



Water productivity of soybeans under regulated surface and subsurface drip irrigation conditions

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Abstract

Increasing population, pollution of current natural resources, global warming and climate change are increasing pressure on water resources. To maintain the food security of the increasing population, it is essential to increase sustainable agricultural production and to use current limited water resources optimally. In this study, the effect of surface drip (SDI) and subsurface drip (SSDI) irrigation methods on water productivity, yield and quality characteristics of soybeans were evaluated. The study was carried out in Batı Akdeniz Agricultural Research Institute located in Antalya, Turkey. To evaluate the performance of the SDI and to compare it with the SSDI, an experiment was conducted based on a randomized blocks design with two factors: irrigation method (SDI and SSDI) and irrigation levels defined as the percentages of available water capacity of the soil profile (100%, 80%, 60%, and 0%). Applied water varied between 45–488 mm and 171–541 mm in the SSDI, and between 50–573 and 164–640 mm in the SDI, during 2016 and 2017, respectively. The yield ranged from 1.98 to 5.61 t ha⁻¹ for SDI and from 2.29 to 6.33 t ha⁻¹ for SSDI. While the increased amount of irrigation water had a positive relationship with the yield, there was a negative relationship with the oil content and fatty acid composition. The SSDI treatments used approximately 90 mm less water than the SDI without any reduction in yield.

Introduction

The Intergovernmental Panel on Climate Change (IPCC) predicted that there would be an average increase of 1 to 3.5 °C in global temperature by 2100 (IPCC 2001). This phenomenon will cause climate change due to changes in temperature and precipitation regimes. Climate change can be a significant driver of desertification and land degradation and can affect food production, thereby influencing food security (Smith et al. 2017). The Mediterranean Region is one of the areas that will be affected the most by global warming.

Agriculture is the largest water user with 70% of total water consumption in the world. The International Institute of Water Management (IWMI) data showed that, by 2025, 1.8 billion people will be living in countries or regions with absolute water scarcity (Rosegrant et al. 2002). This will

lead to an increase in water demand in domestic and industrial areas and a decrease in the amount of water allocated for agriculture. Water scarcity will lead to use of pressurized irrigation methods (especially subsurface and surface drip irrigation methods) that save water and energy and minimize water losses. In addition, these methods will decrease environmental pollution and increase product quality and quantity.

Surface drip irrigation applies water efficiently and with high uniformity. Subsurface drip irrigation has even higher water savings due to the reduction in evaporation.

Soybean (*Glycine max* L.) known as a ‘miracle plant’ and ‘golden plant’, is an important food for humans and animals. It is rich in minerals, vitamins, and high-quality protein and is cholesterol-free and easily digestible. It provides ¼ of the world’s edible oil requirements and produces the most protein per unit area in the world. It is the source of 400 industrial products. Soybean is also a renewable energy source and has the highest energy content of all alternative fuels (Holt 1997; Sincik et al. 2008; Muchlish Adie and Krisnawati 2014).

Water is a critical factor in soybean productivity. Previous studies showed that water stress in soybeans plants affected yield (Demirtaş et al. 2010; Kirnak et al. 2010; Pejic et al.

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2011; Irmak et al. 2014; Aydinsakir 2018), water use efficiency (Scott et al. 1987; Karam et al. 2005; Payero et al. 2005; Irmak et al. 2014), irrigation water use efficiency (Kirnak et al. 2010; Irmak et al. 2014), plant height (Bunce 1977; Hodges and Heatherly 1983; Specht et al. 1989; Desclaux et al. 2000; Atti et al. 2004; Karam et al. 2005; Demirtaş et al. 2010; Candogan and Yazgan 2016), first pod height (Kadhem et al. 1985; Smiciklas et al. 1992; Desclaux et al. 2000; Yordanov et al. 2000; Atti et al. 2004; Oya et al. 2004; Maleki et al. 2013), the number of lateral branches (Bunce 1977; Hodges and Heatherly 1983; Specht et al. 1989; Desclaux et al. 2000; Atti et al. 2004; Karam et al. 2005; Demirtaş et al. 2010; Candogan and Yazgan 2016), 1000-seed weight (Desclaux et al. 2000; Yordanov et al. 2000), protein content (Hobbs and Muendel 1983; Dornbo and Mullen 1992; Kumar et al. 2006; Bellaloui and Mengistu 2008; Rotundo and Westgate 2009), oil content (Boydak et al. 2002; Kirnak et al. 2010), and fatty acids composition (Kirnak et al. 2010; Bellaloui et al. 2013; Aydinsakir 2018). Hunt et al. (2011) determined that subsurface drip irrigation (SSDI) improved soybeans yield by 28% compared to non-irrigated control plot in the United States. Lee et al. (2018) reported soybeans yield in SSDI treatments under full irrigation conditions as 3340 kg ha⁻¹, which was 27% higher yield increase compared to the rainfed treatments (2630 kg ha⁻¹). Indeed, previous studies showed that soybeans yield increased with irrigation.

Oil value is determined by the functional qualities imparted from the fatty acid compositions (Bilyeu et al. 2018). Soybeans seed oil generally consists of five major fatty acids, such as palmitic (12%), stearic (4%), oleic 49 (24%), linoleic (52%) and linolenic (8%) acids (Dhakal et al.

2014). Oleic, linoleic, linolenic and palmitoleic acids are in the group of unsaturated fatty acids, while palmitic, stearic, bahenic and arachidic acids are in the group of saturated fatty acids. These acids are of important in terms of human health (Mesa Garcia et al. 2006; Clemente and Cahoon 2009; Park 2012; Dhakal et al. 2014). Therefore, the primary fatty acid composition targeted for soybeans should be (1) low linolenic acid, (2) high oleic acid, and (3) elevated stearic acid combined with high oleic acid.

The main purpose of this research was to determine and compare the effects of different irrigation methods, surface drip and subsurface drip, in terms of water productivity, yield and quality characteristics of soybeans under deficit irrigation conditions in the West Mediterranean region of Turkey.

Materials and methods

The study was carried out between June 15, 2016 and October 17, 2016, (120 days) and between June 8, 2017 and October 27, 2017 (118 days), in Batı Akdeniz Agricultural Research Institute (BATEM). The study site was located 36° 52' N latitude and 30° 50' E longitude at altitude 15 m. The experiment site has a dominant Mediterranean climate with hot and dry summers and warm and rainy winters. Table 1 shows long-term monthly averages and monthly climatic data during 2016–2017 growing seasons.

Tables 2 and 3 show physical and chemical soil properties and irrigation water quality characteristics, respectively. Soil was loam with low salinity and high in calcium carbonate. Field capacity ranged from 22 to 23%, and

Table 1 Long-term monthly climatic data and monthly climatic data during 2016–2017 growing seasons

Years	Months	Temperature (°C)	Rainfall (mm)	Evaporation (mm)	Wind (m sn ⁻¹)	Relative humidity (%)
1954–2015	June	25.5	7.6	177.5	1.9	55.2
	July	28.3	3.4	195.5	1.9	54.3
	Aug	28.2	1.8	172.4	1.7	56.7
	Sep	24.4	12.3	134.4	1.8	58.8
	Oct	20.0	80.1	150.6	2.0	61.0
2016	June	26.9	–	152.0	1.7	62.8
	July	29.9	–	173.9	1.8	60.3
	Aug	29.5	–	158.0	1.8	66.8
	Sep	26.4	26.2	149.5	1.9	55.0
	Oct	23.3	–	122.3	1.7	56.8
2017	June	26.3	–	125.6	1.8	63.1
	July	30.5	–	161.1	1.9	57.4
	Aug	29.0	–	155.2	1.9	64.4
	Sep	26.9	–	137.3	1.8	62.8
	Oct	22.2	12.6	111.5	1.7	53.2

Table 2 Some physical and chemical properties of the experimental soil

Soil depth (cm)	Texture	Field capacity (g g ⁻¹)	Permanent wilting point (g g ⁻¹)	Bulk density (g cm ⁻³)	pH	Organic matter (%)	Electrical conductivity (dS m ⁻¹)	Lime (%)
0–30	Loam	0.23	0.13	1.31	7.5	1.7	0.10	25.6
30–60	Loam	0.24	0.11	1.38	7.7	0.8	0.11	24.8
60–90	Loam	0.22	0.12	1.43	7.8	0.9	0.16	23.7

Table 3 Quality parameters of irrigation water

pH	EC dS m ⁻¹	Cations (meq L ⁻¹)				Anions (meq L ⁻¹)				SAR
		Na	K	Ca	Mg	CO ₃	HCO ₃	Cl	SO ₄	
7.3	0.56	0.49	0.05	4.23	1.85	–	5.03	0.53	1.06	0.28

EC Electrical conductivity, Na Sodium, K Potassium, Ca Calcium, Mg Magnesium, CO₃ Carbonate, HCO₃ Bicarbonate, Cl Chlorine, SO₄ Sulphate, SAR Sodium absorption rate

permanent wilting point ranged from 11 to 13%. Soil infiltration rate was 13.5 mm h⁻¹. Irrigation water quality was in the acceptable range for soybeans (Table 3). Electrical conductivity (EC) was 0.56 dS m⁻¹, and sodium absorption ratio (SAR) was 0.28 (Ayers and Westcot 1985).

The ATAEM-7 soybean variety, widely grown in the Mediterranean region and registered for BATEM, was grown in the experiment.

The experiment was conducted on 168 m² (8.4 × 20.0 m) plots using a randomized complete block design with three replications. Treatments included two irrigation methods (SDI: surface drip irrigation and SSDI: subsurface drip irrigation) and four irrigation levels (I₁₀₀, I₈₀, I₆₀ and I₀ “rainfed”). Based on infiltration and drifter tests, one lateral was laid per row with 30 cm between drip emitters. Drifter flow rate was 2 L h⁻¹ at 0.1 MPa pressure. In the SSDI method, the laterals were placed at a depth of 40 cm below the soil surface. In both seasons of the study, SDI treatments were irrigated 15 while SSDI treatments were irrigated 14 times.

The soil moisture content of the control (I₁₀₀) treatments was monitored by the gravimetric method to determine irrigation time and irrigation amount. When 30% of the available soil moisture content in the upper 0.90 m soil depth in the full irrigation treatment (I₁₀₀) was consumed, the plants were irrigated. I₁₀₀, I₈₀, and I₆₀ treatments were irrigated as 100%, 80% and 60% of I₁₀₀ treatment. The water budget equation was used to calculate crop evapotranspiration (James 1988).

$$ET_c = I + P \pm \Delta SW - D_p - R_f \quad (1)$$

where ET_c = crop evapotranspiration (mm), I = amount of irrigation water applied (mm), P = precipitation (mm), ΔSW = change in the soil water content (mm), D_p = deep percolation (mm) and R_f = amount of runoff (mm). Since the

amount of irrigation water was controlled, deep percolation and runoff were assumed to be negligible.

The water use efficiency (WUE) and irrigation water use efficiency ($IWUE$) for each irrigation treatment was calculated using Eq. 2 and Eq. 3, respectively (Howell et al. 1990).

$$WUE = \frac{Y}{ET_c} \quad (2)$$

$$IWUE = \frac{Y}{I} \quad (3)$$

where WUE = water use efficiency (kg ha⁻¹ mm⁻¹); Y = yield (kg ha⁻¹); ET_c = crop evapotranspiration (mm); $IWUE$ = irrigation water use efficiency (kg ha⁻¹ mm⁻¹) and I = amount of applied irrigation (mm).

The yield response factor (K_y), which indicates the level of tolerance of a crop to water deficit was calculated using Eq. 4 (Doorenbos and Kassam 1979).

$$1 - \left(\frac{Y_a}{Y_x} \right) = K_y \times \left(1 - \frac{ET_c}{ET_x} \right) \quad (4)$$

where Y_a = actual yield (kg ha⁻¹); Y_x = maximum yield (kg ha⁻¹); K_y = yield response factor; ET_c = crop evapotranspiration (mm); and ET_x = maximum evapotranspiration (mm).

The plants harvested from the middle two rows of each treatment were separated, and then the seed yield (kg ha⁻¹) was calculated by weighing. Growth, yield and fatty acid parameters were measured for each treatment. These parameters were obtained by measurements or observations from 20 plants selected from each replication. Plant height (cm) was measured as the length of the stem from the root throat to the top node. The first pod height (cm) was measured as the length of the stem from the root throat up to the bottom of the first pod. The number of branches

and pods per plant (number of plant⁻¹) were obtained from plants selected at harvest time. To determine the 1000-seed weight (g), 100 grains were counted and repeated four times at each plot, and average seed weight was multiplied by 10. Total oil content was determined using Soxhlet extraction device. The fatty acid composition was made using a gas chromatography capillary column device according to the method given by Christie (1993).

Statistical analyses for each year were calculated separately. Variance analysis was applied to the obtained data in MSTAT_C statistical package software and Duncan Multiple Comparison Test was used to compare the averages (Gomez and Gomez 1984).

Results and discussion

Figure 1 shows soil moisture contents prior to each irrigation. Soil moisture content was between field capacity and permanent wilting point in all irrigation treatments except the rainfed treatment. Approximately 40 days after sowing (July 25), which corresponds to the end of vegetative growth stage, the soil moisture started to differentiate depending on deficit irrigation applications. In the I₀ treatments, soil moisture content fell below the permanent wilting point after the last week of August in both seasons. The highest average amount of water was applied with the SDI method (568 mm for I₁₀₀), and the lowest average value was applied with the SSDI method (48 mm for I₀).

The seasonal crop evapotranspiration (*ETc*) increased with increasing amount of irrigation under both SDI and SSDI methods. Soybeans evapotranspiration varied from 169 to 640 mm in the 2016 growing season, and from 164 to 611 mm in the 2017 growing season (Table 4). Doorenbos and Kassam (1979) and Kanemasu (1981) found that the amount of irrigation water required to obtain the highest yield from soybeans varies depending on climate, region and the length of the growing period. The crop evapotranspiration rate of soybeans was between 26–482 mm (Hobbs and Muendel 1983; Güler 1990) under humid, 380–795 mm (Doorenbos and Kassam 1979; Kanemasu 1981; Derviş and Özel 1987; Ozkara 1991; Candogan 2009) under semi-arid, and 763–1056 mm (Çelik 1989; Yazar et al. 1991; Karam et al. 2005; Çömlekcioglu and Simsek 2011; Saab et al. 2014) under arid conditions. Previous studies showed that there were significant differences in the seasonal *ETc* of the soybeans plant depending on the region and climate conditions.

The yield of soybeans varied between 1982–6326 kg ha⁻¹ in the study, depending on irrigation treatments. In both growing seasons, the yield increased with the amount of irrigation water applied. Compared to the I₁₀₀ treatment, the yield reductions for I₀, I₆₀ and I₈₀ in SSDI were 59%, 29%

and 18% in the first year and 61%, 39% and 20% in the second year, respectively. Similarly, yield reductions for I₀, I₆₀ and I₈₀ in SDI were 72%, 48% and 15% in the first year and, 60%, 44% and 15% in the second year, respectively, compared to I₁₀₀. Indeed, previous studies showed that soybeans yield increased with irrigation. Kırda et al. (1994) stated that the timing of water stressed period for soybeans influenced yield differently and the most sensitive growth stage to water stress were flowering and yield formation stages. However, Demirtaş et al. (2010) reported that soybeans plant might be exposed to drought stress at all stages of development. Pejic et al. (2011) pointed out that the effect of drought stress on the yield of soybeans might depend on genotype, intensity and duration of stress and growth stage. Therefore, the yield of soybeans in previous studies (Kırda et al. 1994; Kirnak et al. 2010; Candogan et al. 2013; Irmak et al. 2014) varied between 2000–4930 kg ha⁻¹.

Water use efficiency (*WUE*) and irrigation water use efficiency (*IWUE*) values were significantly influenced by irrigation treatments (Table 4). *WUE* varied between 5.8 and 11.7 kg ha⁻¹ mm⁻¹ in 2016 and between 6.8 and 13.7 kg ha⁻¹ mm⁻¹ in 2017 for SDI treatments. In SSDI treatments, *WUE* values ranged from 9.6 to 12.9 kg ha⁻¹ mm⁻¹ in 2016 and from 9.5 to 14.6 kg ha⁻¹ mm⁻¹ in 2017. The *IWUE* values were between 7.6–9.5 kg ha⁻¹ mm⁻¹ for 2016 and 8.8–10.4 kg ha⁻¹ mm⁻¹ for 2017 in SDI treatments, while *IWUE* values ranged from 11.3 to 12.6 kg ha⁻¹ mm⁻¹ for 2016 and from 12.5 to 13.0 kg ha⁻¹ mm⁻¹ for 2017 in SSDI treatments. Experimental results showed that crops under SSDI treatments yielded better than under SDI treatments. Payero et al. (2005) stated that *WUE* changed between 2.3–7.4 kg ha⁻¹ mm⁻¹, while Karam et al. (2005) determined that *WUE* ranged from 3.9 to 5.7 kg ha⁻¹ mm⁻¹. Irmak et al. (2014) reported *WUE* and *IWUE* values between 7.7–8.9 kg ha⁻¹ mm⁻¹ and 5.1–10.3 kg ha⁻¹ mm⁻¹, respectively. Under full irrigation and water stress conditions, *IWUE* values were determined between 7.1 and 21.7 kg ha⁻¹ mm⁻¹ by Candogan et al. (2013) and between 4.2 and 6.7 kg ha⁻¹ mm⁻¹ by Kirnak et al. (2010). *WUE* can vary even within the same species depending on whether the particular cultivar was selected for dryland or irrigated conditions and may also be greatly influenced by the timing of water applications (Evans and Sadler 2008). Previous studies also showed that *IWUE* increased with the increasing amount of irrigation water applied for sugar beet (Ucan and Gencoglan 2004), maize (Farre and Faci 2006), silage maize (Kiziloglu et al. 2009), soybeans (Kirnak et al. 2010) and peanut (Aydinsakir et al. 2016). It is clear that *WUE* values obtained from SSDI treatments are higher than that obtained from SDI treatments. According to these results, it can be stated that the SSDI has an advantage in the beneficial use of water because of higher values of *WUE*. This might be due to the uniform distribution of moisture in the effective root

Fig. 1 Change in soil water content before irrigation during the growing season on surface and subsurface drip irrigation treatments *SDI* Surface drip irrigation, *SSDI* Subsurface drip irrigation, I_{100} Full irrigation (control) treatment, I_{80} 80% of control treatment, I_{60} 60% of control treatment, I_0 Rainfed (treatment)

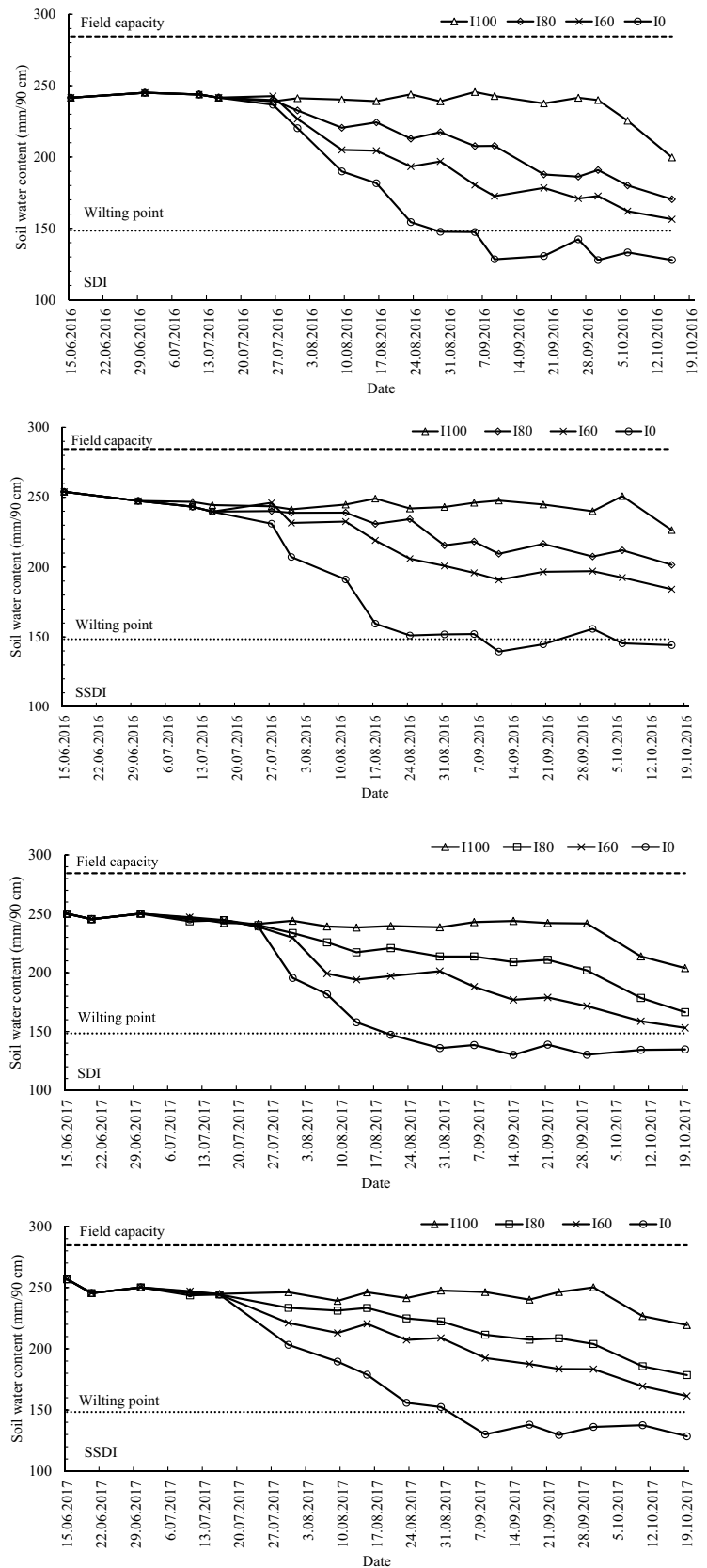


Table 4 The components of water balance, yield, water use and irrigation water use efficiency in the experiment

Years	Irrigation methods	Irrigation levels	Treatments	<i>I</i> (mm)	<i>P</i> (mm)	ΔS (mm)	<i>ETc</i> (mm)	<i>Y</i> (kg ha ⁻¹)	<i>WUE</i> (kg ha ⁻¹ mm ⁻¹)	<i>IWUE</i> (kg ha ⁻¹ mm ⁻¹)		
2016	SDI	I ₁₀₀	SDI ₁₀₀	572.7	26.0	41.8	640.5	5237 a	8.2	9.1		
		I ₈₀	SDI ₈₀	468.1	26.0	71.1	565.3	4464 b	7.9	9.5		
		I ₆₀	SDI ₆₀	363.6	26.0	85.2	474.8	2765 c	5.8	7.6		
		I ₀	SDI ₀	50.0	26.0	93.2	169.2	1982 d	11.7	–		
	SSDI	I ₁₀₀	SSDI ₁₀₀	488.0	26.0	27.4	541.4	5506 a	10.2	11.4		
		I ₈₀	SSDI ₈₀	399.4	26.0	52.3	477.7	4542 b	9.5	11.3		
		I ₆₀	SSDI ₆₀	310.8	26.0	69.7	406.5	3915 c	9.6	12.6		
		I ₀	SSDI ₀	45.0	26.0	105.5	176.5	2288 d	12.9	–		
		2017	SDI	I ₁₀₀	SDI ₁₀₀	562.8	12.6	36.3	611.7	5605 a	9.2	10.0
				I ₈₀	SDI ₈₀	460.3	12.6	71.5	544.4	4795 b	8.8	10.4
I ₆₀	SDI ₆₀			357.7	12.6	91.3	461.6	3149 c	6.8	8.8		
I ₀	SDI ₀			50.0	12.6	101.7	164.3	2258 d	13.7	–		
SSDI	I ₁₀₀		SSDI ₁₀₀	484.5	12.6	30.1	527.3	6326 a	12.0	13.0		
	I ₈₀		SSDI ₈₀	397.6	12.6	71.1	481.3	5079 b	10.5	12.7		
	I ₆₀		SSDI ₆₀	310.7	12.6	87.4	410.7	3899 c	9.5	12.5		
	I ₀		SSDI ₀	50.0	12.6	108.4	171.0	2511 d	14.6	–		

SDI Surface drip irrigation, *SSDI* Subsurface drip irrigation, *I* Amount of irrigation water applied, *P* Precipitation, ΔS Change in the soil water content, *ETc* Crop evapotranspiration, *Y* Yield, *WUE* Water use efficiency, *IWUE* Irrigation water use efficiency

zone and minimizing evaporation from soil surface observed with SSDI method.

There were linear relationships between crop evapotranspiration and yield of soybeans in each growing year for the SDI and SSDI methods (Figs. 2a, b). SSDI and SDI irrigation methods produced different soybeans yield at all irrigation levels as shown in Fig. 2. Similar results were obtained by Schneekloth et al. (1991), Grassini et al. (2015) and Schlegel et al. (2016) in soybeans grown in USA.

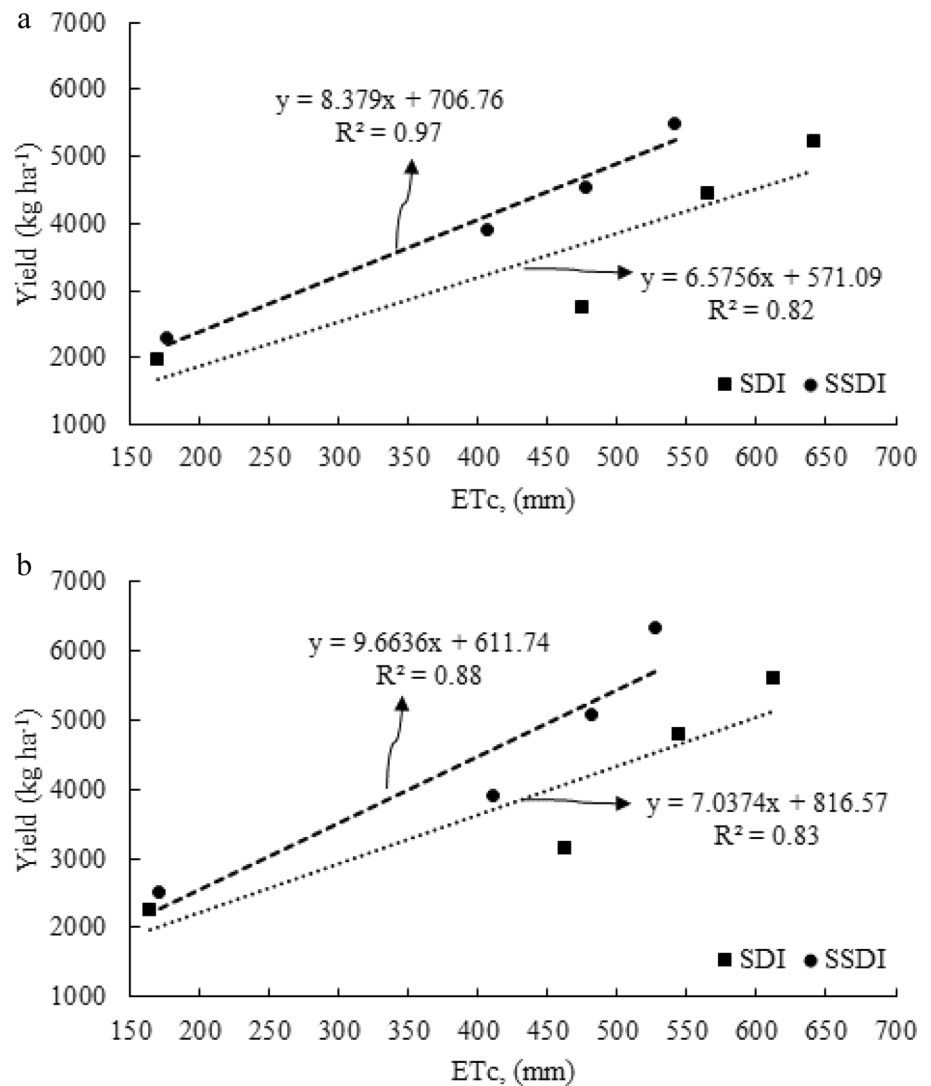
The relationship between relative crop evapotranspiration and relative yield for each drip irrigation methods is given Fig. 3. In the 2016 and 2017 growing seasons, the K_y values were calculated as 0.96 and 0.92, respectively, in the SDI treatment, while it was calculated as 0.92 and 0.99 in the SSDI treatment. It was determined that the soybeans plants irrigated by SDI and SSDI methods in both growing seasons were tolerant to water stress. A similar result was found by Doorenbos and Kassam (1979) (0.85), Pejic et al. (2011) (0.66) and Karakaya and Odemis (2019) (0.81). On the other hand, Güler (1990) (1.02), Kırdı et al. (1999) (1.16) and Candogan and Yazgan (2016) (1.21) reported K_y values greater than 1 and stated that soybeans was sensitive to water stress. These results showed that the value of K_y was affected by climate and soil conditions, irrigation method and applied amount of irrigation water.

The effects of different drip irrigation methods and irrigation levels on the plant height (PH), first pod height (FPH), the number of branches per plant (NB), the number of pods per plant (NP), and 1000-seed weight (SW) of soybeans

were tabulated in Table 5. The effect of the irrigation methods was significant only on the PH in first growing season and not significant on other plant growth parameters. The statistical analysis showed that there were significant differences in PH, NP, and SW based on irrigation levels, but its effect was not significant on FPH and NB in the first growing season, while there were significant differences in FPH, NB, NP, and SW, but its effect was not significant on PH in the second growing season. The effect of the interaction between irrigation methods and irrigation levels was significant only for SW in the second growing season and not significant on other growth parameters.

According to Table 5, the PH of the soybeans irrigated with the SSDI method was found to be statistically higher than irrigated with the SDI method in 2016 ($p < 0.05$). However, no statistically significant difference was found in 2017. In addition, PH was significantly affected by different irrigation treatments in both seasons ($p < 0.01$). Although there was no significant relationship between PH values in the interaction of irrigation method \times irrigation levels, the PH varied between 80.7–109.3 cm in 2016 and 93.0–140.0 cm in 2017. There was no statistically significant difference between the PH of I₁₀₀ and I₈₀ treatments in both seasons. However, these treatments were significantly higher than I₆₀ and I₀ treatments ($p < 0.01$). Plant height is a good indicator used to determine the effect of water stress on the plant. It was concluded that the higher soil moisture content by SDI and SSDI method led to the better growth of soybeans plants. Hodges and Heatherly (1983) argued that water

Fig. 2 The relationship between yield and crop evapotranspiration (ET_c) for surface drip irrigation (SDI) and subsurface drip irrigation (SSDI) methods in 2016 (a) and 2017 (b) growing seasons



stress reduces physiological and morphological parameters in soybeans. In addition, Bunce (1977) and Desclaux et al. (2000) found that water stress occurring in the vegetative stage reduced the length of the internode and accordingly a reduction in PH. Also, Kadhem et al. (1985), Specht et al. (1989), Atti et al. (2004), Karam et al. (2005), Demirtaş et al. (2010) and Candoğan and Yazgan (2016) stated that deficit irrigation practices reduced PH in soybeans.

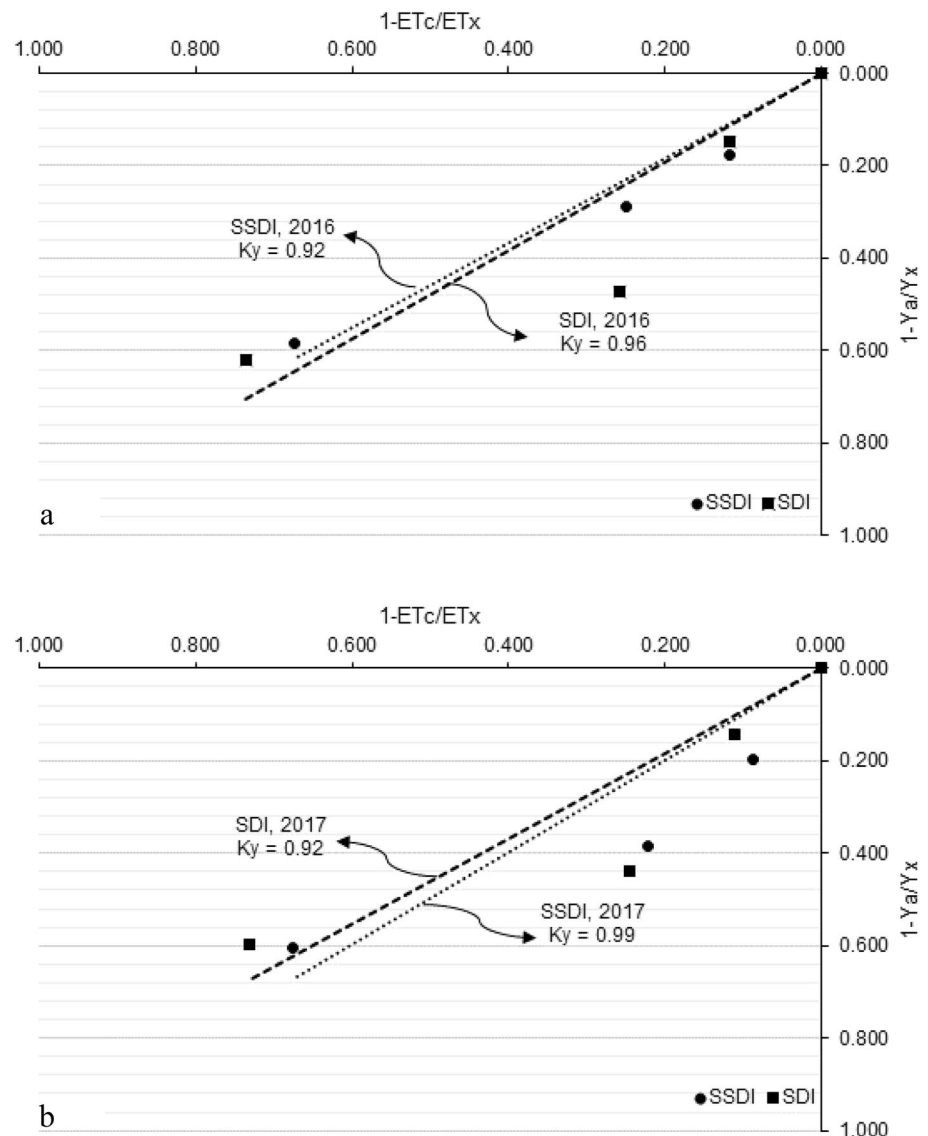
Irrigation method did not have a statistically significant effect on FPH, NB, NP, and SW (Table 5). Although different irrigation levels did not statistically affect FPH in both growing seasons, NB, NP and SW (except NB in 2016) were significantly affected by different irrigation treatments ($p < 0.01$). However, the effect of the interaction of irrigation methods \times irrigation treatments on soybeans growth parameters (except SW in 2017) was not significant in both seasons. When irrigation methods \times irrigation treatment interactions were examined, FPH varied between 4.7–8.3 cm and 5.1–6.5 cm in 2016 and 2017, respectively. İlker et al. (2018)

reported various FPH depending on different genotypes. Kang et al. (2017) indicated that the FPH/PH ratio was a significant factor affecting the seed yield, which decreased with an increase in FPH/PH ratio. In this study, a similar result was obtained. The FPH/PH ratio was between 0.036–0.103, and yield decreased as the ratio increased.

The number of branches per plant varied between 3.3–4.3 and 2.3–5.3 in 2016 and 2017, respectively. Abd El-Mageed et al. (2017) declared that the NB was not affected by the water deficit practice but varied depending on the growing season. Similar results were obtained in this study. Previous studies indicated positive correlation between seed yield and number of pods (Ramgiriy et al. 1998; Malik et al. 2006; Kang et al. 2017).

In this study, although the correlation between yield and NP was not examined, it was determined that the yield and NP increased with irrigation water application rate. Similarly, Kadhem et al. (1985), Smiciklas et al. (1992), Desclaux et al. (2000), Yordanov et al. (2000), Oya et al.

Fig. 3 Seasonal yield response factor (K_y) in soybean for 2016 (a) and 2017 (b) growing seasons. Y_a Actual yield, Y_x Maximum yield, ET_c Crop evapotranspiration, ET_x Maximum evapotranspiration, *SDI* Surface drip irrigation, *SSDI* Subsurface drip irrigation



(2004) and Maleki et al. (2013) determined that the NB, NP and SW decreased under water stress conditions.

The effects of different irrigation methods and irrigation treatments on protein, oil contents and fatty acid contents of soybeans were presented in Figs. 4, 5 and Table 6, respectively. The effect of irrigation treatments on soybeans oil and protein content were significant in both seasons ($p < 0.01$) (Figs. 4 and 5). On the other hand, the effect of irrigation methods \times irrigation treatment interaction was not statistically significant. In both seasons, the protein content did not vary with irrigation method. In contrast, while the oil content of the soybeans plant was higher in SDI compared with the SSDI method in 2017, there was no statistical difference in 2016. Protein content increased and oil content decreased with irrigation rate. In previous studies, there were conflicting research results regarding the protein and oil content of the soybeans plant under water stress conditions. While

Sionit and Kramer (1977) stated that water stress did not affect the protein and oil content, Candogan and Yazgan (2016) announced that the oil content increased in water stress conditions whereas the protein content decreased. Kirnak et al. (2010) stated that the highest protein and oil content was obtained from full irrigation (I_{100}) and rainfed (I_0) applications, respectively. Rotundo and Westgate (2009) reported that protein content increased under water stress conditions, while Specht et al. (2001) and Boydak et al. (2002) reported that it decreased. On the other hand, Specht et al. (2001) and Rotundo and Westgate (2009) declared that water stress reduced the oil content, while Boydak et al. (2002) and Kirnak et al. (2010) announced that water stress increased the oil content. Lobato et al. (2008) stated the reduction in the total soluble proteins determined in the plants under water stress might be due to probable increase in the proteases enzyme activity.

Table 5 Effect of different irrigation methods and irrigation water levels on the growth and yield parameters of soybean

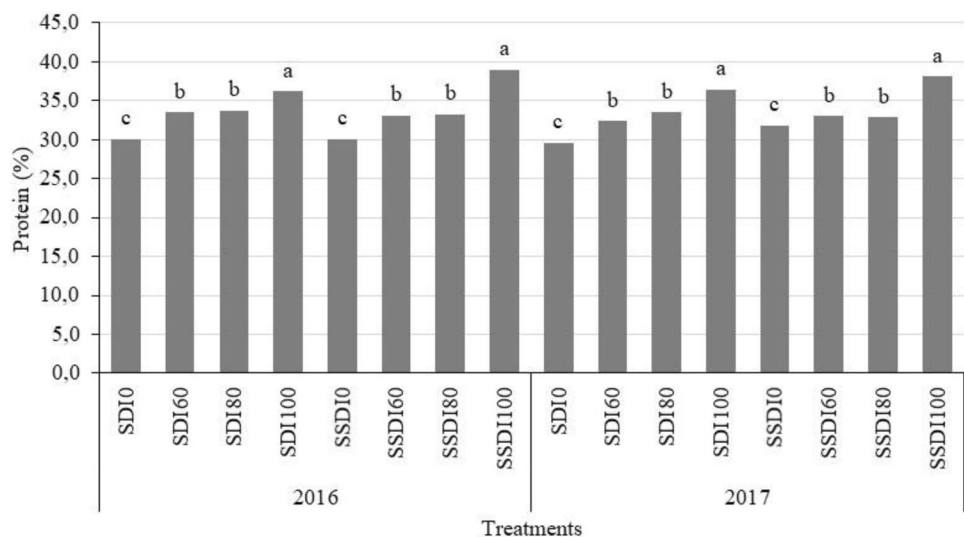
Treatments	Years									
	2016					2017				
	PH (cm)	FPH (cm)	NB (number)	NP (number)	SW (g)	PH (cm)	FPH (cm)	NB (number)	NP (number)	SW (g)
SDI	93.5 b	6.4	3.8	162.2	141.4	119.3	5.6	3.6	162.3	175.8
SSDI	101.0 a	5.9	3.9	188.8	142.2	122.8	5.6	4.1	178.3	172.4
Methods (M)	*	ns	ns	ns	ns	ns	ns	ns	ns	ns
I_0	87.7 b	7.3	3.3	96.3 c	121.5 c	97.2 c	6.3	2.5 c	84.3 d	124.5 d
I_{60}	90.3 b	6.8	3.8	154.0 b	139.4 b	120.5 b	6.0	3.5 b	165.7 c	169.2 c
I_{80}	103.0 a	5.3	4.0	207.5 a	152.2 a	129.3 a	5.4	4.3 ab	191.3 b	193.2 b
I_{100}	108.0 a	5.2	4.3	244.2 a	154.2 a	136.3 a	4.7	5.0 a	239.8 a	209.6 a
Irrigation levels (I)	**	ns	ns	**	**	**	ns	**	**	**
SDI I_0	80.7	8.3	3.3	82.7	119.4	93.0	6.5	2.3	78.7	121.7 d
SDI I_{60}	82.3	7.5	3.7	159.7	140.0	122.0	6.0	3.0	162.3	178.0 c
SDI I_{80}	104.3	5.0	4.0	187.0	153.3	129.7	5.5	4.3	185.0	197.1 b
SDI I_{100}	106.7	4.7	4.3	219.3	153.1	132.7	4.3	4.7	223.3	206.6 a
SSDI I_0	94.7	6.3	3.3	110.0	123.6	101.3	6.2	2.7	90.0	127.3 d
SSDI I_{60}	98.3	6.0	4.0	148.3	138.9	119.0	5.9	4.0	169.0	160.4 c
SSDI I_{80}	101.7	5.7	4.0	228.0	151.1	129.0	5.2	4.3	197.7	189.2 b
SSDI I_{100}	109.3	5.7	4.3	269.0	155.2	140.0	5.1	5.3	256.3	212.7 a
M×I	ns	ns	ns	ns	ns	ns	ns	ns	ns	*

The means indicated with the same small letter in the same column are not significantly different ($p < 0.05$)

SDI Surface drip irrigation, SSDI Subsurface drip irrigation, M Irrigation methods, I Irrigation levels, I_{100} Full irrigation (control) treatment, I_{80} 80% of control treatment, I_{60} 60% of control treatment, I_0 Rainfed treatment, PH Plant height, FPH First pod height, NB The number of branches per plant, NP Number of pods per plant, SW 1000 seed weight

*, **, and ns, Significant at the $p < 0.05$, $p < 0.01$ level, and not significant, respectively

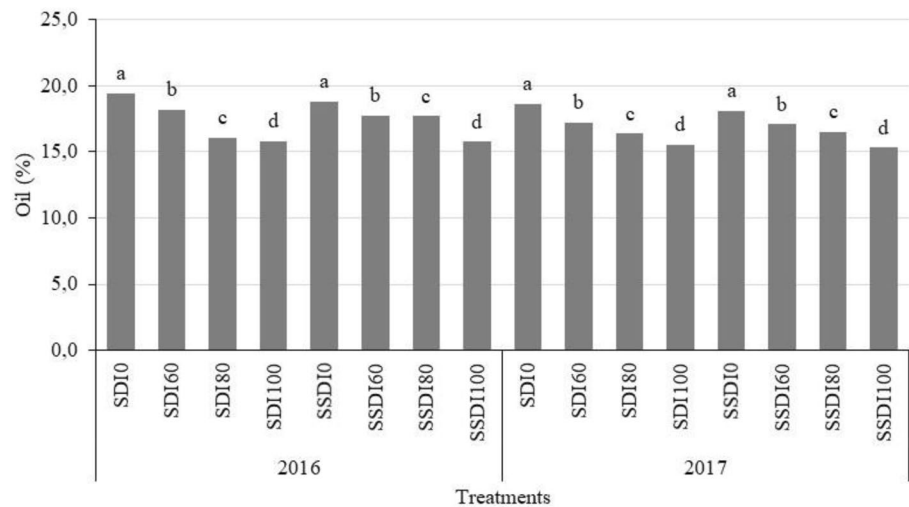
Fig. 4 Effects of different treatments on protein content (%). SDI Surface drip irrigation; SSDI Subsurface drip irrigation, I_{100} Full irrigation (control) treatment, I_{80} 80% of control treatment, I_{60} 60% of control treatment, I_0 Rainfed treatment. Different letters indicate that the means are significant ($p < 0.05$) as determined by Duncan's multiple range test



Fatty acid compositions did not change (except arachidic acid in 2016 and stearic acid in 2017) statistically according to the different irrigation methods in both seasons (Table 6). There was no effect of irrigation method (SDI and SSDI) on oil content. Irrigation levels did have a statistically

significant effect on palmitic acid content, which has a negative effect on human health ($p < 0.01$ in 2016 and $p < 0.05$ in 2017). While water deficit applications in 2016 increased the amount of palmitic acid, it decreased in 2017. The amount of stearic acid, another important saturated fatty acid, was not

Fig. 5 Effects of different treatments on oil content (%). *SDI* Surface drip irrigation; *SSDI* Subsurface drip irrigation, *I*₁₀₀ Full irrigation (control) treatment, *I*₈₀ 80% of control treatment, *I*₆₀ 60% of control treatment, *I*₀ Rainfed treatment. Different letters indicate that the means are significant ($p < 0.05$) as determined by Duncan's multiple range test



affected by irrigation treatments in both seasons. Oleic acid, which is an important fatty acid in terms of healthy nutrition, was statistically affected by deficit irrigation applications in both seasons. The oleic acid content of soybeans increased in water stress conditions. When the yield and oleic acid content were evaluated together, although the yield increased as the amount of irrigation water increased, the oleic acid content decreased as the amount of irrigation water increased. Linoleic acid was also statistically affected by different irrigation treatments in 2016 ($p < 0.01$). But, unlike oleic acid content, linoleic acid content increased as the amount of irrigation water applied increased. Similar results were obtained by Kim et al. (2016) and they reported that oleic acid content decreased as water stress increased. Besides, linoleic acid content increased as water stress increased. Irrigation levels had a statistically significant effect on linolenic acid content ($p < 0.01$ in 2016 and $p < 0.05$ in 2017) and linolenic acid content decreased as water stress increased in both seasons (Table 6). Arachidic and behenic acid content, which were in low amounts compared to other fatty acids, were not statistically affected (except arachidic acid in 2016) by different irrigation treatments. When the different irrigation method \times irrigation levels interactions were examined, the general fatty acid composition obtained from this study consisted of an average of 10.8% for palmitic acid, 4.29% for stearic acid, 23.6% for oleic acid, 53.85% for linoleic acid, 6.85% for linolenic acid, 0.34% for arachidic acid and 0.33% for behenic acid in 2016, while an average of 10.4% for palmitic acid, 5.01% for stearic acid, 25.6% for oleic acid, 51.9% for linoleic acid, 6.56% for linolenic acid, 0.39% for arachidic acid and 0.37% for behenic acid in 2017. Dornbos and Mullen (1992) and Lee et al. (2018) determined that stearic and oleic acid content increased in water stress conditions and decreased linolenic acid in soybeans. Bellaloui et al. (2013) and Kirnak et al. (2010) announced that the amount of fatty acid composition in soybeans was

affected by planting date, climate, genotype, and especially drought stress and their combination. When the results obtained from the research were evaluated in general, it was concluded that protein and fat content were the main factors to determine the nutritional value of the soybeans plant. Water stress affected not only water use and yield but also quality parameters such as the oil and protein content of the soybeans plant.

An economic analysis was carried out using averages of two-year data based on investment, operating and labor costs, and the results were given in Table 7. In general, as the amount of applied irrigation water increased, net income also increased under SDI and SSDI methods. Maximum gross and net income was US\$ 1183,20 and US\$ 660,57 ha⁻¹, respectively, under the SSDI₁₀₀ treatment. The lowest gross and net income was obtained from SDI₀ treatment (US\$ 424,00 and US\$ 7,23 ha⁻¹) followed by SSDI₀ (US\$ 479,90 and US\$ 30,24 ha⁻¹). McKellar et al. (2013) reported net income ranging from US\$ 177 to 444 ha⁻¹ in Australia, while Adeboye et al. (2015) determined the net income for soybeans TGX-1448-2E variety as US\$ 680–1300 ha⁻¹ under Nigerian conditions. Schlegel et al. (2016) reported gross income for 127, 254, and 381 mm of irrigation water as US\$ 798, 1026, and 1112 ha⁻¹ in Kansas, USA. The reason for the difference between the studies can be explained by the difference in labor, operation cost and variety.

Conclusion

In this study, the effects of two different irrigation methods (SDI and SSDI) and 4 different irrigation treatments (*I*₁₀₀, *I*₈₀, *I*₆₀ and *I*₀) on growing, yield, quality and fatty acid compositions of soybeans plants were investigated. The effects of different irrigation levels on yield, plant height, first pod

Table 6 Effect of different irrigation methods and irrigation water levels on the composition of fatty acid contents (%) of soybean

Treatments	Years		2017													
	2016															
	Palmitic	Stearic	Oleic	Linoleic	Linolenic	Arachidic	Behenic	Palmitic	Stearic	Oleic	Linoleic	Linolenic	Arachidic	Behenic		
SDI	10.8	4.28	23.6	54.0	6.78	0.35 a	0.33	10.3	5.21 a	25.5	51.8	6.48	0.41	0.37		
SSDI	10.8	4.31	23.6	53.7	6.93	0.32 b	0.32	10.4	4.81 b	25.6	51.9	6.65	0.38	0.36		
Methods (M)	ns	ns	ns	ns	ns	**	ns	ns	**	ns	ns	ns	ns	ns		
I ₀	10.6 b	4.34	25.1 a	52.8 b	6.51 c	0.36 a	0.33	10.5 a	4.87	26.4 a	51.6	6.17 b	0.40	0.38		
I ₆₀	10.8 b	4.32	23.9 b	53.5 b	6.84 b	0.35 ab	0.32	10.4 a	4.92	25.9 a	51.7	6.22 b	0.41	0.37		
I ₈₀	10.8 ab	4.39	23.4 b	54.7 a	6.90 ab	0.34 b	0.32	10.4 a	5.09	24.9 b	52.0	6.75 a	0.40	0.37		
I ₁₀₀	11.0 a	4.24	22.1 c	54.9 a	7.18 a	0.33 b	0.33	10.1 b	5.15	24.7 b	52.0	6.92 a	0.38	0.34		
Irrigation levels (I)	**	ns	**	**	**	**	ns	*	ns	**	ns	*	ns	ns		
SDI _{I₀}	10.5	4.33	25.4	52.8	6.21 c	0.37	0.33	10.0	5.10	26.3	51.6	6.24	0.40	0.37		
SDI _{I₆₀}	10.8	4.34	24.0	53.6	6.66 bc	0.36	0.32	10.4	5.15	25.7	51.7	6.38	0.41	0.37		
SDI _{I₈₀}	10.7	4.27	23.3	54.2	6.91 b	0.35	0.32	10.4	5.35	24.9	51.9	6.62	0.43	0.39		
SDI _{I₁₀₀}	11.0	4.20	21.6	55.2	7.34 a	0.34	0.33	10.4	5.27	25.0	51.9	6.66	0.39	0.34		
SSDI _{I₀}	10.7	4.34	24.8	52.8	6.81 b	0.35	0.33	10.2	4.64	26.6	51.7	6.10	0.40	0.39		
SSDI _{I₆₀}	10.9	4.31	23.7	53.4	7.01 ab	0.24	0.33	10.4	4.73	26.2	51.8	6.06	0.40	0.36		
SSDI _{I₈₀}	10.8	4.31	23.5	53.9	6.89 b	0.34	0.32	10.5	4.83	25.0	52.1	6.87	0.37	0.35		
SSDI _{I₁₀₀}	11.0	4.27	22.6	54.5	7.01 ab	0.33	0.32	10.6	5.03	24.4	52.1	7.18	0.36	0.34		
M×I	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns		

The means indicated with the same small letter in the same column are not significantly different ($p < 0.05$)

SDI Surface drip irrigation, SSDI Subsurface drip irrigation, M Irrigation methods, I Irrigation levels, I₀₀₀ Full irrigation (control) treatment, I₈₀ 80% of control treatment, I₆₀ 60% of control treatment, I₀ Rainfed treatment

*, **, and ns, Significant at the $p < 0.05$, $p < 0.01$ level, and not significant, respectively

Table 7 The economic analysis of the different irrigation treatments in SDI and SSDI methods

Costs	Quantity	Price (\$)	Treatments							
			SDI ₀	SDI ₆₀	SDI ₈₀	SDI ₁₀₀	SSDI ₀	SSDI ₆₀	SSDI ₈₀	SSDI ₁₀₀
Operating costs										
Fertilizer (kg ha ⁻¹)	200	0.20	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00
Seed (kg ha ⁻¹)	70	0.73	51.10	51.10	51.10	51.10	51.10	51.10	51.10	51.10
Fungicide/Herbicide (kg ha ⁻¹)	5	1.83	9.15	9.15	9.15	9.15	9.15	9.15	9.15	9.15
Irrigation method application (ha)	1	–	166.70	166.70	166.70	166.70	200.00	200.00	200.00	200.00
Irrigation method cleaning (ha)	1	13.15	13.75	13.75	13.75	13.75	13.75	13.75	13.75	13.75
Irrigation water amount (m ³ ha ⁻¹)	–	–	500.00	3607.00	4642.00	5678.00	475.00	3108.00	3985.00	4863.00
Irrigation water price (m ³)	–	0.02	8.00	57.71	74.27	90.85	7.60	49.73	63.76	77.81
Used electricity (h)	–	–	5.20	37.90	48.70	59.60	4.95	34.55	41.85	51.05
Electricity price (kWh)	–	0.06	0.31	2.27	2.92	3.58	0.30	2.07	2.51	3.06
Total input cost	–	–	289.01	340.69	357.89	375.12	321.90	365.80	380.27	394.87
Labor costs										
Pre-harvest machinery (ha)	1	51.30	51.30	51.30	51.30	51.30	51.30	51.30	51.30	51.30
Growing machinery (ha)	1	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Planting (ha)	1	25.60	25.60	25.60	25.60	25.60	25.60	25.60	25.60	25.60
Plant protection (ha)	1	11.45	11.45	11.45	11.45	11.45	11.45	11.45	11.45	11.45
Irrigation (ha)	1	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83
Maintenance of the method (ha)	1	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83
Harvest (ha)	1	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75
Total labor cost	–	–	127.76	127.76	127.76	127.76	127.76	127.76	127.76	127.76
Total cost	–	–	416.77	468.45	485.65	502.88	449.66	493.56	508.03	522.63
Income										
Yield (kg ha ⁻¹)	–	–	2120.00	2957.00	4629.50	5421.00	2399.50	3907.00	4810.50	5916.00
Average soybean cost (\$ kg ⁻¹)	–	–	0.20	0.16	0.10	0.09	0.19	0.13	0.11	0.09
Soybean sale price (\$ kg ⁻¹)	1	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Gross income (\$ kg ⁻¹)	–	–	424.00	591.40	925.90	1084.20	479.90	781.40	962.10	1183.20
Net income (\$)	–	–	7.23	122.95	440.25	581.32	30.24	287.84	454.07	660.57
Proportional income (%)	–	–	1.02	1.26	1.91	2.16	1.07	1.58	1.89	2.26

SDI Surface drip irrigation, SSDI Subsurface drip irrigation, I_{100} Full irrigation (control) treatment, I_{80} 80% of control treatment, I_{60} 60% of control treatment, I_0 Rainfed treatment

height, the number of branches, number of pods, 1000-seed weight, protein, oil and fatty acid composition were found statistically significant. In the study, as the amount of applied irrigation water increased, the protein content increased whereas oil content decreased. Compared with the full irrigation (I_{100}) treatment, the average protein content of the I_{80} , I_{60} , and I_0 treatments decreased in the SSDI by 14%, 15%, and 20%, while it decreased in the SDI by 8%, 10%, and 18%. Compared with the rainfed (I_0) treatment, the average oil content of the I_{100} , I_{80} , and I_{60} treatments decreased in the SSDI by 16%, 7%, and 5%, while it decreased in the SDI by 18%, 15%, and 17%. Higher oleic acid and low linolenic acid content were determined in the rainfed treatment compared with the I_{100} treatment. The amount of palmitic acid varied over the years, while the stearic acid content did not depend on irrigation treatments. Therefore, as the amount of applied irrigation water increased, the yield increased while

the quality of the fatty acid composition decreased. The average amount of crop evapotranspiration in the two experimental seasons were determined as 166.8, 468.2, 554.8 and 626.1 in I_0 , I_{60} , I_{80} and I_{100} treatments of the surface drip irrigation method, respectively, and as 173.8, 408.6, 479.5 and 534.4 mm in I_0 , I_{60} , I_{80} and I_{100} treatments of the subsurface drip irrigation method, respectively. It was calculated that a 20% and 40% reduction in the amount of irrigation water results in an average yield loss of 19% and 34% in the SSDI and 14% and 46% in the SDI method, respectively. In the rainfed treatments, a yield loss of 60% and 61% has occurred in the SSDI and SDI, respectively. The results of the study clearly indicated the significant effects of irrigation levels on yield and quality of soybeans. Full irrigation treatments under both SDI and SSDI produced significantly greater yields than regulated deficit irrigation treatments in the experimental years. Additionally, SSDI method resulted

in higher soybeans yield than SDI method. When the crop evapotranspiration values obtained from the full irrigation treatments (I_{100}) of the SSDI and SDI methods were compared, it was remarkable that approximately 92 mm of water was saved by the SSDI method. Considering the pressures on sectoral water use as a result of global warming, saving as much as 15% of irrigation water was very important in terms of agriculture and overall use of water resources.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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