CHILEANJAR
CHILEAN JOURNAL of AGRICULTURAL RESEARCH

RESEARCH

Rational water use by applying regulated deficit and partial root-zone drying irrigation techniques in tomato under arid conditions

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Received: 2 May 2018; Accepted: 22 August 2018; doi:10.4067/S0718-58392019000100075

ABSTRACT

This study involved exploring the opportunities of using regulated deficit irrigation and partial root zone drying approaches as water-saving irrigation methods in a tomato crop (*Solanum lycopersicum* L.) based on irrigation scheduling. The Partial Root Zone Drying Irrigation practice simply involved interchanging the wet and dry sides in subsequent irrigations. The field experiment was conducted in the Kingdom of Saudi Arabia, during the fall season of 2014-2015 and 2015-2016. The following three irrigation treatments were tested during both years under a drip irrigation system: (1) full irrigation (FI), as a control treatment; (2) regulated deficit irrigation (RDI); and (3) partial root zone drying irrigation (PRD). Both RDI and PRD treatments received 70% of the irrigation water volume of full irrigation (FI). The obtained results indicated that the soil water content of PRD treatment was higher and conserved more soil moisture than that in the RDI treatment. Data for both years indicated that FI exhibited the highest stomatal conductance (g_s) values while PRD exhibited the lowest g_s values among all the treatments. Under PRD treatment, the dry fruit yield was the highest when compared with RDI and FI treatments for both years. Deficit irrigation treatments result in higher abscisic acid (ABA) concentration in the xylem when compared to that in FI. The vast majority of most extreme irrigation water use efficiency (IWUE) values were involved with PRD while most of the minimum IWUE values were coupled with FI. These results indicate the effects of deficit level irrigation on IWUE.

Key words: Full irrigation, irrigation water use efficiency, partial root zone drying, regulated deficit irrigation, *Solanum lycopersicum*.

INTRODUCTION

Water is a central issue on the international agenda for several years. Recently, several parts of the world are affected by water shortage. Available water resources are subjected to an ever-increasing pressure as a result of increasing agricultural water demand for irrigated lands. A long-term perspective with respect to scarcity of fresh water resources especially in the arid and semi-arid areas, demands an urgent solution for new irrigation strategy and agricultural water management (Sepaskhah and Ahmadi, 2010).

The deliberate withholding of irrigation water by a technique known as deficit irrigation (DI) is an effective management approach to manipulate crop water use. PRD differs from RDI as it simultaneously maintains a wet as well as a drying portion of the root zone while RDI strategies create a level of moisture deficit throughout the root zone (White, 2007).

Tomato (*Solanum lycopersicum* L.) is one of the most important vegetables in the world, and it has high water requirements. It is typically grown in Saudi Arabia during fall and spring seasons. The successful irrigation of a tomato crop requires knowledge of both irrigation system and scheduling methods. Improved irrigation methods save water without undermine yield or quality.

Deficit irrigation (DI) is a watering strategy that was proposed many years ago to improve water efficiency and reduce the application of irrigation. In a broad sense, English and Raja (1996) state that DI consists of the deliberate and systematic under-irrigation of crops. Thus, the amount of water that is applied is lower than that needed to satisfy the full crop water requirements. As widely-known, reductions in the water applied generally lowers evapotranspiration (ET) and crop growth rates by limiting their principal component, namely transpiration, and thereby C assimilation. Therefore, the right application of DI needs a thorough understanding of the crop responses to water deficits and the profitable impact of reductions in crop value (Ruiz-Sanchez et al., 2010). Regulated deficit irrigation (RDI) is an irrigation approach to manipulate vegetative growth, yield, and quality with water stress. RDI was successfully employed to maximize WUE and achieve higher yields per unit of irrigation water in different crops (Afshar et al., 2014). With respect to the optimal application of RDI plant and soil, it is necessary to monitor water status to maintain a plant water regime within a certain degree of water stress that does not limit yield. This is the major difficulty when RDI is applied in field conditions.

Specifically, PRD is an irrigation strategy based on split-root technology that involves alternatively wetting and drying at least two spatially separate parts of a plant's root system. The aim of this strategy involves simultaneously maintaining plant water status at the maximum water potential while regulating stomatal behavior and vegetative growth (Kriedemann and Goodwin, 2003). This indicates that half of the root zone is irrigated and the other half is allowed to dry out. The frequency of the switch is determined based on the soil type, genotypes, or other factors such as rainfall and temperature.

If only a part of the root system dries and the remaining roots are maintained as well-watered, the chemical signals manufactured in the drying roots theoretically reduce stomatal aperture and control the vegetative vigor (Wakrim et al., 2005). This mechanism optimizes water use and increases WUE (Shahabian et al., 2012). Thus, the PRD technique achieves the desired change in plant physiological response by elevating abscisic acid (ABA) as a feed-forward mechanism.

Practical results indicated that crops under PRD produced better yields than those under RDI when the same volume of irrigation water is applied (Liu et al., 2006). However, other studies compared PRD and RDI in grapevines and indicated slight or no improvement in crop yield and fruit quality when PRD was used as opposed to RDI (Romero et al., 2014).

The creation of soil moisture gradient is important to explore the beneficial effects of PRD irrigation. Zegbe-Domínguez et al. (2003) reported that the soil water content (SWC) were significantly lower in RDI and in the non-irrigated part of PRD treatment when compared to those in FI.

RDI and PRD are two water saving irrigation techniques that increase the WUE of potatoes, even without declining yield (Shahnazari et al., 2007). Salghi et al. (2012) showed that when compared to the control (control treatment that received 100% of its daily water requirement), RDI (received 50% of its daily water requirement) and PRD (received 50% of its daily water requirement) treatments increase the WUE to 150% and 166% for the RDI and PRD treatments, respectively, with respect to the tomato plant.

Partial stomatal closure occurs due to increased ABA. Accumulated evidence proposes that both hydraulic and chemical signals are operative and integrated into the regulation of leaf growth and stomatal conductance (g_s) when plants are grown under drought stress (Comstock, 2002).

The aim of the present study included exploring the possibilities of using the RDI and PRD methods as a water-saving irrigation technique in a tomato crop based on irrigation scheduling and also comparing the responses of the tomato crop to PRD, RDI and FI under a drip irrigation system in terms of the physiology and productivity of crops and the amount of water saved.

MATERIALS AND METHODS

The experiment was conducted in an experimental field at an educational farm of the Faculty of Food and Agriculture Sciences, King Saud University, Riyadh (24°44' N, 46°36' E; 665 m a.s.l.), Kingdom of Saudi Arabia. The climate is typical of arid areas. The soil was prepared based on the standard methods for plowing, grading, and leveling.

The soil at the experimental site corresponded to sandy loam. Soil samples were collected at 20 cm up to a total depth of 60 cm to determine physical and chemical analyses based on standard methods. The physical analysis investigation included soil texture, field capacity (FC), permanent wilting point (W_P), saturated hydraulic conductivity (KS), saturation moisture content (S), and bulk density (ρb). Chemical analyses included examinations of anions, cations, pH, electrical conductivity (EC), organic matter, total N content, and available N, P and K. The physical and chemical properties, soil fertility, and organic properties are shown in Tables 1, 2, and 3.

An area of 102.7 m^2 (13 m × 7.9 m) was located for the experiment to manage three treatments, each of which was repeated three times. A surface drip irrigation was applied to the established field. The field was divided into three plots. Each plot was divided into three rows, and each row contained 26 plants spaced 0.5 m apart (Figure 1).

The experiment consisted of three regimes, namely regular deficit irrigation (RDI), partial root zone drying irrigation (PRD), and full irrigation (FI). Both RDI and PRD treatments received 70% of the irrigation water volume of FI. Each treatment was repeated three times. The statistical design used in the experiment was a completely randomized block design. The number of experimental units corresponded to nine units. All water treatments were applied either from one side as in FI and RDI or from both sides as in PRD irrigation. Drip lines with a diameter of 18 mm with in-line emitters spaced at a distance of 0.50 m were each delivered 8 L h^{-1} at an operating pressure of 100 kPa. Drip lines were placed at the centers of adjacent crop rows and separated by a distance of 0.7 m in the experimental plots for both FI and RDI treatments. However, the PRD treatment included two drip lines for each row of vegetables, and the distance between the two lateral lines was 0.4 m. These two laterals were laid shiftily from each other by 25 cm, and therefore the emitters correspond to a nested shape, and these two laterals were controlled by a separate valve. The buffer treatment was 0.75 m.

The implementation of PRD irrigation systems necessitates that each row of vegetable is served by dual dripper lines in which each works independently. The irrigation under PRD treatment shifted from one side of the plants to the other every 7 d (Liu et al., 2006) to achieve a long-term effect of PRD on leaf gas exchange, abscisic acid (ABA) signaling, and WUE in the tomato crop.

The irrigation operation was automatically controlled through an automatic controller (ESP-LXME controllers, Rain Bird Corporation, Tucson, Arizona, USA) that was connected with a central control software (IQ v2.0, Rain Bird Corporation, Azusa, California, USA), and the software monitored and adjusted watering schedules for controllers and site from a compatible Windows PC. The water requirement for irrigation was automatically calculated as potential

Table 1. Physical properties of the soil.

	Particle size								
Depth	Sand	Silt	Clay	Texture	FC	W_P	KS	S	ρb
cm	%				%		mm h^{-1}	%	g cm^{-3}
0-20	71.80	16.32	11.88	Sandy loam	19.71	9.68	35.78	35.12	1.62
20-40	66.72	18.02	15.26	Sandy loam	23.80	13.75	23.63	42.14	1.63
40-60	69.10	18.31	12.59	Sandy loam	25.41	15.47	18.59	43.13	1.63

FC: Field capacity; W_P: permanent wilting point; KS: saturated hydraulic conductivity; S: saturation moisture content; ρb: bulk density.

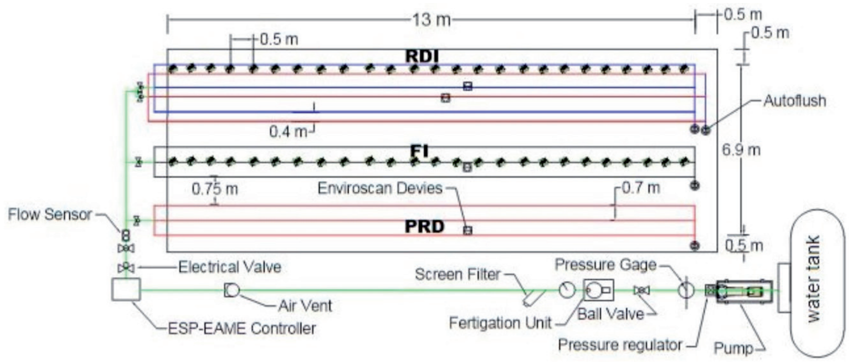
Table 2. Fertility-related properties of the soil.

		Fertility			
Depth	$CaCO_3$	N	P	K	Organic matter
cm	%	mg kg^{-1}			%
0-20	18.61	19.60	0.30	57.97	0.16
20-40	23.39	14.52	0.70	66.82	0.10
40-60	14.05	13.88	0.70	59.50	0.00

Table 3. Chemical properties of the soil.

	Cations				Anions			
Depth	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	CO_3^-	Cl^-	SO_4^-
cm	cmol L^{-1}				cmol L^{-1}			
0-20	12.00	3.60	11.66	0.48	1.40	0.00	11.50	32.30
20-40	11.50	3.50	11.88	0.57	1.30	0.00	10.50	25.20
40-60	11.70	4.50	9.34	0.37	1.10	0.00	11.00	16.80

Figure 1. Experimental layout.



RDI: Regulated deficit irrigation; FI: full irrigation; PRD: partial root zone drying irrigation.

crop evapotranspiration (ET_c) from an ET_o FAO Penman-Monteith equation based on climatic data obtained from the meteorological station (WS-PRO LT Weather Station, Rain Bird), which was established in the experiment field. The standard K_c for each growth stage (initial, mid, and end) of the tomato crop was took from FAO-56 (Allen et al., 1998).

Soil moisture content in the experiments was monitored using capacitance probes (EnviroSCAN Sentek Sensor Technologies, Stepney, South Australia, Australia). Each EnviroSCAN includes five sensors installed at depths of 10, 20, 30, 40, and 50 cm. Just one replicate was monitored from the three of each treatment. Four EnviroSCAN devices were installed in the field and used an EnviroSCAN device with each treatment with the single drip line (FI and RDI) and two EnviroSCAN devices with treatments with the dual drip line (PRD). The two devices were placed at a distance of 40 cm in a diagonal direction. Soil water data were sampled at a frequency that was set at 15 min between readings. The data were then stored in EnviroSCAN's custom built logging system.

The experiment was performed in the experimental field during the fall season of the year 2014-2015 and fall season of the year 2015-2016. The crop corresponded to tomato (*Lycopersicon esculentum* L.) Tomato seeds were germinated in commercial pellets (one seed per pellet; Jiffy-7, Jiffy, Oslo, Norway) in a controlled environment greenhouse. The seed was planted 4 wk prior to transferring the same to the open field. The greenhouse was located in the Dirab area near Riyadh in the Research and Agricultural Experiment Center, College of Food and Agriculture Sciences, King Saud University. The pellets were observed daily to maintain moisture and to observe any problem. After 4 wk, seedlings were transferred to sustainable land in the experiment field after field-preparation steps (e.g., watering, lining, and digging). The distance of planting corresponded to 50 cm within the line and 70 cm between lines.

The actual date of planting in the first year corresponded to 23 September 2015, and harvesting was performed from 19 December 2015 to 23 January 2016. In the second year, the actual date of planting corresponded to 23 September 2016, and harvesting occurred from 25 December 2016 to 25 January 2017. Common cultural practices including fertilizer application and insects and diseases control were conducted. The tomato crop was harvested seven times in the 1^{st} year and eight times in 2^{nd} year.

After commencing the treatments for the tomato crop, stomatal conductance (g_s) (mol m^{-2} s^{-1}), and transpiration rate (T) (mmol m^{-2} s^{-1}) were measured by using LI-6400XT portable photosynthesis system (LI-COR Corporate, Lincoln, Nebraska, USA). The measurements were monitored six times (from 11 November 2015 to 16 December 2015) during the treatment period for the 1^{st} year and 6 times (from 23 November 2016 to 28 December 2016) during the treatment period for 2^{nd} year. The measurement of gas-exchange were performed in each plot and was repeated thrice for each plot. The measurements were collected between 06:00 and 12.00 h local time. Within each plot, the third fully expanded upper canopy leaflets were selected for measurements. A total of nine plants were sampled per round, and the time period corresponded to approximately 0.5 h.

In order to collect the xylem sample from tomatoes, a new approach was adopted in which the xylem sap was collected from the cut stems (Ahmadi et al., 2010). One stem per plot was sampled through the gas exchange measurements in the same plot (1 December, 67 d after transplanting) for the different irrigation treatments in both years. In order to collect approximately 0.5-1.0 mL xylem sap, an overpressure of approximately 0.2-0.4 MPa above the plant equilibrium pressure was applied, and sap was collected using an appropriate pipette (Liu et al., 2006). The xylem ABA samples were immediately frozen in liquid nitrogen and subsequently stored at -80 ºC until the analysis. All samples were used to determine ABA content through an enzyme-linked immunosorbent assay (ELISA) (Asch, 2000).

Fruits were manually collected from each line, weighed, and counted to determine fresh weight and fruit per plant. Number of fruits and fruit weight per plant and the total fresh fruit yield (all the collected fruits) were determined. Harvest-ripe fruits were manually picked and weighed twice a week from 19 December in the 1st year and 25 December in the 2nd year, and this continued until the end of the experiment for both. The dry weight of tomato fruits was determined after oven drying for 48 h at 80 ºC. Therefore, yield components characters were: Total fresh fruit yield (Mg ha^{-1}), total dry fruit yield (Mg ha^{-1}), and number of fruits per plant.

The most important indicator that demonstrates the benefit of a treatment was the irrigation water use efficiency (IWUE) defined as the ratio of crop yield over the applied water (De Pascale et al., 2011) as a function of yield (Y; kg) and applied water (AW; m^3). The AW was measured by the flow sensor installed in the field.

The data were subjected to ANOVA by using SPSS Statistics (IBM, Armonk, New York, USA). The least significant difference (LSD) test at $p < 0.05$ was applied to determine significant differences among the means of irrigation treatment.

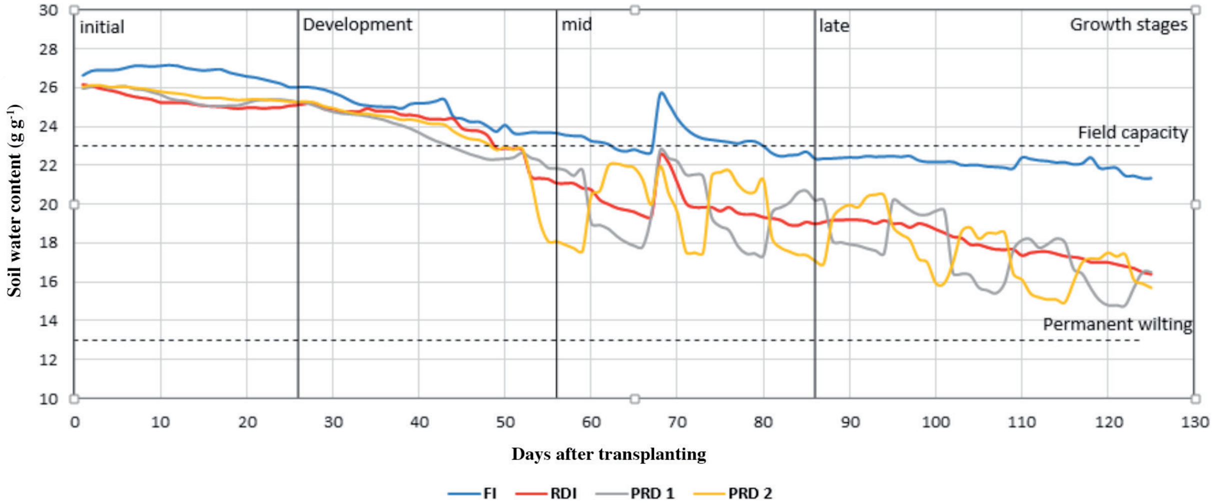
RESULTS AND DISCUSSION

Soil water distribution of different patterns in response to tomatoes irrigation treatments (FI, RDI, and PRD) during 2 yr was continuously monitored by using EnviroSCAN probes. This offered a nondestructive and less tedious method to continuously monitor water content within and below the root zone. Consequently, data were recorded for soil water content (SWC) values that were plotted relative to the number of days after planting. This period was divided into four growth stages, namely the initial 26 d, development 30 d, mid-season 30 d, and late season 38 d, as shown in Figures 2 and 3. The SWC was measured at five soil depths, namely 10, 20, 30, 40, and 50 cm. The average of SWC of these depths was calculated and illustrated as shown in Figures 2 and 3. Field capacity and permanent wilting point were also simultaneously plotted to show the status of plant stress due to the irrigation treatment. Generally, the initial stage and most of the development stage were almost similar to each other for the first and second years respectively, while all treatments received the same amount of water that corresponded to 100% ET.

Evidently, the level of SWC immediately decreased in the root zone after deficit irrigation treatments were applied and was less than that in full irrigation treatment. Conversely, the rate of the SWC constantly decreased when plant growth increased and the uptake of water increased. As observed in all the SWC treatments graphs, the SWC was at an acceptable

Figure 2. Soil water content (SWC) distribution in tomatoes field under different irrigation treatments: full irrigation (FI), regulated deficit irrigation (RDI), and partial root zone drying irrigation (PRD) in the 1st year from the 1st day until 123 d after transplanting.

Figure 3. Soil water content (SWC) distribution in tomatoes field under different irrigation treatments: full irrigation (FI), regulated deficit irrigation (RDI), and partial root zone drying irrigation (PRD) in the 2nd year, from the 1st day until the 125 d after transplanting.



level between FC and WP without plant water stresses. The SWC data under different treatments (Figures 2 and 3) exhibited different patterns of water distribution in response to tomato watering treatment. This was due to the different amounts of water applied in each treatment and growth stage. The SWC was influenced by root development and water extraction. As shown in Figures 2 and 3, the SWC for RDI and PRD treatments were lower than those of the FI treatments for both years.

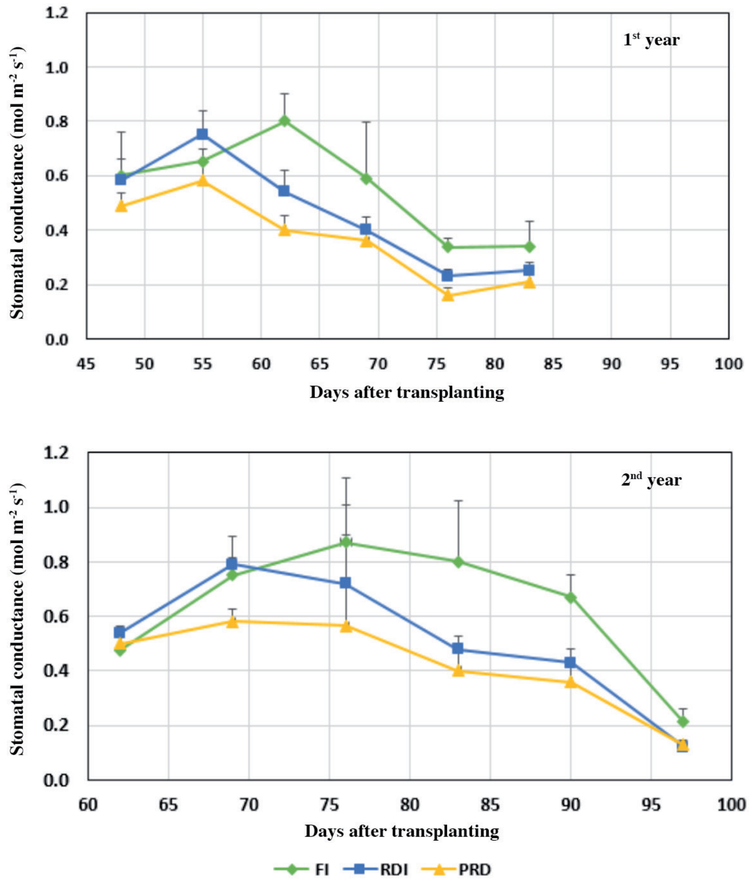
The daily SWC of FI was close to the water field capacity for both years. Correspondingly, the applied deficit irrigation treatments resulted in a decrease in SWC and remained at approximately 15-20 g g^{-1} for the 1st year and ranged between 16-21 g g^{-1} for the 2nd year (Figures 2 and 3). Alternate wetting and drying cycles that result from applying PRD treatments affected SWC in the root-zones (Figures 2 and 3). Therefore, the SWC in PRD root-zone alternately increased and decreased for both PRD lines in the opposite direction.

Figures 2 and 3 indicated that the irrigation switch was applied every 7 d to keep the roots alive, and signaling was sustained. Thus, the differences in SWC between the PRD wet and dry sides were observed during the deficit irrigation treatment application. Despite a significant contrast in the soil water content between the two sides of the PRD (PRD1 and PRD2), the PRD treatment average SWC was close to that of the RDI treatment, thereby indicating that the rates of water use were fundamentally the same between the two treatments. The monitoring of SWC in the PRD treatment indicated a change in root-zone uptake in response to the irrigation method. However, there exist a few lateral soil water movements from the wet side to the dry side after each watering. The results demonstrate that the SWC in each PRD root-zone alternately increased and decreased. This result is in agreement with the results of extant studies on PRD (Kirda et al., 2004).

A similar pattern of soil water dynamics was also observed in PRD-treated tomato and other crops (Zegbe-Domínguez et al., 2006). A higher rate of water uptake in the final stage (Figures 2 and 3) is potentially due to the increased root contact area or improved root hydraulic conductivity after re-watering the dry side as shown by Kang et al. (2001). The un-watered side of the root zone in PRD exhibited a reduction in SWC although sufficient water was available in the wet side of the root zone to supply adequate water to the roots of the plant to maintain plant growth although at a lower level when compared to the FI treatment. With respect to the comparison between PRD and RDI (in which the same amount of water was applied).

The effects of irrigation treatments on stomatal conductance (g_s) are shown in Figure 4. In the 1st year, g_s values in different irrigation treatments in the study varied mainly between 0.16 and 0.8 mol m^{-2} s^{-1}. In the 2nd year, g_s values varied mainly between 0.12 and 0.87 mol m^{-2} s^{-1} (Figure 4). For both years, the two water deficit irrigation treatments (RDI and PRD) exhibited g_s values lower than those in the FI treatment. This indicates their stomatal closure because g_s indicates the degree of stomata opening. This could occur due to the lower water content in both RDI and PRD when compared with

Figure 4. Stomatal conductance for the irrigation.



The data points represent means ± standard error of the mean (n = 3).
FI: Full irrigation; RDI: regulated deficit irrigation; and PRD: partial root zone drying irrigation.

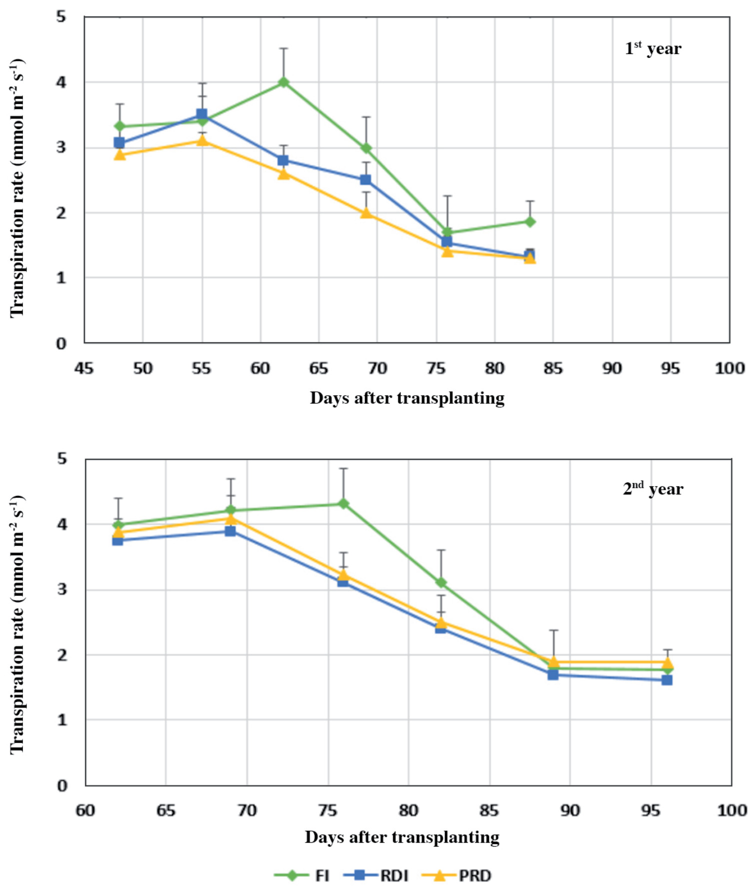
that in the FI treatment as mentioned previously. Consequently, the g_s decreased although water stress on the plant was absent. Therefore, g_s is considered as a common and important plant response to soil drying. These results were consistent with those obtained by Nardella et al. (2012), who reported that the process of stomatal closure was one of the initial events in plant response to soil drying and water stress. Stomatal closure aided in preventing excessive water loss in plants due to transpiration and leads to a better water balance.

In the 1st year, RDI and PRD decreased g_s when compared with FI treatment by 16.99% and 33.82%, respectively. Nevertheless, in the 2nd year, the results exhibited that RDI and PRD decreased the average value of g_s by 18.70% and 32.96%, respectively, when compared with those in the FI. This indicated that FI exhibited the highest g_s values and the PRD exhibited the lowest g_s values among all the treatments. This is potentially because the PRD led to stomatal closure since frequent switches in irrigation from one side of the PRD plants to another could maintain a larger portion of the roots that is exposed to water stress when compared to RDI where more of the root system was in the dry soil. This was clear from the soil water content as shown previously in Figures 3 and 4. An increase in the portion of roots exposed to drying soil with PRD may result in the arrival of increased ABA in the leaves that affects stomatal opening, and thereby reduces water loss. In the 1st year, it was nonsignificantly different between RDI and PRD although there was a significant difference ($p > 0.05$) between deficit irrigation treatments and FI with respect to 62, 76, and 82 d after transplanting (DAT). In the 2nd year, the effects of irrigation treatments on g_s were nonsignificant although the fifth reading indicated significant effects for irrigation treatments on g_s.

Figure 5 shows the effects of the irrigation treatments on the transpiration rate (T) of tomato plants for both years of the study. Figure 5 shows that RDI and PRD treatments decreased the transpiration rate. The T values in the 1st year ranged between 1.30 and 4.0 mmol m^{-2} s^{-1}. However, T values in the 2nd year varied from 1.61 to 4.31 mmol m^{-2} s^{-1} (Figure 5). Generally, in both years, the trend of transpiration rate increased up to mid-season and then decreased. As shown in Figure 5, the lowest value of the transpiration rate in the 1st year (1.30 mmol m^{-2} s^{-1}) was observed with PRD. However, the highest value (4.00 mmol m^{-2} s^{-1}) was obtained with FI. However, in the second year, the lowest value (1.61 mmol m^{-2} s^{-1}) was obtained with RDI, and the highest value (4.21 mmol m^{-2} s^{-1}) was obtained with FI. It was observed that the water saving irrigation techniques (RDI and PRD) decreased the average value of T, when compared with FI treatment, by 15% and 23%, respectively, in the 1st year. Nevertheless, in the 2nd year, the results indicated that the measurements under RDI and PRD decreased the average value of T by 14.17% and 8.8%, respectively, when compared with those in the FI. This occurred because the water content decreased under DI treatments, and thus the abscisic acid concentration increased and triggered the closure of stomata (Gollan et al., 1992), and thereby reduced the transpiration water loss and improved WUE. The results were consistent with those obtained by previous studies including Nangare et al. (2016) that indicated lower T values under drought stress conditions in tomato crop. Yang et al. (2012) concluded that the PRD reduced the leaf transpiration rate of tomato crop when compared to that in FI treatment.

ANOVA indicated the absence of significant differences between RDI and PRD with respect to the effect on transpiration rate for both years. These results indicate that the RDI and PRD are good methods to reduce the transpiration rate, and thereby conserve water.

Figure 5. Transpiration rate of the tomato crop for different irrigation treatments.



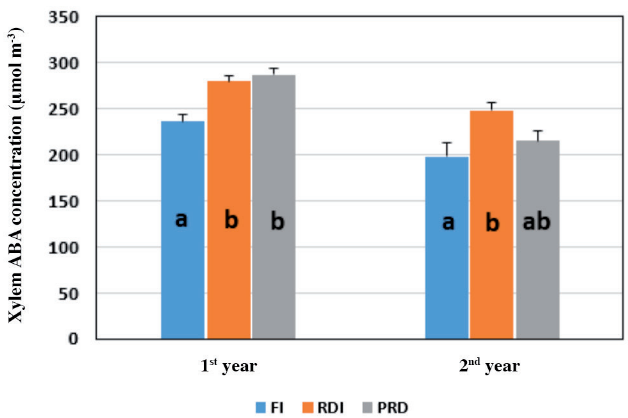
The data points represent means ± standard error of the mean (n = 3).
FI: Full irrigation; RDI: regulated deficit irrigation; and PRD: partial root zone drying irrigation.

The effects of the irrigation treatments on xylem abscisic acid in the tomato crop are shown in Figure 6. The results indicated that the water-saving treatments increased the ABA content of the tomato crop when compared to the FI treatment.

The ABA content of tomato crop was the highest under PRD treatment when compared to FI and RDI treatments in the 1st year as shown in Table 4 and Figure 6. The RDI treatment in which the same amount of irrigation water was received as the PRD treatment exhibited an intermediate ABA concentration between the FI and PRD treatments although it was closer to PRD than FI. In the 2nd year, ABA concentration was the highest under RDI. The FI exhibited the lowest xylem ABA concentration (Figure 6). During the 1st year, xylem ABA concentration for PRD and RDI exceeded FI by 21.61% and 18.64%, respectively. In the 2nd year, xylem ABA concentration for PRD and RDI exceeded FI by 8.59% and 25.25%, respectively. The increase in ABA concentration occurred because the soil water status in the root zone under PRD and RDI treatments was low when compared with FI treatments, and this significantly influenced the ABA concentration in the xylem. The results were consistent with those obtained by Wang et al. (2012), who revealed a significant negative linear relationship between root water potential and the xylem ABA concentration.

Liu et al. (2003) concluded that hydraulic signals are significant when the soil water deficit is severe. This helps the synthesis of ABA in the leaves and maybe adds to controlling the plant's responses to dryness by a decrease in the leaf turgor and g_s (Liu et al., 2003). ANOVA showed that there is a notable effect ($p < 0.05$) of different irrigation treatments on ABA content for both years. The results were consistent with Sun et al. (2013), who suggested that the reduced irrigation regimes significantly affected ABA. Akhtar et al. (2014) indicated that leaf ABA contents were higher under RDI and PRD when compared with FI.

Figure 6. Xylem abscisic acid (ABA) concentration for the tomato crop on 1 December (67 d after transplanting) for the different irrigation treatments in both years.



Different letters inside columns exhibited significant differences between irrigation treatments at $p < 0.05$. Bars denote the means ± standard error of the mean (n = 3).
FI: Full irrigation; RDI: regulated deficit irrigation; and PRD: partial root zone drying irrigation.

Table 4. Xylem abscisic acid (ABA) concentration for the tomato crop on 1 December (67 d after transplanting) for the different irrigation treatments in both years.

Treatments	Xylem [ABA] 1st year	Xylem [ABA] 2nd year
	$\mu mol\ m^{-3}$	
FI	236	198
RDI	280	248
PRD	287	215

FI: Full irrigation; RDI: regulated deficit irrigation; PRD: partial root zone drying irrigation.

Fresh, dry fruit yield per hectare (FW, DW), and the number of fruits per plant for the different irrigation treatments in tomato are shown in Table 5 and Figure 7. Generally, the highest tomato fruit yield was obtained under the full irrigation treatment in the 1st year and 2nd year. This potentially occurred because the soil water content under FI exceeded that in DI treatments.

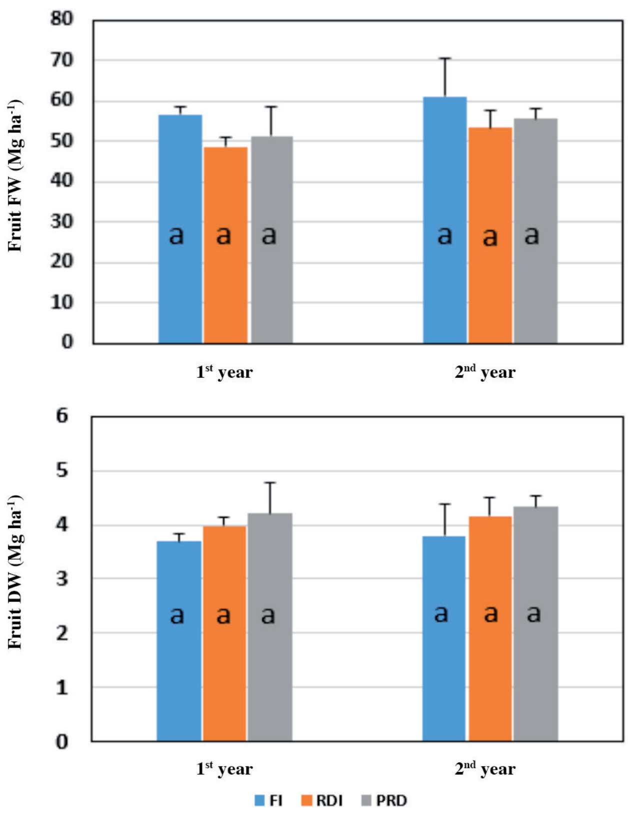
The lowest fruit yield in 1st year was obtained under RDI (48.72 Mg ha^{-1}) and the lowest fruit yield was obtained under RDI (53.37 Mg ha^{-1}) in the 2nd year (Figure 7). In the 1st year, yield reduction under RDI and PRD treatments corresponded to 14.07% and 9.64%, respectively, when compared with FI, while the yield reductions under RDI and PRD treatment in the 2nd year were 12.75% and 9.19%, respectively, when compared with FI.

Table 5. Fruit yield traits of tomato for the different irrigation treatments in both years.

	Treatments	Fruit FW	Fruit DW	Nr fruit plant^{-1}
		Mg ha^{-1}	Mg ha^{-1}	
1st year	FI	56.70	3.69	25
	RDI	48.72	3.98	22
	PRD	51.23	4.21	23
2nd year	FI	61.17	3.80	26
	RDI	53.37	4.16	23
	PRD	55.55	4.32	25

FW: Fresh weight; DW: dry weight; FI: Full irrigation; RDI: regulated deficit irrigation; PRD: partial root zone drying irrigation.

Figure 7. Fresh (FW) and dry weight (DW) tomato fruit yield per hectare for different irrigation treatments.



Different letters inside columns denote significant differences between irrigation treatments at $p < 0.05$.
Bars denote the means ± standard error of the mean (n = 3).
FI: Full irrigation; RDI: regulated deficit irrigation; and PRD: partial root zone drying irrigation.

The explanation for the reduction is that the drying of soil decreases the rate of absorption by roots below the transpiration rate by the plant, and thus constitutes an internal water deficit that affects photosynthesis and results in reduced leaf area, intercellular volume, and cell size. This in turn reduces soil moisture accumulation. The effect of the internal water deficit was higher at the fruit growth stage as the expanding fruit tissues require considerable water at this time.

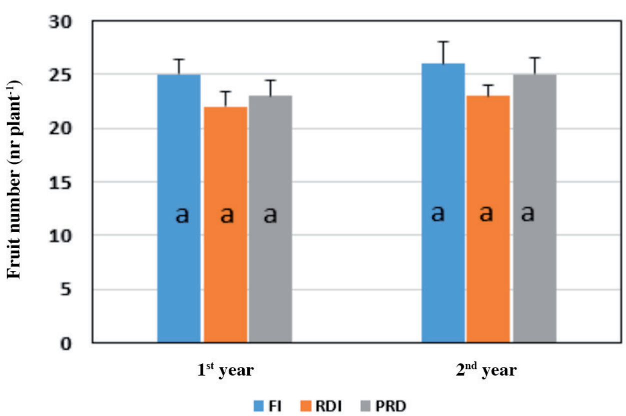
It is assumed that higher fresh weight of FI fruits is the result of a longer ripening period that allowed higher accumulation of water in these fruits when compared to DI fruits (Savic et al., 2008). The results obtained by several previous studies support the present study results. For example, Kirda et al. (2004) and Giuliani et al. (2016) indicated that the marketable yield under FI treatment was the highest values comparing with RDI and PRD. Kuscu et al. (2014) reported that the highest marketable tomato yields were observed with full irrigation, and a decrease in the irrigation rate generally improved the DM of fresh tomato fruits. According to the dry fruit yield responses, the results generally indicated that the deficit irrigation treatments increased the dry fruit yield for most measurements. Evidently, the effect of irrigation method on dry fruit yield was absent. The results in 1st year indicated that the dry fruit yield was the lowest for FI (3.69 Mg ha^{-1}) and the highest (4.21 Mg ha^{-1}) for PRD treatment as shown in Figure 7. The results in the 2nd year revealed that the lowest value of dry fruit yield was observed with FI (3.80 Mg ha^{-1}). Conversely, the highest value was observed with PRD (4.32 Mg ha^{-1}).

Water stress applied to the tomatoes led to an increase in concentrations of sugar and DM of ripe fruit. These phenomena are explained by the fact that water stress did not affect the quantity of DM accumulated by the fruit although it significantly reduced its accumulation of water (Mitchell et al., 1991).

Figure 8 shows a decreasing trend in the number of fruit per plant values under deficit irrigation. A plausible explanation for this was that the average number of flowers per truss decreased with decreases in the water supply. This is consistent with the results of Prieto Losada and Rodriguez del Rincón (1993), who indicated that water stress during flowering reduced the number of flowers. In the 1st year, the number of fruits per plant for RDI and PRD decreased when compared with that of FI by 12% and 8%, respectively. However, in the 2nd year, RDI and PRD decreased the number of fruit per plant by 11.54% and 3.85%, respectively, when compared with FI. The reduction in the fruits number in RDI and PRD (Figure 8) is possibly the result of floral abortion induced by water deficit (Pulupol et al., 1996). Figure 8 shows a decrease in or absence of a significant effect that supports the absence of a pronounced decrease. Furthermore, our results are consistent with those obtained by Zegbe-Domínguez et al. (2003), who suggested that the number of fruits in the tomato crop and fruit water content reduced in RDI and PRD relative to FI. ANOVA in both years indicated that was nonsignificant effect ($p > 0.05$) to irrigation treatments on fresh, dry fruit yield, and fruit number per plant.

The goal of DI is to enhance irrigation water use efficiency (IWUE) by decreasing the amount of water applied with irrigation or by reducing the number of irrigation events (Kirda et al., 2004). Thus, the irrigation water applied (IWA)

Figure 8. Number of tomato fruits per plant for the different irrigation treatments.



Different letters inside columns revealed significant differences between irrigation treatments at $p < 0.05$.
Bars denote the means ± standard error of the mean (n = 3).
FI: Full irrigation; RDI: regulated deficit irrigation; and PRD: partial root zone drying irrigation.

amount for the tomato crop under all treatments (FI, RDI, and PRD) during the 2 yr was recorded (Table 6). The higher amount of applied water at the second season occurred due to the relative humidity was very low at the 2 yr comparing with 1 yr. IWUE values determined for all irrigation treatments are also shown in Figure 9.

With respect to all treatments for the 2 yr, there are nonsignificant effects ($p > 0.05$) on IWUE values. Similarly, the effects of water stress on the IWUE as indicated by several researchers corresponded to the absence of noteworthy differences in IWUE relative to the different water regimes that were used (Giuliani et al., 2016).

In the first year, although there were nonsignificant differences between treatments, IWUE values were 18.34 and 18.89 kg m^{-3} for RDI and PRD, respectively, which were higher than those for FI (17.05 kg m^{-3}) by 7.57% and 10.8%, respectively. During the second year, the IWUE values for RDI, PRD, and FI were 14.83, 15.31, and 13.77 kg m^{-3}, respectively. Accordingly, the IWUE for both RDI and PRD exceeded FI by 7.7% and 11.18%, respectively. Thus, the vast majority of most extreme IWUE values was observed under PRD. However, most of the smallest IWUE values were coupled with FI. These results denote the impacts of deficit levels on IWUE. In most extant studies, increases in the IWUE in tomato were reported under water deficit conditions (Kirda et al., 2004). It was previously observed that the results were consistent with those obtained by Nardella et al. (2012), who illustrated that the IWUE values obtained from PRD and RDI strategies exceeded that of FI, and they reported that PRD strategy exhibited slightly higher IWUE values when compared to RDI.

Kirda et al. (2004) performed a greenhouse experiment by using the restoration of 70% ET_c and indicated that IWUE improvements on fresh-market tomato corresponded to 11.5% and 5.5% under PRD and DI, respectively. Nangare et al. (2016) reported maximum water productivity under RDI80 when deficit irrigation was applied.

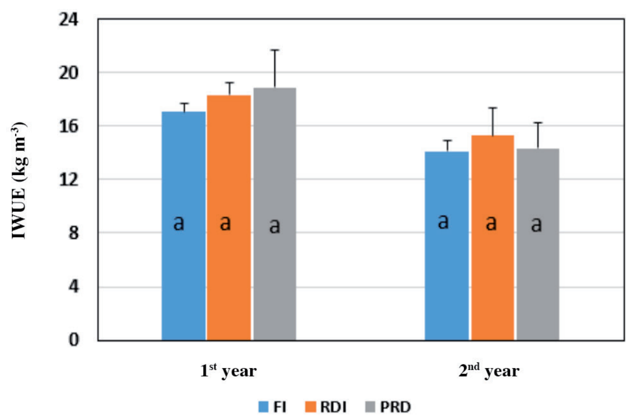
Yang et al. (2012) reported that alternate PRD improved IWUE when compared to conventional irrigation. Akhtar et al. (2014) suggested that IWUE in PRD exceeded that in RDI. The increase in IWUE values under the two DI practices is attributed to the partial stomatal closure observed under RDI and PRD treatments that leads to a decrease in T and potentially to an increase in WUE.

Table 6. Irrigation water applied (IWA) per hectare.

	IWA	
Treatments	1st year	2nd year
	m^3 ha^{-1}	
FI	3325.10	4443.39
RDI	2656.99	3599.22
PRD	2712.65	3627.80

FI: Full irrigation; RDI: regulated deficit irrigation; PRD: partial root zone drying irrigation.

Figure 9. Irrigation water use efficiency (IWUE) for the different irrigation treatments in tomato.



Different letters inside columns denote significant differences between irrigation treatments at $p < 0.05$.
Bars denote the means ± standard error of the mean (n = 3).
FI: Full irrigation; RDI: regulated deficit irrigation; and PRD: partial root zone drying irrigation.

CONCLUSIONS

From all of the above field experimental results, partial root-zone drying and regulated deficit irrigation techniques have proven the efficiency in improving the irrigation water use efficiency and fruit quality and dry fruit yield as compared to full irrigation. In particular, partial root zone drying irrigation, which is the recommended treatment for saving water and maintaining yield.

ACKNOWLEDGEMENT

This Project was funded by the National Plan for Science, Technology and Innovation (MAARIFAH), King Abdulaziz City for Science and Technology, Kingdom of Saudi Arabia, Award Number (11-WAT1978-02).

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