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Water-Saving Irrigation Strategies in Potato Fields: Effects on Physiological Characteristics and Water Use in Arid Region

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Abstract: In this study, field experiments were conducted to investigate the effects of two water-saving practices—partial root-zone drying (PRD) and deficit irrigation (DI)—on potato growth and yield in comparison with full irrigation (FI). The required FI amount was applied to the potato plants to enable 100% crop evapotranspiration, and the plants received 70% and 50% of the irrigation amount of FI for DI (DI70 and DI50) and PRD (PRD70 and PRD50), respectively. The physiological characteristics of the potatoes during the 2014–2015 seasons indicated that the relative chlorophyll contents were not significantly higher for the DI and PRD treatments than for the FI treatment. The DI50 had the lowest net photosynthesis rate ($p < 0.05$) while DI50 and PRD50 had significantly lower stomatal conductance (g_s) values in both years. Meanwhile, the values of the PRD treatments were lower than those of DI treatments based on the transpiration rates. The xylem (abscisic acid) based on PRD50 had an average increase of 0.38 mol/m^2 s due to decreasing g_s values compared with other water-saving irrigation treatments. However, the FI and DI treatments had increased fresh tuber yields compared with the yields of PRD treatments. Furthermore, the PRD70 and PRD50 treatments significantly reduced the water productivity (WP) values by 30.16% and 41.32%, respectively, relative to that of FI.

Keywords: deficit irrigation; partial root-zone drying irrigation; potato; gas-exchanges; water productivity

1. Introduction

The utilization of potato (*Solanum tuberosum* L. cv. Hermes) in human nourishment and the manufacture of starch distinguishes it among other vital crops on the planet [1]. Although it is sensitive to water stress, it can produce more and higher quality tubers when it is watered precisely by soil water tension rather than by under- or over-irrigation [2].

However, water-saving irrigation methods such as deficit irrigation (DI) and partial root-zone drying irrigation (PRD) permit a crop to tolerate some water deficit degrees to decrease the irrigation budget and increase potential revenue. These strategies have been successful for many crops all over the world. Such crops fairly avoid water stress either due to their nature or by deep rooting, which allows their roots to have access to soil moisture in the soil profile. Moreover, the whole root-zone is irrigated to a lesser degree than the maximum crop evapotranspiration in these irrigation methods. Hence, the crop is exposed to a certain level of water stress during the whole growing season, or at a particular stage of its growth [3,4]. Meanwhile, the PRD strategy is an improvement over the DI strategy in which irrigation is alternated spatially and temporally to produce wet–dry cycles in many parts of the root system. Chemical signals are then induced in the roots of the dry soil, thereby leading to a decrease in the stomatal conductance (g_s), transpiration, and shoot growth. This preserves crop water supply from the wet soil through the roots to avoid acute water shortage [5,6]. The roots in dry soil produce chemical signals, such as abscisic acid (ABA), which are transported to the plant leaves, thereby playing a vital role in the chemical signaling of soil moisture and in the regulation of g_s [5,7–13].

The physiological basis for improving water productivity (WP) in DI and PRD strategies involves decreasing g_s using the ABA-based root-to-shoot signaling system, thereby curtailing the transpiration rate through temperate soil drying [14–17]. Various studies have shown that DI and PRD-induced signals regulate g_s and leaf expansion growth to increase WP [12,18]. Hence, root-based ABA may indicate soil drying. This hormone can be transported through the roots in the drying soil before low-water conditions, which causes the production of leaf-induced ABA, are indicated. The hormone is then transported through the transpiration stream to the shoots, where it causes a decline in the leaf development rate and stomatal opening, as observed in wheat [19], tomatoes [20], maize [21], and potatoes [16]. Dodd [12,17] and Wang et al. [18] demonstrated that PRD plants process more prominent xylem (ABA) fixations than DI plants at a comparative level of soil water deficiency in the entire root zone. This prompts a superior control of plant water stress, thereby leading to an additional change in WP. However, photosynthetic rates (A_n) indicate the saturation response by an open stomata, while transpiration rates (T) indicate a more linear response. Thus, the partial closing of the stomata will substantially reduce water loss, with little effect on A_n [22]. Ahmadi et al. [23] observed that g_s is more sensitive to water deficiency than A_n in potato plants.

Therefore, DI and PRD conserve irrigation water and increase WP simultaneously, with no yield reduction [15,16,24–26]. Shahnazari et al. [27] demonstrated that PRD and DI produced similar potato yields to full irrigation (FI), and improved WP by 60% due to the conservation of the applied irrigation water by ~30%. On the other hand, Liu et al. [15,16] discovered that PRD could not enhance yield and WP in potatoes in comparison with DI. They also demonstrated that potato tuber yields significantly decreased for DI and PRD than for FI. Moreover, Ahmadi et al. [28] demonstrated that fresh yields and the WP of potatoes are significantly affected by PRD and DI in comparison to the effect of FI. Furthermore, Yactayo et al. [29] demonstrated that the WP of potatoes improved with no yield decrease when an early PRD was performed six weeks after growing and with a watering level equal to half of FI, in comparison with FI.

However, the shortage of irrigation water and recurrent and extreme droughts have led to further research into water-saving irrigation strategies to increase crop productivity and the requirements for the optimization of irrigation management. Therefore, improvements are required to increase the efficient use of irrigation water. Thus, DI and PRD reduce the irrigation levels of crops in comparison to FI. The degree of irrigation reduction is crop-dependent. It controls excessive vegetative growth and is generally accompanied by minor yield loss [30–33], thereby increasing WP [28]. Hence, the objectives of this study are to (1) compare the physiological responses of potato crops with respect to DI, PRD, and FI irrigation methods in an arid environment, and (2) assess the effect of water-saving (i.e., DI and PRD) irrigation strategies on the yield and WP of potatoes.

2. Materials and Methods

2.1. Experimental Setup and Design

The field experiment was carried out over two successive years (2014–2015), from January to May, in Riyadh, Saudi Arabia. The site is located at 24°44′11.10″ N and 46°37′06.61″ E, at an altitude of 665 m above sea level. A meteorological station that stored weather data from the field location was set-up in the experimental field to measure climate parameters, such as air temperature, relative humidity, and rainfall. The seasonal divergence in weather parameters estimated throughout the whole period is delineated in Figure 1. These climate data were used to calculate daily reference evapotranspiration (ET_o) using the Penman–Monteith FAO-56 equation [34], given by:

$$ET_o = \frac{0.408\ \Delta\ (R_n - G) + \gamma\ \frac{900}{T_a+273}\ u_2\ (e_s -\ e_a)}{\Delta +\ \gamma\ (1 + 0.34\ u_2)} \quad (1)$$

where ET_o represents reference evapotranspiration (mm/day), R_n represents net radiation (MJ/m^2 day), Δ represents the slope of the saturation vapor pressure–temperature curve at mean air temperature (kPa/°C), u_2 represents the wind speed at a height of 2 m (m/s), G represents the soil heat flux (MJ/m^2 day), T_a represents the mean air temperature at a height of 2 m (°C), γ represents the psychrometric constant (kPa/°C), e_a represents actual vapor pressure (kPa), and e_s represents the saturation vapor pressure (kPa).

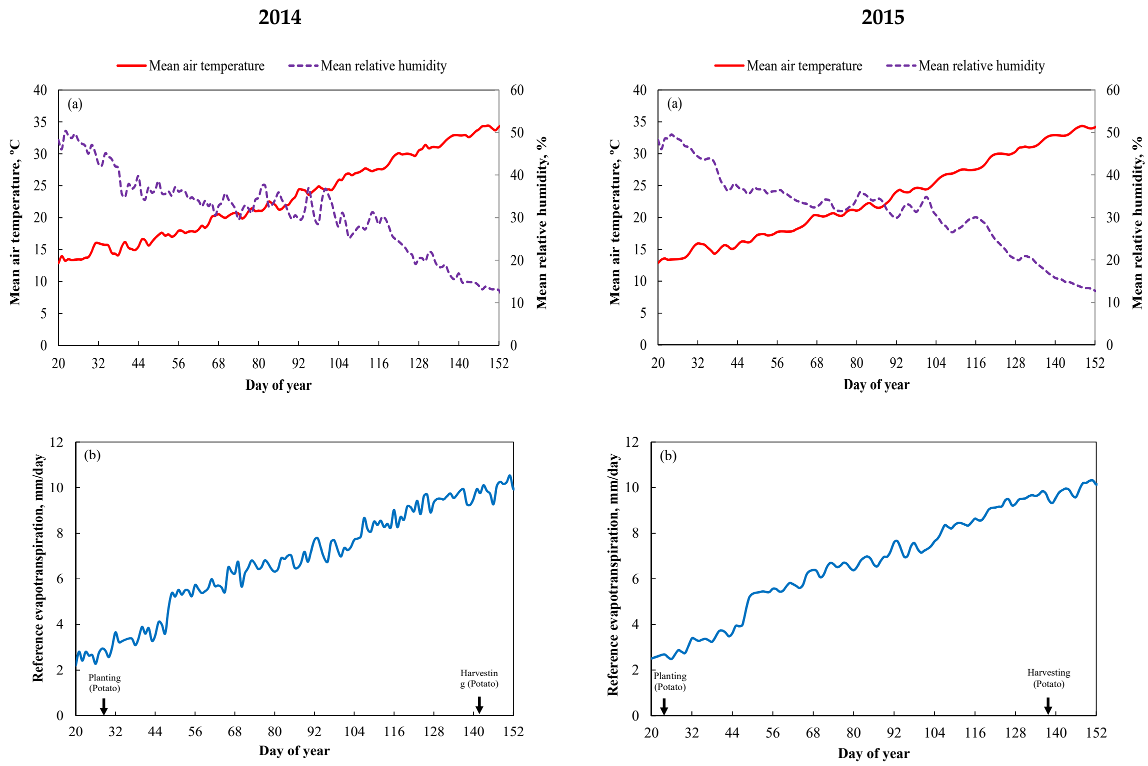

Figure 1. Meteorological variables of (**a**) mean air temperature and mean relative humidity, and (**b**) reference evapotranspiration during the 2014 and 2015 experimental periods.

The actual crop evapotranspiration (ET_c) was estimated at the initial stage, mid stage, and late-season stage using respective crop coefficient (K_c) values of 0.5, 1.15, and 0.75 [35], as follows:

$$ET_c = K_c \times ET_o \quad (2)$$

The efficiency of the drip system was based on the crop water requirements (actual ET_c) for different growth stages, to estimate the amount of irrigation water applied to the crop.

The seed beds for the field experiment were prepared by plowing, grading, and leveling for the irrigation system. Furthermore, physical analysis of the soil was conducted to a depth of 60 cm, as shown in Table 1. The soil water content by weight at the field capacity (<0.3 bar) and wilting point (<15 bar) were also measured [36]. Moreover, the saturated hydraulic conductivity was determined by the constant head method [37] while the soil bulk density was determined by the core method [38]. The field was manually cultivated with potato seeds (*Solanum tuberosum* L. cv. Hermes) by digging small shallow holes into the ground surface and growing them ten centimeters deep below the soil, with a row spacing of 70 cm and plant spacing of 50 cm. The same fertilizer amount appropriate for the potatoes was applied to all the treatment plots. The fertilizers comprising of 230 kg/ha N–P_2O_5–K_2O (20–20–20), 200 kg/ha N–P_2O_5–K_2O (10–10–43), 40 L/ha H_3PO_4, and 4 kg/ha microelements, were applied using a drip irrigation system for five successive days each week.

Table 1. Physical properties of soil used in the experiment.

Depth (cm)	Particle Size (%)			Texture	FC (%)	WP (%)	Ks (mm/h)	ρ_b, (g/cm^3)
	Sand	Silt	Clay					
0–20	71.8	16.3	11.9	sandy loam	14.2	6	37.8	1.6
20–40	66.7	18	15.3	sandy loam	17.1	8.1	24.6	1.6
40–60	69.1	18.3	12.6	sandy loam	18.5	9.9	19.6	1.6

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

The experimental area was 675 m^2 (45 m × 15 m) and was divided into three replicate fields. Each field of area 195 m^2 (13 m × 15 m) included five irrigation treatments: FI with 100% of ET_c, DI70 and PRD70 with 70% of ET_c, and DI50 and PRD50 with 50% of ET_c, using a randomized complete block (RCB) design. The surface dripper lines were comprised of 26 emitters with a discharge rate of 8 L/h. Meanwhile, the PRD-based irrigation was alternately transferred between two sides of the plants on a weekly basis [15], and the irrigation was carried out daily. Furthermore, water-saving strategies such as DI70, DI50, PRD70, and PRD50 were applied at day 31 after planting till harvesting.

2.2. Physiological Measurements

The relative chlorophyll (Chl) content of the potato plants was measured with a portable CCM-200 plus chlorophyll content meter (ADC BioScientific Ltd., Hoddesdon, UK) after the onset of the treatments. An LI-6400XT portable photosynthesis system (LiCor Inc., Lincoln, NE, USA) was used to measure A_n (μmol/m^2 s), g_s (mol/m^2 s), and T (mmol/m^2 s). These measurements were monitored six times (4 April–9 May 2014 and 2 April–May 2015) during the treatment periods and were taken around solar midday. The diurnal measurements were performed in five rounds on 7 April 2015. Meanwhile, one-third of the fully expanded upper canopy leaflets were selected for measurement within each treatment, while samples were taken from 15 plants in each round which lasted ~1.5 h. The same leaves were used for leaf water potential (Ψ_{leaf}) measurements using a xylem-pressure chamber (mod. 301564, Eijkelkamp, Giesbeek, Netherlands).

Meanwhile, a novel and effective approach was adopted to obtain the xylem (ABA) sample from the potato plants [15,23]. One stem per irrigation treatment was sampled after completing the Chl content and gas-exchange measurements were completed for the same treatment. A pressure of ~0.2–0.4 MPa above the plant equilibrium pressure was applied to obtain ~0.5–1.0 mL of xylem sap using an appropriate pipette. The xylem (ABA) samples were then immediately frozen in liquid nitrogen and subsequently stored at −80 °C until they were analyzed. All the samples were used to determine the ABA content using an enzyme-linked immunosorbent assay (ELISA) [39].

2.3. Estimation of Yield and Water Productivity

Plants from three central rows of the plots were harvested on 21 May 2014 and 18 May 2015 to determine their total fresh tuber yields (Mg/ha). In addition, WP (kg/m^3) was used to evaluate the comparative benefits of the irrigation treatments. The WP of each irrigation treatment was computed by dividing the whole mass of harvested fresh tubers (kg/ha) by the quantity of water applied to the crop (additional irrigation, m^3/ha) [40].

2.4. Statistical Analysis

Statistical analyses were performed by CoStat [41] to test the equality means of the treatments under study using RCB design. If significant differences existed between the treatments, the least significant difference (LSD) method was used to test the significant differences between every two means. Hence, the point estimation of the treatment mean ± standard error (SE) was calculated from three replicates of each irrigation treatment. Meanwhile, the non-parametric Kolmogorov–Smirnov test was used to verify the assumption of the normality of the data, where the data had a normal distribution when the null hypothesis was H_o. Furthermore, the Levene test was used to verify the homogeneity of the variance, where all treatments variance were equal when the null hypothesis was H_o.

3. Results

3.1. Physiological Responses

3.1.1. Relative Chlorophyll

Table 2 summarizes the analysis of variances of the Chl content of potato plant for the water-saving irrigation treatments in the 2014 and 2015. The Chl content for DI and PRD treatments were increased, but this effect was often insignificant ($p > 0.05$). The Chl ranges decreased from 9.17–38.08 in 2014 to 8.32–32.67 in 2015. However, significant differences were observed between irrigation treatments in the third ($p < 0.01$) and sixth ($p < 0.05$) measurements in 2014, and in the fourth ($p < 0.05$), fifth ($p < 0.05$), and sixth ($p < 0.01$) measurements in 2015. Meanwhile, the Chl content of the PRD50 and FI treatments had the lowest values in 2014 and 2015, respectively. On the other hand, PRD70 had the highest values of Chl content in all measurements, except the fourth measurement in 2015.

3.1.2. Gas-Exchanges

Tables 3–5 show the variations in A_n, g_s, and T across the six measurements in 2014 and 2015, respectively. The A_n of water-saving irrigation techniques (DI and PRD) decreased in all measurements in 2015 (Table 3). However, the A_n of the PRD treatments were significantly lower than the corresponding values of FI for 69 and 83 days after planting (DAP) in 2014 and 48, 55, 69, and 76 DAP in 2015. The DI50 treatment had the lowest A_n in all measurements, except in the last measurement in 2014.

Table 4 shows that FI had the highest significant g_s values in both years, except at 48, 55, and 76 DAP in 2014, when these were not significantly different from DI and PRD. The average values of g_s in different DI and PRD treatments varied mostly between 0.17 and 0.89 mol/m^2 s in 2014, and between 0.25 and 0.55 mol/m^2 s in 2015. Meanwhile, significant differences were observed between irrigation treatments in the third ($p < 0.01$), fourth ($p < 0.01$), and sixth ($p < 0.01$) measurements in 2014; and in all measurements, except in the third and sixth measurements in 2015. Meanwhile, PRD50 treatment exhibited the lowest values of g_s during the experimental phase in 2015.

Table 5 shows that FI treatment had the highest T value among all treatments in 2014 and 2015. However, no significant difference was observed in the treatments when measured at 48, 55, 76, and 83 DAP in 2014, and 48 DAP in 2015. The T values decreased with increasing water restrictions as expected; however, the decrease was more prominent for DI50 and PRD50 than for DI70 and PRD70. Meanwhile, the T value of PRD-treated plants was significantly lower than the corresponding values of the DI-treated plants when measured at all DAP except the last measurement in 2015. In 2014, the T values of DI70 and PRD70 (average values of the third and fourth measurements) were less than the corresponding value of FI by 42.71% and 41.97%, respectively, while the T values of DI70 and PRD70 (average values of the fourth, fifth, and sixth measurements) decreased by 27.37% and 38.48% in 2015, respectively. The same trend was observed for PRD50, where the T values decreased by 52.17% and 53.62% in 2014 and 2015, respectively; and the corresponding value of DI50 decreased by 66.11% and 32.74% in 2014 and 2015, respectively.

Table 2. Relative chlorophyll contents of potato for the different irrigation treatments in 2014 and 2015.

Year	Treatments	48 DAP	55 DAP	62 DAP	69 DAP	76 DAP	83 DAP
2014	FI	29.63 (±3.44)	32.25 (±3.78)	18.76 (±0.04) [b]	17.37 (±0.87)	19.47 (±3.12)	9.17 (±1.22) [c]
	DI70	33.15 (±2.28)	36.12 (±2.51)	18.52 (±2.69) [b]	19.50 (±3.90)	16.17 (±2.07)	10.00 (±1.27) [bc]
	DI50	32.85 (±3.20)	35.79 (±3.52)	28.35 (±1.92) [a]	19.90 (±3.42)	23.73 (±1.47)	12.10 (±1.60) [abc]
	PRD70	34.93 (±3.30)	38.08 (±3.63)	26.66 (±3.49) [a]	15.80 (±1.37)	22.43 (±2.69)	13.17 (±1.94) [ab]
	PRD50	29.45 (±2.28)	30.30 (±3.05)	16.70 (±1.22) [b]	15.30 (±1.48)	14.77 (±0.94)	14.95 (±1.24) [a]
	p-Value	0.72	0.59	0.01	0.70	0.06	0.05
	LSD 0.05	-	-	6.93	-	-	3.96
2015	FI	24.40 (±2.17)	27.40 (±1.38)	19.37 (±0.84)	14.77 (±1.14) [b]	15.66 (±0.54) [b]	9.32 (±0.63) [b]
	DI70	25.93 (±3.12)	27.82 (±1.55)	19.00 (±1.20)	18.80 (±1.08) [ab]	17.44 (±0.85) [ab]	8.32 (±0.36) [b]
	DI50	26.70 (±2.32)	29.12 (±0.82)	24.57 (±0.32)	22.18 (±1.64) [a]	22.98 (±2.00) [ab]	12.09 (±0.37) [a]
	PRD70	27.60 (±3.27)	32.67 (±1.99	24.95 (±1.05)	21.98 (±1.15) [a]	22.99 (±2.49) [a]	12.91 (±0.52) [a]
	PRD50	24.43 (±2.00)	29.43 (±1.51)	19.37 (±2.71)	17.8 (±1.79) [ab]	18.97 (±0.94) [ab]	9.56 (±1.18) [b]
	p-Value	0.88	0.08	0.06	0.03	0.05	<0.01
	LSD 0.05	-	-	-	4.57	5.57	1.86

The data represent the mean ± standard error of the mean (n = 3). Within each year, the mean values in columns followed by letters [a, b, c] are significantly different based on the LSD test at $p < 0.05$. DAP: days after planting; FI: full irrigation with 100% of ET_c; DI70: deficit irrigation with 70% of ET_c; DI50: deficit irrigation with 50% of ET_c; PRD70: partial root-zone drying irrigation with 70% of ET_c; PRD50: partial root-zone drying irrigation with 50% of ET_c; LSD: least significant difference.

Table 3. Net photosynthesis rate of potato for the different irrigation treatments in 2014 and 2015.

Year	Treatments	48 DAP	55 DAP	62 DAP	69 DAP	76 DAP	83 DAP
2014	FI	26.2 (±1.57) [ab]	28.38 (±1.72) [ab]	21.60 (±2.86) [a]	16.00 (±2.13) [a]	14.92 (±0.73) [a]	25.29 (±0.86) [a]
	DI70	19.00 (±1.22) [bc]	20.45 (±1.35) [bc]	16.15 (±2.75) [b]	5.13 (±1.68) [b]	9.98 (±1.52) [b]	13.90 (±1.98) [bc]
	DI50	16.43 (±1.10) [c]	17.63 (±1.21) [c]	9.59 (±1.81) [c]	8.25 (±0.99) [b]	10.81 (±0.72) [b]	16.97 (±0.27) [b]
	PRD70	28.77 (±0.87 [a]	31.21 (±0.96) [a]	21.83 (±1.44) [a]	9.93 (±1.93) [b]	15.93 (±1.51) [a]	15.05 (±3.54) [bc]
	PRD50	27.77 (±4.84) [a]	30.09 (±5.33) [a]	23.08 (±0.90) [a]	7.59 (±0.92) [b]	14.71 (±0.99) [a]	10.40 (±0.81) [c]
	p-Value	0.02	0.02	<0.01	0.01	0.01	0.01
	LSD 0.05	7.74	8.53	5.09	5.37	3.53	6.49
2015	FI	23.83 (±1.00) [a]	23.81 (±0.52) [a]	22.24 (±1.01)	18.54 (±0.20) [a]	16.99 (±0.64) [a]	15.56 (±0.63)
	DI70	22.38 (±0.30) [a]	22.01 (±1.12) [b]	20.58 (±1.69)	11.27 (±0.09) [b]	13.38 (±0.17) [b]	14.73 (±1.79)
	DI50	18.63 (±0.13) [b]	18.33 (±0.50) [c]	19.65 (±1.05)	8.55 (±1.04) [c]	13.56 (±0.29) [b]	9.34 (±1.05)
	PRD70	21.37 (±1.28) [ab]	20.60 (±1.10) [b]	20.39 (±0.16)	12.26 (±1.32) [b]	14.01 (±0.23) [b]	14.54 (±2.52)
	PRD50	23.45 (±1.44) [a]	18.63 (±0.13) [c]	21.26 (±0.76)	11.29 (±0.24) [b]	7.22 (±0.25) c	11.69 (±1.47)
	p-Value	0.03	<0.01	0.56	<0.01	<0.01	0.06
	LSD 0.05	3.02	1.59	-	2.21	1.29	-

The data represent the mean ± standard error of the mean (n = 3). Within each year, the mean values in columns followed by the letters [a, b, c] are significantly different based on the LSD test at $p < 0.05$. DAP: days after planting; FI: full irrigation with 100% of ET_c; DI70: deficit irrigation with 70% of ET_c; DI50: deficit irrigation with 50% of ET_c; PRD70: partial root-zone drying irrigation with 70% of ET_c; PRD50: partial root-zone drying irrigation with 50% of ET_c; LSD: least significant difference.

Table 4. Stomatal conductance of potato for the different irrigation treatments in 2014 and 2015.

Year	Treatments	48 DAP	55 DAP	62 DAP	69 DAP	76 DAP	83 DAP
2014	FI	0.64 (±0.05)	0.7 (±0.05)	0.89 (±0.09) ^{a}	0.79 (±0.18) ^{a}	0.37 (±0.03)	0.67 (±0.02) ^{a}
	DI70	0.81 (±0.03)	0.89 (±0.04)	0.38 (±0.03) ^{b}	0.28 (±0.07) ^{b}	0.39 (±0.14)	0.55 (±0.04) ^{ab}
	DI50	0.47 (±0.07)	0.51 (±0.08)	0.17 (±0.04) ^{c}	0.36 (±0.04) ^{b}	0.31 (±0.03)	0.43 (±0.10) ^{bc}
	PRD70	0.66 (±0.14)	0.73 (±0.15)	0.56 (±0.03) ^{b}	0.31 (±0.07) ^{b}	0.27 (±0.06)	0.32 (±0.01) ^{c}
	PRD50	0.51 (±0.09)	0.56 (±0.10)	0.47 (±0.05) ^{b}	0.28 (±0.01) ^{b}	0.23 (±0.02)	0.37 (±0.05) ^{c}
	p-Value	0.14	0.14	<0.01	0.01	0.64	<0.01
	LSD 0.05	-	-	0.18	0.28	-	0.13
2015	FI	0.59 (±0.06) ^{a}	0.64 (±0.14) ^{a}	0.89 (±0.23)	0.61 (± 0.08) ^{a}	0.60 (±0.02) ^{a}	0.62 (±0.04)
	DI70	0.53 (±0.03) ^{a}	0.52 (±0.04) ^{abc}	0.52 (±0.15)	0.44 (± 0.10) ^{ab}	0.45 (±0.01) ^{b}	0.39 (±0.11)
	DI50	0.3 (±0.03) ^{b}	0.28 (±0.04) ^{c}	0.47 (±0.10)	0.41 (± 0.03) ^{ab}	0.36 (±0.00) ^{c}	0.32 (±0.04)
	PRD70	0.55 (±0.08) ^{a}	0.53 (±0.02) ^{ab}	0.52 (±0.04)	0.29 (± 0.06) ^{b}	0.29 (±0.01) ^{d}	0.43 (±0.13)
	PRD50	0.45 (±0.10) ^{ab}	0.30 (±0.04) ^{bc}	0.47 (±0.10)	0.26 (± 0.03) ^{b}	0.25 (±0.01) ^{e}	0.36 (±0.08)
	p-Value	0.03	0.04	0.35	0.03	<0.01	0.32
	LSD 0.05	0.17	0.25	-	0.21	0.04	-

The data represent the mean ± standard error of the mean (n = 3). Within each year, the mean values in columns followed by the letters $^{a, b, c}$ are significantly different based on the LSD test at $p < 0.05$. DAP: days after planting; FI: full irrigation with 100% of ET_c; DI70: deficit irrigation with 70% of ET_c; DI50: deficit irrigation with 50% of ET_c; PRD70: partial root-zone drying irrigation with 70% of ET_c; PRD50: partial root-zone drying irrigation with 50% of ET_c; LSD: least significant difference.

Table 5. Transpiration rate of potato for the different irrigation treatments in 2014 and 2015.

Year	Treatments	48 DAP	55 DAP	62 DAP	69 DAP	76 DAP	83 DAP
2014	FI	3.40 (±0.24)	3.29 (±0.26)	4.82 (±0.41) [a]	4.10 (±0.60) [a]	2.38 (±0.15)	2.51 (±0.49)
	DI70	3.83 (±0.15)	3.76 (±0.16)	3.16 (±0.70) [b]	2.01 (±0.41) [b]	2.44 (±0.74)	3.18 (±0.20)
	DI50	2.60 (±0.33)	2.41 (±0.36)	1.21 (±0.25) [c]	1.75 (±0.52) [b]	2.03 (±0.18)	2.66 (±0.56)
	PRD70	3.09 (±0.43)	2.95 (±0.48)	3.36 (±0.17) [b]	1.90 (±0.37) [b]	1.80 (±0.35)	1.97 (±0.08)
	PRD50	2.85 (±0.28)	2.69 (±0.30)	2.53 (±0.34) [bc]	1.77 (±0.06) [b]	1.24 (±0.07)	2.00 (±0.33)
	p-Value	0.11	0.10	<0.01	0.01	0.32	0.27
	LSD 0.05	-	-	1.40	1.21	-	-
2015	FI	3.18 (±0.26)	2.85 (±0.17) [b]	5.17 (±0.52) [a]	2.19 (±0.22) [a]	3.27 (±0.08) [a]	3.4 (±0.18) [a]
	DI70	2.18 (±0.20)	3.14 (±0.18) [ab]	4.63 (±0.77) [a]	1.76 (±0.38) [ab]	2.65 (±0.04) [b]	1.92 (±0.24) [b]
	DI50	2.63 (±0.21)	1.81 (±0.27) [c]	3.48 (±0.31) [b]	1.69 (±0.02) [ab]	2.43 (±0.02) [b]	1.71 (±0.21) [b]
	PRD70	2.54 (±0.43)	3.37 (±0.16) [a]	3.38 (±0.22) [b]	1.11 (±0.19) [bc]	1.80 (±0.04) [c]	2.68 (±0.53) [ab]
	PRD50	2.67 (±0.23)	1.87 (±0.25) [c]	3.35 (±0.44) [b]	0.91 (±0.02) [c]	1.19 (±0.25) [d]	2.05 (±0.16) [b]
	p-Value	0.24	<0.01	0.02	0.02	<0.01	0.03
	LSD 0.05	-	0.46	1.12	0.69	0.37	1.04

The data represent the mean ± standard error of the mean ($n = 3$). Within each year, the mean values in columns followed by different letters [a, b, c] are significantly different based on the LSD test at $p < 0.05$. DAP: days after planting; FI: full irrigation with 100% of ET_c; DI70: deficit irrigation with 70% of ET_c; DI50: deficit irrigation with 50% of ET_c; PRD70: partial root-zone drying irrigation with 70% of ET_c; PRD50: partial root-zone drying irrigation with 50% of ET_c; LSD: least significant difference.

The diurnal variations of Ψ_{leaf}, A_n, g_s, and transpiration efficiency (A_n/T) were measured on 7 April (53 DAP) in 2015, as shown in Figure 2. Significant differences ($p < 0.05$) in Ψ_{leaf} were observed among the treatments for experiments performed at 07:30 (early-morning) and 10:30 (mid-morning). However, the differences were minimal and insignificant at midday and late-evening. The values of Ψ_{leaf} varied based on the amount of water received (maximum in FI, minimum in DI50 and PRD50). Meanwhile, the lowest Ψ_{leaf} corresponded to PRD50 of -1.08 MPa at midday. However, the early-morning and late-evening measurements of A_n were significantly different ($p < 0.01$). Moreover, the values of A_n at midday were highest throughout the whole day for all irrigation treatments. Figure 2 shows the variation in g_s values, which was less evident at early-morning ($p > 0.05$ among treatments). It decreased until midday ($p < 0.001$) and then increased at late-evening ($p > 0.05$). In this study, the values of g_s for different irrigation treatments were affected by water stress because the minimum Ψ_{leaf} was -1.08 MPa. On the other hand, PRD50 treatment had the highest A_n/T values which was particularly significant at midday and late-evening (Figure 2). The A_n/T values of FI were lower in comparison with the values of PRD and DI during all diurnal periods. The average A_n/T values of DI70 and DI50 were higher than the corresponding value of FI by 6.80% and 11.73%, respectively, while the values of PRD70 and PRD50 decreased by 9.96% and 34.11%, respectively.

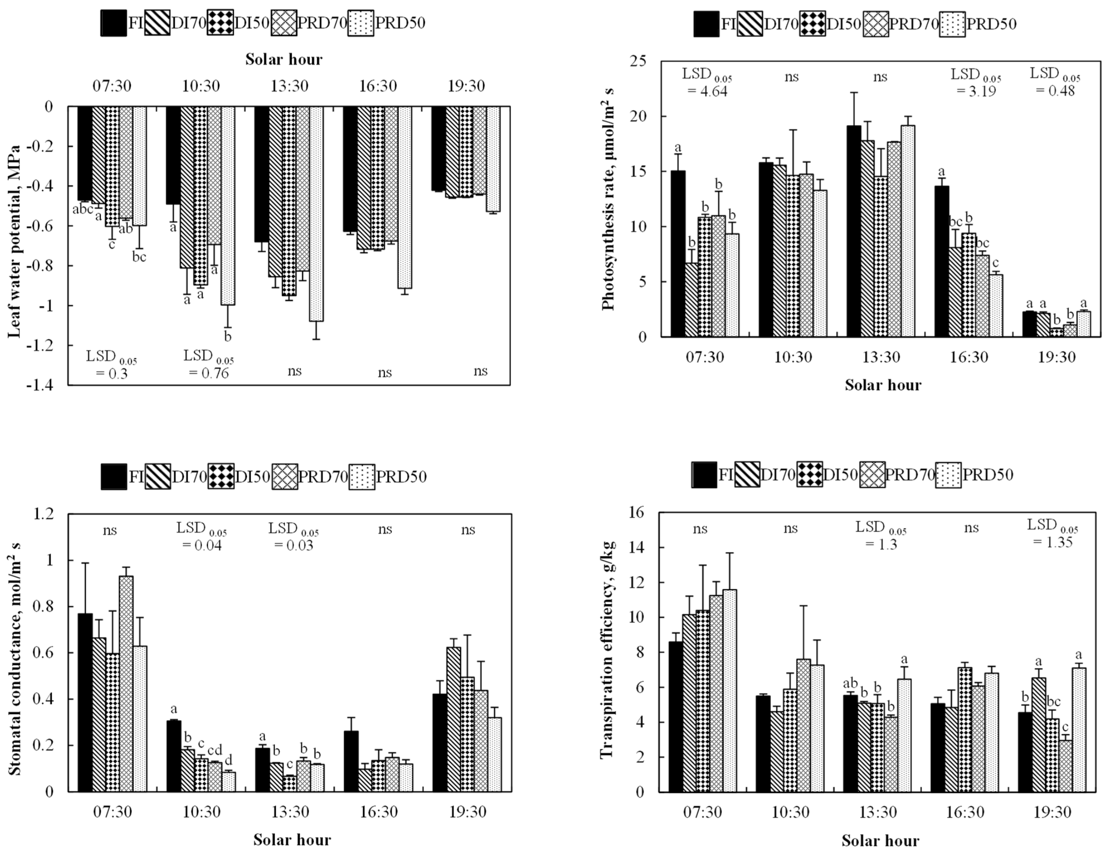

Figure 2. Diurnal variations of leaf water potential, photosynthesis rate, stomatal conductance, and transpiration efficiency carried out on 7 April 2015. The bars give ± standard error of the mean ($n = 3$). The similar letters directly above the columns and the abbreviation of "ns" denote insignificant differences between irrigation treatments based on the LSD test at $p < 0.05$.

3.1.3. Xylem (ABA)

Figure 3 shows the effects of irrigation treatments on the xylem (ABA) of potato plants. The DI and PRD treatments increased the xylem (ABA) in plants in comparison with FI. Meanwhile, these values were statistically insignificant ($p > 0.05$) in both years. On the other hand, PRD50 treatment had the highest xylem (ABA) value while the values of DI70 treatment were equivalent to FI values in both years.

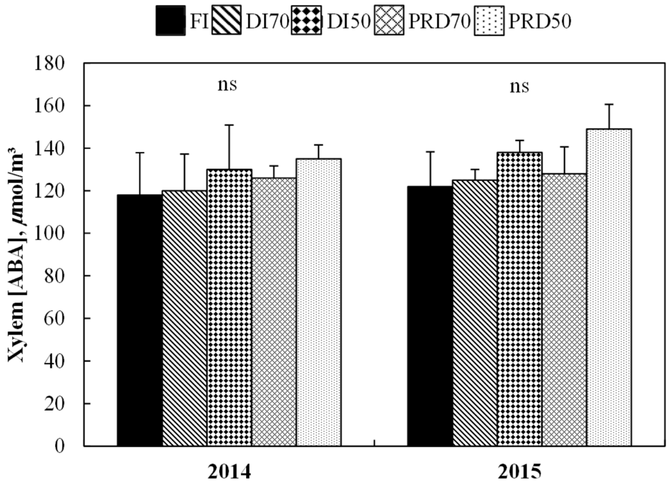

Figure 3. Xylem (ABA) values for potato on 15 April 2014 and 20 April 2015 for the different irrigation treatments. The bars give the mean ± standard error of the mean (n = 3). The abbreviation of "ns" denotes insignificant differences between irrigation treatments in each year based on the LSD test at $p < 0.05$.

3.2. Tuber Yields

Figure 4 shows that significant differences ($p < 0.01$) exist for fresh tuber yields for all irrigation treatments in the 2014 and 2015. These differences are indicated by letters directly above the bar graphs. The FI treatment resulted in the highest fresh tuber yields of 31.77 Mg/ha in 2014 and 35.91 Mg/ha in 2015. However, the PRD treatments reduced the fresh yield in comparison with FI and DI treatments. The yields of PRD70- and PRD50-treated plants reduced by 53.24% and 65.15%, respectively, and by 47.18% and 72.02% in 2015, respectively. Meanwhile, DI70 treatment produced the highest fresh tuber yield among the water-saving treatments, while PRD50 had the lowest yield value. In addition, the fresh tuber yield values of PRD70 decreased by 17.28% and 23.54% in comparison with DI70 in 2014 and 2015, respectively. Furthermore, the fresh tuber yield values of PRD50 decreased by 17.03% in 2014 and by 50.02% in 2015 in comparison with DI50.

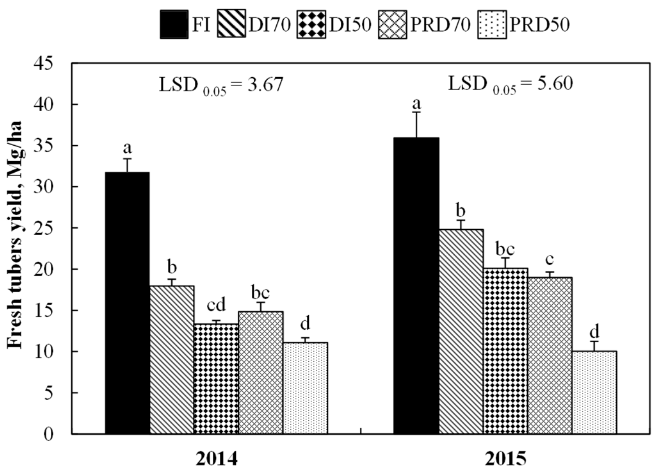

Figure 4. Fresh tuber yield per hectare for different irrigation treatments in 2014 and 2015. The bars give the mean ± standard error of the mean (n = 3). The similar letters directly above the columns in each year denote insignificant differences between irrigation treatments based on the LSD test at $p < 0.05$.

3.3. Water Productivity

The amounts of total irrigated water per hectare for FI, DI70, and DI50 treatments were 1505, 1049, and 812 mm, respectively, during the entire growing season of 2014. However, 1062 mm of PRD70-based water and 820 mm of PRD50-based water were received during the same year. On the other hand, 1495 mm of FI-based water, 1070 mm of DI70-based water, 797 mm of DI50-based water, 1075 mm of PRD70-based water, and 783 mm of PRD50-based water were received in 2015. The WP values of the water-saving treatments in both years were significantly ($p < 0.01$) lower than the corresponding value in 2015, except for the WP values of DI50 treatment (Figure 5). In 2014, the WP of PRD70 and PRD50 treatments were significantly reduced by 33.76% and 36.05%, respectively, in comparison to the WP of FI. However, PRD70 and PRD50 treatments decreased by 26.57% and 46.59% in 2015, respectively. When the WP of DI and PRD treatments were compared, DI70 (4.28 kg/m^3) and DI50 (4.11 kg/m^3) had higher WP values than PRD70 (3.50 kg/m^3) and PRD50 (3.37 kg/m^3) in 2014, respectively. A similar case was also observed in 2015.

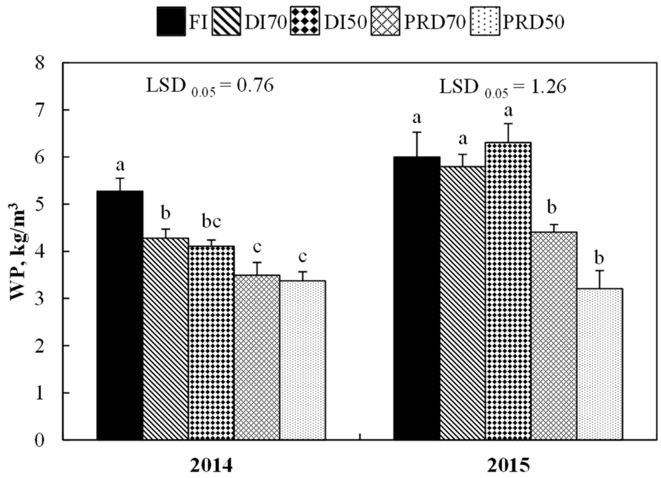

Figure 5. Water productivity (WP) in potato for different irrigation treatments in 2014 and 2015. The bars give the mean ± standard error of the mean ($n = 3$). The similar letters directly above the columns in each year denote insignificant differences between irrigation treatments based on the LSD test at $p < 0.05$.

4. Discussion

In this study, the Chl content values of PRD and DI were similar to the corresponding value of FI, which agree with the results of Yactayo et al. [29]. Generally, a decreasing trend in Chl content values was observed in the measurements during the growing season. Thus, the higher Chl content values obtained by DI and PRD treatments suggest that water restriction has a considerable effect on the onset and process of leaf senescence. Moreover, the A_n values of DI and PRD treatments were often statistically lower in comparison with the corresponding value of FI. This also agrees with earlier studies that presented lower A_n values for potatoes under drought stress situations in potatoes [23,42]. However, the A_n values of the PRD and FI treatments had insignificant differences for the same potato cultivar [42]. This inconsistency in results is found in other studies and could be attributed to climate variation [43] as the experiments were performed during hot summer conditions. Thus, the A_n of potatoes may only be affected when the water stress of the plants are under extremely severe conditions [44,45]. On the other hand, DI and PRD treatments did not have any significant effect on g_s values in 2014, which is consistent with the results of Shahnazari et al. [27] and Ahmadi et al. [23], who discovered that no significant difference exists for most g_s observations measured in stressed and unstressed field-grown. Moreover, the g_s values in 2014 and 2015 were consistent with the results of Liu et al. [15,16]. The lowest g_s corresponding to the PRD treatment caused stomatal closure, which occurs whenever the roots experience drought such that chemical signals involved in stomatal regulation are produced [9]. Generally, a water restriction of 50% reduced the T value by more than 30%, while the T values of DI and PRD treatments were lower than the corresponding value of FI treatment. Hence, our T values for DI and PRD are consistent with the results of Liu et al. [15,16].

Meanwhile, the A_n values for DI- and PRD-treated plants decreased due to exposure to sunlight intensity and other environmental factors. The lowest g_s values at midday indicate that the plants experienced the highest water stress levels (i.e., lowest Ψ_{leaf}), which could be due to high atmospheric evaporation. In such conditions, root water uptake may be insufficient to cater for the water lost through transpiration [46]. In addition, low Ψ_{leaf} values affected the values of g_a at midday, which is consistent with the results of Shimsi et al. [47] and Levy [48], who discovered that decreased g_s values of potatoes were associated with Ψ_{leaf} values less than -0.6 MPa. However, Stark [49] reported a lower Ψ_{leaf} value of -1.0 MPa as the critical threshold value in a field study of potato. Furthermore, PRD and DI had the highest A_n/T values as g_s reduced early and decreased more than A_n underwater stress, thereby increasing A_n/T [23,50]. The A_n/T values for PRD treatments were higher than the corresponding values of the DI treatments, because the g_s value for PRD was lower than the corresponding value of DI while the A_n value for PRD was higher than the corresponding value of DI.

Furthermore, the FI had the highest fresh tuber yields in both years; these are common potato yields [28,51,52]. Meanwhile, the fresh tuber yields of PRD treatments were lower in comparison with the yields of DI treatments. This is attributed to two reasons: (1) the climate exhibited high air temperatures, thereby making the potatoes sensitive to drought; and (2) the soil water content within the root zone of the potatoes was different due to the application of different irrigation treatments [28,53]. Hence, the WP values of the water-saving treatments were lower than the value of FI in 2014, which agrees with the results of Ahmadi et al. [54] who discovered that the WP values of the PRD treatments significantly decreased by 31% to 41% in comparison with FI treatment. Moreover, DI treatments had higher WP values than PRD treatments, which is consistent with the results of Liu et al. [16] and Ahmadi et al. [54]. Hence, PRD and DI are ineffective in the arid environments under current field management. This is because water reduction in arid environments contributes ~30% of crop water requirements to soil evaporation [28,29,55,56], despite the prevailing idea that the yield and WP of PRD are better than those of FI and DI [57]. Therefore, PRD strategy can be made effective by reducing the wet/dry cycle to minimize severe water stress on the plants, as determined by Sepaskhah and Parand [58] and in arid and semi-arid regions.

5. Conclusions

The effects of DI and PRD on the physiological characteristics, yield, and WP of potato were studied in comparison with FI in an arid area of Saudi Arabia. The results clearly indicate that DI and PRD do not affect the relative chlorophyll contents of potato plants compared with FI, but have negative impacts on the gas-exchange. Moreover, a 50% water deficit for the PRD insignificantly reduced xylem (ABA) in comparison with FI. A comparison of the treatments where the potato plants received the same amount of water over the whole growing season showed that the fresh tuber yields of PRD treatments were lower than the yields of DI treatments. Meanwhile, the application of 50% water use in PRD decreased WP compared with the results of FI and DI. Thus, a high amount of the applied water in an arid environment might be lost due to soil evaporation, thereby resulting in poor crop performance and WP.

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