Deficit irrigation and irrigation methods as on-farm strategies to maximize crop water productivity in dry areas

Hussein M. Al-Ghobari and Ahmed Z. Dewidar

ABSTRACT

An *in-situ* field study on two types of irrigation methods and three irrigation regimes was conducted in a sandy loam soil located at King Saud University, Riyadh, Saudi Arabia in 2015 and 2016. The study was to assess the effects of different irrigation methods on physiological and yield responses of tomato crops under water shortage conditions. The tested irrigation methods were surface drip irrigation (SDI) and subsurface drip irrigation (SSDI) systems. Irrigation treatments consisted of three strategies: (1) plants were irrigated with a water depth of 100% of the full irrigation supply; (2) plants were irrigated with a water depth of 80% of the full irrigation supply; and (3) plants were irrigated with a water depth of 60% of the full irrigation supply. Results indicated that water shortage significantly affected yield and quality response for each season. Over a 2-year average, yield increase was greatest in T1-SSDI followed by T2-SSDI and then T1-SDI. The yield response factor was 0.95 and 1.05 for SSDI and SDI, respectively. The highest water use efficiency values were obtained in T2-SSDI (16.3 kg m^{-3}) and T1-SSDI (15.6 kg m^{-3}), and the lowest ones, those estimated in T1-SDI (10.9 kg m^{-3}) and T3-SDI (9.5 kg m^{-3}).

Key words | arid areas, surface and subsurface drip irrigation, tomato, water stress, water use efficiency, yield response factor

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INTRODUCTION

Water scarcity is a progressively important issue in many parts of the world. Climate change forecasts of increase in temperature and decrease in rainfall mean water will become even scarcer (Fan *et al.* 2014). This is especially the case in arid regions of Saudi Arabia subject to frequent droughts and where restricted supply of good quality water is the most important factor limiting crop production.

Irrigated crop production in the arid and semi-arid regions of the world is critical to sustaining the increasing human population. According to the recent report of the Inter-Governmental Panel on Climate Change (IPCC 2007), there will be decreasing water availability in many semi-arid and arid areas due to climate change. This is expected to lead to decreased food security and increased vulnerability of poor rural farmers, especially in the arid and semi-arid tropics (Islam *et al.* 2012). Therefore, efficient use of unconventional water application methods is becoming increasingly important and may contribute substantially to attain the twin objectives of higher productivity and optimum use of water.

The trend in recent years has been towards conversion of surface to drip and subsurface drip irrigation systems because cost of installation has relatively decreased with the easy access to subsidized drip irrigation equipment made possible recently (Fan *et al.* 2014). The experience from many countries has shown that farmers who switch from surface irrigation to drip systems can cut their water use by 30% to 60% and crop yields often increase at the

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same time (Enchalew *et al.* 2016). With drip irrigation systems, water and nutrients can be applied directly to the crop at the root level, resulting in positive effects on yield, water savings, and increasing irrigation performance (Shahein *et al.* 2012). Machado *et al.* (2003) indicated that subsurface drip irrigation (SSDI) for tomatoes could increase commercial production without affecting quality. Wang *et al.* (2010) demonstrated that the maximum amount of water with the highest water use efficiency (WUE) was provided by the SSDI system.

Another innovative approach to address the issue of water shortage is through development of new irrigation scheduling techniques such as deficit irrigation (DI), which are not necessarily based on full crop water requirement (Toscano *et al.* 2014). DI provides a means of reducing water consumption while minimizing adverse effects on yield (Pereira *et al.* 2012). In this method, the crop is exposed to a certain level of water stress either during a particular period or throughout the whole growing season. The expectation of this approach is that any yield reduction will be insignificant compared to the benefits that are gained from the conservation of water (Fan *et al.* 2014). However, the grower must have prior knowledge of the crop yield responses to DI. Many investigations have been carried out worldwide regarding the effects of DI on yield of mainly horticultural crops (de Santa Olalla *et al.* 2004; Bekele & Tilahun 2007; Sezen *et al.* 2008). Several studies have demonstrated that the crop response to DI positively affects water use and fruit quality (Ozbahce & Tari 2010). Kumar *et al.* (2007) investigated the impact of DI strategies on onion yield and water savings. They reported that applying 80% and 60% of crop water requirements resulted in yield decreases of 14% and 38%, and saved 18% and 33% of irrigation water compared to full irrigation in 2 years, respectively.

Information is limited about DI scheduling of tomato, especially under arid climate, where tomato is classified as a sensitive plant, and is one of the important horticultural crops in arid regions of Saudi Arabia (Maas & Hoffman 1977). Thus, there is a need to develop strategies based on irrigation restrictions during the whole growing period that may help to save water under conditions of high evaporative demand and chronic shortages without substantially affecting yields. Therefore, various DI strategies under surface and subsurface drip irrigation systems have been applied to tomato crops. Considering the aspects analyzed above, the objectives of the study were to: (i) assess the impacts of water deficits and enhanced irrigation systems' performance on the physical and water productivity of irrigated tomato in Riyadh, Saudi Arabia; and (ii) analyze the response factor (K_y) of the tomato crop when water stress is imposed under different irrigation techniques.

DATA AND METHODOLOGY

Weather and soils data

Environmental conditions were monitored by an *in-situ* meteorological station located at the experimental site of King Saud University (24.43° N, 46.43° E and 635 m elevation), retrieving data on solar radiation, wind speed, air temperature, relative humidity, and rainfall. The continental climate of the region was described as semi-arid, with an average annual precipitation of 100 mm. The weather parameters recorded during the tomato growing cycle in 2015 and 2016 are depicted in Figure 1. The reference evapotranspiration (ET_o) computed on a daily basis with the FAO-PM method (Allen *et al.* 1998) is shown in Figure 2.

Soil data are summarized in Table 1. The soil profile in the upper 0–60 cm soil layer was a sandy loam texture consisting of 72.6% sand, 12.75% silt, and 14.65% clay. The average soil water content at field capacity from the surface soil layer down to a 60 cm depth at 20 cm intervals was 15.97%, and the permanent wilting point for the corresponding depths was 6.15%, respectively.

Scenario characterization

A 1,446 m^2 area located at the educational station of King Saud University, Riyadh, Saudi Arabia was prepared, leveled and then divided into two main fields separated with buffer zones of 6 m. Each field was subdivided into nine plots with surface-area dimensions of 7 m wide × 10 m long (Figure 3). The plants were separately irrigated, in which surface drip irrigation (SDI) was used in first field (nine plots), and

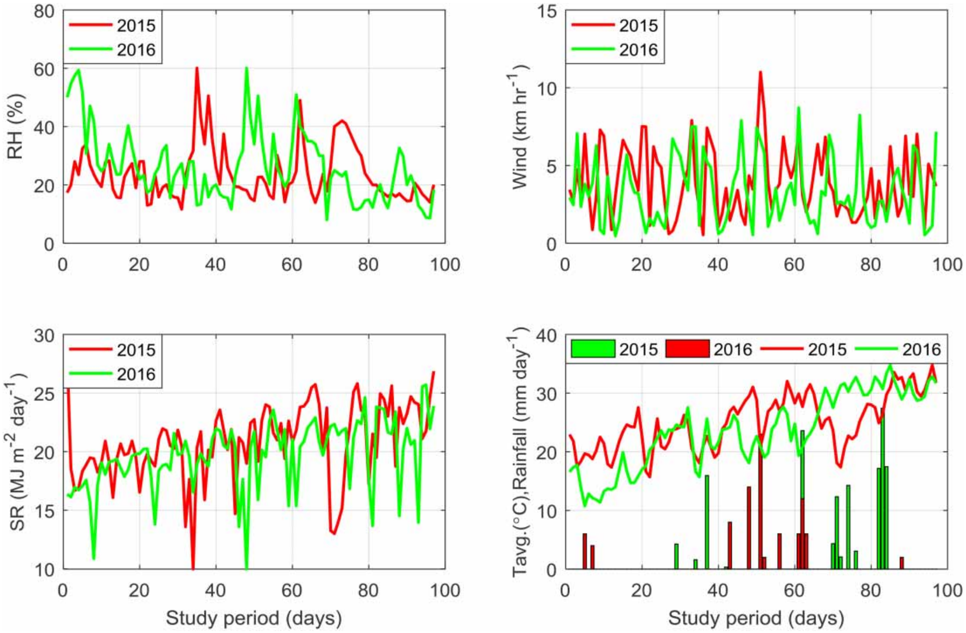

Figure 1 | Daily values of climatic conditions at the experimental site during the growing cycles of tomatoes in 2015 and 2016.

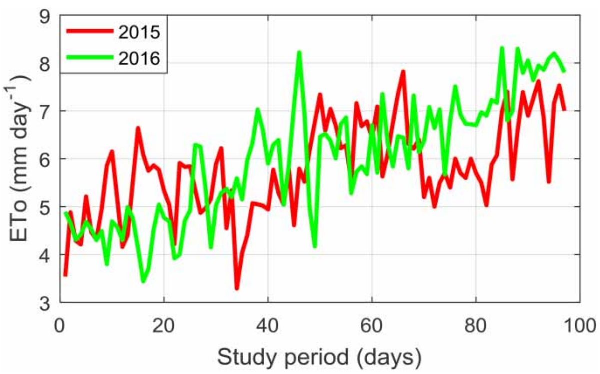

Figure 2 | Daily values of reference evapotranspiration (ET_o) during the tomato growing cycle in 2015 and 2016.

SSDI was used in the second field (nine plots). The irrigation system consisted of a head unit, and main and sub-main delivery polyethylene pipes that were 75 mm and 63 mm in diameter, respectively. The main line was connected to the sub-main line that leads water to sub-areas through the lateral lines. The lateral lines for the SSDI and SDI systems were 32 mm in diameter. The drippers/emitters were placed either on the soil surface (SDI) or buried 15 cm below the soil surface (SSDI).

Tomato plants in both fields were irrigated on a daily basis by different amounts of water according to ET_o values acquired from an automated weather station (Davis Vantage Pro2) located within 10 m of the experimental site. The irrigation treatments consisted of three strategies: in strategy 1, plants were irrigated with a water depth of 100% of the full irrigation supply; in strategy 2, plants were irrigated with a water depth of 80% of the full irrigation supply; and in strategy 3, plants were irrigated with a water depth of 60% of the full irrigation

Table 1 | Physical characteristic of different soil layers

Soil layer depth (cm)	Sand (%)	Silt (%)	Clay (%)	ρ_d (gcm^{-3})	θ_{FC} (m^3m^{-3})	θ_{wp} (m^3m^{-3})
0–20	74.81	11.77	13.42	1.64	14.74	5.32
20–40	72.64	11.65	15.71	1.61	17.27	6.54
40–60	70.35	14.82	14.83	1.59	15.90	6.58

ρ_d is for bulk density, θ_{FC} is for field capacity and θ_{wp} is for wilting point.

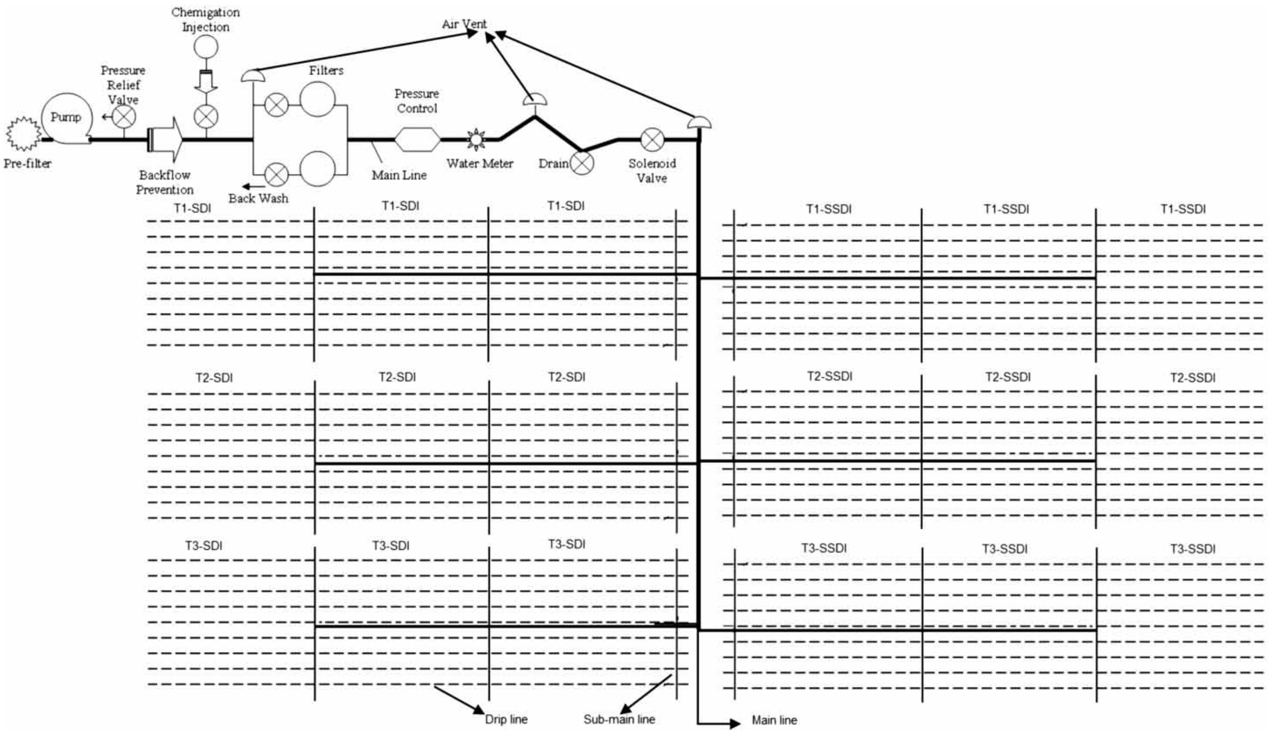

Figure 3 | Schematic of the experimental field for two types of irrigation methods (SDI and SSDI) and three irrigation regimes: T1 (full irrigation supply), T2 (80% of full irrigation supply), and T3 (60% of full irrigation supply).

supply. The treatments (T1 through T3) were replicated three times under SSDI and SDI for a total of 18 plots (Figure 4). Thereafter, the operational required time for each treatment was applied using Equation (1) to start various time-based irrigation schedules on tomato crop. The amounts of water were measured at each irrigation event by multi-jet dry dial water meters, which were fixed to the sub sub-main lines.

$$T_i = \frac{ET_o \times K_c \times A_p \times P_w}{Ea \times (1 - LR) \times Q_s} \quad (1)$$

where T_i is irrigation time (m); ET_o is reference evapotranspiration (mm day^{-1}); K_c is crop coefficient (0.7, 1.15, 0.9,

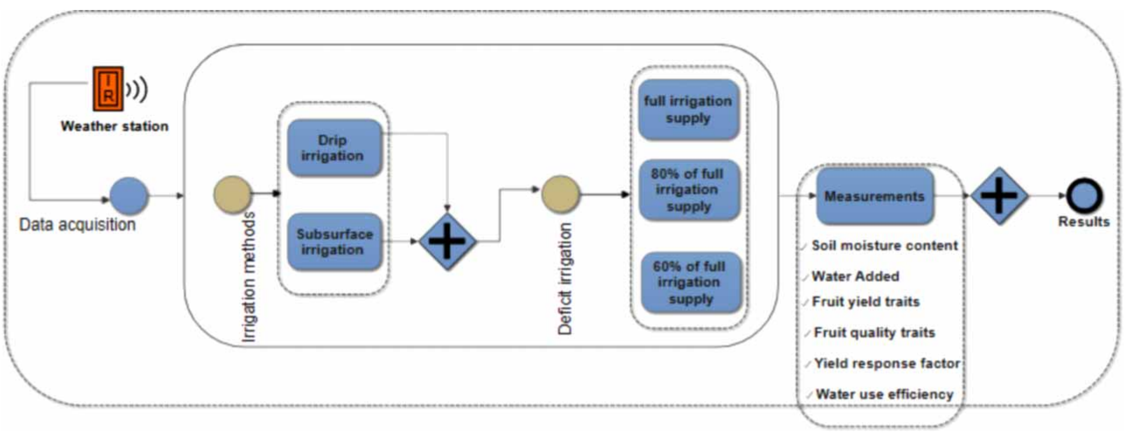

Figure 4 | Flow chart for the research methodology used in the work.

and 0.75 at initial, developmental, middle, and late season stages, respectively); A_p is plot area (70 m^2); P_w is wetted area percentage (33%); E_a is irrigation system efficiency (90%); LR is leaching requirements (10%); and Q_s is irrigation system discharge (L/m).

Leaching is the process of dissolving and transporting soluble salts by downward movement of water through the soil. The fraction of irrigation water that must be leached from the root zones to keep salinity of the soil below a specific limit is termed the leaching requirement (LR). Mathematically it can be expressed as (Doorenbos & Pruitt 1977):

$$LR = \left(\frac{EC_w}{2\max .EC_e}\right) \times \frac{1}{LE} \quad (2)$$

where EC_w is electrical conductivity of water (mmho/cm); EC_e is electrical conductivity of soil extract (mmho/cm); $max\ EC_e$ is maximum electrical conductivity of soil extract tolerated by tomato plants (mmho/cm); and LE is leaching efficiency (90%) for sandy and loamy sands.

Measurements and WUE

Tomato plants (*Lycopersicon esculentum* Mill, GS-12) were transplanted into the site on February 12, 2015 and February 12, 2016. The seedlings were planted in a single row in each bed, with a row spacing of 0.8 m and an interplant spacing of 0.4 m. The plants were provided with optimal growing conditions and all the necessary requirements suggested by the Agriculture Ministry recommendations for the selected experimental region. Other cultivation practices were performed following a scheduled tomato crop program. The chemicals and pesticides were applied identically to all plants as needed. Fertilizers were divided and delivered in accordance with farm management practices. Nitrogen and potassium sulfate were added at a rate of 300 kg/ha and 100 kg/ha, respectively, during the growth period.

Tomato WUE was estimated based on Equation (3):

$$WUE = \sum_{i=1}^{n}\left([Y] \times [W_A]^{-1}\right) \quad (3)$$

where WUE is water use efficiency, kgm^{-3}; n is number of plots with each irrigation strategy; Y is yield achieved, kg; and W_A is water applied, m^3.

Soil samples were taken with a 4 cm auger from the middle row of every plot after transplanting and at 3 days after irrigation during the initial, development, mid-season, and at harvest stages. Each plot was sampled every 15 cm to a depth of 60 cm at eight sites perpendicular to the drip line, at distances 15 cm from the line. Then, soil samples were dried for 48 h at 105°C and soil water content using the gravimetric method was determined.

The crop yield response factor, K_y, is defined as the decrease in yield per unit decrease in water use as expressed by following the procedure given by (Doorenbos & Kassam 1979)

$$\left(1 - \frac{Y_r}{Y_m}\right) = K_y \times \left(1 - \frac{ET_r}{ET_m}\right) \quad (4)$$

where K_y is crop yield response factor to water deficit, dimensionless; Y_r is real yield, kg ha^{-1}; Y_m is maximum yield, kg ha^{-1}; ET_r is real evapotranspiration, mm; and, ET_m is maximum evapotranspiration, mm.

K_y was used to evaluate the plant response to water deficit conditions in relation to non-water deficit conditions. The maximum values of yield and evapotranspiration were obtained with total water depths equivalent to 100% of crop evapotranspiration (ET_c), and the real values with total water depths equivalent to 80% and 60% of ET_c. In other words, maximum values were considered as those at the optimal water depth of 100% of ET_c and the real ones those estimated in the other treatments. Calculations of Y_m, ET_m, and ET_r are well documented (Doorenbos & Pruitt 1977). Tomato sensitivity to water deficit was classified by FAO Bulletin No. 66 as: 'very sensitive' ($K_y > 1$), 'proportionally sensitive' ($K_y = 1$), and 'little sensitive' ($K_y < 1$) (Steduto *et al.* 2012).

Statistical analysis

The data were analyzed using SPSS Version-21 statistical software to obtain descriptive statistics for sampled data. However, analysis of variance (ANOVA) was used for comparison among different plots. All the treatment means were compared for any significant differences using Fisher's least significant difference (LSD) at a significance level of $p <$ 0.05 (Robinson 1961).

RESULTS AND DISCUSSION

Soil moisture content

Figure 5 illustrates the average soil moisture content, field capacity (FC), permanent wilting point (PWP), total available water (TAW), and readily available water (RAW) for the SDI and SSDI methods. These parameters are presented for the planting, development, mid-season, and harvest stages of the tomato crop. Moisture was directly correlated with the amount of water applied in full or deficit-irrigated treatments by irrigation method. Initially, the soil profile for both systems showed high moisture content in all treatments. This is because of the high amount of water that had been added to ensure adequate water in the root zone area during the transplanting stage.

In the initial, development, mid-season, and harvest periods, there were significant differences between the soil moisture content of the subsurface irrigated plots and those irrigated with the surface drip system. For treatments T1-SDI, T1-SSDI, T2-SSDI, and T3-SSDI, the soil water contents fell in the area located between the FC and RAW lines. Conversely, the soil water content values for treatments T3-SDI and T3-SSDI were under the RAW line during the whole growth periods except for the initial stage. The soil water content for T2-SDI and T3-SSDI was close to the RAW line without any serious water stress. Considering the results analyzed above, the use of only 60% of crop evapotranspiration under two systems of drip irrigation for tomato production may result in a severe water stress, lower quantity of yield, and may shorten the plant's life.

Overall, for each irrigation method, the soil moisture content under the fully irrigated treatments (T1-SDI and T1-SSDI) was significantly higher than that in the deficit-irrigated treatments ($p < 0.05$). Meanwhile, the SSDI plots had a higher water content in their soil profiles under water stressed treatments compared to the SDI plots, particularly during the initial and mid-season stages. These observations are consistent with the findings by Camp (1998), which suggested that SSDI can maintain a drier soil surface without undergoing soil moisture and crop water deficit.

Change in evapotranspiration and water use

The quantity of water applied to all sub-areas under different irrigation treatments (T1 = 100%; T2 = 80%; and T3 = 60% of crop evapotranspiration) for the SDI and SSDI plots were separately graphed on a weekly basis (Figure 6). It was observed that the amounts of water applied to the T1 treatment under SDI and SSDI were generally greater

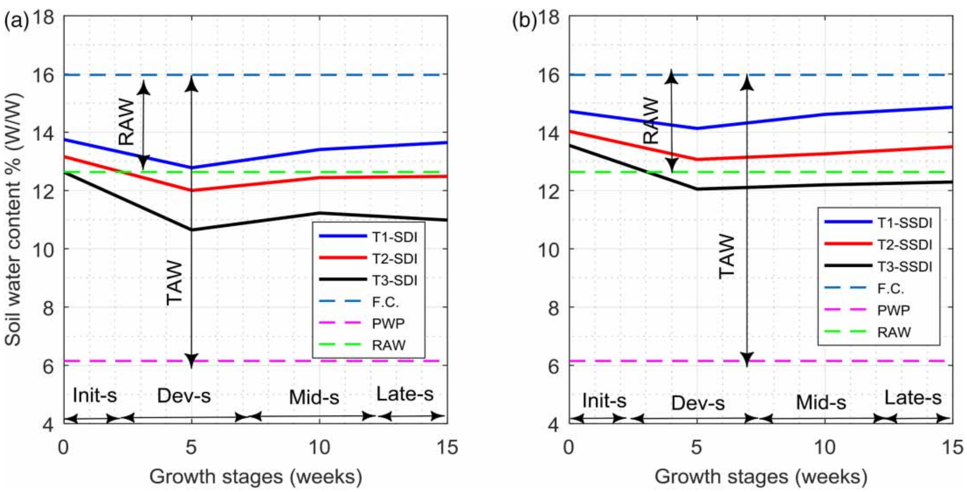

Figure 5 | Average values of soil moisture content under different irrigation strategies (T1 = 100%; T2 = 80%; and T3 = 60% of crop evapotranspiration) for surface (SDI) and subsurface irrigation (SSDI) systems during the growth stages of the tomato crops. SMC, soil moisture content; FC, field capacity; RAW, readily available water; TAW, total available water; and PWP, permanent wilting point.

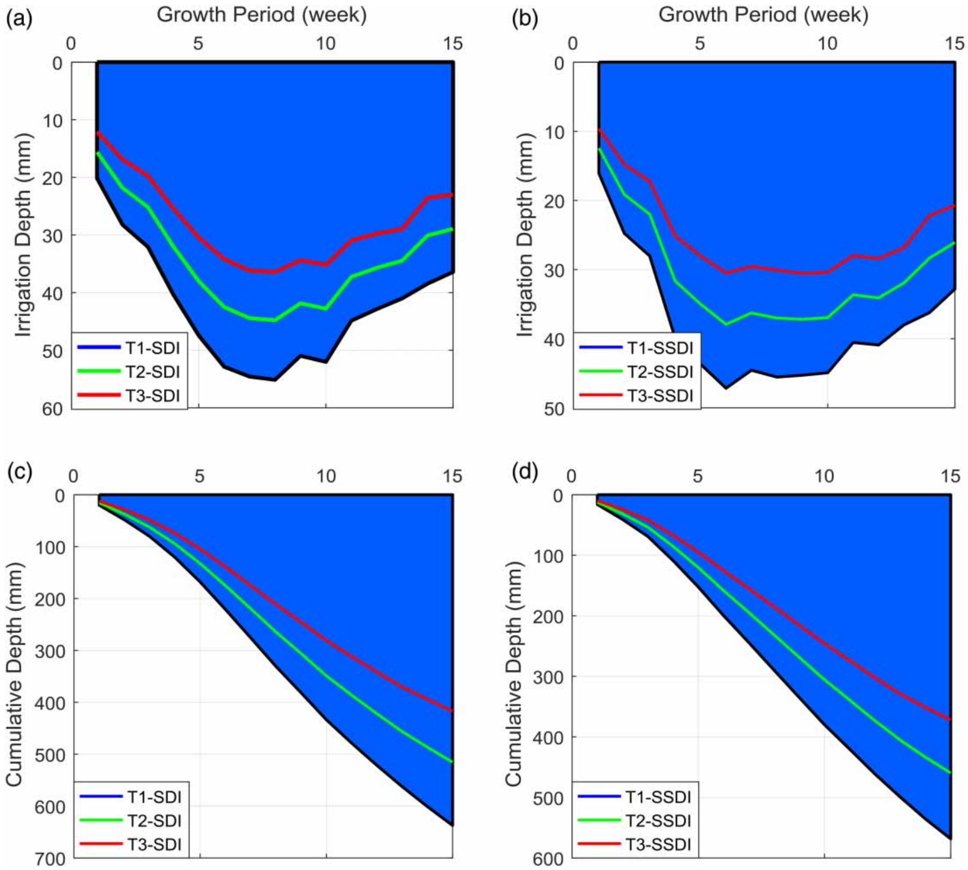

Figure 6 | Average amounts of water applied under different irrigation treatments (T1 = 100%; T2 = 80%; and T3 = 60% of crop evapotranspiration) using the surface (SDI) and subsurface drip irrigation (SSDI) systems.

than those for the T2 and T3 treatments under SDI and SSDI. The average irrigation depths added to the T1-SDI, T2-SDI, and T3-SDI treatments in both the initial and vegetative growth phases were 41 mm, 33 mm, and 26 mm, respectively. The averages values of irrigation depth at the corresponding phases were 36 mm, 29 mm, and 23 mm in T1-SSDI, T2-SSDI, and T3-SSDI, respectively.

As the temperature increased, there was a gradual increase in irrigation depth over the flowering and fruiting stages: irrigation depths reached 46 mm, 38 mm, and 31 mm for T1-SDI, T2-SDI, and T3-SDI, respectively. The increases in irrigation depth for T1-SSDI, T2-SSDI, and T3-SSDI during the same period were 42 mm, 35 mm, and 29 mm, respectively. In the late season, there was a downward trend, where the average depth values of the water applied for T1-SDI, T2-SDI, and T3-SDI fell to 37 mm, 29 mm, and 23 mm, respectively. Similarly, the decrease in irrigation depth values for T1-SSDI, T2-SSDI, and T3-SSDI were 34 mm, 27 mm, and 21 mm, respectively.

Comparing the accumulative irrigation depths of the T1, T2, and T3 treatments using SDI with the corresponding treatments using SSDI during the crop growth period showed that their values were close only in the initial stage and varied gradually during the rest of the season. Moreover, SSDI and SDI treatments had great potential to save water which ranged from 8% by T1-SDI to 46% by T3-SSDI as compared to conventional methods (700 mm in average) practiced by the local farmers in the area (MOA 2012). These results were found to be in line with recommendations introduced by Bates (2009), which suggested that water scarcity management in the face of climate change needs to adopt a scenario-based approach, since climate change poses a conceptual challenge to water managers by introducing uncertainty in future hydrological conditions. It may also be very difficult to detect an underlying trend, meaning that adaptation decisions may have to be made before it is clear how hydrological regimes may actually be changing (Wilby & Harris 2006).

DI impact on agronomical characteristics

The response of the tomato crop during the growing period in both seasons demonstrated that the variation in the water applied by SDI and SSDI had significant effects on the agronomical traits (vegetative growth, fruit quality, and fruit yield traits) as presented in Tables 2–4. The highest values of vegetative growth traits were obtained from T1 using both the systems SDI and SSDI (Table 2). It might be due to the fact that water applied at 100% of crop evapotranspiration adequately meets the crop water requirement. The analyzed results obtained from this table indicated that values of the plant height, number of branches, leaf fresh weight (g), stem fresh weight (g), plant fresh weight (g), leaf dry weight (g), stem dry weight (g), and plant dry weight (g) were significantly increased by 24%, 39%, 27%, 15%, 26%, 27%, 25%, and 24% in T1-SSDI as compared to T3-SSDI. Similarly, the increases in the corresponding vegetative traits in T1-SDI were 27%, 41%, 26%, 15%, 28%, 27%, 27%, and 26% as compared to T3-SDI. This could be attributed to (i) the increased uniform distribution of irrigation water and nutrients using SSD and (ii) the suitable conditions created by SSDI in the root zone during the plant growth.

With reference to fruit yield traits, the highest values were recorded in T1-SSDI, T2-SSDI, and then T1-SDI, respectively (Table 3). In contrast, the treatments T3-SSDI, T2-SDI, and T3-SDI showed lower total yields. This should be attributed to (i) the higher amount of water applied in the fully irrigated treatments and (ii) the lower amount of evaporation losses using the SSDI. Moreover, the results of the analysis listed in Table 3 indicate that the values of total yields were significantly increased in T1-SSDI by 15.5%, 38%, 22%, 35%, and 55% as compared to T2-SSDI, T3-SSDI, T1-SDI, T2-SDI, and T3-SDI, respectively. The increases in total yields in T2-SSDI were 26%, 7%, 23%,

Table 2 | Average vegetative growth traits for tomato plants using different irrigation strategies during the growth cycles in 2015 and 2016

Irrigation system	Irrigation treatments	APH (cm)	NOB	LFW (g)	SFW (g)	PFW (g)	LDW (g)	SDW (g)	PDW (g)
Subsurface (SSDI)	T1	75.5	8.7	705.4	196.7	818.3	86.7	50.4	125.7
	T2	62.7	6.9	606.8	181.7	675.5	71.5	45.3	113.3
	T3	57.3	5.2	512.9	165.9	603.9	63.1	37.4	94.6
Drip (SDI)	T1	71.6	7.2	678.3	187.6	763.4	82.2	48.0	120.8
	T2	58.5	5.7	579.1	168.7	598.5	68.0	42.6	109.6
	T3	51.7	4.2	495.8	159.3	543.2	59.3	34.8	89.1
LSD at 0.05%		3.63	0.94	9.38	5.78	10.57	2.46	2.35	2.59

LSD, least significant difference; APH, average plant height; NOB, number of branches; LFW, leaf fresh weight; SFW, stem fresh weight; PFW, plant fresh weight; LDW, leaf dry weight; SDW, stem dry weight; PDW, plant dry weight.

Table 3 | Average fruit quality traits for tomato plants using different irrigation strategies during the growth cycles in 2015 and 2016

Irrigation system	Irrigation treatments	Fruit length (cm)	Fruit diameter (cm)	Dry matter (%)	TSS (%)	Vitamin C (g/100 g FW)	TA (%)
Subsurface (SSDI)	T1	5.96	5.86	5.71	6.78	29.56	0.69
	T2	4.73	4.75	4.54	5.43	24.23	0.57
	T3	3.53	3.55	3.81	3.99	18.12	0.44
Drip (SDI)	T1	5.71	5.69	5.49	6.57	28.22	0.62
	T2	4.49	4.45	4.42	5.21	22.37	0.48
	T3	3.28	3.32	3.67	3.89	16.51	0.36
LSD at 0.05%		0.22	0.11	0.1	0.1	0.96	0.02

LSD, least significant difference; TSS, total soluble solid; TA, total acidity.

Table 4 | Average fruit yield components for tomato plants using different irrigation strategies during the growth cycles in 2015 and 2016

Irrigation system	Irrigation treatments	Early yield (ton ha^{-1})	Total yield (ton ha^{-1})	Fruit weight (g)	Fruit number/ plant
Subsurface (SSDI)	T1	53.46	88.75	149.23	31.46
	T2	45.94	74.97	138.61	26.92
	T3	38.56	55.25	91.57	23.61
Drip (SDI)	T1	47.27	69.60	140.91	28.91
	T2	36.93	58.01	129.50	25.05
	T3	29.64	39.85	84.76	21.48
LSD at 0.05%		1.03	1.58	2.01	0.72

LSD, least significant difference.

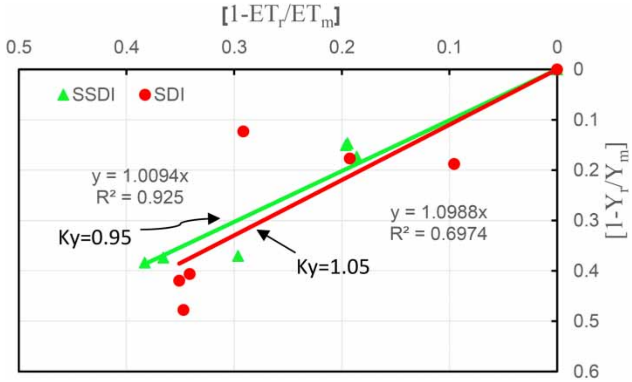

Figure 7 | Relative yield reduction with respect to relative evapotranspiration reduction, measured in tomato plants using surface (SDI) and subsurface drip irrigation (SSDI) systems. K_y is crop yield response factor; Y_r is real yield; Y_m is maximum yield; ET_r is real evapotranspiration; and ET_m is maximum evapotranspiration.

and 48% as compared to T3-SSDI, T1-SDI, T2-SDI, and T3-SDI, respectively.

Table 4 shows that the highest values of fruit quality traits were found in the T1-SSDI and T1-SDI treatments. Similarly, T2-SDI and T2-SSDI reflected a similar trend for fruit quality, but they were of less quality in comparison with T1-SSDI and T1-SDI. This may be attributed to the fact that fully irrigated plots received more irrigation than the deficit-irrigated plots. Finally, it is concluded that the appropriate use of full SDI and SSDI can allow growers to sustain good fruit quality traits. These results are in agreement with the findings reported (Machado *et al.* 2003; del Amor & del Amor 2007; Al-Omran *et al.* 2010; Wang *et al.* 2010).

Yield response factor

The yield response factor (K_y) to water stress was obtained by plotting relative yield reduction with respect to relative evapotranspiration reduction (Figure 7). It is observed that relative yield decreased linearly with increasing relative evapotranspiration. The K_y values varied with irrigation treatments using both surface and subsurface drip irrigation regimes. The values of K_y for T2-SSDI and T3-SSDI during the season were 0.81 and 1.09. The corresponding K_y values for T2-SDI and T3-SDI were 0.87 and 1.23, respectively. The average K_y values for SSDI and SDI treatments were 0.95 and 1.05, respectively. The obtained results confirm the validity of the yield response coefficient to water as a synthesis parameter to quantify the crop tolerance to water stress, where tomatoes with K_y values lower than 1 show good tolerance to water deficit regimes with substantial stability to efficiently use water. On the contrary, tomatoes with K_y values greater than 1 show sensitivity to water stress with marketable yield decrements and a decrease in WUE. From this we deduce that tomato plants were not sensitive to water deficiency in SSDI plots since $K_y < 1$ compared to SDI, with $K_y > 1$. These different results can be attributed to (i) the variation in cultivars, environmental conditions (Shrestha *et al.* 2010) and (ii) agronomic practices with a particular regard to water management strategies and the phonological phases during which the water stress occurred.

Water use efficiency

Figure 8 illustrates the WUE for fully irrigated and DI treatments. It is obvious that increasing the amounts of irrigation applied showed decreasing values of WUE, confirming that DI can improve the WUE in tomato plants. As can be seen from Figure 8, the highest WUE was obtained from T2-SSDI (16.3 kg m^{-3}) and T1-SSDI (15.6 kg m^{-3}). Contrarily, the lowest WUE (14.8 and 9.5 kg m^{-3}) was found in T3-SSDI and T3-SD, respectively. This indicated that when irrigation water decreased, the WUE increased to a certain point. However, when the crop water requirement is dramatically decreased WUE decreased, mainly due to the significant decline in productivity.

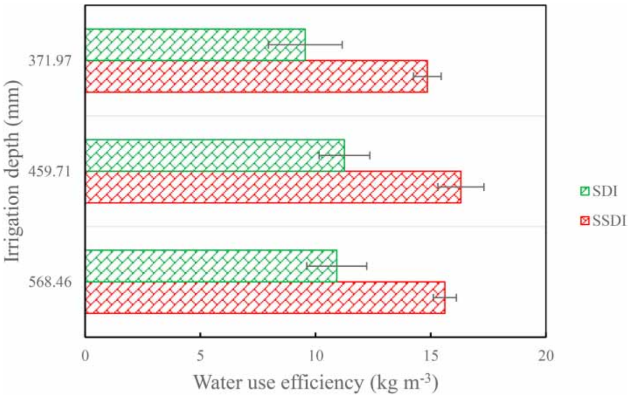

Figure 8 | WUE responses to seasonal water supply under low (T3), medium (T2), and high (T1) irrigation strategies using surface (SDI) and subsurface irrigation (SSDI) systems.

Finally, it has been concluded that SSDI technologies can be used together with DI strategies to improve WUE and tomato yield under conditions of water scarcity, especially in the arid regions. These results are in agreement with those obtained by Beuhler (2003) and Simonovic & Li (2003), which suggested that the improvements in irrigation efficiency are critical to ensure the availability of water both for food production and for competing human and environmental needs under future climate change.

CONCLUSIONS

This study analyzed the combined effects of full and DI strategies, using surface (SDI) and subsurface drip irrigation (SSDI) systems on yield of tomato and the WUE. The goal was to provide additional insights into the improvement of crop management practices under limited water availability and climate variability. The results confirmed that severe water restrictions in each of the irrigation systems have negative effects on both the tomato yield and WUE. The highest values of fruit yield were recorded in T1-SSDI and T1-SDI, and the lowest yield values those obtained from T3-SDI and T3-SSDI. The yield response factor, K_y, was determined to be 0.95 and 1.05 for SSDI and SDI, respectively. Because $K_y < 1$ for SSDI, tomato plants were not sensitive to water deficiency compared to SDI, with $K_y > 1$. Finally, it can be concluded that T2-SSDI could be recommended for the irrigation of tomato crops in the arid climate of northwest Saudi Arabia. Moreover, this treatment could be used particularly for similar crops, where limited water application and low rainfall occur during the growing season.

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