



# Effects of different surface and subsurface drip irrigation levels on growth traits, tuber yield, and irrigation water use efficiency of potato crop

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## Abstract

Increased water demands and climate change have reduced agricultural water resources in areas that experience water shortages. Therefore, a field experiment was conducted in an arid region of Saudi Arabia to evaluate the effects of two drip irrigation systems [surface (DI) and subsurface (SDI)] and three irrigation levels [100%, 70%, and 50% of crop evapotranspiration ( $I_{100}$ ,  $I_{70}$ , and  $I_{50}$ , respectively)] on the growth traits, tuber yield, and irrigation water use efficiency (IWUE) of potato (*Solanum tuberosum* L.) during the 2017 and 2018 growing seasons.  $\theta_v$  was 13.74 and 23.85% lower under the DI system and 11.90 and 24.14% lower under the SDI system with the  $I_{70}$  and  $I_{50}$  treatments, respectively, than with the  $I_{100}$  treatment, and was also lower under the DI system than under the SDI system. The fresh and dry vegetative parts of the plants were heavier with the  $I_{100}$  treatment under the SDI system than with the  $I_{70}$  and  $I_{50}$  treatments under the DI system, and the leaf area indexes were also significantly lower with  $I_{70}$  and  $I_{50}$  than with  $I_{100}$  but were not affected by the irrigation system. The fresh and dry tuber yields were lowest with the  $I_{50}$  treatment (23.97 and 3.93 Mg ha<sup>-1</sup>, respectively), followed by  $I_{70}$  (28.61 and 4.98 Mg ha<sup>-1</sup>, respectively), and  $I_{100}$  (34.43 and 6.67 Mg ha<sup>-1</sup>, respectively) and were higher under the SDI system than under the DI system. By contrast, IWUE was highest with the  $I_{50}$  treatment (6.49 and 7.02 kg m<sup>-3</sup>) and lowest with the  $I_{100}$  treatment (5.62 and 5.85 kg m<sup>-3</sup>) under the DI and SDI systems, respectively. These findings indicate that full irrigation ( $I_{100}$ ) with the SDI system maximizes potato yield but decreases IWUE, whereas integration of the SDI system with deficit irrigation is effective in improving water productivity due to less water being consumed, allowing these practices to be used under scarce water conditions.

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## Introduction

Over 40% of global food production comes from irrigated land, and the agricultural sector has the highest water consumption, using 70% of our existing freshwater resources (FAO 2017; Mancosu et al. 2015). With an expected 8 billion people needing to be fed by 2025, food security can only be guaranteed if the irrigated land area and crop yield increase by more than 20 and 40%, respectively (Lascano and Sojka 2007). Therefore, the efficiency of water consumption in agriculture needs to be maximized to ensure maximum productivity with minimal water input. Improving agricultural water management is a promising way to achieve this goal (Unver et al. 2017), as it will allow water, energy, and soil resources to be conserved while meeting growing demands for crops, foods, and fibers (Kassam et al. 2007).

Flood and sprinkler irrigation systems are often associated with high water wastage and a low irrigation water use

efficiency (IWUE), as well as adverse soil salinity and drainage conditions (Yazar et al. 2002), which has resulted in drip irrigation systems becoming increasingly popular (Şimşek et al. 2004). Drip irrigation supplies a large number of crops with a uniformly distributed and frequent water application using a low-pressure emitter to trickle water onto the soil and is suitable for different soil types and all topographic conditions (Dağdelen et al. 2009; Liu et al. 2017). Emitters are either placed on the surface of the soil (surface drip irrigation, DI), which results in the formation of a shallow pond or buried (subsurface drip irrigation, SDI), which leads to the formation of a saturated bulb surrounded by a wet-bulb of unsaturated soil (Cook et al. 2006). SDI can increase the yield and net profit margin, reduce nitrate loss from deep percolation, minimize soil water evaporation, and increase IWUE and the quality of agricultural products (Douh and Boujelben 2010; Odhiambo and Irmak 2015; Yuan et al. 2003) compared with other irrigation systems, including DI (Camp 1998).

Other water management techniques include deficit irrigation, which allows larger agricultural areas to be irrigated under limited water resources (Chaves et al. 2010; Sezen et al. 2014). This technique strongly affects irrigation scheduling because crops respond to water stress in different ways in their various growth stages. It has been stated that important considerations when applying deficit irrigation are the timing and degree of water stress experienced by the plants (Jovanovic and Stikic 2012; Loveys et al. 2004; Yang et al. 2017), as well as crop evapotranspiration ( $ET_c$ ) and responses to water stress (Capra et al. 2008). Under adequate deficit drip irrigation, crops develop deep roots that allow them to reach the soil water, resulting in significant water savings without crop yield reduction (i.e., IWUE increases) and an increased profit margin for farmers (Chai et al. 2016; Evett and Tolk 2009; Kato et al. 2006; Kirda 2002; Stikic et al. 2010).

Deficit irrigation has been found to promote plant growth and IWUE for a variety of crops in different countries. For example, Geets and Kirk (2009) confirmed that deficit irrigation increases the IWUE of different crops without reducing their yield when water stress is induced during drought-sensitive growth stages, while Ngouajio et al. (2007) showed that tomato (*Solanum lycopersicum* L.) yields in southern Michigan, USA, could be increased by preventing irrigation in the first few weeks after transplantation, as long as the water content in the soil at the time of transplanting was sufficient. Similarly, Sharma et al. (2014) showed that deficit irrigation under SDI in arid environments of the USA led to a moderate decrease in the yield of melon (*Cucumis melo* L.) but no reduction in fruit quality. Müller et al. (2016) reported that the optimum soil matric potentials for DI of eggplant (*Solanum melongena* L.) in Burkina Faso during the early growth and fruit-setting stages were  $-15$  and  $-40$  kPa, respectively.

Shammout et al. (2018) also found that irrigation at 80%  $ET_c$  gave the highest yield of bell pepper (*Capsicum annum* L.) in Jordan and that there was no difference in IWUE between 80 and 100%  $ET_c$ , while Mattar et al. (2020) indicated that irrigation at 70%  $ET_c$  increased tomato yield, fruit quality, and IWUE compared with 100%  $ET_c$  in Saudi Arabia.

Potato (*Solanum tuberosum* L.) is one of the most economically important crops globally, ranking fourth in the world in terms of its nutritional value (Fabeiro et al. 2001). However, it is sensitive to drought (Obidiegwu et al. 2015), making it particularly difficult to manage (Shock and Feibert 2002). Drip irrigation can significantly improve potato growth under adverse arid conditions (Erdem et al. 2006; Onder et al. 2005; Zin El-Abedin et al. 2017), and several studies have examined the response of potato crops to deficit irrigation to further improve its IWUE (Cantore et al. 2014; Elhani et al. 2019; Jovanovic et al. 2010; Nagaz et al. 2016; Shahnazari et al. 2007). Among these, Shahnazari et al. (2007) showed that there was no significant difference in potato yield under deficit and full irrigation, but IWUE was 1.6 times higher under deficit irrigation (approximately 30% water saving), while Jovanovic et al. (2010) reported that water savings of 38% could be made without significantly affecting tuber yield. In addition, Cantore et al. (2014) indicated that irrigation at 50%  $ET_c$  generated satisfactory potato yields in Italy, with a tuber quality similar to or better than that obtained under full irrigation, and Nagaz et al. (2016) found that 70%  $ET_c$  provided the best trade-off between tuber yield and IWUE, while 50%  $ET_c$  gave the highest IWUE. Finally, Elhani et al. (2019) reported that deficit irrigation improved vegetative growth and tuber quality in a glasshouse and increased IWUE compared with full irrigation.

Freshwater resources are scarce not only in arid and semi-arid regions but also in areas that experience heavy rainfall, and agriculture has the greatest potential to solve this global issue. Therefore, there is a need for research that focuses on maintaining the yield and quality of crops and water productivity using pressurized irrigation systems under limited water conditions to ensure the effective use of available freshwater resources in irrigated agriculture. The objectives of this study were to (1) investigate the effects of different water levels on the soil water status under DI and SDI systems; and (2) evaluate the performance of DI and SDI systems with deficit irrigation in terms of vegetative growth, tuber yield, and IWUE in potato.

## Materials and methods

### Study site

Field experiments were conducted at the Educational Farm of King Saud University, Riyadh ( $24^{\circ}44'11.10''N$ ,

46°37'06.61"E; 665 m a.s.l), during the 2017 and 2018 growing seasons (January–May). A weather station was installed near the experimental area to monitor and record meteorological data (Fig. 1). This region has an arid climate, with hot and dry summers. The mean air temperature was 22.6 °C and 22.2 °C, the mean relative humidity was 35.1 and 38.6%, and the total rainfall was 25.7 mm and 72.6 mm in the 2017 and 2018 growing seasons, respectively. Reference evapotranspiration ( $ET_0$ ;  $\text{mm day}^{-1}$ ) was calculated from the recorded meteorological data using the FAO-56 Penman–Monteith equation (Allen et al. 1998) as shown in Eq. (1):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

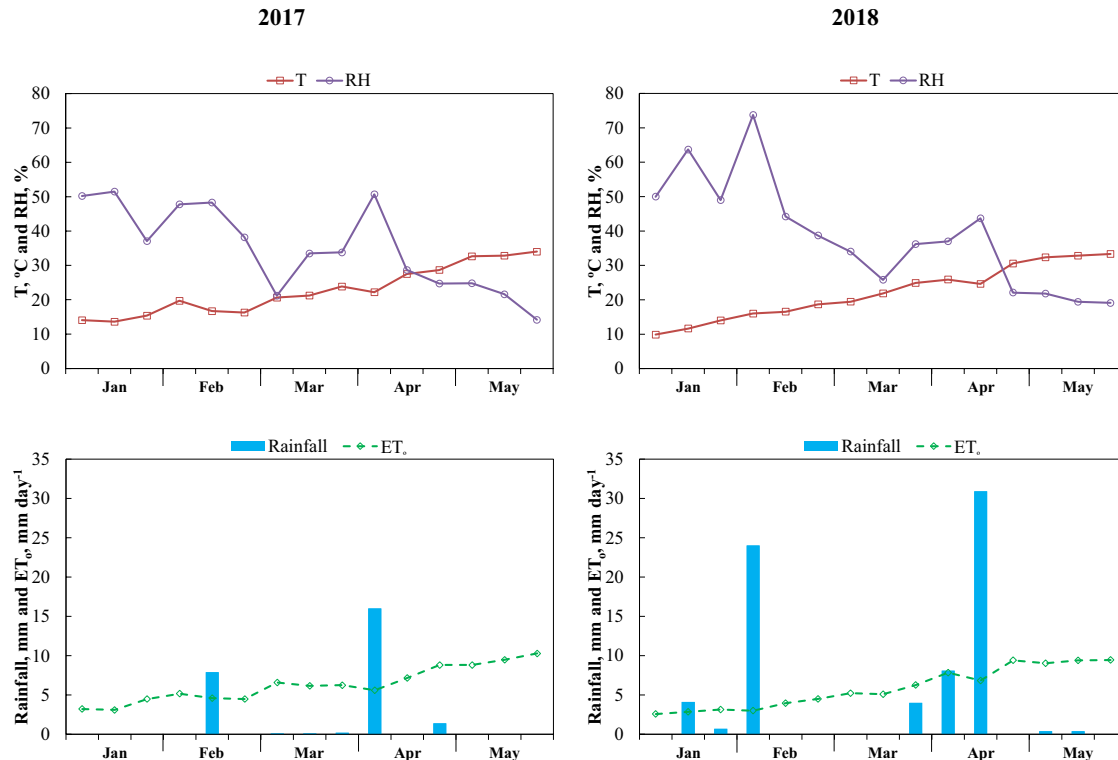
where  $\Delta$  is the slope of the saturation vapor pressure–temperature curve at mean air temperature ( $\text{kPa } ^\circ\text{C}^{-1}$ ),  $R_n$  is the net radiation ( $\text{MJ m}^{-2} \text{day}^{-1}$ ),  $T$  is the mean air temperature at 2-m height ( $^\circ\text{C}$ ),  $u_2$  is the wind speed at 2-m height ( $\text{m s}^{-1}$ ),  $\gamma$  is the psychrometric constant ( $\text{kPa } ^\circ\text{C}^{-1}$ ),  $G$  is the soil heat flux ( $\text{MJ m}^{-2} \text{day}^{-1}$ ), and  $e_s$  and  $e_a$  are the saturation and actual vapor pressures, respectively (kPa).  $ET_0$  was between 3.1 and 10.3  $\text{mm day}^{-1}$  during the 2017 season

and between 2.6 and 9.4  $\text{mm day}^{-1}$  during the 2018 season (Fig. 1).

Before the start of the experiment, soil samples were collected to a depth of 60 cm and the soil physical characteristics were recorded at each 20-cm depth interval (see Table 1). This showed that the soil had a sandy loam texture with a mean bulk density of  $1.6 \text{ g cm}^{-3}$  and a soil water content of 138 mm at field capacity (FC) and 78 mm at wilting point (WP), indicating that the available water in the soil profile was 60 mm.

## Experimental procedure

The experiment was set up using a randomized complete block design with six treatments (two irrigation systems  $\times$  three irrigation levels) and three replicates per treatment. The two irrigation systems (DI and SDI) were applied at the block level and the three irrigation levels [full irrigation at 100%  $ET_c$  ( $I_{100}$ ) and regular deficit irrigation at 70% and 50%  $ET_c$  ( $I_{70}$  and  $I_{50}$ , respectively)] were randomly assigned within these blocks using separate randomization for each block. The experimental area was divided into three fields (one for each replicate) that were separated by 2-m buffer zones (Fig. 2). Each field contained two blocks that were each further divided into three equal plots, leaving a



**Fig. 1** Ten-day average air temperature (T), relative humidity (RH), and reference evapotranspiration ( $ET_0$ ), and the summed rainfall during the 2017 and 2018 growing seasons

**Table 1** Soil physical properties at the experimental site

Depth (cm)	Particle size (%)			Texture	FC (vol.%)	WP (vol.%)	Ks (mm h <sup>-1</sup> )	ρ <sub>b</sub> (g cm <sup>-3</sup> )
	Sand	Silt	Clay					
0–20	71.8	16.3	11.9	Sandy loam	19.7	9.7	35.8	1.6
20–40	66.7	18.0	15.3	Sandy loam	23.8	13.8	23.6	1.6
40–60	69.1	18.3	12.6	Sandy loam	25.4	15.5	18.6	1.6

FC field capacity, WP wilting point, Ks saturated hydraulic conductivity, ρ<sub>b</sub> bulk density

0.75-m interval between the plots to avoid lateral leakage from the irrigation treatment applied in adjacent plots. The irrigation level plots (I<sub>100</sub>, I<sub>70</sub>, and I<sub>50</sub>) in the DI and SDI blocks were irrigated daily based on the daily ET<sub>c</sub> (mm day<sup>-1</sup>), which was calculated as shown in Eq. (2) (Allen et al. 1998):

$$ET_c = ET_o \times K_c \tag{2}$$

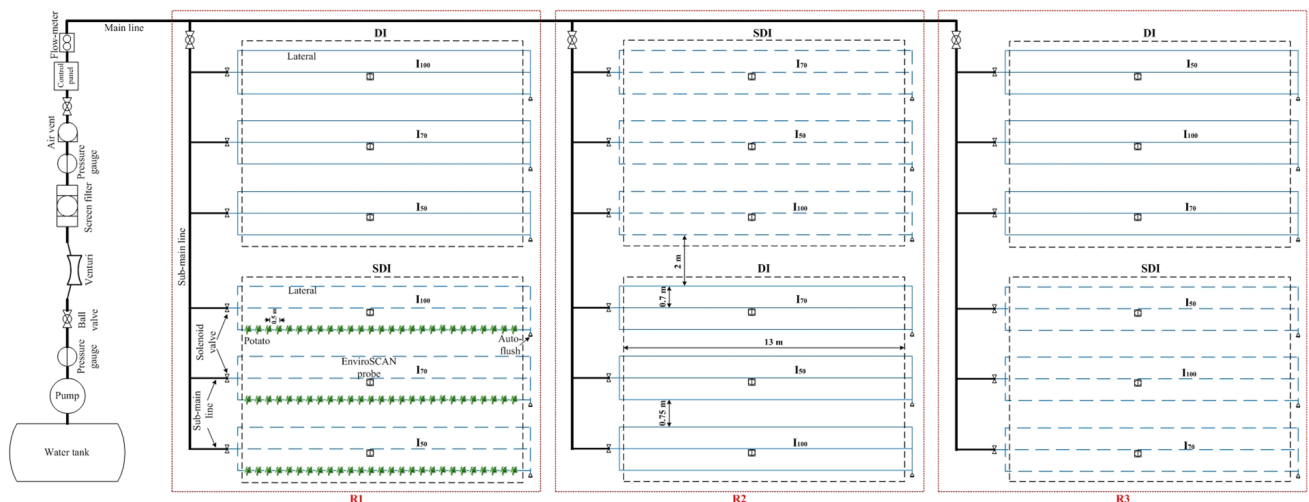
where K<sub>c</sub> is the stage-specific crop coefficient. The lengths of the main growth stages, K<sub>c</sub>, and the total amounts of water applied for each treatment during the 2017 and 2018 growing seasons are presented in Table 2. The same amount of water was applied to all treatments until 30 days after planting (DAP), at which time the deficit irrigation treatments (I<sub>70</sub> and I<sub>50</sub>) were applied under both the DI and SDI systems.

Preliminary field preparations for the potato seedbeds included plowing, grading, and leveling. The soil was ridged with 70-cm spacing and 30-cm height to create furrows, following which a DI and SDI systems were set up that comprised a water tank, a pump unit, a pressure regulator, a fertigation unit, a screen filter, an air vent, manual and solenoid valves, flow meters, and flush valves (Fig. 2). Main and sub-main lines were buried beneath the soil surface, while

manifold lines were positioned above the soil surface. The drip lines consisted of built-in emitters that had a discharge of 8 L h<sup>-1</sup> at an operating pressure of 100 kPa and were laid manually above (DI) or 10 cm below (SDI) the soil surface at the center of each crop row at 70-cm intervals from adjacent rows and with 50-cm intervals between emitters. The irrigation systems were controlled automatically in this study. Potato tubers of the cultivar Hermes were planted by hand at a density of five plants per m<sup>2</sup> on January 27, 2017 and January 24, 2018. A soil ridge was maintained 15 cm above the tubers in the prepared furrows. Compound NPK fertilizer was applied at the same concentration to all treatment plots via the irrigation systems from 7 DAP based on the following scheduled program: N–P<sub>2</sub>O<sub>5</sub>–K<sub>2</sub>O (20:20:20) at rates of 180, 250, and 270 kg ha<sup>-1</sup> and N–P<sub>2</sub>O<sub>5</sub>–K<sub>2</sub>O (10:10:43) at rates of 150, 250, and 200 kg ha<sup>-1</sup> up to 37, 67, and 88 DAP, respectively. Potato tubers were harvested on May 24, 2017 and May 21, 2018.

**Soil water measurements**

The volumetric soil water content (θ<sub>v</sub>) was measured in 10-cm increments up to a depth of 50 cm using multi-sensor capacitance probes (EnviroSCAN®; Sentek Sensor



**Fig. 2** Schematic diagram of the experimental fields. DI surface drip irrigation, SDI subsurface drip irrigation, I<sub>100</sub> 100% of crop evapotranspiration (ET<sub>c</sub>), I<sub>70</sub> 70% ET<sub>c</sub>, I<sub>50</sub> 50% ET<sub>c</sub>

**Table 2** Dates and crop coefficient ( $K_c$ ) values for each potato (*Solanum tuberosum*) growth stage and the total amount of water applied during the study period

Growth stage	Date (number of days at the stage) <sup>a</sup>		$K_c^a$	$(K_c)_{\text{adjusted}}^b$	Water applied <sup>c</sup> (mm)						
	2017	2018			2017			2018			
			$I_{100}$	$I_{70}$	$I_{50}$	$I_{100}$	$I_{70}$	$I_{50}$			
Planting	Jan 27	Jan 24									
Initial (until the beginning of stem elongation)	Feb 20 (25)	Feb 17 (25)	0.50	0.20	18	18	18	17	17	17	
Crop development (until tuber formation)	March 25 (33)	March 22 (33)			123	92	71	122	91	71	
Mid-season (until tuber enlargement)	April 24 (30)	April 21 (30)	1.15	1.25	226	169	130	225	167	131	
Late season (maturity)	May 24 (30)	May 21 (30)	0.75	0.87	235	175	136	234	174	136	
<b>Seasonal</b>	<b>(118)</b>	<b>(118)</b>			<b>602</b>	<b>454</b>	<b>355</b>	<b>598</b>	<b>448</b>	<b>354</b>	

$I_{100}$  100% of crop evapotranspiration ( $ET_c$ ),  $I_{70}$  70%  $ET_c$ ,  $I_{50}$  50%  $ET_c$

<sup>a</sup>Obtained from FAO-56 data (Allen et al. 1998)

<sup>b</sup>Adjusted from the FAO-56 (Allen et al. 1998) based on the percentage of soil surface wetted, wind speed at 2-m height and minimum relative humidity

<sup>c</sup>Irrigation plus rainfall

Technologies, Stepney, Australia). These probes continuously monitored  $\theta_v$  in the root zone throughout the growing season after being calibrated at the experimental site following Sentek (2001) and Jabro et al. (2005). A total of 18 probes (six treatments  $\times$  three replicates) were inserted vertically into the middle of the ridge of each drip line in each experimental field.

### Agronomic measurements

In each growing season, three plants were randomly selected from each plot (treatment) at 90 DAP and prepared for analysis of the fresh weight of the vegetative parts (leaf and stem;  $\text{Mg ha}^{-1}$ ), plant height (cm), number of branches ( $\text{plant}^{-1}$ ), and leaf area index (LAI), which was measured using an LI-3100 leaf area meter (Licor Inc., Lincoln, Nebraska, USA). The vegetative samples were then dried at 60 °C for 48 h (Ahmadi et al. 2014) using a forced-air oven to determine the dry weight ( $\text{Mg ha}^{-1}$ ).

The potato harvesting area in each treatment consisted of three 13-m-long rows. After harvesting, the total fresh tuber yield ( $\text{Mg ha}^{-1}$ ), fresh weight (g), mean weight (g), and number of tubers per plant were measured. The tubers were then oven-dried for 24 h at 85 °C (Liu et al. 2006) to measure their dry weights ( $\text{Mg ha}^{-1}$ ). After excluding any deformed and diseased tubers, the remaining tubers were classified according to their diameter, following the method of Shahnazari et al. (2007), whereby < 50 mm was considered small, 50–80 mm was moderate (marketable tubers), and > 80 mm was large. The tubers were then counted and weighed as a percentage of the total weight.

### Irrigation water use efficiency (IWUE) and yield response factor

IWUE ( $\text{kg m}^{-3}$ ) was calculated by dividing the total fresh tuber weight ( $\text{kg ha}^{-1}$ ) by the total amount of water applied (irrigation plus rainfall,  $\text{m}^3 \text{ha}^{-1}$ ) during each growing season (Kirda et al. 2005).

The yield response factor ( $K_y$ ) was calculated from the fresh tuber yield for each irrigation system using the pooled data across the two experimental years (Doorenbos and Kassam 1979), as shown in Eq. (3):

$$\left(1 - \frac{Y_a}{Y_x}\right) = K_y \left(1 - \frac{ET_a}{ET_x}\right) \quad (3)$$

where  $Y_a$  is the tuber yield ( $\text{Mg ha}^{-1}$ ) obtained from the  $I_{70}$  or  $I_{50}$  treatment,  $Y_x$  is the tuber yield ( $\text{Mg ha}^{-1}$ ) obtained from the  $I_{100}$  treatment,  $ET_a$  is the crop water consumption ( $\text{m}^3 \text{ha}^{-1}$ ) under deficit irrigation (70% or 50%  $ET_c$ ), and  $ET_x$  is the crop water consumption ( $\text{m}^3 \text{ha}^{-1}$ ) under full irrigation (100%  $ET_c$ ). Similarly, the biomass response factor ( $K_{ss}$ ) was calculated from the dry biomass yield (tuber plus vegetative parts), as shown in Eq. (4):

$$\left(1 - \frac{SS_a}{SS_x}\right) = K_{ss} \left(1 - \frac{ET_a}{ET_x}\right) \quad (4)$$

where  $SS_a$  and  $SS_x$  are the dry biomass yields ( $\text{Mg ha}^{-1}$ ) under full irrigation and deficit irrigation, respectively.  $K_y$  and  $K_{ss}$  are indicate the relationship between relative yield and relative crop water consumption (Lovelli et al. 2007; Singh et al. 2010), with values > 1 indicating that the crop is very sensitive to water stress, values < 1 indicating that the crop is more tolerant to water stress, and values of 1

indicating that the relative yield reduction is equal to the relative water use reduction (Steduto et al. 2012).

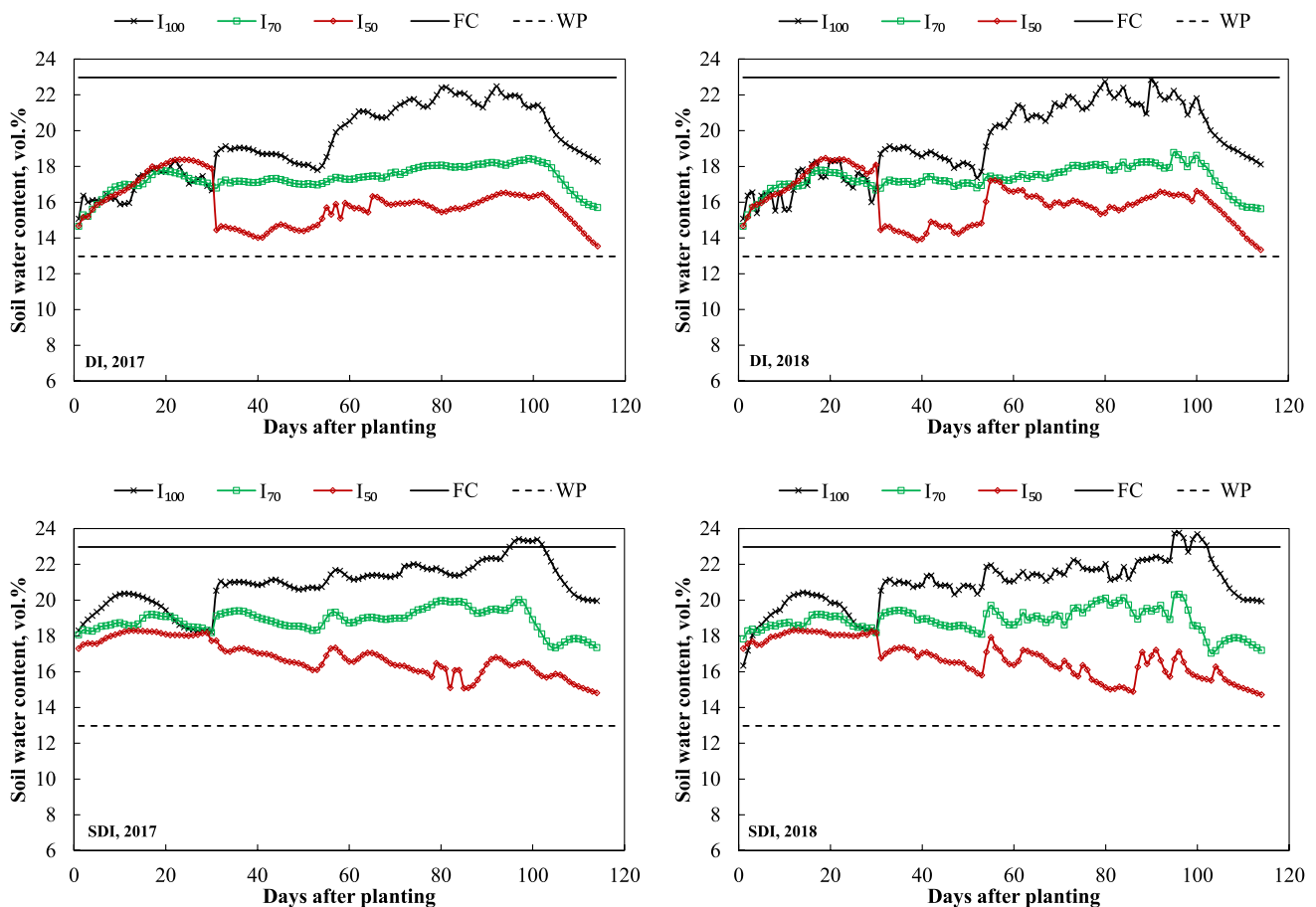
## Data analysis

Differences in the vegetative growth traits, tuber yield, yield components, and IWUE among treatments were statistically analyzed by two-way analysis of variance (ANOVA) (irrigation system  $\times$  irrigation level) for each experimental year with three replicates per treatment using CoStat version 6.003 (CoHort, USA, 1998–2004). In addition, three-way ANOVA (year  $\times$  irrigation system  $\times$  irrigation level) was performed to evaluate the statistical significance of annual variations. The significance of differences between means was assessed using the least significant difference (LSD) test at a 5% probability level ( $p \leq 0.05$ ). Data are presented as means  $\pm$  standard errors (SE) of the three replicates. Finally, the relationships among the fresh tuber yield and the number and mean weight of tubers per plant were examined using regression analysis.

## Results

### Soil water

Differences in soil water storage between the two drip irrigation systems (DI and SDI) and three irrigation levels ( $I_{100}$ ,  $I_{70}$ , and  $I_{50}$ ) were determined by calculating the average  $\theta_v$  of five sampling points at depths of 10, 20, 30, 40, and 50 cm each day throughout the 2017 and 2018 growing seasons for all treated plants (Fig. 3). There were no differences in the  $\theta_v$  profile among the different irrigation levels up to 30 DAP in either season because the same amount of irrigation water (corresponding to 100%  $ET_c$ ) was applied to each. However, the average  $\theta_v$  values were higher for SDI (18.66 and 18.63% for 2017 and 2018, respectively) than for DI (16.98 and 17.04% for 2017 and 2018, respectively) during this period. From 31 DAP onward, the  $\theta_v$  values for the  $I_{100}$  treatment remained above 50% of the available soil water (i.e., the median  $\theta_v$  value between FC and WP).



**Fig. 3** Volumetric soil water content (%) of the average of five points at depths of 10, 20, 30, 40, and 50 cm under different irrigation systems and with different irrigation levels in the 2017 and 2018 grow-

ing seasons. *DI* surface drip irrigation, *SDI* subsurface drip irrigation,  $I_{100}$  100% of crop evapotranspiration ( $ET_c$ ),  $I_{70}$  70%  $ET_c$ ,  $I_{50}$  50%  $ET_c$ , *FC* field capacity, *WP* wilting point

and WP or 18%) and were close to the FC, averaging 20.14 and 21.39% under the DI and SDI systems, respectively, across both growing seasons. By contrast, the application of deficit irrigation treatments at 31 DAP resulted in the temporal variance of  $\theta_v$  under both irrigation systems due to a gradual decrease in soil water content until the end of both seasons. However, while the  $\theta_v$  values for the  $I_{70}$  treatment dropped below 50% of the available soil water under the DI system (average: 17.39 and 17.35% for 2017 and 2018, respectively), they remained above 50% of the available soil water under the SDI system (average: 18.86 and 18.84% for 2017 and 2018, respectively), though were still lower than values obtained under the  $I_{100}$  treatment. The  $\theta_v$  values for the  $I_{50}$  treatment remained between 50% of the available soil water and the WP and were lower than the values reported for the  $I_{100}$  and  $I_{70}$  treatments, ranging from 12.91 to 16.53% in 2017 and 12.77–17.21% in 2018 under the DI system and from 14.71 to 17.74% in 2017 and 14.69–17.92% in 2018 under the SDI system.

## Vegetative growth traits

The irrigation system significantly affected the fresh and dry weights of the vegetative parts, with the SDI system resulting in 30.20 and 41.32% higher weights, respectively, in the 2017 season and 32.82 and 34.29% higher weights, respectively, in the 2018 season than the DI system (Table 3). There were also significant differences in these weights between the growing seasons. Irrespective of the irrigation system used, the fresh and dry weights of the vegetative parts were significantly lower with the  $I_{70}$  and  $I_{50}$  treatments than with the  $I_{100}$  treatment in both growing seasons, with the fresh weights decreasing by 33.61 and 34.52%, respectively, and the dry weights decreasing by 28.93 and 35.03%, respectively. There were no significant interaction effects between the irrigation systems and levels on the fresh or dry weights in either season (Table 3).

There were no significant differences in plant height between treatments in the 2017 season (Table 4). However, in 2018, plants grown under SDI were significantly taller than those grown under DI ( $p < 0.05$ ), and plants exposed

**Table 3** Fresh and dry weights of the vegetative parts of potato (*Solanum tuberosum*) plants under different irrigation systems and with different irrigation levels in the 2017 and 2018 growing seasons

Factor	Vegetative parts FW (Mg ha <sup>-1</sup> )			Vegetative parts DW (Mg ha <sup>-1</sup> )		
	2017 <sup>B</sup>	2018 <sup>A</sup>	Mean	2017 <sup>B</sup>	2018 <sup>A</sup>	Mean
<b>Irrigation system</b>						
DI	10.53 <sup>b</sup>	11.67 <sup>b</sup>	11.10 <sup>b</sup>	1.21 <sup>b</sup>	1.40 <sup>b</sup>	1.30 <sup>b</sup>
SDI	13.71 <sup>a</sup>	15.50 <sup>a</sup>	14.60 <sup>a</sup>	1.71 <sup>a</sup>	1.88 <sup>a</sup>	1.80 <sup>a</sup>
<i>p</i> -value	0.009**	0.003**	<0.001***	0.008**	0.011*	<0.001***
LSD <sub>0.05</sub>	2.18	2.20	1.42	0.34	0.35	0.21
<b>Irrigation level</b>						
$I_{100}$	14.95 <sup>a</sup>	18.31 <sup>a</sup>	16.63 <sup>a</sup>	1.86 <sup>a</sup>	2.09 <sup>a</sup>	1.97 <sup>a</sup>
$I_{70}$	10.58 <sup>b</sup>	11.49 <sup>b</sup>	11.04 <sup>b</sup>	1.31 <sup>b</sup>	1.49 <sup>b</sup>	1.40 <sup>b</sup>
$I_{50}$	10.83 <sup>b</sup>	10.96 <sup>b</sup>	10.89 <sup>b</sup>	1.20 <sup>b</sup>	1.35 <sup>b</sup>	1.28 <sup>b</sup>
<i>p</i> -value	0.007**	<0.001***	<0.001***	0.012*	0.008**	<0.001***
LSD <sub>0.05</sub>	2.67	2.70	1.74	0.41	0.43	0.25
<b>Irrigation system × level</b>						
<b>DI</b>						
$I_{100}$	13.25 (±0.38)	16.14 (±0.11)	14.70 (±0.74)	1.56 (±0.11)	1.91 (±0.13)	1.73 (±0.11)
$I_{70}$	8.50 (±0.76)	9.65 (±0.16)	9.07 (±0.71)	1.04 (±0.16)	1.09 (±0.15)	1.07 (±0.10)
$I_{50}$	9.83 (±1.39)	9.23 (±0.21)	9.53 (±0.81)	1.03 (±0.21)	1.20 (±0.26)	1.12 (±0.16)
<b>SDI</b>						
$I_{100}$	16.64 (±2.18)	20.48 (±0.18)	18.56 (±1.48)	2.16 (±0.29)	2.27 (±0.17)	2.21 (±0.15)
$I_{70}$	12.67 (±0.36)	13.33 (±0.06)	13.00 (±0.72)	1.59 (±0.06)	1.89 (±0.20)	1.74 (±0.12)
$I_{50}$	11.82 (±0.37)	12.69 (±0.06)	12.25 (±0.48)	1.38 (±0.05)	1.50 (±0.14)	1.44 (±0.07)
<i>p</i> -value	0.665 <sup>ns</sup>	0.932 <sup>ns</sup>	0.727 <sup>ns</sup>	0.787 <sup>ns</sup>	0.388 <sup>ns</sup>	0.365 <sup>ns</sup>
LSD <sub>0.05</sub>	–	–	–	–	–	–

Different lower-case letters within each column and different upper-case letters within the header row for planting season for each characteristic indicate significant differences at the 0.05 level. Values are presented as means (± SE)

FW fresh weight, DW dry weight, DI surface drip irrigation, SDI subsurface drip irrigation,  $I_{100}$  100% of crop evapotranspiration (ET<sub>c</sub>),  $I_{70}$  70% ET<sub>c</sub>,  $I_{50}$  50% ET<sub>c</sub>, LSD least significant difference, ns non-significant ( $p > 0.05$ ), \*0.05 ≥  $p > 0.01$ , \*\*0.01 ≥  $p > 0.001$ , \*\*\* $p \leq 0.001$

to the  $I_{100}$  treatment were significantly taller than those exposed to the  $I_{70}$  and  $I_{50}$  treatments ( $p < 0.05$ ), which were not significantly different from each other, irrespective of the irrigation system employed. In 2018, the shortest plants were produced with the  $I_{70}$  treatment under both DI (33.50 cm) and SDI (41.53 cm), while the tallest plants were obtained with the  $I_{100}$  treatment under DI (46.50 cm) and the  $I_{50}$  treatment under SDI (43.20 cm). There was no significant difference in the branch number per plant among the irrigation level treatments when considered alone or in combination with the DI and SDI systems in either season (Table 4). However, plants managed under the SDI system had 40.42 and 28.38% more branches per plant than those managed under the DI system in 2017 and 2018, respectively, irrespective of the irrigation level. By contrast, the irrigation system did not have a significant effect on LAI, but plants treated with  $I_{50}$  and  $I_{70}$  had significantly lower LAI values (average: 3.00 and 3.13, respectively) than those subjected to the  $I_{100}$  treatment (3.53). Under both DI and SDI, the  $I_{70}$  and  $I_{50}$  treatments

had a lower LAI than the  $I_{100}$  treatment in both seasons, though these differences were not significant ( $p > 0.05$ ).

### Tuber yield

The fresh tuber yield significantly differed between the irrigation systems and among the irrigation levels in both the 2017 and 2018 growing seasons, while the dry tuber yield only significantly differed among the irrigation levels in both seasons (Table 5). There were also significant differences in the fresh tuber yield between growing seasons, but no such differences for the dry tuber yield. The fresh tuber yield was 7.90 and 5.52% higher under the SDI system than under the DI system in 2017 and 2018, respectively. The fresh and dry tuber yields with  $I_{100}$  were 32.33 and 6.55 Mg ha<sup>-1</sup>, respectively, in 2017 and 36.53 and 6.78 Mg ha<sup>-1</sup>, respectively, in 2018. A 30% reduction in the amount of irrigation water ( $I_{70}$ ) resulted in the fresh and dry tuber yields decreasing by 17.23 and 21.22%, respectively, in 2017 and 16.64 and 34.35%, respectively, in 2018, while a 50% reduction in the amount

**Table 4** Physical characteristics of potato (*Solanum tuberosum*) plants under different irrigation systems and with different irrigation levels in the 2017 and 2018 growing seasons

Factor	Plant height (cm)			Number of branches (plant <sup>-1</sup> )			LAI		
	2017	2018	Mean	2017	2018	Mean	2017 <sup>B</sup>	2018 <sup>A</sup>	Mean
<b>Irrigation system</b>									
DI	42.33	38.79 <sup>b</sup>	40.56 <sup>b</sup>	5.22 <sup>b</sup>	5.11 <sup>b</sup>	5.17 <sup>b</sup>	3.17	3.36	3.27
SDI	44.22	42.58 <sup>a</sup>	43.40 <sup>a</sup>	7.33 <sup>a</sup>	6.56 <sup>a</sup>	6.94 <sup>a</sup>	3.11	3.23	3.17
<i>p</i> -value	0.417 <sup>ns</sup>	0.025 <sup>*</sup>	0.039 <sup>*</sup>	0.024 <sup>*</sup>	0.036 <sup>*</sup>	0.001 <sup>***</sup>	0.359 <sup>ns</sup>	0.304 <sup>ns</sup>	0.140 <sup>ns</sup>
LSD <sub>0.05</sub>	–	3.19	2.69	1.77	1.33	0.98	–	–	0.13
<b>Irrigation level</b>									
$I_{100}$	44.00	44.75 <sup>a</sup>	44.38 <sup>a</sup>	6.17	5.83	6.00	3.45 <sup>a</sup>	3.61 <sup>a</sup>	3.53 <sup>a</sup>
$I_{70}$	41.83	37.52 <sup>b</sup>	41.89 <sup>ab</sup>	6.17	6.33	6.25	3.05 <sup>b</sup>	3.21 <sup>b</sup>	3.13 <sup>b</sup>
$I_{50}$	44.00	39.78 <sup>b</sup>	39.68 <sup>b</sup>	6.50	5.33	5.92	2.93 <sup>b</sup>	3.07 <sup>b</sup>	3.00 <sup>b</sup>
<i>p</i> -value	0.669 <sup>ns</sup>	0.006 <sup>**</sup>	0.024 <sup>*</sup>	0.926 <sup>ns</sup>	0.424 <sup>ns</sup>	0.840 <sup>ns</sup>	< 0.001 <sup>***</sup>	0.013 <sup>*</sup>	< 0.001 <sup>***</sup>
LSD <sub>0.05</sub>	–	3.91	3.29	–	–	1.21	0.16	0.34	0.16
<b>Irrigation system × level</b>									
<b>DI</b>									
$I_{100}$	45.33 (± 0.88)	46.50 (± 1.50) <sup>a</sup>	45.92 (± 0.82) <sup>a</sup>	6 (± 0.88)	5 (± 0.93)	5 (± 0.58)	3.48 (± 0.03)	3.68 (± 0.09)	3.58 (± 0.06)
$I_{70}$	39.67 (± 4.67)	33.50 (± 1.76) <sup>c</sup>	36.58 (± 2.62) <sup>c</sup>	4 (± 1.00)	5 (± 0.90)	5 (± 0.68)	3.09 (± 0.06)	3.23 (± 0.19)	3.16 (± 0.10)
$I_{50}$	42.00 (± 0.58)	36.36 (± 1.72) <sup>bc</sup>	39.18 (± 1.50) <sup>bc</sup>	6 (± 1.53)	5 (± 0.33)	5 (± 0.76)	2.93 (± 0.10)	3.18 (± 0.12)	3.06 (± 0.09)
<b>SDI</b>									
$I_{100}$	42.67 (± 3.18)	43.00 (± 0.53) <sup>a</sup>	42.83 (± 1.44) <sup>ab</sup>	7 (± 1.20)	6 (± 0.87)	6 (± 0.68)	3.41 (± 0.11)	3.54 (± 0.20)	3.48 (± 0.10)
$I_{70}$	44.00 (± 0.58)	41.53 (± 1.53) <sup>ab</sup>	42.77 (± 0.92) <sup>ab</sup>	8 (± 0.33)	7 (± 0.67)	8 (± 0.40)	3.00 (± 0.03)	3.18 (± 0.15)	3.09 (± 0.08)
$I_{50}$	46.00 (± 3.61)	43.20 (± 3.67) <sup>a</sup>	44.60 (± 2.38) <sup>a</sup>	7 (± 0.58)	6 (± 1.00)	7 (± 0.56)	2.92 (± 0.02)	2.96 (± 0.16)	2.94 (± 0.07)
<i>p</i> -value	0.387 <sup>ns</sup>	0.015 <sup>*</sup>	0.013 <sup>*</sup>	0.193 <sup>ns</sup>	0.789 <sup>ns</sup>	0.141 <sup>ns</sup>	0.880 <sup>ns</sup>	0.842 <sup>ns</sup>	0.940 <sup>ns</sup>
LSD <sub>0.05</sub>	–	5.53	4.66	–	–	–	–	–	–

Different lower-case letters within each column and different upper-case letters within the header row for planting season for each characteristic indicate significant differences at the 0.05 level. Values are presented as means (± SE)

LAI leaf area index, DI surface drip irrigation, SDI subsurface drip irrigation,  $I_{100}$  100% of crop evapotranspiration (ET<sub>c</sub>),  $I_{70}$  70% ET<sub>c</sub>,  $I_{50}$  50% ET<sub>c</sub>, LSD least significant difference, ns non-significant ( $p > 0.05$ ), \* 0.05 ≥  $p > 0.01$ , \*\* 0.01 ≥  $p > 0.001$ , \*\*\*  $p ≤ 0.001$



**Table 5** Fresh and dry yields of potato (*Solanum tuberosum*) tubers under different irrigation systems and with different irrigation levels in the 2017 and 2018 growing seasons

Factor	Fresh tuber yield (Mg ha <sup>-1</sup> )			Dry tuber yield (Mg ha <sup>-1</sup> )		
	2017 <sup>B</sup>	2018 <sup>A</sup>	Mean	2017	2018	Mean
Irrigation system						
DI	26.09 <sup>b</sup>	30.05 <sup>b</sup>	28.07 <sup>b</sup>	5.17	4.94	5.06
SDI	28.15 <sup>a</sup>	31.71 <sup>a</sup>	29.93 <sup>a</sup>	5.50	5.16	5.33
<i>p</i> -value	0.006 <sup>**</sup>	0.002 <sup>**</sup>	<0.001 <sup>***</sup>	0.199 <sup>ns</sup>	0.661 <sup>ns</sup>	0.296 <sup>ns</sup>
LSD <sub>0.05</sub>	1.32	0.85	0.67	–	–	–
Irrigation level						
I <sub>100</sub>	32.33 <sup>a</sup>	36.53 <sup>a</sup>	34.43 <sup>a</sup>	6.55 <sup>a</sup>	6.78 <sup>a</sup>	6.67 <sup>a</sup>
I <sub>70</sub>	26.76 <sup>b</sup>	30.45 <sup>b</sup>	28.61 <sup>b</sup>	5.16 <sup>b</sup>	4.81 <sup>b</sup>	4.98 <sup>b</sup>
I <sub>50</sub>	22.28 <sup>c</sup>	25.66 <sup>c</sup>	23.97 <sup>c</sup>	4.30 <sup>c</sup>	3.57 <sup>b</sup>	3.93 <sup>c</sup>
<i>p</i> -value	<0.001 <sup>***</sup>	<0.001 <sup>***</sup>	<0.001 <sup>***</sup>	<0.001 <sup>***</sup>	0.001 <sup>***</sup>	<0.001 <sup>***</sup>
LSD <sub>0.05</sub>	1.62	1.05	0.82	0.64	1.32	0.64
Irrigation system × level						
DI						
I <sub>100</sub>	31.57 (±0.72)	35.91 (±0.64)	33.74 (±1.06)	6.43 (±0.47)	6.63 (±0.85)	6.53 (±0.44)
I <sub>70</sub>	25.49 (±0.68)	29.41 (±0.27)	27.45 (±0.94)	4.87 (±0.22)	4.73 (±0.39)	4.80 (±0.20)
I <sub>50</sub>	21.22 (±0.69)	24.83 (±0.27)	23.03 (±0.87)	4.22 (±0.13)	3.46 (±0.38)	3.84 (±0.25)
SDI						
I <sub>100</sub>	33.09 (±0.68)	37.16 (±0.34)	35.12 (±0.97)	6.68 (±0.31)	6.93 (±0.42)	6.80 (±0.24)
I <sub>70</sub>	28.03 (±0.72)	31.49 (±0.23)	29.76 (±0.84)	5.43 (±0.04)	4.73 (±0.87)	5.16 (±0.41)
I <sub>50</sub>	23.33 (±0.46)	26.48 (±0.62)	24.91 (±0.78)	4.38 (±0.19)	3.46 (±0.34)	4.03 (±0.23)
<i>p</i> -value	0.784 <sup>ns</sup>	0.683 <sup>ns</sup>	0.516 <sup>ns</sup>	0.771 <sup>ns</sup>	0.993 <sup>ns</sup>	0.963 <sup>ns</sup>
LSD <sub>0.05</sub>	–	–	–	–	–	–

Different lower-case letters within each column and different upper-case letters within the header row for planting season for each characteristic indicate significant differences at the 0.05 level. Values are presented as means (± SE)

DI surface drip irrigation, SDI subsurface drip irrigation, I<sub>100</sub> 100% of crop evapotranspiration (ET<sub>c</sub>), I<sub>70</sub> 70% ET<sub>c</sub>, I<sub>50</sub> 50% ET<sub>c</sub>, LSD least significant difference, ns non-significant ( $p > 0.05$ ), \*\* 0.01 ≥  $p > 0.001$ , \*\*\*  $p \leq 0.001$

of irrigation water (I<sub>50</sub>) decreased these yields by 31.09 and 29.06%, respectively, in 2017 and 29.76 and 47.35%, respectively, in 2018 compared with values obtained with I<sub>100</sub>. There was no significant interaction effect between the irrigation system and level on the fresh and dry tuber yields in either season.

### Components of tuber yield

The fresh tuber weight per plant significantly differed between the irrigation systems and among the irrigation levels in both the 2017 and 2018 growing seasons (Table 6), with plants grown under the SDI system and with the I<sub>100</sub> treatment having the highest value. The fresh tuber weight per plant was, on average, ( $p < 0.05$ ) 10.39 and 35.16% lower for the DI system and 27.65 and 35.55% lower for the SDI system with the I<sub>50</sub> treatment than with the I<sub>70</sub> and I<sub>100</sub> treatments, respectively. The mean tuber weight was, on average, 14.12% lower under the SDI system than under the DI system. The mean tuber weight was significantly lower in plants subjected to the I<sub>50</sub> treatment than in those subjected

to the I<sub>100</sub> and I<sub>70</sub> treatments under both irrigation systems ( $p < 0.001$ ), whereas there was no significant difference between the I<sub>100</sub> and I<sub>70</sub> treatments. In both growing seasons, the number of tubers per plant was highest with the I<sub>100</sub> treatment, with the DI and SDI systems resulting in an average of 11 and 15 tubers per plant, respectively, for I<sub>100</sub> compared with 9 and 15 tubers per plant, respectively, for I<sub>70</sub> and 10 and 11 tubers per plant, respectively, for I<sub>50</sub>.

There was a strong positive, albeit non-significant, correlation between the fresh tuber yield per hectare and the number of tubers per plant ( $r = 0.40$ ,  $p > 0.05$ ; Fig. 4). There was also a strong positive correlation between the fresh tuber yield per hectare and the mean tuber weight ( $r = 0.63$ ,  $p < 0.05$ ), indicating that the reduction in fresh tuber yield in treated plants was mainly due to a lower tuber weight, and a negative but non-significant correlation between the mean tuber weight and the number of tubers per plant ( $r = -0.36$ ,  $p > 0.05$ ).

Plants that were exposed to the I<sub>50</sub> treatment had a smaller tuber diameter under both the DI and SDI systems, exhibiting an increased proportion of tubers in the < 50 mm

**Table 6** Fresh tuber weight per plant, mean tuber weight, and tuber number per plant for potato (*Solanum tuberosum*) under different irrigation systems and with different irrigation levels in the 2017 and 2018 growing seasons

Factor	Fresh tuber weight (g plant <sup>-1</sup> )			Mean tuber weight (g)			Number of tubers (plant <sup>-1</sup> )		
	2017	2018	Mean	2017 <sup>B</sup>	2018 <sup>A</sup>	Mean	2017 <sup>A</sup>	2018 <sup>B</sup>	Mean
<b>Irrigation system</b>									
DI	653.89 <sup>b</sup>	695.56 <sup>b</sup>	674.72 <sup>b</sup>	62.53 <sup>a</sup>	69.91	66.22 <sup>a</sup>	10 <sup>b</sup>	10 <sup>b</sup>	10 <sup>b</sup>
SDI	753.89 <sup>a</sup>	795.56 <sup>a</sup>	774.72 <sup>a</sup>	50.56 <sup>b</sup>	63.16	56.87 <sup>b</sup>	15 <sup>a</sup>	13 <sup>a</sup>	14 <sup>a</sup>
<i>p</i> -value	0.002 <sup>**</sup>	0.025 <sup>**</sup>	<0.001 <sup>***</sup>	0.003 <sup>**</sup>	0.104 <sup>ns</sup>	<0.001 <sup>***</sup>	0.001 <sup>***</sup>	<0.001 <sup>***</sup>	<0.001 <sup>***</sup>
LSD <sub>0.05</sub>	51.76	84.68	50.52	6.97	–	4.94	1.64	0.83	1.01
<b>Irrigation level</b>									
I <sub>100</sub>	910.00 <sup>a</sup>	860.00 <sup>a</sup>	885.00 <sup>a</sup>	65.39 <sup>a</sup>	71.05 <sup>a</sup>	68.22 <sup>a</sup>	14 <sup>a</sup>	12 <sup>a</sup>	13 <sup>a</sup>
I <sub>70</sub>	680.83 <sup>b</sup>	753.33 <sup>b</sup>	717.08 <sup>b</sup>	55.24 <sup>b</sup>	70.48 <sup>a</sup>	62.86 <sup>a</sup>	13 <sup>a</sup>	11 <sup>b</sup>	12 <sup>b</sup>
I <sub>50</sub>	520.83 <sup>c</sup>	623.33 <sup>c</sup>	572.08 <sup>c</sup>	49.01 <sup>b</sup>	58.09 <sup>b</sup>	53.55 <sup>b</sup>	11 <sup>b</sup>	11 <sup>b</sup>	11 <sup>c</sup>
<i>p</i> -value	<0.001 <sup>***</sup>	0.002 <sup>**</sup>	<0.001 <sup>***</sup>	0.005 <sup>**</sup>	0.031 <sup>*</sup>	<0.001 <sup>***</sup>	0.007 <sup>**</sup>	0.015 <sup>*</sup>	0.001 <sup>***</sup>
LSD <sub>0.05</sub>	63.39	103.71	61.88	8.54	10.28	6.05	2.01	1.02	1.23
<b>Irrigation system × level</b>									
<b>DI</b>									
I <sub>100</sub>	886.67 (± 69.60) <sup>ab</sup>	820.00 (± 52.92)	853.33 (± 28.60) <sup>ab</sup>	74.76 (± 5.34)	76.08 (± 4.30)	75.42 (± 3.08) <sup>a</sup>	12 (± 1.00) <sup>b</sup>	11 (± 0.61) <sup>b</sup>	11 (± 0.59) <sup>b</sup>
I <sub>70</sub>	561.67 (± 89.18) <sup>c</sup>	673.33 (± 37.12)	617.50 (± 33.51) <sup>c</sup>	62.92 (± 5.61)	76.39 (± 6.05)	69.65 (± 4.76) <sup>a</sup>	9 (± 0.58) <sup>c</sup>	9 (± 0.47) <sup>c</sup>	9 (± 0.33) <sup>c</sup>
I <sub>50</sub>	513.33 (± 63.33) <sup>c</sup>	593.33 (± 54.57)	553.33 (± 34.42) <sup>c</sup>	49.91 (± 2.69)	47.25 (± 3.65)	53.58 (± 2.61) <sup>b</sup>	10 (± 0.88) <sup>bc</sup>	10 (± 0.35) <sup>b</sup>	10 (± 0.42) <sup>bc</sup>
<b>SDI</b>									
I <sub>100</sub>	933.33 (± 44.10) <sup>a</sup>	900.00 (± 35.47)	916.67 (± 26.38) <sup>a</sup>	56.02 (± 1.82)	66.02 (± 3.87)	61.02 (± 2.94) <sup>b</sup>	17 (± 0.67) <sup>a</sup>	14 (± 0.33) <sup>a</sup>	15 (± 0.75) <sup>a</sup>
I <sub>70</sub>	800.00 (± 47.70) <sup>b</sup>	833.33 (± 44.10)	816.67 (± 24.18) <sup>b</sup>	47.56 (± 2.93)	64.57 (± 3.54)	56.06 (± 4.32) <sup>b</sup>	17 (± 1.53) <sup>a</sup>	13 (± 0.58) <sup>a</sup>	15 (± 1.17) <sup>a</sup>
I <sub>50</sub>	528.33 (± 23.33) <sup>c</sup>	653.33 (± 35.28)	590.83 (± 33.75) <sup>c</sup>	48.11 (± 1.33)	58.92 (± 3.57)	53.51 (± 2.96) <sup>b</sup>	11 (± 0.58) <sup>bc</sup>	11 (± 0.20) <sup>b</sup>	11 (± 0.27) <sup>b</sup>
<i>p</i> -value	0.006 <sup>**</sup>	0.545 <sup>ns</sup>	0.027 <sup>*</sup>	0.113 <sup>ns</sup>	0.325 <sup>ns</sup>	0.038 <sup>*</sup>	0.008 <sup>**</sup>	0.014 <sup>*</sup>	<0.001 <sup>***</sup>
LSD <sub>0.05</sub>	89.64	–	87.51	–	–	8.56	2.84	1.44	1.75

Different lower-case letters within each column and different upper-case letters within the header row for planting season for each characteristic indicate significant differences at the 0.05 level. Values are presented as means (± SE)

DI surface drip irrigation, SDI subsurface drip irrigation, I<sub>100</sub> 100% of crop evapotranspiration (ET<sub>c</sub>), I<sub>70</sub> 70% ET<sub>c</sub>, I<sub>50</sub> 50% ET<sub>c</sub>, LSD least significant difference, ns non-significant ( $p > 0.05$ ), \* 0.05 ≥  $p > 0.01$ , \*\* 0.01 ≥  $p > 0.001$ , \*\*\*  $p ≤ 0.001$

class (39.63 and 34.09%, respectively) and a corresponding decreased proportion in the > 80 mm class (23.73 and 27.58%, respectively) (Fig. 5). The opposite trend was observed with the I<sub>100</sub> treatment, though these differences were not significant.

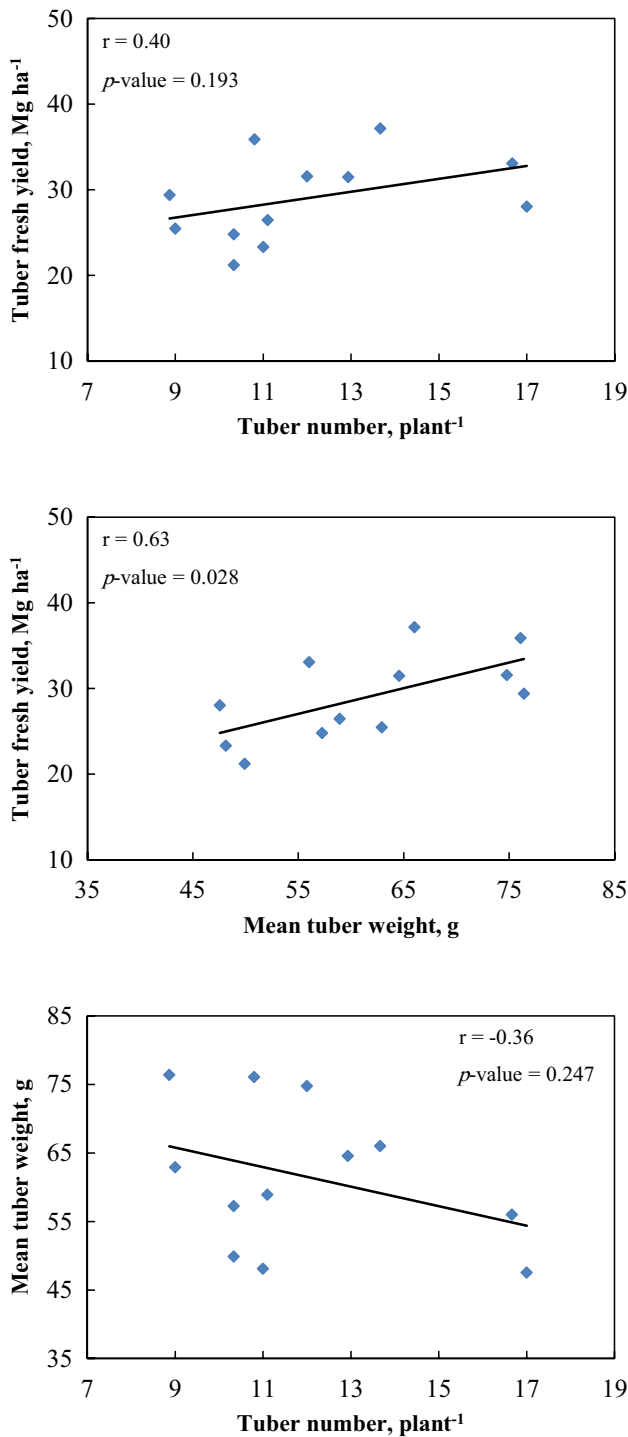
## IWUE

IWUE significantly differed between the two growing seasons and was significantly affected by the irrigation system in both seasons ( $p < 0.01$ ), with plants grown under SDI having 8.38% higher IWUE in 2017 and 5.82% higher IWUE in 2018 than those grown under the DI system (Fig. 6). There were also significant differences in IWUE among the three irrigation levels under each irrigation system in

both seasons ( $p < 0.01$ ), with the exception of DI in 2017 ( $p = 0.07$ ). Under the DI system, IWUE was significantly higher with the I<sub>50</sub> treatment (7.01 kg m<sup>-3</sup>) than with the I<sub>70</sub> and I<sub>100</sub> treatments in 2018, with differences of 6.70 and 16.83%, respectively. Under the SDI system, IWUE with the I<sub>50</sub> treatment was 6.31 and 19.45% higher in 2017 and 6.25 and 20.45% higher in 2018 compared with the I<sub>70</sub> and I<sub>100</sub> treatments, respectively.

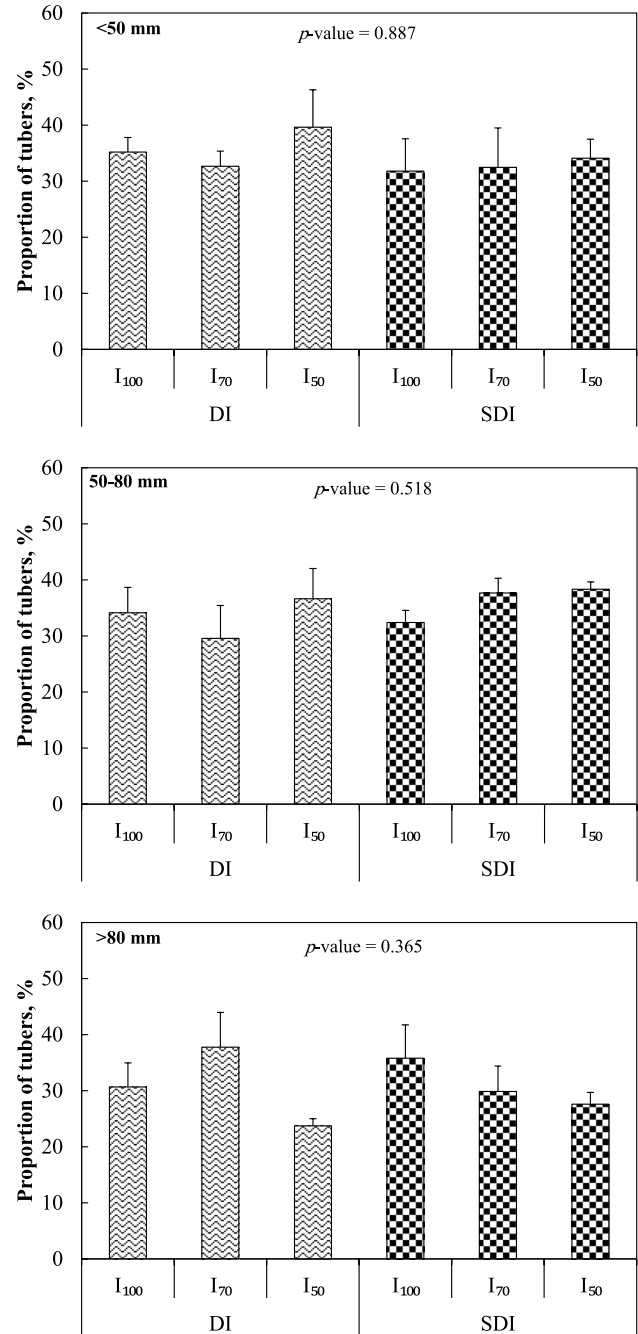
## Yield and biomass response factors

Ky and Kss were estimated for the DI and SDI systems using the fitted regression approach with pooled data from the two growing seasons to provide an indication of the level of tolerance of the crop to water stress (Fig. 7). Both factors



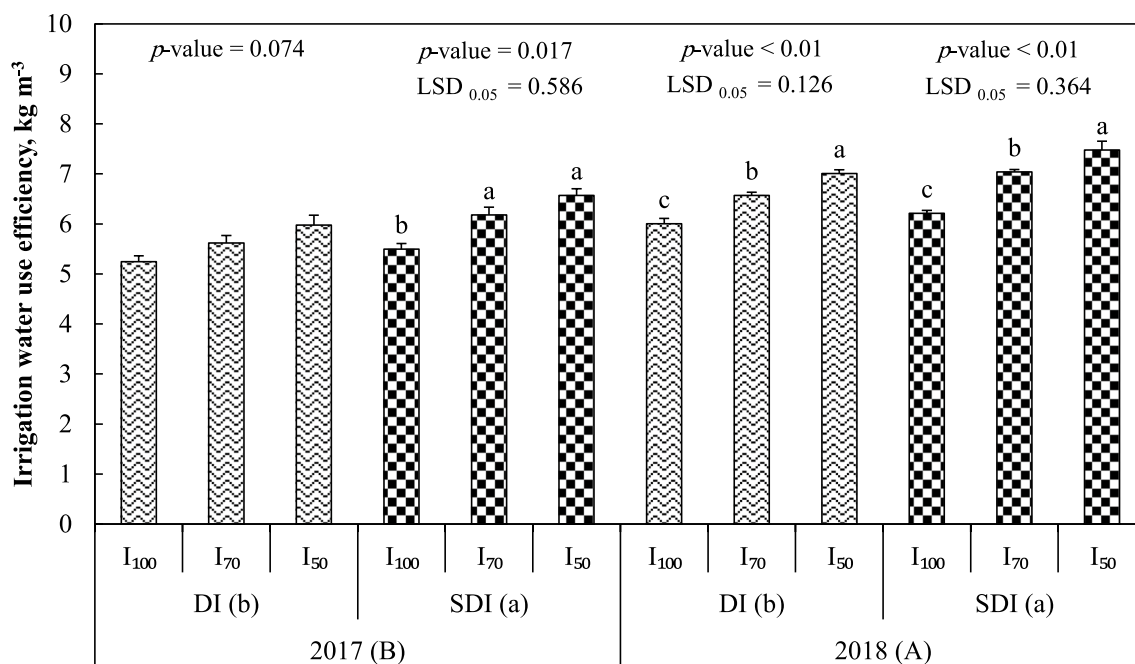
**Fig. 4** Relationships between the fresh tuber yield per hectare, the number of tubers per plant, and the mean tuber weight of potato (*Solanum tuberosum*) based on pooled data from the 2017 and 2018 growing seasons

were < 1 under both irrigation systems, with the exception of Kss under the DI system, which was slightly higher than 1. Both Ky and Kss were higher under the DI system than



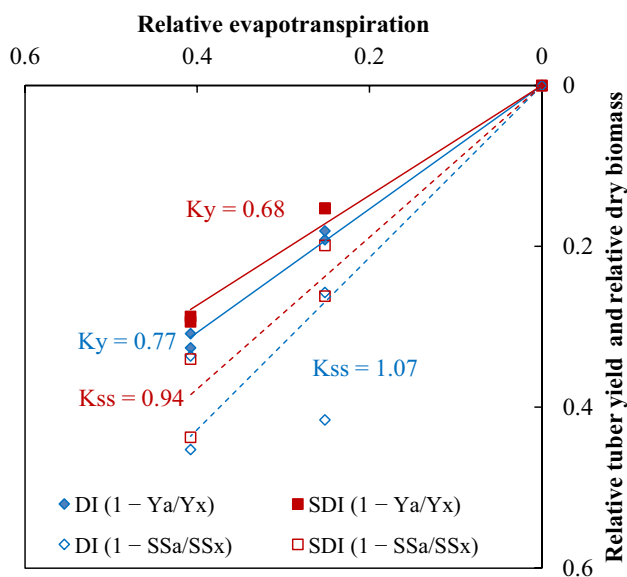
**Fig. 5** Proportion of tubers in different diameter classes (<50 mm, 50–80 mm, and >80 mm) under different irrigation systems and with different irrigation levels in the 2018 growing season. DI surface drip irrigation, SDI subsurface drip irrigation, I<sub>100</sub> 100% of crop evapotranspiration (ET<sub>c</sub>), I<sub>70</sub> 70% ET<sub>c</sub>, I<sub>50</sub> 50% ET<sub>c</sub>. Bars represent means ± SE (n = 3)

under the SDI system, with values of 0.77 and 1.07, respectively, under DI and 0.68 and 0.94, respectively, under SDI.



**Fig. 6** Irrigation water use efficiency (IWUE) of potato (*Solanum tuberosum*) plants under different irrigation systems and with different irrigation levels during 2017 and 2018 growing seasons. Bars represent means  $\pm$  SE ( $n=3$ ). Different lower-case letters directly above the bars for each irrigation system and season represent significant differences among irrigation levels, while different lower-case

letters in parentheses for each season represent significant differences between the irrigation systems and different upper-case letters in parentheses represent significant differences between the seasons (LSD test,  $p < 0.05$ ). *DI* surface drip irrigation, *SDI* subsurface drip irrigation,  $I_{100}$  100% of crop evapotranspiration ( $ET_c$ ),  $I_{70}$  70%  $ET_c$ ,  $I_{50}$  50%  $ET_c$ . *LSD* least significant difference



**Fig. 7** Relationship between relative evapotranspiration ( $1 - ET_a/ET_x$ ) and both the relative tuber yield ( $1 - Y_a/Y_x$ , solid lines) and relative dry biomass ( $1 - SS_a/SS_x$ , dashed lines) for potato (*Solanum tuberosum*) under surface drip irrigation (DI) and subsurface drip irrigation (SDI) based on pooled data collected during the 2017 and 2018 growing seasons

### Discussion

The  $\theta_v$  value in the root zone of the potato plants was lower with the  $I_{70}$  and  $I_{50}$  treatments under the DI system than with the  $I_{100}$  treatment under the SDI system across both growing seasons, supporting the previous findings of Demir and Sahin (2017) and Mattar et al. (2020) that  $\theta_v$  is significantly lower for plants managed with deficit irrigation than for those managed with full irrigation. It has been reported that the high  $\theta_v$  provided by the SDI system facilitates water transport to the area around the root (Patel and Rajput 2007; Vyrlas et al. 2014) and results from limited capillary flow to the surface in combination with reduced evaporation losses, which eliminate the effects of surface infiltration properties and saturation status with pond water under the DI system (Ayars et al. 2015; Elmaloglou and Diamantopoulos 2009).

The agronomic trait analysis of the potato plants showed that both the fresh and dry weights of the vegetative parts were higher under the SDI system than under the DI system, which agrees with the results of Al-Ghobari and Dewidar (2018) for tomato. The fresh and dry weights of the vegetative parts also decreased with a decreasing irrigation level, which is consistent with the adverse effects of water stress on plant development. Many studies have reported a reduction in the weight of the vegetative parts under deficit irrigation

(Badr et al. 2018; Cantore et al. 2014; Eid et al. 2020), indicating a higher fruit absorption strength than the rest of the plant parts (Zegbe et al. 2004). This difference is most likely due to the significant decrease in the soil–root contact area that occurs under soil water depletion (Jensen et al. 1993), which may act as a limiting factor for vegetative growth (Ahmadi et al. 2010a). Karam et al. (2009) and Passioura and Angus (2010) showed that underwater shortage conditions, the most common cause for low vegetative growth in vegetable species is a shortened annual crop cycle and accelerated leaf aging.

Plants that were exposed to the  $I_{70}$  and  $I_{50}$  treatments under DI also had the lowest height while plants treated with DI had fewer branches than SDI, which agrees with the findings of Al-Ghobari and Dewidar (2018) for tomato and Meligy et al. (2020) for potato. However, Elhani et al. (2019) detected no statistically significant difference in either the plant height or the number of branches between different irrigation levels. LAI was not significantly affected by the irrigation system in either season, supporting the results of Çolak et al. (2015) for eggplant. However, there was a significant difference in LAI between the deficit irrigation treatments and the full irrigation treatment in the present study, which is consistent with the results of Liu et al. (2006), Zin El-Abedin et al. (2017), and Romero et al. (2017) for potato, as well as Karam et al. (2011) for eggplant. Shahnazari et al. (2007) and Deshi et al. (2015) reported that LAI values  $> 3$ , as observed in this study, are optimal for maximizing the growth rate and light interception in potato.

The SDI system had a significant positive effect on the fresh tuber yield, and similarly Patel and Rajput (2007) and El-Mokh et al. (2014) reported that SDI at 10–15 cm depth can result in a higher tuber yield. An SDI depth of 15–25 cm has commonly been used for crop production in many studies on tomato (Lamm 2016), and it has been shown that SDI outperforms DI in increasing eggplant (Douh and Boujelben 2010) and tomato (Lamm 2016) yields. The ability of the SDI system to improve tuber productivity can be attributed to the reduction in evaporation loss from the soil surface and maintenance of the optimum soil water content in the root zone, resulting in optimal crop production (Ayars et al. 2015; Selim et al. 2009). In terms of the irrigation level, the fresh tuber yield was highest in plants treated with  $I_{100}$  followed by those subjected to the  $I_{70}$  and  $I_{50}$  treatments, respectively, which agrees with the findings of Cantore et al. (2014) and Ahmadi et al. (2014), as well as those of Çolak et al. (2017) for eggplant and Meligy et al. (2020) for potato, who established that crop yield is positively correlated with the amount of irrigation water applied and vegetative growth. Iqbal et al. (1999) also stated that deficit irrigation during the early development stages of potato may cause a sharp drop in the final fresh yield, though treatments in the present study were applied after the tuber initiation stage. By

contrast, Patel and Rajput (2007) reported that potato yield was not significantly affected by a 20% decrease in irrigation water, and Onder et al. (2005) reported that while irrigation levels significantly affected the tuber yield of potato, the irrigation system had no significant effect. The dry tuber yield of plants was also higher with the  $I_{100}$  treatment than with the  $I_{70}$  and  $I_{50}$  treatments, supporting the findings of Ahmadi et al. (2014) for potato and Shao et al. (2008) for bell pepper. Similarly, Elhani et al. (2019) showed that the dry tuber yield was significantly reduced under water stress treatments compared with 100% FC. However, Schafleitner (2009), Ahmed et al. (2017), and Petropoulos (2020) found that the dry tuber yield also depends on the crop variety, which is an important factor in the adaptation of potatoes to water-scarce conditions. Camargo et al. (2015) and Ierna and Mauromicale (2018) suggested that increasing levels of irrigation water lead to increases in the dry matter weight in all stages of potato growth. One possible explanation for this may be that potato is a shallow-root crop, so any differences in soil water content in the top 10–30 cm soil layer can have a large effect, while differences in the soil water content in deep soil layers (30–50 cm) may have much less of an effect due to the low density of plant roots (Kaman et al. 2011; Zin El-Abedin et al. 2017). Passioura and Angus (2010) reported that the lower growth and production levels under water-scarce conditions result from a decrease in the transportation of assimilates from the leaves and stems to the fruits in crops that usually mature in increasingly unfavorable water supply conditions.

The fresh tuber weight, mean tuber weight, and number of tubers per plant grown were significantly higher under the SDI system with the  $I_{100}$  treatment than with any other treatment combination in both seasons and lowest under the DI system with the  $I_{50}$  treatment, which is consistent with the results of Elhani et al. (2019). Demirel et al. (2014) and Sharma et al. (2014) reported that reduced amounts of irrigation water (50%  $ET_c$ ) decreased the fruit volume in eggplant and melon, respectively. Previous studies have found that water stress induced at different stages of growth reduces the number of tubers per plant (Cantore et al. 2014; Monnem et al. 2015; Nagaz et al. 2016). Similarly, Marouelli and Silva (2007) observed that the number of commercially suitable tomato fruit per plant decreased with soil water tension during growth, and Amer (2011) and Zin El-Abedin et al. (2017) found that fewer fruit were produced when squash (*Cucurbita pepo* L.) and potato plants, respectively, were exposed to 50% and 75%  $ET_c$  under a DI system. Ahmadi et al. (2014) reported that the number of potato tubers in the  $> 80$  mm size class was highest with 100%  $ET_c$ , whereas Erdem et al. (2006) obtained the highest number of tubers per plant with a low irrigation level. This inconsistency may be due to differences in the plant varieties studied, as well as other environmental conditions, such as soil type

and air temperature (Rykaczewska 2013; Walworth and Carling 2002). Alva et al. (2012) noted that a decrease in the number, weight, and size of tubers per plant as a result of insufficient irrigation resulted in a lower yield. In the present study, a set amount of water was provided for all irrigation level treatments during the initial growth stage to ensure regular germination and stem elongation. Therefore, the tuber developmental stage was affected by water stress, which reduced tuber weight without increasing the number of tubers (O'Brien et al. 1998), ultimately decreasing the yield of fresh tubers.

Plants that were managed with the SDI system and subjected to the  $I_{50}$  treatment had the highest IWUE. Similarly, Patel and Rajput (2007) and El-Mokh et al. (2014) recommended that a higher IWUE could be achieved by applying the SDI system at a depth of 10–15 cm, and Kashyap and Panda (2003), Liu et al. (2006), Ahmadi et al. (2014), and Ierna and Mauromicale (2018) showed that the IWUE of potato was higher under deficit irrigation than under full irrigation. Increased values of IWUE under deficit irrigation have also been observed for watermelon [*Citrullus lanatus* (Thunb) Matsum & Nakai] (Leskovar et al. 2004), tomato (Al-Qerem et al. 2012), red pepper (Sezen et al. 2014), bell pepper (Bladia and AbdArahman 2016), and eggplant (Çolak et al. 2015, 2017), while Geets and Kirk (2009) confirmed that deficit irrigation successfully increased the IWUE of different crops without decreasing crop yield in dry regions. The increased IWUE in plants exposed to water stress is induced by physiological processes that control the  $CO_2$  and  $H_2O$  gradients between the leaves of the plant and the air surrounding the leaves. A high  $CO_2$  concentration surrounding the leaves is beneficial in water-stressed plants because partial stomatal closure reduces transpiration and enhances photosynthesis, whereas this has little effect on well-watered plants (Bloch et al. 2006; Hatfield and Dold 2019; Lopes et al. 2011). However, severe water stress may lead to complete stomatal closure and reduce IWUE and the potato tuber yield (Zin El-Abedin et al. 2019). By contrast,  $K_y$  and  $K_{ss}$  were lower in plants grown under the SDI system than in those grown under the DI system, which suggests that potato plants are more sensitive to water stress under the DI system. Unlu et al. (2006) similarly found that different methods of irrigation appeared to affect the  $K_y$  values of potato (0.68 for DI and 1.05 for sprinkler irrigation). Since the  $K_y$  value is an important indicator of the sensitivity of a crop to drought, it may be influenced by factors besides water deficiency, such as the soil and water management conditions, climatic conditions, length of the growing season, and irrigation method (Ferreira and Gonçalves 2007; Greaves and Wang 2017).

## Conclusion

Minimizing water use while maintaining crop production levels has become a key goal of experimental research in agriculture due to the limited availability of water and rising demand for food globally, and this is particularly important in arid environments. Therefore, the present study investigated the effects of full (100%  $ET_c$ ) and deficit (50% and 30% reduction in  $ET_c$ ) irrigation under DI and SDI systems on the soil water, vegetative growth traits, tuber yield and its components, and IWUE of potato during the 2017 and 2018 growing seasons in an arid region of Saudi Arabia. It was found that a 50% reduction in irrigation water under the SDI system improved the distribution of soil water and reduced evaporation, which had a positive effect on IWUE but reduced the tuber yield. Furthermore, the yield response factor to water was less than 1, indicating that potato can tolerate some water deficits, which will allow the yield to be maintained while reducing water loss in arid environments. However, if the purpose is to obtain the highest tuber yield regardless of the IWUE, then full irrigation should be applied with the SDI system. Therefore, the beneficial effects of a given irrigation strategy will depend on both the irrigation method being used and the amount of water being provided to elicit plant responses.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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