during 2014 and 2015 seasons

Treatments	ψ_l (bar)			
	9/4/2014	27/4/2014	28/4/2015	14/5/2015
SIFG ₁₀₀	-20.8^{cde*}	-22.27^{bc}	-19.45^{cd}	-21.60^{bc}
SIFG ₇₅	-21.28^{def}	-22.63^{bcd}	-20.05^{de}	-21.85^{bcd}
SIFG ₅₀	-22.39^{gh}	-24.23^{ef}	-20.65^{efg}	-22.70^{defg}
SIFG ₂₅	-22.64^{hi}	-24.80^{fg}	-21.05^{fgh}	-23.10^{fg}
CI ₁₀₀	-17.90^a	-20.67^a	-16.3^a	-20.15^a
CI ₇₅	-18.88^b	-22.17^b	-17.85^b	-21.30^b
CI ₅₀	-20.11^c	-23.11^{cd}	-19.10^c	-22.05^{bcde}
CI ₂₅	-21.54^{defg}	-24.21^{ef}	-19.95^{cde}	-22.75^{defg}
SIF ₁₀₀	-20.91^{cde}	-24.12^{ef}	-19.15^c	-22.95^{efg}
SIF ₇₅	-21.73^{efgh}	-24.25^f	-19.95^{cde}	-23.07^{fg}
SIF ₅₀	-22.18^{fgh}	-24.92^{fg}	-20.75^{efgh}	-23.50^g
SIF ₂₅	-22.44^{gh}	-25.10^{fg}	-21.20^{gh}	-23.55^g
SIG ₁₀₀	-20.60^{cd}	-22.81^{bcd}	-17.7^b	-21.55^{bc}
SIG ₇₅	-20.90^{cde}	-23.32^{de}	-17.85^b	-21.75^{bcd}
SIG ₅₀	-21.72^{efgh}	-24.45^{fg}	-20.25^{def}	-22.45^{cdef}
SIG ₂₅	-22.60^{hi}	-24.92^{fg}	-20.85^{efgh}	-23.20^{fg}
RF	-23.50^i	-25.40^g	-21.65^h	-23.70^g

*The similar-letters-treatments have no significant differences

2 and 4 days after irrigation in the first and second year, respectively, whereas under SIF and SIFG measurements were taken 10 and 12 days after irrigation (under more severe water stress) in 2014 and 2015 growing seasons, respectively.

The results revealed clear differences between irrigation levels and strategies in the 2014 growing season where the full conventional irrigation and all three full supplemental irrigation treatments (SIFG₁₀₀, SIF₁₀₀ and SIG₁₀₀) had significantly increased (less negative values) amounting to 31.2, 12.9, 12.3 and 14% of the rain-fed control, respectively. These values in the second year were higher with a slight difference compared to the first year reaching 32.8, 11.3, 13 and 22.3%, corresponding to the above mentioned treatments. ψ_l values in the second season were higher compared with the first season; consequently, the difference between full irrigation treatments and RF was higher (Table 2). The results reflect the ability of dry conditions to decrease ψ_l values that might have occurred due to increased respiration and decreased transpiration resulting from stomatal closure. Leaf water potential had decreasing trend with time and fluctuated depending on drying and rewatering alternated of soil water content, and with developing growth stages observed at milky grain filling stage (157 and 158 DAP during 2014 and 2015 crop seasons) ψ_l became much lower (more negative) which ranged from -20.15 bar for CI₁₀₀ to -25.4 bar for rain-fed

in the second and first seasons, respectively, whereas ψ_1 at water filling stage was higher (less negative) and varied between -16.3 and -23.5 bar under the same treatments in the 2015 and 2014 growing seasons, respectively. Steadily decreasing ψ_1 values of wheat with increasing days of drying (or after irrigation) were previously reported by Liang et al. (2002), and Waraich and Ahmed (2010). Our results are in line with the findings of Siddique et al. (2000) who reported that exposure of wheat to drought led to a noticeable decrease in leaf water potential.

In general, the results indicated that ψ_1 values at milky grain stage under full irrigation treatments CI, SIFG, SIF and SIG, respectively, were higher 22.8, 14.0, 5.3 and 11.3% in the first year, and to 17.6, 9.7, 3.2 and 9.9% in the second year as compared with rain-fed conditions. This relative reduction in ψ_1 values in milky grain filling stage might be attributed to decreasing soil water content under rain-fed; in addition, plant leaves started to senesce with the progress of growth stages. The flag leaf senescence level was estimated by a SPAD 502 portable chlorophyll meter (Minolta, Tokyo, Japan) by observing the chlorophyll concentration during the whole grain filling stages (data not shown). Thus decreased chlorophyll content in advanced stages accelerated flag leaves to senesce quickly and ψ_1 achieved lower values as compared to other stages. These results confirmed the findings of Matic (2008); Ali et al. (2014), who found midday Ψ_1 ranging for (CI₁₀₀ and RF) from -14.22 to -17.78 bar at flowering and from -18 to -24.03 bar at grain filling stage and dropping linearly with decreasing irrigation levels from 100% ET_a to 60% ET_a.

Regarding the supplemental irrigation under flowering growth stage (SIF), average ψ_1 was the more negative compared with other strategies, where average ψ_1 was -24.12 bar in the SIF₁₀₀ and -20.67 , -22.27 and -22.81 bar, respectively, and in other full irrigation strategies CI₁₀₀, SIFG₁₀₀ and SIG₁₀₀ in 2014. In the second year, ψ_1 in SIF₁₀₀ treatment (-22.95 bar) was lower by 12.2, 5.8 and 6.1% which corresponds to the treatments CI₁₀₀, SIFG₁₀₀ and SIG₁₀₀, respectively. The decrease in ψ_1 under SIF₁₀₀ strategy was due to prolonged drought spell which was just irrigated once at flowering stage (130 DAP), whereas other strategies were to irrigate during flowering and grain filling stages; these findings are in agreement with conclusions of Puri and Swamy (2001); Jiang et al. (2013).

In general, the ψ_1 values in the drier year, with increasing soil drought conditions were lower compared to the wetter year. In addition, the ψ_1 value was influenced by the growth stage of wheat where it was lower in the advanced growth stages of wheat that due to the effect of physiological factors such as reduced photosynthetic rate, chlorophyll content and other processes (Ali et al. 2014); consequently, the plant leaves start to senesce and dry toward the end of the season.

Grain, biomass yield and water use efficiency

The grain yield reflected strongly high sensitivity to water stress conditions where full conventional irrigation treatment achieved significantly greater grain yield during both growing seasons (Table 3). Similar results were reported by Sezen and Yazar (2006), who observed the highest average wheat grain yield was under full irrigation with a 7-day interval using sprinkler line source system in the Mediterranean region. As for water regimes, SIFG₁₀₀ and SIF₁₀₀ resulted in water saving about 10.7 and 45.9%, in the first year and this percentage reached 13.0 and 61.2% in the second year respectively, in comparison with CI₁₀₀. Rain-fed control resulted in decreased yields of 49.2, 39.8 and 46.4% compared to SIFG₁₀₀, SIF₁₀₀ and SIG₁₀₀, respectively, in the dry season, whereas these values decreased to 25.4, 16.3 and 22.3%, respectively, in the wet season due to the relative increase of soil moisture in the field in the beginning of season. The increase in grain yield with conventional irrigation over supplemental irrigation strategies was likely because of meeting water requirements of wheat fully during the growing season, whereas the relative reduction of yield under supplemental irrigation strategies (SIF, SIG and SIFG) compared to CI can be explained by the occurrence of water stress during flowering and grain filling stages. It was observed that irrigating at grain filling stage SIG₁₀₀ increased the grain yield by 12 and 7% compared to irrigation at flowering stage (SIF₁₀₀) during the first and second seasons, respectively. This is evident for all irrigation treatment levels when comparing grain yields of all SIG_x treatment plots with SIF_x plots and is in agreement with Tari (2016), who concluded that water deficit should be applied during the milky grain stage to minimize yield losses of wheat. Our results also confirm the findings of Rao et al. (2012), who reported that treatments under the higher deficit irrigation reduced grain yield markedly in comparison with well-watered treatments.

Water use efficiency values for different treatments under various irrigation strategies for the experimental years are presented in Table 3. In 2014, the highest WUE was 1.26 kg m⁻³ in treatment CI₇₅ and minimum value was obtained in SIF₂₅ as 0.75 kg m⁻³. Similar results were obtained in the second year when a slightly higher maximum WUE of 1.35 kg m⁻³ was recorded in CI₇₅ and the SIF₂₅ treatment resulted in minimum WUE of 1.16 kg m⁻³. The highest WUE occurred in CI₇₅ instead of CI₁₀₀ because of the relatively lower yield under CI₇₅. In relation to irrigation scheduling effect and wheat growth stages on WUE, the additional irrigation applied during tillering stage in conventional strategy as compared with the irrigation applied at both flowering and grain filling stages (SIFG) and at flowering stage SIF increased WUE by 7.9 and 14.6% in the two cropping seasons. These findings are in line with those of of Mandal

Table 3 The effect of interaction between the irrigation strategies and irrigation levels on grain, biomass yield, WUE and seasonal average CWSI in 2014 and 2015 cropping seasons

Season	2014				2015				
	Treatment	Grain yield (kg ha ⁻¹)	Biomass (kg ha ⁻¹)	WUE (kg m ⁻³)	Seasonal average CWSI	Grain yield (kg ha ⁻¹)	Biomass (kg ha ⁻¹)	WUE (kg m ⁻³)	Seasonal average CWSI
	SIFG ₁₀₀	4910 ^{c*}	14500 ^b	1.06 ^{cd}	0.19	7675 ^b	19958 ^a	1.25 ^{def}	0.18
	SIFG ₇₅	4518 ^{de}	12333 ^{cd}	1.07 ^c	0.25	7495 ^{bc}	18108 ^{bc}	1.31 ^b	0.21
	SIFG ₅₀	4182 ^g	11917 ^{cde}	1.03 ^{cdef}	0.33	6375 ^g	16575 ^{def}	1.18 ^{hi}	0.31
	SIFG ₂₅	3793 ^{hi}	9458 ^{gh}	1.01 ^{def}	0.55	6004 ^{hi}	15800 ^{ef}	1.19 ^{hi}	0.38
	CI ₁₀₀	5868 ^a	16333 ^a	1.21 ^b	0.18	8258 ^a	20550 ^a	1.28 ^{bcd}	0.12
	CI ₇₅	5466 ^b	15083 ^{ab}	1.26 ^a	0.24	8096 ^a	18750 ^b	1.35 ^a	0.17
	CI ₅₀	4181 ^g	12667 ^c	1.02 ^{def}	0.30	7258 ^d	17258 ^{cd}	1.29 ^{bc}	0.25
	CI ₂₅	3803 ^{hi}	11250 ^{def}	1.04 ^{cde}	0.55	6533 ^g	16400 ^{def}	1.26 ^{def}	0.34
	SIF ₁₀₀	4138 ^g	11083 ^{def}	0.96 ^{gh}	0.26	6841 ^f	17458 ^{cd}	1.24 ^{fg}	0.23
	SIF ₇₅	4211 ^{fg}	10583 ^{efg}	1.05 ^{cd}	0.35	6791 ^f	16417 ^{def}	1.28 ^{bcd}	0.30
	SIF ₅₀	3649 ⁱ	8333 ^{hi}	0.94 ^h	0.44	5987 ⁱ	15742 ^f	1.16 ⁱ	0.38
	SIF ₂₅	2705 ^k	7500 ⁱ	0.75 ^k	0.61	5745 ^j	15367 ^f	1.16 ⁱ	0.42
	SIG ₁₀₀	4670 ^d	12167 ^{cd}	0.99 ^{fgh}	0.24	7366 ^{cd}	18125 ^{bc}	1.24 ^{ef}	0.22
	SIG ₇₅	4380 ^{ef}	10417 ^{fg}	1.00 ^{efg}	0.31	7066 ^c	17000 ^{cde}	1.27 ^{cdef}	0.25
	SIG ₅₀	3875 ^h	8667 ^{hi}	0.99 ^{fgh}	0.41	6182 ^h	15950 ^{ef}	1.18 ^{hi}	0.32
	SIG ₂₅	3159 ^j	8083 ⁱ	0.89 ⁱ	0.62	5923 ^{ij}	15450 ^f	1.19 ^{hi}	0.38
	RF	2491 ^l	7417 ⁱ	0.84 ^j	0.88	5723 ^j	15333 ^f	1.20 ^{gh}	0.50

*The similar-letters-treatments have no significant differences

et al. (2005) who reported higher WUE values when irrigation was applied in the critical stages of plant development. Regarding the supplemental irrigation strategies, the interaction of deficit and supplemental irrigation treatment SIFG₇₅ accomplished the greater value of WUE than SIF₂₅ by 42.6 and 12.6% in 2014 and 2015 growing seasons, respectively. The highest values (under 75% level in each strategy) in the second year improved the WUE by 22.8, 7.4, 22.2 and 27.3% over the first year which correspond to SIFG₇₅, CI₇₅, SIF₇₅ and SIG₇₅ strategy, respectively, due to occurrence of an increase in ratio of wheat yield to the crop water use in the second season compared with the first season. In general, the deficit supplemental irrigation level 75% achieved the highest WUE compared to other irrigation levels in each supplemental and conventional strategy. These results are similar to a number of studies (Zhang et al. 1998; Li et al. 2001b; Rao et al. 2012) suggesting that limited supplemental irrigation during the growth season can significantly increase WUE and wheat yield.

The greatest above-ground dry matter yield was produced with full conventional irrigation, followed by conventional deficit irrigation (CI₇₅) and then by full supplemental irrigation SIFG₁₀₀ (except SIFG₁₀₀ in the second year which was greater than CI₇₅). There was no significant difference in biomass yield between CI₁₀₀ and CI₇₅ in the first year and among the full irrigation treatment of CI and SIFG strategies in the second year when decrease in biomass yield in CI₇₅ treatment reached 7.6 and 8.7% and the corresponding

decrease in SIFG₁₀₀ amounted to 11.2 and 2.8% in comparison with full conventional irrigation in the first and the second experimental year, respectively (Table 3).

In relation to full SI, when it was supplied at the grain filling stage, the total biomass yield increased by 9.7 and 3.6% compared to irrigation at the flowering stage during the cropping seasons of 2014 and 2015, respectively. The biomass yield was influenced by the interaction of supplemental irrigation and crop growth stage. Compared with irrigation at flowering and grain filling stages (SIFG), wheat irrigated in flowering stage (SIF) resulted in a significant decrease in biomass by 23.5 and 12.5% in the 2014 and 2015 seasons, respectively, whereas the corresponding decrease in biomass yield of wheat irrigated during grain filling stage (SIG) became insignificant and reduced by 16.0 and 9.1%, respectively, in the experimental years. These results confirmed the findings of Zhang et al. (2006) who concluded that the biomass yield production varies based on the magnitude and period of the water deficit applied.

Decreasing irrigation from 194 mm in SIG₇₅ to 142 mm in SIG₅₀ in first year and from 108 to 72 mm in second year led to remarkable differences in biomass yield that equaled to 1750 and 1050 kg ha⁻¹, respectively. However, the corresponding differences between CI₇₅ and CI₅₀ of biomass production were 2416 and 1492 kg ha⁻¹ during first and second growing seasons, respectively. The reason for increased biomass yield under CI₁₀₀ and SIFG₁₀₀ might be due to the capability of those treatments to maintain higher

soil moisture for longer periods by increasing lateral and deeper root growth and increasing green production. This is in general agreement with the findings of Zhang et al. (2006); Pedhi et al. (2010) and Tari (2016), who stated biomass yields of wheat differed depending on irrigation quantity and its application growth stage.

Relationships between CWSI, grain yield, ψ_1 and available water

The relationships between CWSI (as the independent variable) and grain yield (as the dependent variable) are presented in Fig. 7a. In general, the CWSI correlated significantly ($P < 0.01$) and negatively with grain yield, indicating that grain yield of wheat declined with increasing CWSI values. A similar negative relation was reported by Wang et al. (2005). For the growing seasons, the relationship between CWSI and grain yield had close determination coefficients that recorded $R^2 = 0.81$ and 0.80 in first and second year, respectively. These results confirmed the findings of Zia et al. (2012) who reported a linear relationship between CWSI and yield of wheat with $R^2 = 0.80$. The good

correlation of simple linear equation of yield and CWSI can be used for predicting yield quantity both under irrigated and drought stressed conditions.

As for the relation between CWSI and leaf water potential (ψ_1), CWSI was considered as an independent variable (Fig. 7b). The ψ_1 —CWSI relation was significant and the regression coefficient of the parameters was ($R^2 = 0.61$) in first season and 0.69 in the second growing season. These findings are in line with those of Howell et al. (1986) who found the corresponding leaf water potential values correlated to CWSI depending on the crop phenology, and who suggested that this phenological response in ψ_1 may be due to differences in water relations between wheat flag leaves and canopy leaves. In the present study, the leaf water potential correlated with CWSI negatively, which means that the CWSI increases as the leaf water potential decreases. This is in agreement with Wang et al. (2005) who stated the CWSI increased with decreasing ψ_1 when wheat was under water stress.

The determination coefficient (R^2) for the relation between ψ_1 and grain yield was 0.81 and 0.76 in 2014 and 2015, respectively (Fig. 7c). The linear relationship between

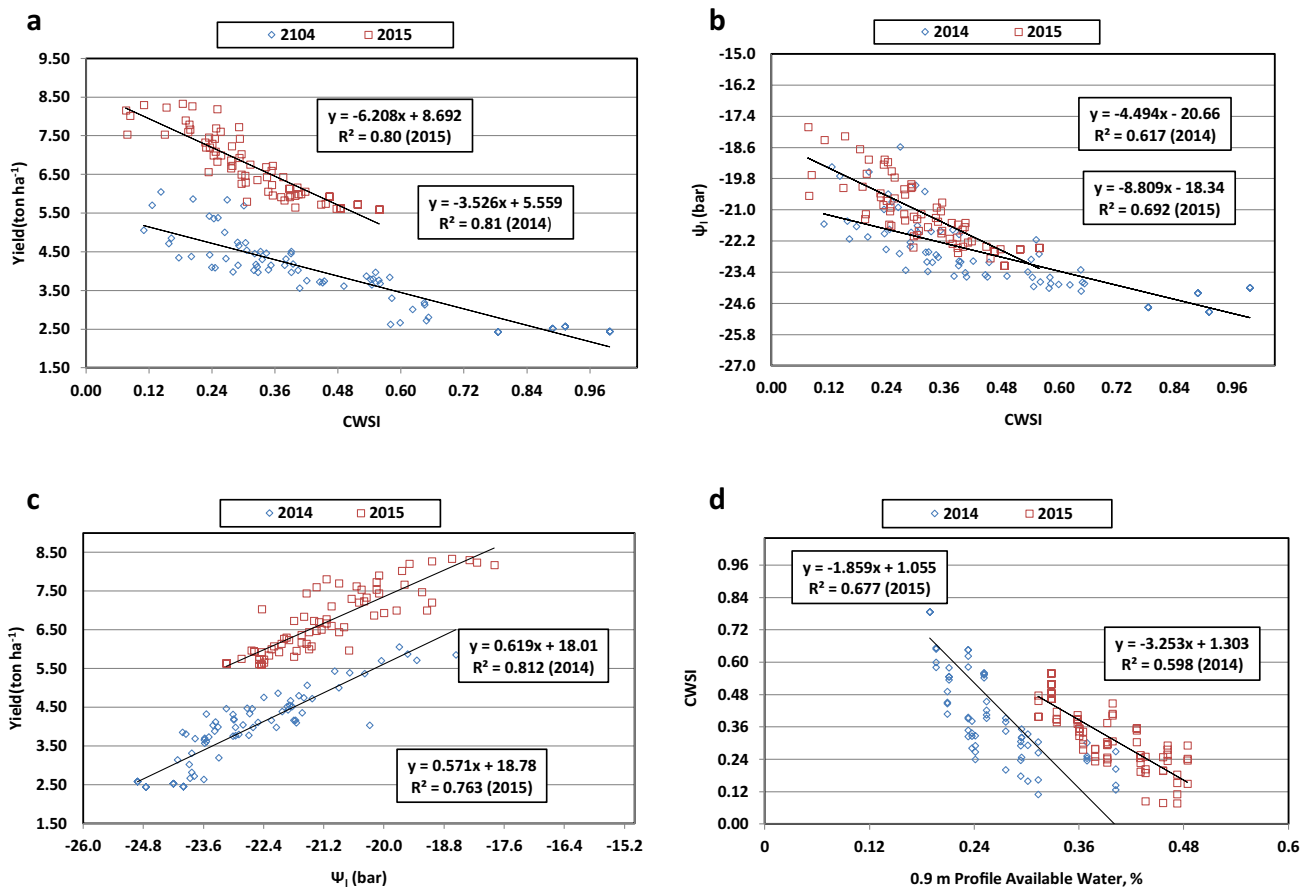


Fig. 7 The relations between: **a** Grain Yield-CWSI; **b** ψ_1 -CWSI; **c** Grain Yield- ψ_1 ; **d** CWSI-Available Water in 90 cm soil depth in 2014 and 2015 growing seasons

ψ_l and grain yield was positive and the regression slope ranged between 0.57 in second season and 0.61 in first season. A similar relationship was found by Xue et al. (2006) who also showed decreased wheat grain yield as a function of decreased leaf water potential.

The relationship between crop water stress index and available water is presented in Fig. 7d, considering the available water percentage as the independent variable and CWSI as the dependent variable. The simple regression equation showed determination coefficient of 0.59 in the first year and 0.67 in the second year. Additionally, available water and CWSI were strongly and significantly negatively correlated. A similar negative response of CWSI to available water in the soil was obtained for sunflower by Orta et al. (2002) who reported that as percent available soil water decreased, the stomata closed, transpiration rates declined, and leaf temperatures and CWSI increased.

Conclusions

The present study evaluated the crop water stress index (CWSI) and midday flag leaf water potential (ψ_l) for wheat (*Triticum aestivum* L. Adana 99) under the three different supplemental and conventional irrigation strategies during 2014 and 2015 growing seasons in the Mediterranean region. The lower baselines developed were represented by the equations $LL = -1.22 VPD + 0.49$ ($R^2 = 0.54$) and $LL = -1.11 VPD + 0.77$ ($R^2 = 0.49$) in the first and second growing seasons. Statistically, grain yield correlated with CWSI in the phenological stages of pre and post-anthesis, suggesting use of CWSI as an index for predicting yield of winter wheat. Furthermore, the linear equations in wheat growing seasons between CWSI and available root zone water: $CWSI = -3.25 AW + 1.30$ ($R^2 = 0.59$) and $CWSI = -1.85 AW + 1.05$ ($R^2 = 0.67$) can be used to monitor crop water status by observing the increase of canopy temperature with decreasing soil water content. The grain yields ranged from 4138 to 6841 kg ha⁻¹ in SIF₁₀₀ and 5868–8258 kg ha⁻¹ in CI₁₀₀ in the dry and wet seasons, respectively. These yield values corresponded to irrigations scheduled at CWSI value less than 0.26, further supporting CWSI as a practical tool for timing irrigation.

The findings confirmed the effect of the amount of water applied on midday flag leaf water potential (ψ_l); high irrigation levels 75 and 100% had significantly higher ψ_l than irrigation level 25% and rain-fed for all irrigation strategies (except SIF strategy) during both growing seasons. Additionally, midday ψ_l decreased depending on drying and wetting cycle of soil, and with advanced growth stages it ranged from -17.9 to -25.4 bar in the dry season and -16.3 to -23.7 bar in the wet season; however, ψ_l during the milky

grain stage decreased to more negative values as compared to the early grain filling stage.

In reference to irrigation scheduling of supplemental irrigation, terminating irrigation at grain filling stage (SIF₁₀₀ strategy) decreased the grain yield by 17 and 29% in wet and dry years as compared to full conventional strategy. However, the corresponding decrease in grain yield varied from 10 to 20% when irrigation was cut off at flowering stage (SIG₁₀₀ strategy), which means that irrigation during grain filling stage increased yield by 12 and 7% compared to SIF₁₀₀ strategy in 2014 and 2015 growing seasons, respectively.

The seasonal evapotranspiration affected the biomass production markedly decreasing ET from 528.8 to 399.9 mm for SIF₇₅ and from 570.6 to 421.6 mm for SIFG₇₅ in wet and dry seasons that led to decreased biomass yield that amounted to 35.5 and 31.8%, respectively.

In general, the deficit irrigation level 75% for all supplemental irrigation strategies (SIF₇₅, SIG₇₅ and SIFG₇₅) raised water use efficiency to the greatest values compared to other levels (25, 50 and 100%) in both 2014 and 2015. Therefore, the deficit irrigation level 75% can be considered as the appropriate schedule of irrigation instead of full irrigation under each strategy for maximizing WUE which leads to saving more water and achieving the better economic wheat grain yield under supplemental irrigation conditions in regions which facing water scarcity.

The supplemental strategy SIFG₇₅ resulted in 29 and 34% water savings and yield reduction of 23 and 9% in comparison to CI₁₀₀ in dry and wet growing seasons, respectively, indicating the importance of deficit supplemental irrigation strategies under conditions of water scarcity. The full irrigation strategy can be recommended for obtaining greater grain and biomass yields during wet growing seasons, where the yield penalty for deficit irrigations is minimized. However, for water saving in drought years, supplemental irrigation SIFG strategy with 75% irrigation level can be recommended for sustainable wheat production in the Mediterranean region.

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