Scientia Horticulturae 225 (2017) 525–532

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

Comparative effects of two water-saving irrigation techniques on soil water status, yield, and water use efficiency in potato

Tarek K. Zin El-Abedin[a,b], Mohamed A. Mattar[a,c,*], A.A. Alazba[a,d], Hussein M. Al-Ghobari[a]

[a] Agricultural Engineering Department, College of Food and Agriculture Sciences, King Saud University, Riyadh 11451, Saudi Arabia
[b] Agricultural Engineering Department, College of Agriculture, Alexandria University, Alexandria, Egypt
[c] Agricultural Engineering Research Institute (AEnRI), Agricultural Research Centre, Giza, Egypt
[d] Alamoudi Water Research Chair, King Saud University, Riyadh 11451, Saudi Arabia

ARTICLE INFO

Keywords:
Partial root-zone drying
Deficit irrigation
Water use efficiency
Potato

ABSTRACT

This study was conducted to compare two water-saving techniques: deficit irrigation (DI) and partial root-zone drying (PRD) with full irrigation (FI) on potato (*Solanum tuberosum* L.). These techniques were studied using drip irrigation in an arid region of Saudi Arabia in 2014 and 2015. Five irrigation treatments, i.e., FI (control treatment where the full amount of irrigation water was applied to both sides of the plant), DI70, DI50 (70% and 50% of the FI treatment, respectively, supplied to both sides of the plant), PRD70, and PRD50 (70% and 50% of the FI treatment, respectively, supplied to a single side of each plant in an alternating manner), were applied. The dry and wet sides of the plant in the PRD treatments were switched weekly. The soil water content was the highest in the FI treatment followed by DI70 and PRD70 and DI50 and PRD50 thereafter in 2014 and 2015. The fresh weight of the vegetative parts for both the FI and PRD70 treatments (average of 14.7 Mg ha^{-1} and 11.9 Mg ha^{-1}, respectively) was significantly ($p < 0.05$) higher than that of the other irrigation treatments. The FI and PRD70 treatments increased ($p < 0.05$) the dry weight of the vegetative parts by approximately 48.3%–57.7% relative to the other treatments in 2014. The highest number of branches per plant occurred in the PRD treatments, and the lowest number was in the DI70 treatment. The DI and PRD treatments decreased ($p < 0.01$) the fresh and dry tuber yield compared to FI. The FI produced the highest number of tubers per plant. The DI treatments did not have a significantly lower irrigation water use efficiency (IWUE) compared to FI in 2014, whereas PRD had significantly ($p < 0.01$) lower IWUE than FI in both years.

1. Introduction

Potato (*Solanum tuberosum* L.) is one of the most important crops in the world in terms of its use as a food for people and in the starch industry (Fabeiro et al., 2001). Potato production ranks fourth in the world after rice, wheat and maize and is expected to continue to increase, providing an important source of food, nutrition and income (Bowen, 2003). Due to its sparse and shallow root system, potato is highly sensitive to drought stress (Jefferies, 1993), and tuber yield may be considerably reduced by soil moisture deficits (Porter et al., 1999).

In areas with water scarcity, such as Saudi Arabia, irrigation is necessary for successful agricultural production. The increasing shortage of water resources requires the optimization of irrigation management in order to increase crop productivity and improve the irrigation water use efficiency (IWUE). Innovations are needed to increase IWUE.

Many crop irrigation investigations have been conducted to maximize performance, efficiency and profitability. Deficit irrigation (DI) and partial root-zone drying irrigation (PRD) are water-saving irrigation methods that decrease the amount of water that is used compared to the full irrigation (FI).

DI is a strategy where crops are irrigated with lower amounts of water and the minor stress that develops has minimal effects on the yield (English and Raja, 1996). In this mode of irrigation, the entire root-zone is irrigated at less than the maximum rate of crop evapotranspiration. Knowing when to apply water is necessary for the successful implementation of DI because the sensitivity of the crop to water stress is different at different growth stages (Andersen et al., 2002; Kirda, 2002; Liu et al., 2004). DI was developed to improve the control of vegetative vigor in order to optimize fruit size, fruitfulness and fruit quality. DI is usually applied during the period of slow fruit growth when shoot growth is rapid. DI can generate considerable water savings. Thus, DI can be useful for reducing excessive vegetative vigor, and for minimizing irrigation and nutrient loss through leaching (Chaves et al., 2007, 2010; Santos et al., 2007). Shock and Feibert (2002) found

* Corresponding author at: Agricultural Engineering Department, College of Food and Agriculture Sciences, King Saud University, P.O. Box 2460, Riyadh 11451, Saudi Arabia.
E-mail addresses: mmattar@ksu.edu.sa, dr.mohamedmattar@gmail.com (M.A. Mattar).

http://dx.doi.org/10.1016/j.scienta.2017.07.044
Received 18 April 2017; Received in revised form 24 July 2017; Accepted 25 July 2017
0304-4238/

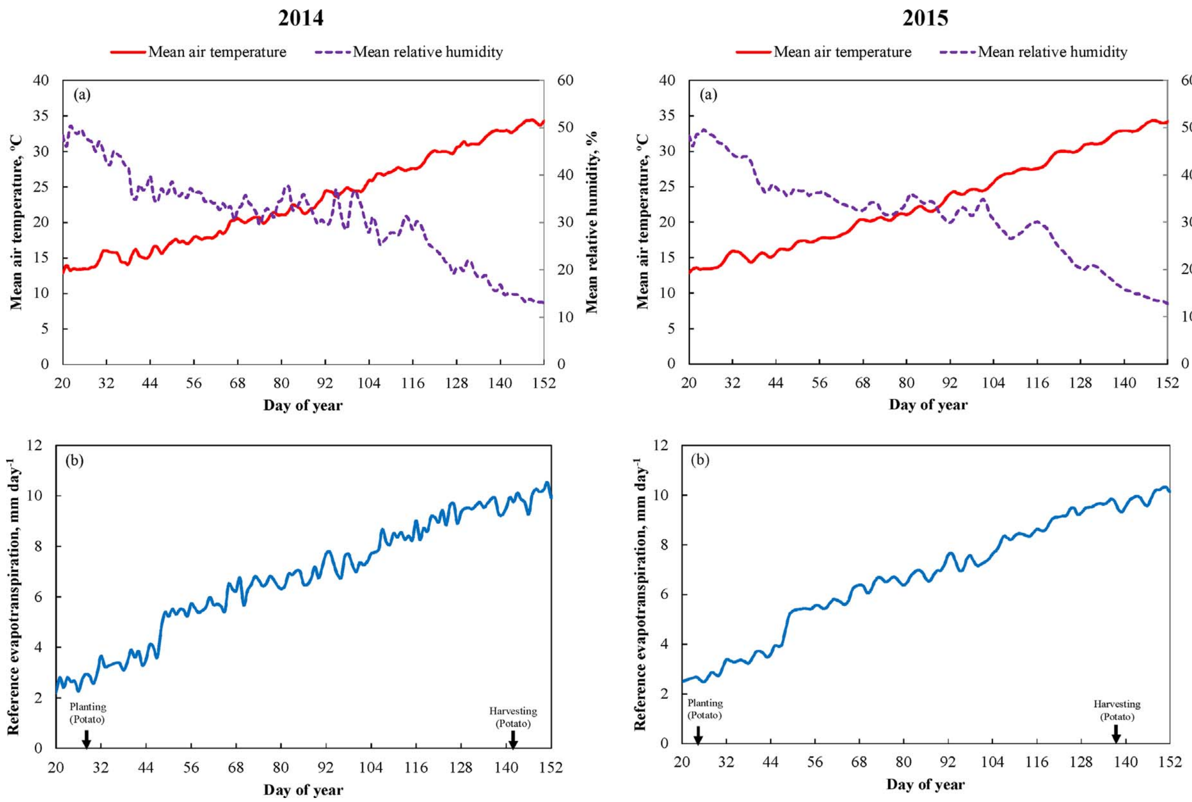

Fig. 1. Meteorological variables of (a) mean air temperature and mean relative humidity, and (b) reference evapotranspiration during the 2014 and 2015 experimental periods.

that DI was not useful for sprinkler-irrigated potato in a semi-arid environment.

PRD is a new innovation in DI and is commonly applied as part of a DI strategy because it does not require the application of more than 50%–70% of the water used in a fully irrigated strategy. PRD is a system of alternating irrigation in space and time to generate wet/dry cycles in different sections of the root system. This system seeks to promote chemical signals from roots in dry soil, thereby reducing stomatal conductance and transpiration and shoot growth while maintaining the water supply from the roots in the wet soil fraction, thereby avoiding a severe water deficit (Davies et al., 2002; Morison et al., 2008). The wetting and drying of each side of the roots is dependent on the crop, growth stage, evaporative demands, soil texture and the soil water balance (Saeed et al., 2008).

DI and PRD irrigation have been tested in several field crops and fruit trees across the globe, such as bean (Samadi and Sepaskhah, 1984); sugar beet (Sepaskhah and Kamgar-Haghighi, 1997); grapes (Kriedmann and Goodwin, 2003); maize (Kang and Zhang, 2004); green bean (Gencoglan et al., 2006); apple (Leib et al., 2006); peach (Gong et al., 2005); potato (Shayannejad, 2009; Ahmadi et al., 2010a,b); and tomato (Wang et al., 2013).

PRD has improved yield per unit of applied water with respect to conventional irrigation using FI (Kirda et al., 2007; Morison et al., 2008). PRD has been shown to be successful in grapevines (Stoll et al., 2000) and in fruit trees (Kang et al., 2002) and is also said to be promising for field crops (Kang et al., 1998, 2000a,b; Kirda et al., 2005) and vegetables (Dorji et al., 2005; Zegbe-Domínguez et al., 2006). However, Wakrim et al. (2005) reported no significant difference between IWUE of bean in PRD and DI, but these irrigation strategies did result in a substantial increase in IWUE compared to FI. There is evidence that PRD is able to save water with little or no effect on yield when compared with FI plants (Davies et al., 2002; Kang and Zhang, 2004). PRD irrigation has since been found to increase IWUE in a variety of crops (e.g., sunflower, maize) by reducing evaporative losses during periods of limited soil moisture availability or high evaporative potential (Kang et al., 2000a,b; Loveys et al., 1997, 1998).

Shahnazari et al. (2007) showed that DI and PRD produced potato yields in Denmark that were similar to FI and increased IWUE by 60%, as approximately applied 30% of the irrigation water was saved. Liu et al. (2006b) found that PRD did not improve the yield and IWUE in potatoes compared to DI in Denmark. Saeed et al. (2005) showed that PRD could also modify shoot growth and increase IWUE in potatoes grown in United Kingdom. Ahmadi et al. (2010a) showed that DI and PRD did not have significant effects on the fresh yield and IWUE of potatoes grown in Iran compared to FI. Yactayo et al. (2013) in Peru found that early use of PRD in potatoes, initiated 6 weeks after planting with a watering level equivalent to 50% of full irrigation, increased IWUE with no yield reduction relative to full irrigation. The objective of our experiment was to compare the responses of potato to DI and PRD irrigation and FI under a surface drip irrigation system by assessing the effect of DI and PRD irrigation on the soil water status, yield, and IWUE of potato in arid climatic conditions.

2. Materials and methods

2.1. Experiment location and climate conditions

The field experiment was conducted over two consecutive years (2014–2015) from January to May in the northwestern section of Riyadh, Saudi Arabia. The site is located at 24°44′11.10″ N and 46°37′06.61″ E at an elevation of approximately 665 m above sea level. A Rain Bird® WS-PROLT meteorological station collected and stored weather data from experimental field according to the specifications of the World Meteorological Organization. This station measured air temperature, solar radiation, relative humidity, wind speed, wind direction and rainfall. Daily climatic data was used to calculate daily reference evapotranspiration (ET_o) using the Penman-Monteith equation (Allen et al., 1998).

The daily crop evapotranspiration (ET_c) was estimated using crop coefficients (K_c) with values of 0.5, 1.15 and 0.75 during initial, midseason and late season stage, respectively (Doorenbos and Pruitt, 1977):

$$ET_c = K_c.\ ET_o \quad (1)$$

The seasonal variation in the climate variables measured throughout the growing season is illustrated in Fig. 1. In addition to the measured rainfall, the ET_o is shown. Mean air temperature varied between 16.2 °C and 34.3 °C. Mean daily relative humidly ranged between 13.2 and 38.6%. The ET_o varied between 4.7 and 11.1 mm day^{-1} during the growing season.

2.2. Preliminary field preparation and growth conditions

The experimental field was planted with potatoes by hand. Before planting, the seed potatoes (*Solanum tuberosum* L.) were exposed to temperatures of 12–14 °C with a constant dim overhead lighting for sprouting. During planting, only one sprout from each potato was retained. The seed tubers were planted with a spacing of 50 cm between rows and 50 cm between plants. The soil was ridged to 15 cm above the tubers in prepared furrows. The height of the ridge from the top of the ridge to the bottom of the furrows was approximately 30 cm. All of the treatment plots received the same amount of total fertilizer appropriate for potato. Fertilizers were added through drip irrigation system five consecutive days per week. The fertigation programme was as follows: a) From 2nd to 5th weeks of the plant growth stage at rates of 180 kg ha^{-1} N-P_2O_5-K_2O (20-20-20),150 kg ha^{-1} N-P_2O_5-K_2O (10-10-43), 50 L ha^{-1} H_3PO_4, 20 kg CaO, 4.5 kg ha^{-1} micro elements; b) From 6th to 9th weeks at rates of 250 kg ha^{-1} N-P_2O_5-K_2O (20-20-20), 250 kg ha^{-1} N-P_2O_5-K_2O (10-10-43), 40 L ha^{-1} H_3PO_4, 40 kg CaO, 5 kg ha^{-1} micro elements; c) From 10th to 12th weeks at rates of 270 kg ha^{-1} N-P_2O_5-K_2O (20-20-20), 200 kg ha^{-1} N-P_2O_5-K_2O (10-10-43), 30 L ha^{-1} H_3PO_4, 20 kg CaO, 2.5 kg ha^{-1} micro elements.

2.3. Soil analysis

Soil samples were taken every 20 cm up to total depth of 60 cm for physical analysis, to get information on the soil texture, field capacity (FC), wilting point (WP), saturated hydraulic conductivity (Ks), saturation moisture content (S), and bulk density (ρ_b) (Table 1).

2.4. Experiment design and irrigation treatments

An area of 675 m^2 (45 m × 15 m) was used for the experiments, which included five treatments with three replications of each treatment. The area was divided into three replicates that were separated by 3-m buffer zones. Each replicate had an area of 195 m^2 (13 m × 15 m). Surface drip was installed to the established fields. Each field was divided into 5 plots which were bordered by a 1.2 m wide buffer zone for the potatoes. The experiment was designed as a randomized complete block (RCB) with three replications and consisted of five irrigation treatments. Full irrigation (FI), irrigated with 100% of the ET_c. Two treatments were established for the deficit irrigation (DI), DI70 and DI50, which used 70% and 50% of the irrigation water volume of the FI, respectively. Two other treatments were established for the partial root-zone dry irrigation (PRD), PRD70 and PRD50, which used 70% and 50% of the irrigation water volume of FI, respectively. The watering in the PRD method was shifted every 7 days from one side of the plants to the other (Liu et al., 2006a). At 30 days after planting (DAP), the DI70, DI50, PRD70, and PRD50 treatments were initiated.

Irrigation water was supplied through the control head of a water tank with a capacity of 8 m^3. This tank consisted of a pump unit, pressure regulator, filtration system, fertigation unit, air vent, main manual and electrical valves and flow sensors. The drip lines were installed in the field according to the treatment distribution. The drip lines consisted of 26 built-in GR emitters with a discharge of 8 L h^{-1} at an operating pressure of 100 kPa with a spacing of 50 cm between the emitters. Lateral drips were placed at the centers of adjacent crop rows in the experimental plots for both the FI and DI treatments. However, for the PRD irrigation there were two lateral lines placed in each row of potatoes separated by a distance of 0.4 m.

2.5. Measurement of soil water content

Once the experiment began, the volumetric soil water content (θ_v) was measured daily to a depth of 0.5 m at 0.1 m intervals in each of the irrigation treatments using multi-sensor capacitance probes (EnviroSCAN). The EnviroSCAN device is a complete soil-moisture monitoring system (model EnviroSCAN®, Sentek Sensor Technologies, Stepney, South Australia, Australia) that continuously monitors the θ_v over several depths in the root zone.

For the three treatments with a single drip line (Fl, DI70, and DI50) 9 EnviroSCAN devices ($3_{treatments} \times 3_{devices}$) were used. In addition, the two treatments with two lines each (PRD70 and PRD50) required 12 EnviroSCAN devices ($2_{treatments} \times 6_{devices}$). Therefore, a total of 21 EnviroSCAN devices were installed in the field. The two access tubes per PRD treatment per crop were laid 40 cm apart in a diagonal direction.

2.6. Measurement of vegetative growth traits

At 76 DAP (May 4) and 73 DAP (May 1) during 2014 and 2015, respectively, plants were harvested from the center of each plot to determination the fresh weight of the vegetative parts (both leaf and stem), the vegetative parts dry weight, number of branches, and leaf area index (LAI). Three plants per plot (do not interfere with the harvest in Section 2.7) were randomly chosen from the three central rows within the plot. The vegetative parts (leaf and stem) were placed in paper bags and labeled. The leaf and stem dry weight was then determined by drying the parts at 60 °C for 48 h (Shao et al., 2008; Ahmadi et al., 2014; Ramírez et al., 2014) using a forced-air oven. LAI was measured with a leaf area meter (Licor 3100, Licor Inc., Nebraska, USA).

2.7. Measurement of yield, yield components, irrigation water use efficiency, and tuber size

At the time of harvest, on May 21 in 2014 and May 18 in 2015, the total fresh tuber yields (Mg ha^{-1}); tuber weight (g plant^{-1}) and number of tubers per plant were determined by the plants harvested (75 plants) from the three central rows of the plots. The potato tubers dry

Table 1
Physical properties of soil used in the experiment.

Depth (cm)	Particle size (%)			Texture	FC (%)	WP (%)	Ks (mm/h)	S (%)	ρ_b, (g cm^{-3})
	Sand	Silt	Clay						
0–20	71.8	16.3	11.9	sandy loam	14.2	6.0	37.8	22.3	1.6
20–40	66.7	18.0	15.3	sandy loam	17.1	8.1	24.6	26.2	1.6
40–60	69.1	18.3	12.6	sandy loam	18.5	9.9	19.6	26.7	1.6

FC: field capacity; WP: wilting point; Ks: saturated hydraulic conductivity; S: saturation moisture content; ρ_b: bulk density.

weight (Mg ha^{-1}) was determined after oven drying for 24 h at 85 °C (Liu et al., 2006b; Ahmadi et al., 2014). Therefore, the yield components included the tuber fresh weight per plant and the number of tubers per plant. Irrigation water use efficiency (IWUE, kg m^{-3}) was used to evaluate comparative benefits of the irrigation treatments. IWUE of each irrigation treatment was calculated as dividing the total fresh tuber weight (kg ha^{-1}) at harvest by the amount of water applied (m^3 ha^{-1}) to the crop (supplemental irrigation plus rainfall) (Kirda et al., 2005).

Harvested potato tubers were graded into three categories according to their diameter: category C1 for those below 50 mm; C2 for those between 50 and 80 mm; and C3 for those above 80 mm. The tuber size category C2 was considered marketable tubers (Shahnazari et al., 2007).

2.8. Data analysis and statistics

Statistical analyses were performed by ANOVA following a RCB design with three replicates of each treatment using CoStat (Version 6.303, CoHort, USA, 1998–2004). RCB design was used to assess the statistical significance of the treatment differences observed in the measured parameters. The data were presented as the mean of three replicates ± standard error (SE). Least significant differences (LSD) tests at $p \leq 0.05$ were applied to compare treatment means of the measured parameters.

3. Results

3.1. Soil water status

Fig. 2 shows the θ_v data for the different patterns of distribution in response to the different irrigation treatments in 2014 and 2015. The θ_v values during the initial stage (until 30 DAP) were similar to each other in 2014 and 2015. The θ_v values at depths of 0.1, 0.2, 0.3, 0.4, and 0.5 m were either above or near the FC (not shown). After starting the irrigation treatments at 31 DAP, the level of θ_v was the highest in the FI treatment followed by the DI70 and PRD70 treatments and later by DI50 and PRD50 treatments in 2014 and 2015. The relative increase of θ_v for FI that was observed after 52 DAP was the result of tuber initiation. The value of θ_v for the PRD treatments depended on the wetting and drying cycle. In the third cycle in PRD70 (for example), the value of θ_v on the left (wet) side of the root-zone was, on average, 17.3%, whereas 15.8% was recorded for the right (dry) side in 2014. In 2015, the value of θ_v on the wet side of the root-zone was 17.4%, whereas 15.9% was recorded for the dry side. The corresponding values in the PRD50 treatment were 14.1% and 13.6% for the wet and dry sides of the root-zone, respectively, in 2014; whereas in 2015, the values of θ_v were 14.3% and 13.4%. The differences in θ_v between the different sides in the PRD treatments (left and right/wet and dry) were significant during the entire experiment, except for the period of 100–116 DAP when the differences were smaller. θ_v values in the irrigation treatments decreased at the beginning of the leaf yellowing stage, in addition to the increased evaporative demand due to the rising temperature at this stage.

3.2. Vegetative growth

The DI and PRD treatments decreased the fresh vegetative parts of the potato in the 2014 and 2015 experimental periods, except in the PRD70 treatment in 2014 (Table 2). The fresh vegetative parts for the DI70, DI50, and PRD50 treatments were decreased by 35.9%, 25.8% and 38.4% compared to FI in 2014, respectively. In 2015, the DI70, DI50, PRD70, and PRD50 treatments showed decreases of 40.2%, 42.8%, 35.6%, and 50%, respectively, compared to FI. Water-saving irrigation treatments significantly decreased the fresh vegetative parts (Table 2) in both years. Significant decreases in the fresh vegetative

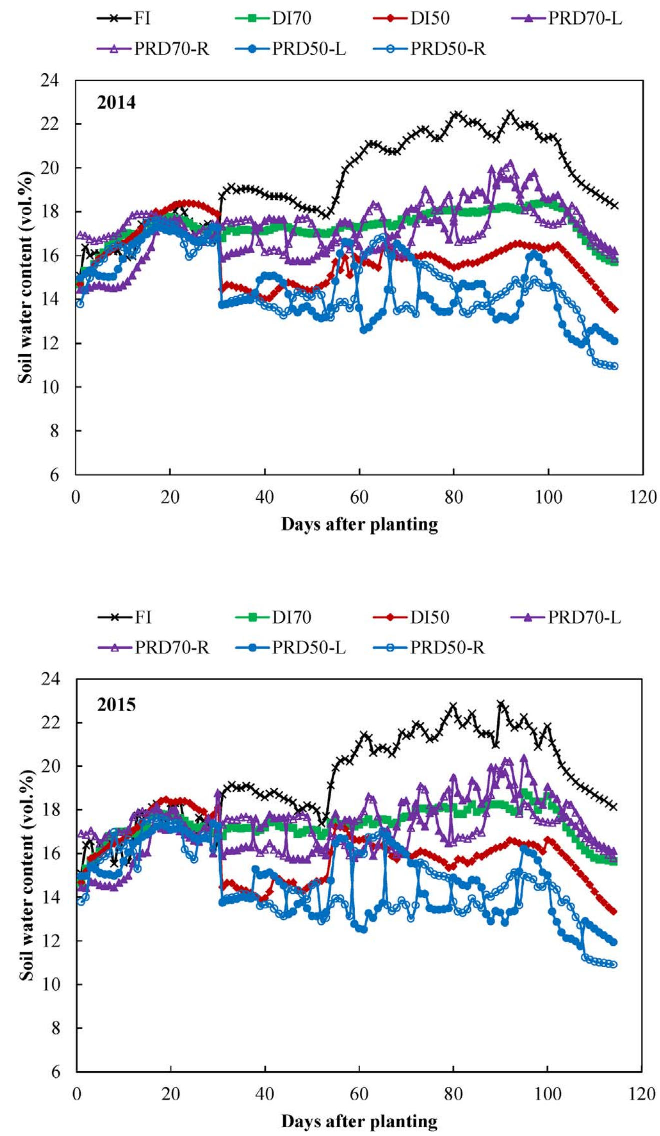

Fig. 2. Daily average volumetric soil water content (%) for full irrigation (FI), partial root-zone drying (PRD), and deficit irrigation (DI) treatments of potato during the 2014 and 2015 where PRD-L and PRD-R denote the left and right sides of the PRD treated plant, respectively. Data are the means of the three replicates.

parts observed under the PRD50 treatment were consistent with the commonly known adverse effects of water stress on plant development.

The dry weight of the vegetative parts were significantly ($p < 0.05$) different between the irrigation treatments in 2014, while they were not significantly different in 2015 (Table 2). The FI and PRD70 treatments in 2014 produced the highest weight of the dry vegetative parts compared to the other irrigation treatments. Among the DI and PRD treatments, the dry vegetative parts in the PRD50 treatment (0.99 Mg ha^{-1}) in 2014, were the lowest and were followed by DI50 (1.03 Mg ha^{-1}).

The number of branches per plant was not statistically different ($p > 0.05$) (Table 2) between treatments both years. LAI of the DI and PRD treatments in 2014 was significantly ($p < 0.01$) less (11.1%–26.6%) than that of FI as shown in the ANOVA (Table 2). In 2015, there were no significant differences between LAI of potato under FI, DI and PRD treatments.

3.3. Tuber yields, and yield components

The fresh tuber yields were significantly ($p < 0.01$) different

Table 2
Vegetative growth parameters of potato for the different irrigation treatments in the 2014 and 2015 experimental periods.

Year	Treatments	Vegetative parts FW (Mg ha^{-1})	Vegetative parts DW (Mg ha^{-1})	Number of branches ($plant^{-1}$)	LAI
2014	FI	13.25 (± 0.38) ab	1.56 (± 0.11) a	6 (± 0.88)	3.48 (± 0.03) a
	DI70	8.50 (± 0.76) c	1.04 (± 0.16) b	4 (± 1.00)	3.09 (± 0.06) b
	DI50	9.83 (± 1.39) bc	1.03 (± 0.21) b	6 (± 1.53)	2.93 (± 0.10) b
	PRD70	13.50 (± 1.76) a	1.54 (± 0.16) a	9 (± 1.76)	2.92 (± 0.12) b
	PRD50	8.17 (± 0.73) c	0.99 (± 0.10) b	8 (± 1.15)	2.55 (± 0.05) c
	p-value	0.02	0.05	0.24	< 0.01
	LSD 0.05	2.80	0.49	–	0.26
2015	FI	16.14 (± 0.70) a	1.91 (± 0.13)	5 (± 0.93)	3.68 (± 0.09)
	DI70	9.65 (± 1.28) b	1.09 (± 0.15)	5 (± 0.90)	3.18 (± 0.25)
	DI50	9.23 (± 2.04) b	1.20 (± 0.35)	5 (± 0.33)	3.23 (± 0.36)
	PRD70	10.24 (± 0.53) b	1.29 (± 0.19)	7 (± 1.00)	2.82 (± 0.00)
	PRD50	8.07 (± 1.27) b	0.90 (± 0.21)	8 (± 1.32)	2.64 (± 0.16)
	p-value	0.02	0.07	0.15	0.07
	LSD 0.05	4.31	–	–	–

The data represent the means ± SE of the mean (n = 3).
Within each year, mean values in columns followed with different letters are significantly different based on LSD test at $p < 0.05$.
FW: fresh weight; DW: dry weight; LAI: leaf area index.

Table 3
Yield and yield components of potato for the different irrigation treatments in the 2014 and 2015 experimental periods.

Year	Treatments	Tuber FW (Mg ha^{-1})	Tuber DW (Mg ha^{-1})	Tuber FW per plant (g $plant^{-1}$)	Number of tubers ($plant^{-1}$)
2014	FI	31.77 (± 1.63) a	6.42 (± 0.16) a	887 (± 70) a	12 (± 1.00)
	DI70	17.96 (± 0.81) b	3.43 (± 0.21) b	562 (± 897) b	9 (± 0.58)
	DI50	13.34 (± 0.43) cd	2.65 (± 0.08) cd	5137 (± 637) b	10 (± 0.88)
	PRD70	14.86 (± 1.13) bc	2.93 (± 0.20) bc	640 (± 1677) ab	11 (± 2.33)
	PRD50	10.07 (± 0.63) d	2.16 (± 0.16) d	365 (± 747) b	9 (± 1.00)
	p-value	< 0.01	< 0.01	0.04	0.58
	LSD 0.05	3.67	0.55	315	–
2015	FI	35.91 (± 3.14) a	6.71 (± 1.23) a	820 (± 53)	11 (± 0.61)
	DI70	24.81 (± 1.12) b	3.97 (± 0.22) b	673 (± 225)	9 (± 2.38)
	DI50	20.10 (± 1.28) bc	2.80 (± 0.33) b	593 (± 55)	10 (± 0.35)
	PRD70	18.97 (± 0.69) c	3.55 (± 0.23) b	600 (± 92)	10 (± 1.86)
	PRD50	10.05 (± 1.20) d	2.20 (± 0.20) b	375 (± 60)	8 (± 1.00)
	p-value	< 0.01	< 0.01	0.21	0.77
	LSD 0.05	5.60	1.93	–	–

Data represent the means ± SE of the mean (n = 3).
Within each year, mean values in columns followed with different letters are significantly different based on LSD test at $p < 0.05$.
FW: fresh weight; DW: dry weight.

between the irrigation treatments in 2014 and 2015 (Table 3). The FI treatment had higher fresh tuber yields 31.77 Mg ha^{-1} and 35.91 Mg ha^{-1} in 2014 and 2015, respectively. The PRD treatments decreased the fresh yield relative to FI and DI. The PRD70 and PRD50 treatments decreased yields by 53.2% and 65.2%, respectively, compared with FI plants in 2014. In 2015, the fresh tuber yields from the PRD70 and PRD50 treatments were decreased by 47.2% and 72%, respectively. Compared with DI70, the fresh tuber yield for PRD70 decreased by 17.3% and 23.5% in 2014 and 2015, respectively. The fresh tuber yield for PRD50 were decreased 17% and 50%, compared to the DI50 treatment in 2014 and 2015, respectively.

The same trends were also found for dry tuber yields because all of the PRD and DI treatments caused a significant ($p < 0.01$) decrease, between 46.6% and 66.3%, compared to the FI treatment in 2014, and a reduction in dry tuber yields of 40.9%–67.2% was also observed in the water-saving treatments compared to the FI in 2015 as shown in Table 3. The tuber dry weights in the PRD treatments (PRD70 and PRD50) were substantially and significantly lower than in the FI and DI treatments (DI70 and DI50). The PRD50 treatment had the lowest dry tuber yield of 2.16 Mg ha^{-1} and 2.20 Mg ha^{-1} in 2014 and 2015, respectively. It is noteworthy that the moisture content of the tubers was different among the irrigation treatments. Although PRD70 and PRD50 produced the lowest amount of fresh tuber yield, they had the highest tuber moisture content (79.3% and 78%, respectively, in 2015) compared with the DI70 and DI50 treatments, which had tuber moisture contents of 73.2% and 76.8%, respectively.

The fresh tuber yield per plant for the DI and PRD treatments in 2014 were significantly ($p < 0.05$) less than that in the FI treatment. Among the water-saving treatments, the fresh tuber yield per plant in the PRD70 treatment in 2014 was the highest (640 g $plant^{-1}$). The fresh tuber yield per plant for the irrigation treatments in 2015 were not significant different ($p > 0.05$). In addition FI, PRD, and DI treated plants showed no significant differences ($p > 0.05$) in the number of tubers per plant either year.

3.4. *Irrigation water use efficiency*

For the entire 2014 growing season, the FI treatment was irrigated with 1505 mm. The DI70 and DI50 treatments were irrigated with 1049 mm and 812 mm, respectively. The PRD70 and PRD50 treatments received 1062 and 820 mm, respectively. In 2015, FI, DI70, DI50, PRD70, and PRD50 received 1495, 1070, 797, 1075, and 783 mm, respectively. The differences in the irrigation water use efficiency (IWUE) between the irrigation treatments were significant ($p < 0.01$), as shown in Fig. 3. Both the PRD70 and PRD50 treatments in 2014 caused a significant reduction in IWUE of 33.8% and 36.1%, respectively, compared to FI, whereas in 2015, there was a reduction in IWUE of 26.6% and 46.6%, respectively. In 2014, DI70 and DI50 decreased the

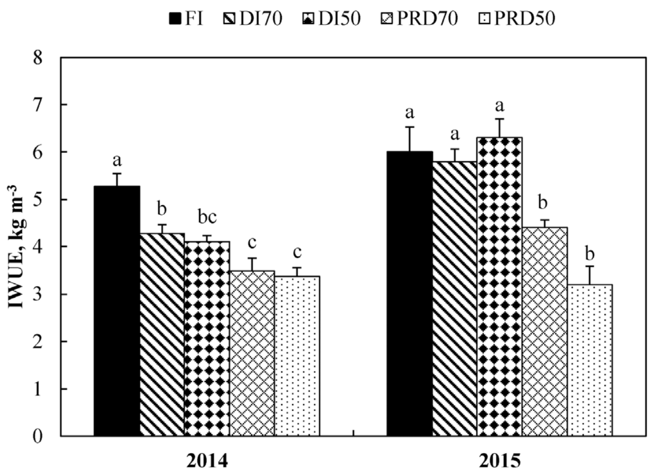

Fig. 3. Irrigation water use efficiency (IWUE) for the different irrigation treatments in the 2014 and 2015. Within each year, different letters on top of the columns indicate significant differences between irrigation treatments based on LSD (0.05). Bars give the means ± standard error of the mean (n = 3).

IWUE by 18.94% and 22.19%, respectively, compared to FI. On the contrary, the DI treatments were similar (not significant) to the FI treatment in 2015. Comparing the DI treatments with the PRD treatments, the DI70 (4.28 kg m^{-3}) and DI50 (4.11 kg m^{-3}) treatments had higher IWUE than PRD70 (3.50 kg m^{-3}) and PRD50 (3.37 kg m^{-3}) in 2014. In 2015, the DI70 (5.80 Mg m^{-3}) and DI50 (6.30 kg m^{-3}) treatments had higher IWUE than PRD70 (4.41 kg m^{-3}) and PRD50 (3.21 kg m^{-3}).

3.5. Tuber grade

At the final harvest, the tubers from each treatment were classified into three size categories: C1–C3 (Fig. 4). Differences between the number of tubers under the various irrigation treatments were not observed for the C1 class (< 50 mm) and the C2 class (marketable size, 50–80 mm), significant ($p > 0.05$).

For the C3 class (> 80 mm), the number of tubers in the PRD treatments (PRD70 and PRD50) was the lowest. A significantly higher number of tubers (134,564 tuber ha^{-1}) was observed under the FI treatment. Under the water-saving treatments, the DI50 treatment produced 51%, 72.8%, and 136.9% more tubers than did DI70, PRD70, and PRD50 treatments, respectively.

4. Discussion

In this study, the value of θ_v for the FI treatment was the highest due to the different amounts of water applied to each treatment. Although the θ_v of the wetted side in the PRD treatments was higher than that of the drying side, as a result of irrigation, the θ_v was found to be relatively constant or to have increased slightly for several days after irrigation in the non-irrigated side. This phenomenon may be caused by lateral infiltration or the redistribution of water through the root systems (Du et al., 2008). The un-watered side of the root-zone in the PRD70 and PRD50 treatments, and the bottom layer of the soil in the DI70 and DI50 treatments showed a reduction in θ_v relative to FI (were much higher than WP), but there was still enough water available in the wetted side of the root-zone and the top layer to supply sufficient water to the aerial parts of the plant to maintain plant growth, although at a lower rate compared to the FI treatment.

The fresh vegetative parts of the potato for the DI70, DI50, PRD70, and PRD50 treatments were significantly less than that of FI. This reduction was consistent with the commonly known adverse effects of water stress on potato plant development. Many studies have reported a reduction in fresh vegetative parts under DI and PRD (Gowing et al., 1990; Dry and Loveys, 1998; Shao et al., 2008). The dry weight of the vegetative parts for the FI and PRD70 was the highest. This result is similar to those reported by Ahmadi et al. (2014). Among the DI and PRD treatments, the dry vegetative parts in the PRD50 and DI50 treatments were the lowest. Probably, the soil water depletion in the soil-root contact area, which was very much reduced in the DI50 and PRD50 treatments, acted as the limiting factor to the vegetative growth in these treatments. The DI and PRD treatments had decreased LAI relative to the other irrigation treatments. This is in agreement with previous observations that concluded that LAI is significantly inhibited in potatoes under DI and PRD irrigation (Jefferies and Mackerron, 1989; Gautier et al., 2001; Liu et al., 2006b; Ahmadi et al., 2010a).

The FI treatment produced the highest fresh tuber yields;equivalent to typical commercial potato yields (Shae et al., 1999; Darwish et al.,

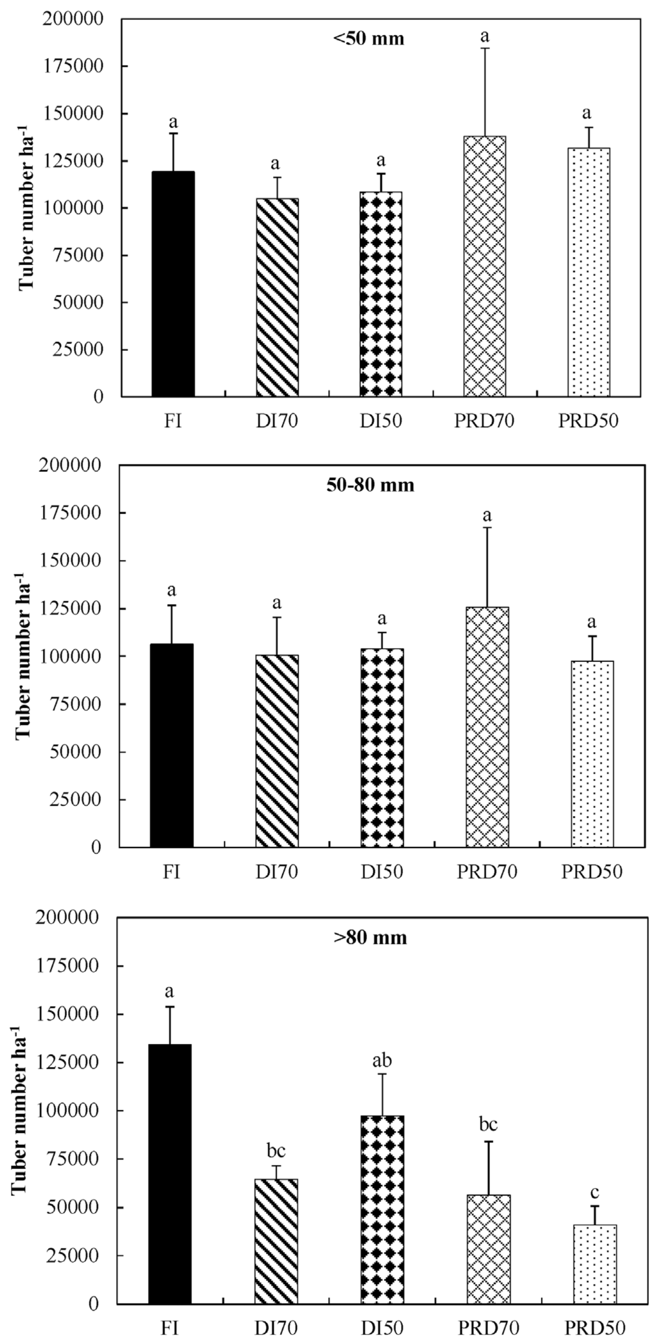

Fig. 4. Distribution of tuber grade for the different irrigation treatments in 2015. Bars give the means ± standard error of the mean (n = 3).

2006; Ahmadi et al., 2010a). The PRD treatments decreased the fresh yield relative to FI and DI. These results are, however, in agreement with the results of Liu et al. (2006b), Brocic et al. (2009), and Ahmadi et al. (2014), but contradict the results of Shahnazari et al. (2007, 2008), Saeed et al. (2008), and Ahmadi et al. (2010a), who found that PRD did not significantly decrease the fresh tuber yield compared to FI. The differences in the previous literature may be due to climate, water supply and growth stage soil texture (Bowen, 2003; Saeed et al., 2008; Ahmadi et al., 2010a). In our study, the reason for the low productivity under DI and PRD could be attributed to the climate, where the high air temperatures may have affected the drought sensitive potato. Another reason for this could be that potato is shallow rooted crop, and therefore the differences in θ_v in the 10–30 cm of the top soil layer in the water-saving (DI and PRD) treatments were great. In contrast, the θ_v in the deeper soil layers (30–50 cm) may not vary considerably because of the low density of plant roots at depth in the water-saving treatments (Ahmadi et al., 2010a; Kaman et al., 2011), and it is probable that the dense layer of roots in the top soil layer absorbs the water before it is able to infiltrate to deeper layers (Wang et al., 2009). Consistent with findings by Gautier et al. (2001), the reduced LAI and vegetative growth (Table 2) observed in this work suggest that photosynthesis assimilates were predominantly partitioned to tuber growth such that significant yield reduction was prevented under the water-saving treatments.

The PRD and DI treatments decreased dry tuber yields, compared to the FI treatment. Our findings were in agreement with the results reported by Ahmadi et al. (2014) on potato and Shao et al. (2008) on pepper. The PRD treatments had the highest tuber moisture content. This may be due to the fact that the wet side of the root system in the PRD strategy receives more water than DI in each irrigation event, and the roots on the irrigated side in the PRD treatments absorb more water to maintain a higher crop water balance (Sepaskhah and Ahmadi, 2010; Liu et al., 2006a).

The lowest IWUE was obtained in the PRD treatments. This result is consistent with results of Ahmadi et al. (2014), who reported that the PRD treatments showed significantly lower IWUE values, as they decreased the IWUE by 31% to 41%, relative to FI. The DI treatments had higher IWUE than PRD treatments. Similar results were reported by Liu et al. (2006b) and Ahmadi et al. (2014) for potatoes, and Wakrim et al. (2005) and Kirda et al. (2005) showed that DI had higher IWUE values than PRD in bean and maize, respectively. Inconsistent with our study, Shahnazari et al. (2007), Ahmadi et al. (2010a), and Jovanovic et al. (2010) reported that PRD had higher IWUE values in potatoes than DI. It is likely that the differences between the IWUE values reported in these previous studies could be due to the experimental set up, crop variety, soil textures, climatic demands, soil water balance, and root distribution (De la Hera et al., 2007; Ahmadi et al., 2010a; Ahmadi et al., 2014).

As shown above, PRD might not be a successful water-saving irrigation strategy in this arid region. The current results contradict the general idea that maintaining yield and improving IWUE are often the advantages of PRD over FI and DI (Kriedmann and Goodwin, 2003). Potato plants subjected to PRD, with reduced water compared to FI, are exposed to an elevated level of water stress because of both the reduction in water and the dry roots in the non-watered side where air temperature is high and soil evaporation constitutes nearly 30% of the total crop evapotranspiration. The crops in DI are only exposed to water stress due to a reduction in water. The duration of the wet/dry cycle under field conditions is a function of soil type, climate and cultivar, and it influences the intensity of the PRD response (De la Hera et al., 2007; Ahmadi et al., 2010a; Yactayo et al., 2013). Sepaskhah and Parand (2006) reported that PRD could be a successful irrigation strategy in this arid and semi-arid region provided that the duration of the wet/dry cycling in PRD is decreased such that the crops are not exposed to extreme and severe water stress. This argument might be valid in our study where the PRD treatments received only part of the water that was supplied in the FI treatment throughout the growing season, which may have had a very adverse effect on potato yields and IWUE.

For the C3 tuber size class, the number of potato tubers was highest in the FI treatment consistent with the findings of Ahmadi et al. (2014) who showed that PRD treatments under-produced tuber numbers compared to FI and DI treatments. In contrast Shahnazari et al. (2007) reported that PRD produced higher tuber numbers than FI.

5. Conclusions

Field grown potatoes were cultivated under three different irrigation techniques: full (FI), deficit (DI), and partial root-zone drying (PRD) irrigations. DI received 70% and 50% of FI, and the same was true for PRD. Our results clearly demonstrated that the soil water contents under FI were the highest, followed by DI70 and PRD70. The fresh and dry vegetative parts under both FI and PRD70 treatments were similar and were significantly greater than the other irrigation treatments. Although there were not significant differences between the number of branches per plant among the irrigation treatments, the leaf area index of the treated plants was significantly different among the treatments. There was a significant effect of the irrigation treatments on the fresh and dry tuber yields. The FI treatment recorded the highest fresh and dry tuber yields compared to the other treatments. The FI plants produced the highest irrigation water use efficiency (IWUE), and DI70 and DI50 plants produced significantly higher IWUE than PRD70 and PRD50. These potatoes water-saving techniques are not recommended. Therefore, the strong effect of PRD might be due to the decreased duration of the wet/dry cycling, which could help to achieve a successful PRD technique in this arid region. Future studies should be undertaken to test the agronomy parameters and yield components of potato plants with different wet/dry cycle and soil varieties.

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).

References

Ahmadi, S.H., Andersen, M.N., Plauborg, F., Poulsen, R.T., Jensen, C.R., Sepaskhah, A.R., Hansen, S., 2010a. Effects of irrigation strategies and soils on field grown potatoes: yield and water productivity. Agric. Water Manag. 97, 1923–1930.

Ahmadi, S.H., Andersen, M.N., Plauborg, F., Poulsen, R.T., Jensen, C.R., Sepaskhah, A.R., Hansen, S., 2010b. Effects of irrigation strategies and soils on field grown potatoes: gas exchange and xylem [ABA]. Agric. Water Manag. 97, 1486–1494.

Ahmadi, S.H., Agharezaee, M., Kamgar-Haghighib, A.A., Sepaskhah, A.R., 2014. Effects of dynamic and static deficit and partial root zone drying irrigation strategies on yield, tuber sizes distribution, and water productivity of two field grown potato cultivars. Agric. Water Manag. 134, 126–136.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. FAO, Rome.

Andersen, M.N., Asch, F., Wu, Y., Jensen, C.R., Naested, H., Mogensen, V.O., Koch, K.E., 2002. Soluble invertase expression is an early target of drought stress during the critical abortion-sensitive phase of young ovary development in maize. Plant Physiol. 130, 591–604.

Bowen, W.T., 2003. Water productivity and potato cultivation. In: Kijne, J.W., Barker, R., Molden, D. (Eds.), Water Productivity in Agriculture: Limits and Opportunities for Improvement. CABI Publishing, pp. 332.

Brocic, Z., Jovanovic, Z., Stikic, R., Radovic, B.V., Mojevic, M., 2009. Partial root drying: new approach for potato irrigation. Cereal Res. Commun. 37 (Suppl. S), 229–232.

Chaves, M.M., Santos, T.P., Souza, C.R., Ortuño, M.F., Rodrigues, M.L., Lopes, C.M., Maroco, J.P., Pereira, J.S., 2007. Deficit irrigation in grapevine improves water-use efficiency while controlling vigor and production quality. Ann. Appl. Biol. 150, 237–252.

Chaves, M.M., Zarrouk, O., Francisco, R., Costa, J.M., Santos, T., Regalado, A.P., Rodrigues, M.L., Lopes, C.M., 2010. Grapevine under deficit irrigation: hints from physiological and molecular data. Ann. Bot. 105, 661–676.

CoStat Version 6.303 Copyright_ 1998–2004 CoHort Software 798 Lighthouse Ave. PMB 320, Monterey, CA, 93940, USA.

Darwish, T.M., Atallah, T.W., Hajhasan, S., Haidar, A., 2006. Nitrogen and water use efficiency of fertigated processing potato. Agric. Water Manag. 85, 95–104.
Davies, W.J., Wilkinson, S., Loveys, B.R., 2002. Stomatal control by chemical signaling and the exploitation of this mechanism to increase water use efficiency in agriculture. New Phytol. 153, 449–460.
De la Hera, M.L., Romero, P., Gomez-Plaza, E., Martinez, A., 2007. Is partial root-zone drying an effective irrigation technique to improve water use efficiency and fruit quality in field–grown wine grapes under semiarid conditions? Agric. Water Manag. 87, 261–274.
Doorenbos, J., Pruitt, W.O., 1977. Guidelines for predicting crop water requirements. Irrigation and Drainage Paper No. 24. FAO, Rome, pp. 179.
Dorji, K., Behboudian, M.H., Zegbe-Domínguez, J.A., 2005. Water relations, growth, yield, and fruit quality of hot pepper under deficit irrigation and partial rootzone drying. Sci. Hortic. 104, 137–149.
Dry, P.R., Loveys, B.R., 1998. Factors influencing grapevine vigor and the potential for control with partial root-zone drying. Aus. J. Grape Wine Res. 4, 140–148.
Du, T., Kang, S., Zhang, J., Li, F., 2008. Water use and yield responses of cotton to alternate partial root-zone drip irrigation in the arid area of north-west China. Irrig. Sci. 26, 147–159.
English, M.J., Raja, S.N., 1996. Perspectives on deficit irrigation. Agric. Water Manag. 32, 1–14.
Fabeiro, C., Martín de Santa Olalla, F., de Juan, J.A., 2001. Yield and size of deficit irrigated potatoes. Agric. Water Manag. 48, 255–266.
Gautier, H., Guichard, S., Tchamitchian, M., 2001. Modulation of competition between fruits and leaves by flower pruning and water fogging, and consequences on tomato leaf and fruit growth. Ann. Bot. 88, 645–652.
Gencoglan, C., Altunbey, H., Gencoglan, S., 2006. Response of green bean (P: Vulgaris L.) to subsurface drip irrigation and partial root zone drying irrigation. Agric. Water Manag. 84, 274–280.
Gong, D., Kang, Sh., Zhang, J., 2005. Responses of canopy transpiration and canopy conductance of peach (Prunus persica) trees to alternate partial root zone drip irrigation. Hydrol. Process. 19, 2575–2590.
Gowing, D.J.G., Davies, W.J., Jones, H.G., 1990. A positive root-sourced signal as an indicator of soil drying in apple, Malus domestica Borkh. J. Exp. Bot. 41, 1535–1540.
Jefferies, R.A., Mackerron, D.K.L., 1989. Radiation interception and growth of irrigated and drought-stressed potato (Solanum tuberosum). Field Crops Res. 22, 101–112.
Jefferies, R.A., 1993. Responses of potato genotypes to drought. 1. Expansion of individual leaves and osmotic adjustment. Ann. Appl. Biol. 122, 93–104.
Jovanovic, Z., Stikic, R., Vucelic-Radovic, B., Paukovic, M., Brocic, Z., Matovic, G., Rovcanin, S., Mojevic, M., 2010. Partial root-zone drying increases WUE, N and antioxidant content in field potatoes. Eur. J. Agron. 33 (2), 124–131.
Kaman, H., Kirda, C., Sesveren, S., 2011. Genotypic differences of maize in grain yield response to deficit irrigation. Agric. Water Manag. 98, 801–807.
Kang, S.Z., Zhang, J.H., 2004. Controlled alternate partial root-zone irrigation: its physiological consequences and impact on water use efficiency. J. Exp. Bot. 55, 2437–2446.
Kang, S.Z., Liang, Z.S., Hu, W., Zhang, J.H., 1998. Water use efficiency of controlled alternate irrigation on root-divided maize plants. Agric. Water Manag. 38, 69–76.
Kang, S.Z., Liang, Z.S., Pan, Y.H., Shi, P.Z., Zhang, J.H., 2000a. Alternate furrow irrigation for maize production in an arid area. Agric. Water Manag. 45, 267–274.
Kang, S.Z., Shi, W.J., Zhang, J., 2000b. An improved water use efficiency for maize grown under regulated deficit irrigation. Field Crops Res. 67, 207–214.
Kang, S.Z., Hu, X.T., Goodwin, I., Jerie, P., Zhang, J., 2002. Soil water distribution, water use and yield response to partial root zone drying under flood-irrigation condition in a pear orchard. Sci. Hortic. 92, 277–291.
Kirda, C., Topcu, S., Kaman, H., Ulger, A.C., Yazici, A., Cetin, M., Derici, M.R., 2005. Grain yield response and N-fertilizer recovery of maize under deficit irrigation. Field Crops Res. 93, 132–141.
Kirda, C., Topcu, S., Cetin, M., Dasgan, H.Y., Kaman, H., Topaloglu, F., Derici, M.R., Ekici, B., 2007. Prospects of partial root zone irrigation for increasing irrigation water use efficiency of major crops in the Mediterranean region. Ann. Appl. Biol. 150, 281–291.
Kirda, C., 2002. Deficit irrigation scheduling based on plant growth stages showing water stress tolerance. Deficit Irrigation Practice. Water Rep. 22. FAO, Rome, pp. 3–10.
Kriedmann, P.E., Goodwin, I., 2003. Regulated deficit irrigation and partial root-zone drying. Irrigation Insights No. 4. Land and Water Australia, Canberra 102p.
Leib, B.G., Caspari, H.W., Redulla, C.A., Andrews, P.K., Jabro, J., 2006. Partial root-zone drying and deficit irrigation of 'Fuji' apples in a semi-arid climate. Irrig. Sci. 24, 85–99.
Liu, F.L., Jensen, C.R., Andersen, M.N., 2004. Pod set related to photosynthetic rate and endogenous ABA concentration in soybeans subjected to different water regimes and exogenous ABA and BA at early reproductive stages. Ann. Bot. 94, 405–411.
Liu, F., Shahnazari, A., Andersen, M.N., Jacobsen, S.E., Jensen, C.R., 2006a. Physiological responses of potato (Solanum tuberosum L.) to partial root-zone drying: ABA signaling, leaf gas exchange, and water use efficiency. J. Exp. Bot. 57, 3727–3735.
Liu, F., Shahnazari, A., Andersen, M.N., Jacobsen, S.E., Jensen, C.R., 2006b. Effects of deficit irrigation (DI) and partial root drying (PRD) on gas exchange, biomass partitioning, and water use efficiency in potato. Sci. Hortic. 109, 113–117.
Loveys, B., Grant, J., Dry, P., Mccarthy, M., 1997. Progress in the Development of Partial Root-Zone Drying. The Australian Grapegrower & Winemaker.
Loveys, B., Stoll, M., Dry, P., Mccarthy, M., 1998. Partial Root-Zone Drying Stimulates Stress Responses in Grapevine to Improve Water Use Efficiency While Maintaining Crop Yield and Quality. The Australian Grapegrowers and Winemakers.
Morison, J.I.L., Baker, N.R., Mullineaux, P.M., Davies, W.J., 2008. Improving water use in crop production. Philos. Trans. R. Soc. B Biol. Sci. 363, 639–658.
Porter, G.A., Opena, G.B., Bradbury, W.B., McBurnie, J.C., Sisson, J.A., 1999. Soil management and supplemental irrigation effects on potato. I. Soil properties, tuber yield, and quality. Agron. J. 91, 416–425.
Ramírez, D.A., Yactayo, W., Gutiérrez, R., Mares, V., De Mendiburu, F., Posadas, A., Quiroz, R., 2014. Chlorophyll concentration in leaves is an indicator of potato tuber yield in water-shortage conditions. Sci. Hortic. 168, 202–209.
Saeed, H., Grove, I.G., Kettlewell, P.S., Hall, N.W., 2005. Potato root and shoot growth under different water management strategies. Asp. Appl. Biol. 73, 85–91.
Saeed, H., Grove, I.G., Kettlewell, P.S., Hall, N.W., 2008. Potential of partial root zone drying as an alternative irrigation technique for potatoes (Solanum tuberosum). Ann. Appl. Bot. 152, 71–80.
Samadi, A., Sepaskhah, A.R., 1984. Effects of alternate furrow irrigation on yield and water use efficiency of dry beans. Iran Agric. Res. 3, 95–115.
Santos, T.P., Lopes, C.M., Rodrigues, M.L., de Souza, C.R., Ricardo-da-Silva, J.M., Maroco, J.P., Pereira, J.S., Chaves, M.M., 2007. Effects of deficit irrigation strategies on cluster microclimate for improving fruit composition of Moscatel field-grown grapevines. Sci. Hortic. 112, 321–330.
Sepaskhah, A.R., Ahmadi, S.H., 2010. A review on partial root-zone drying irrigation. Int. J. Plant Prod. 4, 241–258.
Sepaskhah, A.R., Kamgar-Haghighi, A.A., 1997. Water use and yields of sugar beet grown under every-other furrow irrigation with different irrigation intervals. Agric. Water Manag. 34, 71–79.
Sepaskhah, A.R., Parand, A.R., 2006. Effects of alternate furrow irrigation with-supplemental every-furrow irrigation at different growth stages on the yield of maize (Zea mays L.). Plant Prod. Sci. 9, 415–421.
Shae, J.B., Steele, D.D., Gregor, B.L., 1999. Irrigation scheduling methods for potatoes in the northern Great Plains. Trans. ASAE 42, 351–360.
Shahnazari, A., Liu, F., Andersen, M.N., Jacobsen, S.E., Jensen, C.R., 2007. Effects of partial root-zone drying on yield, tuber size and water use efficiency in potato under filed conditions. Field Crops Res. 100, 117–124.
Shahnazari, A., Ahmadi, S.H., Laerke, P.E., Liu, F., Plauborg, F., Jacobsen, S.E., Jensen, C.R., Andersen, M.N., 2008. Nitrogen dynamics in the soil–plant system under deficit and partial root-zone drying irrigation strategies in potatoes. Eur. J. Agron. 28 (2), 65–73.
Shao, G., Zhang, Z., Liu, N., Yu, S., Xing, W., 2008. Comparative effects of deficit irrigation (DI) and partial root-zone drying (PRD) on soil water distribution, water use, growth and yield in greenhouse grown hot pepper. Sci. Hortic. 119, 11–16.
Shayannejad, M., 2009. Effect of every – other furrow irrigation on water use effciency, starch and protein contents of potato. Agric. Sci. 1, 107–112.
Shock, C.C., Feibert, E.B.G., 2002. Deficit irrigation of potato. In: Moutonnet, P. (Ed.), Deficit Irrigation Practices. Food and Agriculture Organization of the United Nations, Rome, pp. 47–55 Water Reports 22.
Stoll, M., Loveys, B.R., Dry, P., 2000. Hormonal changes induced by partial root-zone drying of irrigated grapevine. J. Exp. Bot. 51, 1627–1634.
Wakrim, R., Wahbi, S., Tahi, H., Aganchich, B., Serraj, R., 2005. Comparative effects of partial root drying (PRD) and regulated deficit irrigation (RDI) on water relations and water use efficiency in common bean (Phaseolus vulgaris L.). Agric. Ecosyst. Environ. 106, 275–287.
Wang, J., de Kroon, H., Wang, L., de Caluwe, H., Bögemann, G.M., van der Weerden, G.M., Kang Sh Smits, A.J.M., 2009. Root foraging and yield components underlying limited effects of partial root-zone drying on oilseed rape, a crop with an indeterminate growth habit. Plant Soil 323, 163–176.
Wang, Y., Liu, F., Jensen, L.S., de Neergaard, A., Jensen, C.R., 2013. Alternate partial root-zone irrigation improves fertilizer-N use efficiency in tomatoes. Irrig. Sci. 31, 589–598.
Yactayo, W., Ramírez, D.A., Gutiérrez, R., Mares, V., Posadas, A., Quiroz, R., 2013. Effect of partial root-zone drying irrigation timing on potato tuber yield and water use efficiency. Agric. Water Manag. 123, 65–70.
Zegbe-Domínguez, J.A., Behboudian, M.H., Clothier, B.E., 2006. Responses of "Petopride" processing tomato to partial root-zone drying at different phonological stages. Irrig. Sci. 24, 203–210.