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Water productivity and water use efficiency of sunflower under conventional and limited irrigation

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Abstract

This study was carried out to understand the effects of conventional irrigation (CI), regulated deficit irrigation (RDI_{70} and RDI_{50}) and partial root zone drying (PRD_{70} and PRD_{50}) treatments on water productivity and water use efficiency of sunflower in the Ahwaz Plain, Iran. Irrigation water productivity for seed yield (WP(Ir)Y) and water use efficiency for seed yield (WUE(Y)) were not significantly affected by conventional and limited irrigation treatments. In this study, the highest (WP(Ir) Y) was obtained by limited irrigation treatments (RDI_{50}, PRD_{50} and RDI_{70} treatments, with mean 11.62, 11.37 and 11.12 kg mm^{-1}, respectively.), whereas the lowest (WP(Ir)Y) was obtained from the CI treatment (10.74 kg mm^{-1}). The maximum WUE(Y) was related to RDI_{50}, PRD_{50} and RDI_{70} treatments, averaged 13.88, 13.59 and 13.29 kg mm^{-1}, respectively. The minimum one was also associated with CI treatment. averaged 12.48 kg mm^{-1}. It is concluded that the CI treatment is the best choice for maximum yield under the local conditions, but this irrigation scheme must be re-considered in areas where water resources are more limited.

Key words: Sunflower, water productivity, water use efficiency, conventional irrigation, regulated deficit irrigation, partial root zone drying.

Introduction

Water is essential for both the human society and the ecological systems that humans rely on, but this essential resource is finite. With the population growth and economic development, water has become increasingly scarce in a growing number of countries and regions in the world. As the largest water user, the agricultural sector is facing a challenge to produce more food with less water. This requires an increase in water productivity (WP) and water use efficiency (WUE) [27, 37, 49].

One of indexes used in plant yield and water use discussions, economically based is WP which is defined as crop yield to water use ratio. Water use consists of rainfall, irrigation or irrigation plus rainfall. WP indicates production level per input. WP indexes have been stricted attention of researchers because of different aspects (irrigation water productivity in overproduction than rainfed conditions (or any other treatments), irrigation water productivity in total yield, rainfall productivity and productivity of irrigation water + rainfall in total yield) [29-31, 37, 42, 48].

In addition to WP index, WUE is applied in optimization [21], achieving from seed yield to real plant evapotranspiration ratio. In some references evapotranspiration productivity is referred to WUE and would be indicated as WP_{ET} [9, 45, 47].

Sunflower (*Helianthus annuus* L.) is commonly grown as a dryland crop. Research and farmer testimony have demonstrated that sunflower responds to irrigation with yield increases of 100 to 200% over dryland yields common on droughty soils and in extremely dry years. Sunflower adapts to a wide range of soils and climatic conditions. Low sunflower yields may be caused by any of the following: incorrect plant population, poor soil fertility, lack of weed control, diseases, insect damage, bird depredation, lodging, late planting and harvesting losses. Management of all factors listed plus sound water management are essential [4].

In studies [1] on the effect of irrigation interval on yield, yield components and water productivity of sunflower mean values for WP(Ir)Y (irrigation water productivity for seed yield) were 5.19, 5.09 and 3.95 kg seed mm^{-1} for 1986/87 crop season and 5.79, 5.33 and 3.87 kg seed mm^{-1} for 1987/88 crop season corresponding to I-1 (40% depletion of available water), I-2 (60% depletion of available water) and I-3 (80% depletion of available water) treatments, respectively. In investigation [13] of the water use characteristics of sunflower (*Helianthus annuus* L.) under deficit irrigation (Irrigation – Precipitation) water productivity for seed yield (WP(Ir – P)Y) and water use efficiency for seed yield WUE(Y) were between 1.9-3.8 and 5.2-9.3 kg mm^{-1}, respectively, for the treatments.

In studies of Karaa *et al.* [24] average WUE(Y) of sunflower fully irrigated control was 0.80 kg m^{-3} while WUE(Y) values of the deficit-irrigation treatments were 0.76, 0.81 and 0.87 kg m^{-3}, in S1, S2 and S3, respectively. At biomass basis, water use efficiency for biomass yield WUE(B) varied from 3.79 kg m^{-3} in the control to 3.46 kg m^{-3} in S1 treatment, 3.70 kg m^{-3} in S2 and 4.07 kg m^{-3} in S3.

In studies of Karam *et al.* [25] on evapotranspiration, seed yield and water use efficiency of drip irrigated sunflower under full and deficit irrigation conditions, seed yield at dry weight basis on the well-irrigated treatment was 5.36 t ha^{-1}. Deficit irrigation at early (WS1) and mid (WS2) flowering stages reduced seed yield by 25% and 14% ($P < 0.05$), respectively, in comparison with the control. However, deficit irrigation at early seed formation increased slightly seed yield in WS3 treatment (5.50 t ha^{-1}). WUE(Y) was found to vary significantly ($P < 0.05$) among treatments, where the highest (0.83 kg m^{-3}) and the lowest (0.71 kg m^{-3}) values were obtained from WS3 and WS1 treatments, respectively.

Goksoy *et al.*[17] investigated the responses of sunflower (*Helianthus annuus* L.) to full and limited irrigation at different growth stages. They indicated that WUE(Y) did not significantly change when irrigation amount increased. However, WUE(Y) values ranged from 7.66 and 7.12 kg mm^{-1}, respectively, for M and rainfed (control) treatments, to 5.09 and 5.59 kg mm^{-1}, respectively, for HM and H treatments.

Demir *et al.* [10] studied the response of sunflower (*Helianthus annuus* L.) to 14 irrigation treatments in a sub-humid environment (Bursa, Turkey). The yield increased with irrigation water amount, and the highest seed yield (3.95 t ha^{-1}) was obtained from the HFM treatment (full irrigation); 82.9 and 85.4% increases, respectively, compared to the control. Also, the highest WUE(Y) (7.80 kg mm^{-1}) and (Irrigation – Precipitation) water productivity for seed yield WP(Ir – P)Y (10.19 kg mm^{-1}) were obtained from the F treatment (deficit irrigations at flowering stage).

Todorovic *et al.* [44] investigated the deficit irrigation of sunflower under Mediterranean environmental conditions. The experiment excludes five irrigation regimes: A optimal water supply; B application of 100% of water requirement up to flowering and 70% thereafter; C application of 70% of water requirement through the whole season; D application of 70% of water requirement up to flowering and rainfed condition thereafter and E rainfed conditions during the whole season. The average yield was related to the amount of water supply in all treatment except of treatment D. The highest average yield was obtained for treatment A with optimal water supply (6.14 t ha^{-1}). Water use efficiency was established also referred to the yield (WUE(Y)). The greatest WUE(Y) is for the full irrigation treatment (1.3 kg m^{-3}), followed by treatment B (1.19 kg m^{-3}), rainfed treatment (1.15 kg m^{-3}), treatment C (1.0 kg m^{-3}) and treatment D (0.72 kg m^{-3}).

Rana *et al.* [33] studied the effect of basin, furrow and raingun sprinkler irrigation systems on irrigation efficiencies and yield of sunflower. The results indicated significant differences in the three irrigation systems. Highest WUE(Y), i.e. 0.85 kg m^{-3}, was obtained in case of raingun sprinkler irrigation system as compared to 0.61 and 0.55 kg m^{-3} for furrow and basin irrigation systems, respectively.

Asgari and Najafi [3] compared the effects of treated municipal waste water and different irrigation systems on maize and sunflower yields and water use efficiency (WUE(Y)) were studied in a southern waste water treatment plant in Isfahan, Iran. The treatments were furrow irrigation with normal water (FIN), surface drip irrigation with waste water (SDI), sub-surface drip irrigation with waste water at 15 cm depth (SDI 15), sub-surface drip irrigation with waste water at 30 cm depth (SDI 30) and furrow irrigation with waste water (FIW). SDI 30 resulted in the highest seed yield and WUE(Y), while FIN and FIW registered the lowest values for these parameters.

Although sunflower is known as a drought tolerant crop or grown under dryland conditions, substantial yield increases are achieved by irrigation. There is no research on sunflower irrigation in the region (Ahwaz Great Plains and all of Khuzestan province) where the study was carried out. Therefore, the main objective of this research was to compare the effects of conventional irrigation (CI), regulated deficit irrigation (RDI) and partial root zone drying (PRD) on water productivity and water use efficiency of sunflower (*Helianthus annuus* L.) in Ahwaz Plain.

Materials and Methods

The experiment was carried out during the growing season of 2010, between February and June, on the irrigation research station of Ahwaz Shahid Chamran University, in the Khuzestan province, located in the Southwest of Iran, latitude 31° 18’18’’ N, longitude 48°39’68’’ E and altitude 18 m above sea level. The local climate is arid, summers are hot and dry and winters are sub mild. According to long-term meteorological data (1966-2009), annual mean rainfall, temperature and relative humidity are 230.3 mm, 25.4 °C and 48.9%, respectively (Table 1) [26]. An arid climate prevails in the region according to mean rainfall amount, and rainfall amounts are low in the winter period. Seasonal rainfall amount is 111 mm, which coincides with 48% of total annual rainfall, for the winter period (January, February and March). Additionally, total annual evaporation is nearly tenfold of annual rainfall (2035.3 mm) and seasonal evaporation in the winter months is twofold higher than seasonal rainfall amount [26]. Climatologic data of trial years were measured at the synoptic meteorological station nearby the experimental area.

The Karun River supplies all of the water demands of the region. The application of irrigated agriculture has been common in the study area. The soils of the trial field are Aridic Ustifluvents according to American Taxonomic Classification [38] and Calcaric Fluvisol according to FAO/UNESCO Classification System, in which soils are alluvial. The soil of the area is of Entisols orders. Also, the soil moisture regime is Ustic while the soil temperature regime is Hyperthermic. The type of soil in research area was loam (average 24% clay, 35% silt and 44% sand content), having 0.07%

Table 1. Mean air temperature, relative humidity and total monthly rainfall and evaporation (1966-2009) at Ahwaz.

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Temperature (°C)	12.2	14.3	18.6	24.5	30.6	35.0	37.2	36.7	33.2	27.7	20.2	14.2	25.4
Relative humidity (%)	74.1	66.5	57.1	47.7	36.5	29.4	31.2	34.5	36.6	44.2	57.3	72	48.9
													Total
Rainfall (mm)	48.4	37.2	26	22.6	10.3	0.2	0.0	0.1	0.2	2.5	30.2	52.6	230.3
Evaporation (mm)	53	71.96	124	174.9	249	301	300	274.4	209.2	143	82	53	2035.5

total nitrogen content (Kjeldahl method), 0.11 kg ha^{-1} phosphorus (Olsen method, P_2O_5), 1.26 kg ha^{-1} exchangeable potassium (ammonium acetate method, K_2O), 1.1% organic matter (Walkley-Black method), EC 5.7 dS m^{-1}, and a bulk density of 1.59, 1.57, 1.50 and 1.49 g cm^{-3} in 0-0.30, 0.30-0.60, 0.60-0.90 and 0.90-1.20 m profile, respectively. The soil pH was 7.97. The water holding capacity (WC) of the experimental site was 133.1 mm in a 0.9 m soil profile. WC was determined by the difference between the water content at field capacity (FC) and at permanent wilting point (PWP). There is no waterlogging problem in the area, and the water table of soil is deeper than 170 cm in early spring.

The sunflower hybrid Hysun 33, characterized with early flowering and maturity and medium yield potential was sown on a total surface area of about 1200 m^2 of a rectangular shape. In the experiments, plot size was 400 m^2 (25 × 16 m^2) at harvest. The crops were hand sown on 17th February 2010, row spacing was 0.5 m; plant-plant spacing was 0.15 m, and hand harvested on 1st June 2010, using fertilizer rate of 250, 125 and 250 kg ha^{-1} of N, P and K, respectively. Weed control was realized manually at monthly basis without any chemical input. Forty five plants were randomly selected from each plot (treatment) (at maturity period of the plants) for measurement of biomass and seed yield. Biomass was estimated by weighing the total dry matter at harvest and obtaining its water content from a sub-sample that was oven-dried at 70°C until constant weight.

The crop evapotranspiration (ETc) was calculated by following equation [2]:

$$\mathrm{ETc} = Kc \times ETo \quad (1)$$

where *ETo* = reference crop evapotranspiration (measured from class A pan) and *Kc* = the effects of both crop transpiration and soil evaporation are integrated in a single crop coefficient.

Irrigation water was delivered to the plots with polyethylene pipes, 75 mm in diameter, and was applied to the trial plots as controlled by a tank which has a water meter. Required irrigation water was applied to the plots by short blocked-end furrows. Therefore, runoff and runon was assumed as zero because the plots had earthen embankments. Deep percolation was assumed as zero in practice [18]. There was no recorded problems with water quality.

Three irrigation methods, i.e. conventional irrigation (CI, both sides (both furrows) of plant row watered; applied 100% of water requirements during the whole season), regulated deficit irrigation (RDI_{70} and RDI_{50}, both sides of plant row watered; applied 100% of water requirements up to V8 stage (plant with 8 leaves) then 70% and 50%, respectively, thereafter), partial root-zone drying (PRD_{70} and PRD_{50}, both sides of plant row alternatively watered; applied 100% of water requirements up to V8 stage (plant with 8 leaves) then 70% and 50%, respectively, thereafter) and rainfed (RF, non-irrigated) were applied.

The individual irrigation application depths were determined on the basis of soil water storage depletion. Soil water contents were monitored prior to irrigation (each 1-2 days before irrigation) using the gravimetric method [5] from the plots of the second replication of the various treatments, and then these values were converted to volumetric water contents using bulk density. According to the soil water contents measured, the plots of the treatments were irrigated from deficit moisture content (60% depletion of available water) of 0-90 cm soil layer to FC at each irrigation.

Under full irrigation condition (conventional irrigation), irrigation water was applied to 0.9 m of the soil profile to achieve FC, but for limited irrigation treatments, they were applied 100% of water requirements up to V8 stage (plant with 8 leaves) then70% (RDI_{70} and PRD_{70}) and 50%(RDI_{50} and PRD_{50}), respectively, thereafter. The greatest amount of irrigation water was applied to the CI treatment (623 mm), and the lowest of irrigation amount was applied to the RDI_{50} and PRD_{50} irrigation treatments (311.5 mm). The layout of the experiments was a completely randomized block design with three replications.

Water productivity and water use efficiency indexes were determined to evaluate the productivity of irrigation and evapotranspiration in the treatments. Water productivity indexes for seed yield was calculated by following equations:

$$\mathrm{WP(Ir)Y} = YLD/IRG \quad (2)$$

where WP(Ir) Y = irrigation water productivity for seed yield (kg mm^{-1}); *YLD* = the seed yield obtained from irrigation treatments (kg); and *IRG* = the seasonal irrigation amount (mm).

$$\mathrm{WP(Ir+P)Y} = YLD/(RAI + IRG) \quad (3)$$

where WP(Ir + P)Y = (irrigation+ precipitation) water productivity for seed yield (kg mm^{-1}); *YLD* = the seed yield obtained from irrigation treatments (kg); *RAI* = the seasonal rain amount (mm); and *IRG* = the seasonal irrigation amount (mm).

$$\mathrm{WP(Ir-P)Y} = (YLD_{Irrigation} - YLD_{Rainfed})/IRG \quad (4)$$

where WP(Ir – P)Y = (irrigation – precipitation) water productivity for seed yield (kg mm^{-1}); $YLD_{Irrigation}$ and $YLD_{Rainfed}$ = the seed yields obtained from irrigation treatments and rainfed treatment, respectively (kg); and *IRG* = the seasonal irrigation amount (mm).

Water productivity indexes for biomass yield are defined as the following:

$$\mathrm{WP(Ir)B} = BIO/IRG \quad (5)$$

where WP(Ir)B = irrigation water productivity for biomass yield (kg mm^{-1}); *BIO* = the biomass yield obtained from irrigation treatments (kg); and *IRG* = the seasonal irrigation amount (mm).

$$\mathrm{WP(Ir+P)B} = BIO/(RAI + IRG) \quad (6)$$

where WP(Ir + P)B = (irrigation+ precipitation) water productivity for biomass yield (kg mm^{-1}); *BIO* = the biomass yield obtained from irrigation treatments (kg); *RAI* = the seasonal rain amount (mm); and *IRG* = the seasonal irrigation amount (mm).

$$\mathrm{WP(Ir-P)B} = (BIO_{Irrigation} - BIO_{Rainfed})/IRG \quad (7)$$

where WP(Ir – P)B = (irrigation – precipitation) water productivity for biomass yield (kg mm^{-1}); $BIO_{Irrigation}$ and $BIO_{Rainfed}$ = the biomass yields obtained from irrigation treatments and rainfed treatment, respectively (kg); and *IRG* = the seasonal irrigation amount (mm).

Water use efficiency indexes for seed and biomass yields estimated by following equations:

$$\mathrm{WUE\,(Y)} = YLD/ETa \tag{8}$$

where WUE(Y) = water use efficiency for seed yield (kg mm^{-1}); *YLD* = the seed yield (kg); and *ETa* = the actual crop evapotranspiration amount (mm).

$$\mathrm{WUE(B)} = BIO/ETa \tag{9}$$

where WUE(B) = water use efficiency for biomass yield (kg mm^{-1}); *BIO* = the biomass yield (kg); and *ETa* = the actual crop evapotranspiration amount (mm).

Data analysis: All statistical analysis were carried out using SAS[35], to determine significance among irrigation treatments. Duncan's multiple range test ($\alpha = 0.01$, $\alpha = 0.05$) was used for mean separation. Also, EXCEL [14] was used to draw the histograms.

Results and Discussion

Biomass: A significant difference was found at the 1% probability level between different irrigation treatments in biomass (Table 2). On this basis, the maximum biomass was related to CI treatment (average 26,920 kg ha^{-1}), PRD_{70} treatment (average 18,987 kg ha^{-1}) was found the next rank and RDI_{70} treatment (average 16,858kg ha^{-1}) was ranked in the third place, RDI_{50} and PRD_{50} irrigation treatments (in yield average of 13,575 and 14,146 kg ha^{-1}, respectively) were the fourth rank and finally the minimum biomass (8093 kg ha^{-1}) was related to rainfed treatment (Table 3).

Proper water consumption would likely be resulted in increase in leaf activity in CI treatment and thereafter led to increase in photosynthesis and production food materials and as a result plant biomass weight would be increased. While occurring drought stress through the leaf area loss and their falling would be result of dropping in photosynthetic supply and falling in enzyme activities influencing on this process and as a result plant biomass weight would be reduced. Turner *et al.* [46] found that water deficit in sunflower reduces dry leaf, stem and root weight and results in lowering of dry plant weight (biomass) and impeding growth trend. Karam *et al.* [25] stated that the maximum biomass was related to well-irrigated treatment (averaged 19.87 t ha^{-1}) and the minimum biomass was related to WS1(deficit irrigation at early flowering stages)and WS2 (deficit irrigation at mid flowering stages) irrigation treatments in yield (average 16.48 and 17.89 t ha^{-1}, respectively). Todorovic *et al.* [44] reported that the full irrigation treatment A had the highest final above ground dry biomass of 14.9 t ha^{-1}. Afterward, treatment B had 13.0 t $ha^{-1}$of biomass (87.5% of treatment A) and for treatment C (70% irrigation supply) the biomass was only 9.9 t ha^{-1}, or about 66.5% of the full irrigation treatment. The treatment D had at harvesting approximately the same dry biomass (around 6.5 t ha^{-1} or 43.6% of full irrigation treatment).Our results are in close agreement with the above mentioned researches.

Seed yield: In these tests irrigation treatment effects on sunflower seed yield were significant at the 1% level of probability (Table 2).On this basis the maximum seed yield was related to CI treatment (6687.7 kg ha^{-1}), RDI_{70} and PRD_{70} irrigation treatments were found the next rank (averaged 4845.3 and 4721.7, respectively). Then, PRD_{50} and RDI_{50} irrigation treatments (averaged 3537.3 and 3615.3 kg ha^{-1}, respectively) were found in the third place. The minimum seed yield (averaged 2370 kg ha^{-1}) was related to rainfed treatment (Table 3). Seed yield decreased as irrigation water level was reduced, moisture stress leads to loss of the final crop yield components. Seed yield reduction in deficit irrigation conditions seems to be assigned to reduce in growth period and seed filling, head diameter, seed numbers in head, 1000 seed weight and increase in head emptiness. In Ferere *et al.* [15] water deficit was found to lead to fall of seed yield through reduction in seed number in head, dropping photosynthesis and increase in the seed emptiness percentage. Pankovic *et al.* [32] announced that moisture deficit during budding process to end of flowering had the maximum negative effect on sunflower hybrid yields because of reduction in head diameter and seed number in head.

Balanced water consumption during different development processes like flowering and seeding seems to result in improving of sunflower seed yield because two important components of seed yield (seed number in head and 100 seed weight) would be formed during these processes, while enough irrigation in vegetative process leads to desired development of leaf area and plant photosynthesis. Desirable seed yield in conventional irrigation exhibits such due to having high durability of leaf area in reproductive process, rapid physiologic growth, transferring enough photosynthetic materials to reproductive organs and eventually good benefiting from environmental feasibilities. It could be come to conclusion, therefore, that reason of desirable seed yield in conventional irrigation is to assign better and more the photosynthetic materials in favor of reproduction process and seed filling. Therefore, due to drought stress could be such justified that improper irrigation treatment accelerates leaf ageing and reduced production level and decrease in leaf area and photosynthesis amount.

Mazaheri Laqab *et al.* [28] in this regard stated that improper irrigation treatment caused loss of the seed yield and reduction in leaf area and early ageing. Some researcher, of course [20, 22], know the main reason of seed yield loss due to drought stress as photosynthesis reduction and retaining of photosynthates during seed filling process. Drought stress effects on some physiological characteristics and yield components of sunflower are severe

Table 2. Results of variance analysis (mean square) of biomass and seed yield of sunflower at Ahwaz region (2010).

Source	Degrees of Freedom (DF)	Biomass	Seed yield
Replicates	2	19917581.2*	271976.06ns[a]
Treatments	5	119784894.6**	6570831.96**
Error	10	3041250.1	232280.12
Coefficients variance(CV)	-	10.61	11.21

[a]Non-significant.
*Significant at the 5% of probability level ($P < 0.05$).
**Significant at the 1% of probability level ($P < 0.01$).

Table 3. The effect of irrigation treatments on biomass and seed yield of sunflower at Ahwaz region (2010).

Treatments	Biomass (kg ha^{-1})	Seed yield (kg ha^{-1})
CI	[a]26920a	6687.7a
RDI_{70}	16858bc	4845.3b
RDI_{50}	13575c	3615.3bc
PRD_{70}	18987b	4721.7b
PRD_{50}	14146c	3537.3bc
RF	8093d	2370c

[a]The values with the same letter are statistically homogeneous in Duncan.

reduction of seed yield, biomass and length of time of vegetative process [23].

Extreme moisture stress in flowering, pollination and seeding causes the maximum seed yield loss. Bonari *et al*. [6] stated that water deficit and occurring drought stress leads to reduction in leaf activity and consequently the yield. D'Andria *et al*. [8] come to conclusion during separated tests that reducing the irrigation frequencies and increasing irrigation times could be helpful in making the maximum seed yield. Karam *et al*. [25] stated that sunflower seed yield at dry weight basis on the well-irrigated treatment was 5.36 t ha^{-1}. Deficit irrigation at early (WS1) and mid (WS2) flowering stages reduced seed yield by 25% and 14% ($P < 0.05$), respectively, in comparison with the control. However, deficit irrigation at early seed formation was found to increase slightly seed yield in WS3 treatment (5.50 t ha^{-1}). Our findings were in agreement with the above reported results.

Irrigation water productivity for seed yield (WP(Ir)Y): No significant difference was observed between different irrigation treatments in WP(Ir)Y based on variance analysis results (Table 4).

According to average comparison test (Table 5) the maximum WP(Ir)Y averaged 11.62, 11.37 and 11.12 kg mm^{-1} (1.16, 1.13 and 1.11 kg m^{-3}) and was associated with RDI_{50}, PRD_{50} and RDI_{70} treatments, respectively. PRD_{70} and CI treatments averaged 10.83 and 10.74 kg mm^{-1} (1.08 and 1.07 kg m^{-3}) and were of the minimum WP(Ir)Y.

Al-Ghamedi *et al*. [1] studied the effect of irrigation interval on yield, yield components, and water productivity of sunflower (*Helianthus annuus* L.) on a sandy-clay-loam soil under field conditions in 1986/87 and 1987/88 crop seasons. They regarded 3 soil water consumption treatments: 1- 40% depletion of available water 2- 60% depletion of available water and 3-80% depletion of available water treatments, respectively. Mean values for WP(Ir)Y were 5.19, 5.09 and 3.95 (kg seed mm^{-1}) for 1986/87 crop season and 5.79, 5.33 and 3.87 (kg seed mm^{-1}) for 1987/88 crop season corresponding to I-1 (40% depletion of available water), I-2 (60% depletion of available water) and I-3 (80% depletion of available water) treatments, respectively. The results obtained strongly suggest that an irrigation interval of 10 days, equivalent to 60% depletion of available water, is optimum for reasonable sunflower production in Al-Ahsa, Saudi Arabia.

De Rodriguez *et al*. [11] found WP(Ir)Y of sprinkler, furrow and basin irrigations as 0.85, 0.61 and 0.55 (kg m^{-3}) for sunflower, respectively. Goksoy *et al*. [17] investigated sunflower reaction to complete irrigation and deficit irrigation in different growth processes and found the highest WP(Ir)Y as 10.19 kg mm^{-1} which meets this study findings.

Todorovic *et al*. [44] considered effect of deficit irrigation on sunflowers in Mediterranean weather of Italy. In this study they reported WP(Ir)Y in different treatments as follows: A treatment (full irrigation) WP(Ir)Y=1.3 kg m^{-3}; B treatment (application of 100% water requirements up to flowering and 70% thereafter) WP(Ir)Y=1.19 kg m^{-3}; C treatment (application of 70% water requirements through the whole season) WP(Ir)Y=1.0 kg m^{-3}; D treatment (application of 70% water requirements up to flowering and and rainfed condition thereafter) WP(Ir)Y= 0.72 kg m^{-3} and E treatment (rainfed): WP(Ir)Y=1.15 kg m^{-3}.

(Irrigation+ precipitation) water productivity for seed yield (WP(Ir+P)Y): No significant difference was found between different irrigation treatments in WP(Ir+P)Y (Table 4). According to results of (Table 5) RDI_{50}, RDI_{70} and CI treatments averaged 10.19, 10.11 and 10.04 kg mm^{-1} (1.02, 1.01 and 1 kg m^{-3}) and were in the first rank, respectively. PRD_{50} and PRD_{70} averaged 9.97 and 9.85 kg mm^{-1} (0.99 and 0.98 kg m^{-3}) and were of the least WP(Ir+P)Y, respectively. Goksoy *et al*. [17] investigated sunflower interaction to complete and deficit irrigation in different growth process and reported the highest WP(Ir+P)Y 7.80 kg mm^{-1}.

(Irrigation − precipitation) water productivity for seed yield (WP(Ir-P)Y): In these tests different irrigation treatments did not affect significantly WP(Ir-P)Y (Table 4). The maximum WP(Ir-P)Y averaged 6.94 kg mm^{-1} (0.69 kg m^{-3}) and was related to CI treatment. RDI_{70} and PRD_{70} treatments averaged 5.68 and 5.40 kg mm^{-1}(0.57 and 0.54 kg m^{-3}) WP(Ir-P)Y and were found to the second rank,

Table 4. Results of variance analysis (mean square) of WP(Ir)B, WP(Ir)Y, WP(Ir+P)B , WP(Ir+P)Y, WP(Ir-P)B, WP(Ir-P)Y, WUE (B) and WUE(Y) of sunflower at Ahwaz region (2010).

Source	Degrees of Freedom (DF)	WP(Ir)B	WP(Ir)Y	WP(Ir+P)B	WP(Ir+P)Y	WP(Ir-P)B	WP(Ir-P)Y	WUE(B)	WUE(Y)
Replicates	2	116.10**	2.48ns[a]	95.61**	1.96ns	116.14**	2.47ns	165.94**	3.54ns
Treatments	4	18.96ns	0.39ns	13.34ns	0.051ns	78.85**	5.11ns	27.16ns	0.56ns
Error	8	8.60	1.53	7.27	1.24	8.60	1.53	12.29	2.18
Coefficients variance(CV)	-	6.83	11.11	6.97	11.13	13.04	24.05	6.83	11.11

[a] Non-significant.

*Significant at the 5% of probability level ($P < 0.05$).

**Significant at the 1% of probability level ($P < 0.01$).

Table 5. The effect of irrigation treatments on WP(Ir)B, WP(Ir)Y, WP(Ir+P)B , WP(Ir+P)Y, WP(Ir-P)B, WP(Ir-P)Y, WUE(B) and WUE(Y) (kg mm^{-1}) of sunflower at Ahwaz region (2010).

Treatment	WP(Ir)B (kg mm^{-1})	WP(Ir)Y (kg mm^{-1})	WP(Ir+P)B (kg mm^{-1})	WP(Ir+P)Y (kg mm^{-1})	WP(I-P)B (kg mm^{1})	WP(Ir-P)Y (kg mm^{1})	WUE (B) (kg mm^{-1})	WUE (Y) (kg mm^{-1})
CI	[a]43.24ab	10.74a	40.43a	10.04a	30.24a	6.94a	51.69ab	12.84a
RDI_{70}	38.69b	11.12a	35.18a	10.11a	20.11bc	5.68ab	46.24b	13.29a
RDI_{50}	43.61ab	11.62a	38.28a	10.19a	17.61c	4.00b	52.14ab	13.88a
PRD_{70}	43.57ab	10.83a	39.62a	9.85a	25.00ab	5.39ab	52.09ab	12.95a
PRD_{50}	45.45a	11.37a	39.89a	9.97a	19.45bc	3.75b	54.32a	13.59a

[a] The values with the same letter are statistically homogeneous in Duncan test.

respectively. RDI_{50} and PRD_{50} averaged 4 and 3.75 kg mm^{-1} (0.4 and 0.37 kg m^{-3}) and were of the minimum WP(Ir-P)Y (Table 5 and Fig. 3).

Erdem *et al.* [13] reported that WP(Ir-P)Y was between 1.9- 3.8 kg mm^{-1}, for the treatments. Schneekloth [36] found that WP(Ir-P)Y for dry farming oil seed sunflower were 2.59, 1.67, 9.45, 3.87 kg mm^{-1}, respectively and for complete irrigation 1.63 kg mm^{-1}. Goksoy *et al.* [17] indicated that the highest WP(Ir-P)Y value obtained from the F treatment (irrigation applied only at flowering period) averaged 9.18 kg mm^{-1} and the lowest value from the H treatment (irrigation applied only at heading period) 4.22 kg mm^{-1}.

Demir *et al.* [10] reported that the WP(Ir-P)Y did not significantly change when irrigation amount increased. The maximum WP(Ir-P)Y for sunflower was 10.19 kg mm^{-1} (applying irrigation in flowering process) and the minimum WP(Ir-P)Y 4.74 kg mm^{-1} (applying irrigation in head appearing process and flowering process). The result showed that flowering process is the far most important process of irrigation for sunflower (with respect to this sunflower is a highly sensitive plant to water stress in flowering as compared with other growth stages).

Rinaldi [34] reported that when seasonal irrigation water was limited, one or two irrigations in the central phase (heading and flowering stages) is profitable for WP(Ir-P)Y and net income. Also, Rinaldi [34] reported that in a water-limited environment; even a single irrigation would double net income as compared to a rainfed treatment.

Irrigation water productivity for biomass yield (WP(Ir)B): No significant difference was found between different irrigation treatments in WP(Ir)B (Table 4). The maximum WP(Ir)B was related to PRD_{50} treatment which averaged 45.45 kg mm^{-1} (4.54 kg m^{-3}), RDI_{50}, PRD_{70} and CI treatments averaged 43.61, 43.57 and 43.24 kg mm^{-1} (4.36, 4.35 and 4.32 kg m^{-3}) and got the next rank, respectively (Table 5). Finally, the minimum WP(Ir)B was related to RDI_{70} treatment and averaged 38.69 kg mm^{-1} (3.87kg m^{-3}).

(Irrigation+precipitation) water productivity for biomass yield (WP(Ir+P)B): WP(Ir+P)B in this study was not observed significant by different irrigation treatments (Table 4). Building on this (Table 5) the largest WP(Ir+P)B was related to CI, PRD_{50}, PRD_{70} and RDI_{50} treatments which averaged 40.43, 39.89, 39.62 and 38.28 kg mm^{-1} (4.04 , 3.99 , 3.96 and 3.83 kg m^{-3}), respectively. RDI_{70} treatment, finally, averaged 35.18 kg mm^{-1} (3.52 kg m^{-3}) and had the least WP(Ir+P)B.

(Irrigation− precipitation) water productivity for biomass yield (WP(Ir-P)B): Based on variance analysis (Table 4) a significant difference was found at the 1% level of probability between different irrigation treatments in the terms of WP(Ir-P)B. According to average comparison test (Table 5), the maximum WP(Ir-P)B was related to CI treatment averaging 30.24 kg mm^{-1} (3.02 kg m^{-3}), then PRD_{70} averaging 25 kg mm^{-1} (2.5 kg m^{-3}) got the second rank. After that, RDI_{70} and PRD_{50} with average WP(Ir-P)B of 20.11 and 19.44 kg mm^{-1} (2.01 and 1.94 kg m^{-3}) got the next rank. The minimum WP(Ir-P)B was related to RDI_{50} treatment and averagd 17.61 kg mm^{-1} (1.76 kg m^{-3}).

Water use efficiency for seed yield (WUE(Y)): According to variance analysis results (Table 4), different irrigation treatments did not affect significantly WUE(Y). Average comparison test result (Table 5) showed that the highest WUE)Y) was related to RDI_{50}, PRD_{50} and RDI_{70} treatments and averaged 13.88, 13.59 and 13.29 kg mm^{-1}, respectively. The least WUE(Y) associated with PRD_{70} and CI treatments averaged 12.95 and 12.48 (kg mm^{-1}), respectively.

Karaa *et al.* [24] studied the improving of water use efficiency of sunflower through regulated deficit irrigation, and average WUE(Y) of fully irrigated control was of 0.80 kg m^{-3} while WUE(Y) values of the deficit-irrigation treatments were 0.76, 0.81 and 0.87 kg m^{-3}, in S1, S2 and S3, respectively. Karam *et al.* [25] stated that WUE(Y) in deficit irrigation treatments is higher than in conventional ones (which agree with the study results), and WUE(Y) amount in WS2 and WS3 deficit irrigation treatments was 0.76 and 0.83 kg m^{-3} and in conventional irrigation treatment 0.71 kg m^{-3}. Flénet *et al.* [16] found that WUE(Y) was greater in stressed treatments than in the well irrigated control, while Stone *et al.* [41] and Goksoy *et al.* [17] found that WUE(Y) did not significantly change when irrigation amount increased.

However, in Goksoy *et al.* [17] study the lowest WUE(Y) was 5.09 kg mm^{-1} (HM treatment, irrigation at heading and milking periods) and the highest one related to M treatment (irrigation applied only at milking period) averaged 7.66 kg mm^{-1} .

Demir *et al.* [10] stated that WUE(Y) did not significantly change when irrigation amount increased and obtained WUE(Y) amount between 6 kg mm^{-1} (irrigation applied at heading and flowering stages) and 7.8 kg mm^{-1} (irrigation applied only at flowering stage). Previous studies indicated that WUE(Y) ranged from 5.39 to 10.5 kg mm^{-1} [7, 34, 41]. The maximum values of WUE(Y) reported in the literature were 10.5 kg mm^{-1} in Connor *et al.* [7], referring to a field experiment and 12.3 kg mm^{-1} in Flénet *et al.* [16], referring to an experiment in plastic pots. Our results are in agreement with all the above studies that seed yield increased with irrigation frequency and seasonal irrigation amount, and the WUE(Y) between treatments was not significantly different.

Water use efficiency for biomass yield (WUE(B)): Test result showed that no significant difference was observed in different irrigation treatments in the terms of WUE(B) (Table 4). PRD_{50} treatments averaged 54.32 kg mm^{-1} and was of the maximal WUE(B), and RDI_{50} , PRD_{70} and CI treatments averaged 52.14, 52.09 and 31.69 kg mm^{-1}) and got the second rank (Table 5). RDI_{70} treatment (46.24 kg mm^{-1}) had the minimum WUE(B).

Karaa *et al.* [24] stated that, WUE(B) varied from 37.9 kg mm^{-1} in the control to 34.6 kg mm^{-1} in S1 treatment,37.0 kg mm^{-1} in S2 and 40.7 kg mm^{-1} in S3. Karam *et al* [25] improved water use efficiency for some annual crops such as sunflower through regulated deficit irrigation. A 2-year experiment (2003-2004) was conducted at Tal Amara Research Station in the Bekaa Valley of Lebanon to investigate sunflower response to deficit irrigation. Field soil was deep having high clay percentage (44%) and good drainage state. Sunflower seasonal evapotranspiration was 765 mm in 2003 and 882 mm in 2004. WUE(B) was 3.46 and 4.1 kg m^{-3} during 2003 and 2004. Flowering was found to be the most critical stage of sunflower for applying deficit water conditions and this state should be avoided.

The crop water production function: The crop water production function (CWP function) expresses the relation between obtained marketable yield (Ya) and the total amount of water evapotranspired (ETa) [12, 19, 40, 43]. Its axes are made dimensionless by plotting relative yield (Yrel ratio of actual Ya to maximum possible yield under given agronomic conditions Ym) versus relative evapotranspiration (ETrel ratio of actual evapotranspiration ETa to crop ET under non-stressed, standard conditions ETc). A linear relationship was found between relative yield and relative evapotranspiration (Fig. 1). Seed yield responded linearly to applied water, i.e. the seed yield increases as irrigation amount is increased ($R^2 = 0.87$). Our finding support the previous work of Soriano *et al*. [39] who reported that a linear relationship was found between irrigation and sunflower seed yield ($R^2 = 0.64$). Also, Karam *et al*. [25] studied the relationships between sunflower seed yield and irrigation during 2003 and 2004 growing seasons. There was poor linear relationship in 2003 between seed yield and evapotranspiration, which resulted in ($R^2 = 0.40$), while in 2004 the relationship resulted in a better correlation ($R^2 = 0.71$). The poor relationship obtained in 2003 could be due to the higher amount of rainfall and more particularly to its variable distribution in time with comparison to 2004.

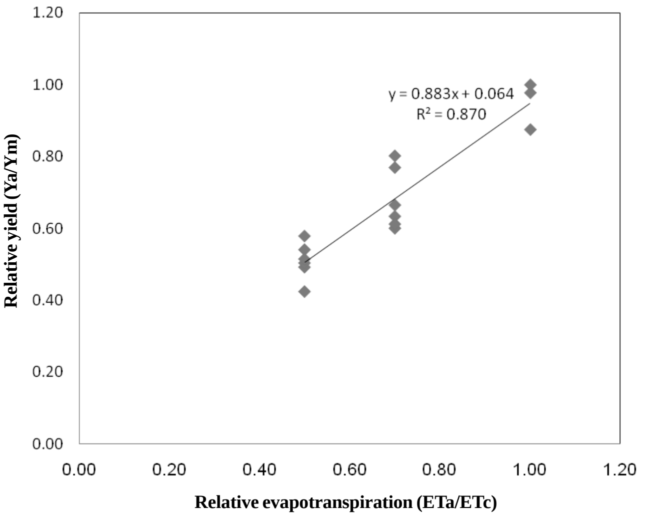

Figure 1. Relationship between relative yield and relative evapotranspiration of sunflower during 2010 season.

Conclusions

This study was carried out to investigate the effects of conventional irrigation, regulated deficit irrigation and partial root zone drying treatments on water productivity and water use efficiency of sunflower in the Ahwaz Plain of Iran. Seed and biomass yields were significantly affected by irrigation amount. When considering the seed and biomass yields, it was concluded that the seed and biomass yields increased with irrigation amount, and the highest seed and biomass yields were obtained from the CI treatment with no water stress (6687.7 and 26,920 kg ha^{-1}, respectively). Irrigation water productivity for seed yield (WP(Ir)Y) and water use efficiency for seed yield (WUE(Y)) were not significantly affected by conventional and limited irrigation treatments. Perhaps it was better to, therefore, start deficit irrigation treatments (RDI & PRD) slightly sooner than (V8) stage. Also, there was extra irrigation water amount for deficit irrigation treatments (that applied 50% and 30% deficit irrigation followed by (V8) stage for sunflower), and it was better to apply deficit irrigation of lower irrigation water amount (for example 60% and 40% deficit water followed by (V8) stage). In this study, the highest (WP(Ir)Y) was obtained by limited irrigation treatments (RDI_{50}, PRD_{50} and RDI_{70} treatments, with mean 11.62, 11.37 and 11.12 kg mm^{-1}, respectively), whereas the lowest (WP(Ir)Y) was obtained from the conventional irrigation (CI) treatment(10.74 kg mm^{-1}). The maximum WUE(Y) was related to RDI_{50}, PRD_{50} and RDI_{70} treatments which averaged 13.88, 13.59 and 13.29 kg mm^{-1}, respectively. The minimum one was also associated with CI treatment and averaged 12.48 kg mm^{-1}. The greatest amount of irrigation water was applied to the CI treatment (623 mm), and the lowest irrigation amount was applied to the RDI_{50} and PRD_{50} irrigation treatments (311.5mm). A linear relationship was found between relative yield and relative evapotranspiration. Seed yield responded linearly to applied water, i.e. the seed yield increases as irrigation amount is increased. It is concluded that the CI treatment is the best choice for maximum yield under the local conditions, but this irrigation scheme must be re-considered in areas where water resources are more limited.

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