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Tomato yield, physiological response, water and nitrogen use efficiency under deficit and partial root zone drying irrigation in an arid region

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Summary

Water scarcity in arid regions is a serious problem, which calls for innovative irrigation water management. Partial root zone drying (PRD) technique can considerably reduce irrigation amount for crops. To investigate this further, tomato plants were imposed to either surface drip (SUR) with full irrigation (FI) at 100% of evaporative demands and regulate deficit irrigation (RDI) at 50% water of FI or subsurface drip irrigation (SDI) with fixed PRD at 75 (PRD_{75}) and 50% (PRD_{50}) of the FI. Surface evaporation under SUR with FI constitutes a large fraction of water losses from cropped fields while SDI with PRD_{75} preserved more water for plant uptake. Plants grown under water saving treatments showed lower stomatal conductance and transpiration rates compared to FI plants. Tomato yield under SDI with PRD_{75} was comparable to yield under SUR with FI for both tested seasons along with 25% water saving and 30% increase in water use efficiency (WUE). Otherwise, PRD_{50} reduced yield by 18-20%, but a substantial amount of irrigation water was saved along a 60 and 65% higher WUE compared to FI treatment. Fruit dry weight and harvest index (HI) were significantly higher with PRD_{75} compared to the other treatments. Seasonal N uptake and in turn N recovery was higher in PRD_{75} than any other treatment associated with improving N use efficiency.

Keywords: deficit irrigation, PRD irrigation, N uptake and recovery, soil moisture, WUE, *Solanum lycopersicum*.

Introduction

Limited resources of fresh water and severity of droughts in arid and semi-arid regions are continuously threats for food productions, so that it is difficult to grow more crops or even to meet full biological plant demands. Moreover, due to climate change, the climatic water balance between precipitation and evapotranspiration is projected to become increasingly negative in the future, where water is required in large quantities (Bisbis et al., 2018). Therefore, more efficient use of water is the major target to cope with the growing water shortage. For the different ways of water application, drip irrigation is one of the most efficient methods of applying water and nutrients to the crops. This method of irrigation provides various unique agronomic, water and energy conservation benefits that address many of the challenges facing irrigated lands. Consequently, the use of drip irrigation is rapidly increasing in arid and semi-arid regions with the aim to improve water use efficiency (WUE) of plants. In the design of a drip irrigation system for improving water use and optimizing crop production, factors to be considered include plant spacing and plant canopy cover as well as soil texture and topography, potential evaporation, water quality (Cetin and Uygan, 2008). Especially subsurface drip irrigation has the ability to minimizes soil evaporation compared to surface drip (Hanson et al., 2006; Badr et al., 2010).

Deficit irrigation (DI) has been developed to meet the minimum crop water requirement without significant reduction in crop yield (Davies et al., 2002). Moreover, a novel deficit irrigation technique named partial root zone drying (PRD) has been raised and attracted considerable interest (Davies et al., 2000; Kang and Zhang, 2004). In PRD one half of the root zone is irrigated while the other half is allowed to dry out. The treatment is then periodically reversed, allowing the previously watered side of the root system to dry out while irrigating the previously dry side (Stoll et al., 2000; Topcu et al., 2007). The wetting side of the plant has plentiful supply of water and therefore the plant never became stressed as deficit as that of conventional irrigation method. In most cases, PRD has the potential to increase WUE, decrease plant growth and maintain yield and quality when compared with classical irrigation methods (Davies et al., 2000; Tahi et al., 2007).

Fixed PRD is one form of this irrigation technique where water is applied only from one side of the root system while the other side is exposed to continuous dry conditions. Fixed PRD was used as water saving irrigation technique compared to alternate PRD and conventional irrigation. Moreover, fixed PRD can be employed in row crops as a cost effective and less energy consuming method since it requires lower irrigation equipment and does not involve complexities compared to typical PRD (Lekakis et al., 2011). The practical use of PRD was developed based on the knowledge of physiological regulations of plants grown under dry soil conditions. However, stomatal conductance of leaves might decline with increasing the measurable abscisic acid (ABA) that flow from roots to leaves through the transpiration stream to reduce stomatal aperture and leaf growth. The increased concentration of ABA in the xylem flow from roots to leaves triggers closure of stomata was proved in tomato (Campos et al., 2009) and other crops (Kang and Zhang, 2004). As consequences of plant physiological response, the aperture of stomata can be regulated so that a partial closure of stomata at a certain level of soil water deficit may lead to limit transpiration rate and increase WUE (Liu et al., 2005a).

PRD causes spatially and temporally heterogeneous distribution of soil moisture and hereby causing uneven availability of nutrients in the soil and uneven absorptions by the roots in different root zones (Hu et al., 2006; Li et al., 2007). More recently, Hu et al. (2009) used alternate and fixed PRD technique to investigate the dynamic change of plant N absorption and accumulation from root zones. The authors reported increased root N absorption in the irrigated zone significantly when compared to that of conventional irrigation and the re-irrigated half resumed high N inflow rate, suggesting that alternate PRD had compensatory effect on N uptake. Otherwise, under fixed PRD, the N accumulation in plant was mainly from the irrigated root zone and the recovery rate, loss percentage of N applied to the irrigated zone was higher, and the residual percentage of N in soil was lower if compared to those of the non-irrigated zone.

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Both fixed and alternate PRD increased N and water use efficiencies but only consumed about 70% of the irrigated water when compared to conventional irrigation. However, the extended wetting and drying processes under PRD give local soil water content close to field capacity and thus may enhance the radial flow rate of nitrate to the root surfaces.

Tomato plants have the highest cultivated area of any vegetable crop in the world and can tolerate drought to some degree (Hanson and May, 2004; Abdelmageed and Gruda, 2009). Under arid and semi-arid conditions, adoption of irrigation management strategy that utilizes deficit irrigation may be a viable option to improve irrigation WUE. Therefore, greater emphasis is being placed on water management for dry conditions with the aim of crop yield maintenance, which is highly dependent on improving WUE. The projected shift in precipitation pattern, as well as increasing weather variability and extreme weather events such as heat waves, or drought, make furthermore water management a key factor in combating the adverse impacts of climate change (Bisbis et al., 2018).

The present study was carried out to describe the soil moisture variations in the root zone from different drip line positions. Furthermore, yield performance, physiological response, N uptake and recovery and WUE were investigated under different drip irrigation treatments in an arid region where irrigation is the only way for crop production.

Materials and methods

Site and soil description

Field experiments were conducted in a vegetable farm located at Serapium area, Ismailia province east of Nile Delta, Egypt during the late summer growing season (August-December) 2015 and 2016 using drip irrigation system. This area is a desert region included in the agricultural expansion program and recently became productive lands for many crops. The site is located in the arid climate at latitude 30°58 N and longitude 32°23 E with an elevation of 13 m above mean sea level. The area has hot and dry summer months with some ineffective rains in winter and usually bright, sunny days with mild and cold nights. The mean monthly evapotranspiration ranged from 6.8 to 2.5 mm in the respective cropping season. The climate parameters recorded during the growing season of tomato are summarized in (Tab. 1). The soil of the experimental site was deep, well drained sandy profile which was classified as an *Entisol-Typic Torripsamments* comprising of 84.2% sand, 11.5% silt, 4.3% clay and 0.46% organic matter in the topsoil (0-80 cm depth) with an alkaline pH 8.2, EC 0.78 dS m^{-1}, $CaCO_3$ 1.4% and bulk density 1.46 g cm^{-3}. The average soil water content at field capacity from surface soil layer down to 60 cm depth at 20 cm intervals was 0.21 (v/v) and the permanent wilting point for the corresponding depth was 0.11 (v/v), respectively. Average available N, P and K from surface soil layer down to 60 cm depth at 20 cm intervals was 15, 7 and 78 mg kg^{-1} soil, respectively prior to experiment initiation.

Experimental design and treatments

The experiment was laid in a complete randomized block design with three replications. Four drip irrigation treatments were investigated: surface drip (SUR) with full irrigation (FI) at 100% of ET crop and regulate deficit irrigation (RDI) at 50% of FI where the water amount was applied uniformly to the entire plant root zone or subsurface drip (SDI) with two fixed partial root zone drying (PRD_{75}) and (PRD_{50}) at 75 and 50% of FI, respectively in which half of the root zone is irrigated while the other half is exposed continuously to dry conditions. The experimental design also included unfertilized treatment which was used for calculation of N recovery. The plot area was 120 m^2 (6 m × 20 m), with one meter between two neighboring plots to protect water from lateral movement. Drip irrigation (twin-wall, 15 mm inner diameter, in-line drippers at 40 cm distance delivering 2.5 liter h^{-1} at operating pressure 100 kPa) was either laid out directly on soil surface with FI and DI or buried at 15 cm beneath soil surface with both PRD treatments. Twenty-five-day old seedlings of tomato (*Solanum lycopersicum* L.) cultivar 'TY 70/70'F1 hybrid was directly transplanted to the main field at 25 cm intervals along drip lines (32 000 plants ha^{-1}) on the middle of August. Plants were arranged in north south oriented soil beds pre-furrowed to receive 40 t ha^{-1} of organic manure and arranged either in single rows at 100 cm apart for FI and DI or in paired rows at 40/160 cm alternately for both PRD treatments, so that the total number of plant rows was the same for all the treatments. Before tomato transplanting, one drip line was placed along each row in FI and DI or in the center of the paired rows in both PRD treatments as the treatments specified in (Fig. 1). All treatments received 150 kg P ha^{-1} as single super phosphate and 250 kg K ha^{-1} as potassium sulfate before transplanting which incorporated into the soil beds. Nitrogen fertilizer was applied at the rate of 320 kg N ha^{-1} as ammonium nitrate in water soluble form at 7 days interval through the drip irrigation system using Venturi type injector. Fertigation events of N were started two weeks after planting in 12 equal doses and stopped 30 days prior to the end of the growing season.

Tab. 1: Average monthly maximum (T_{max}) and minimum (T_{min}) temperature, relative humidity, rainfall, evapotranspiration (ET_0) and wind speed during the growing season.

Month	T_{max} (°C)	T_{min} (°C)	Relative humidity (%)	Rain fall (mm)	ET_0 (mm d^{-1})	Wind speed (km h^{-1})
2015						
August	36.6	22.1	56	0.0	7.2	8.9
September	35.5	20.2	56	0.0	6.3	8.9
October	31.5	17.4	58	0.0	4.7	7.2
November	27.4	13.5	59	6.7	3.2	6.9
December	25.7	13.1	59	8.3	2.6	8.3
2016						
August	35.6	20.2	53	0.0	6.8	8.9
September	32.8	18.4	50	0.0	5.8	9.3
October	30.2	16.2	56	2.3	4.5	8.5
November	25.7	12.8	59	7.5	2.9	7.8
December	21.2	8.8	60	4.4	2.5	7.8

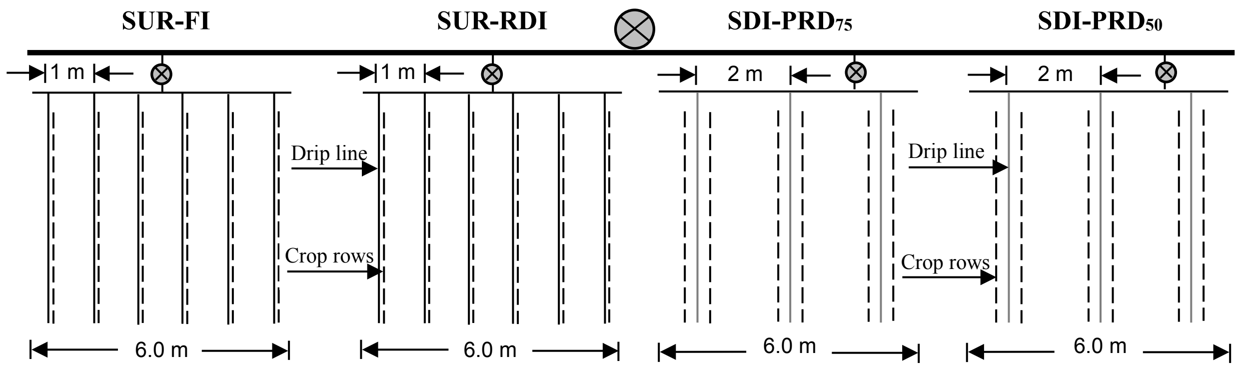

Fig. 1: Layout of the experimental plots showing drip line positions and arrangement of tomato plants under different drip irrigation treatments. FI = full irrigation; PRD = partial root zone drying; RDI = regulate deficit irrigation; SDI = subsurface drip irrigation; SUR = surface drip irrigation.

Soil water and N measurements

The volumetric water content on the wetted soil volume of the bed was monitored every 12 hours during the development stage (30-75 DAT) by time domain reflectometry (TDR) probes (PICO-BT).The TDR probes were installed vertically under the dripper to measure the soil moisture in the profile at 10 (range 0-20) and 30 (range 20-40) cm intervals for each treatment. The time interval of measuring of soil water content was daily during sampling and no less than 2 h after an irrigation event which was considered enough time for irrigation water to infiltrate within sand particles and provide the appropriate balance between the soil and the access tube. To determine ammonium and nitrate in the root zone at the last harvest, soil samples were collected from below the drippers at depths of 10 cm down to 40 cm using tube auger from the wetted area and composite samples were placed on ice and refrigerated until further analysis. The samples from each depth increment were air-dried and ground to pass through 2-mm sieve. Analysis of 2 *M* KCl extractable ammonium and nitrate were performed by steam distillation and total N was determined by the micro-Kjeldahl method modified to recover NO_3^--N (Bremner and Mulvaney, 1982).

Physiological measurements and sampling

Leaf area index (LAI) was measured monthly on cut plant samples taken on fully expanded youngest leaves in each replicate with a leaf area meter (3050 Li-Cor Inc., Lincoln EN USA). Monitoring diurnal change of stomatal conductance, photosynthetic rate and transpiration rate were conducted with a portable photosynthesis system (ADC Bio-Scientific, UK) and leaf water potential (LWP) using a pressure chamber (PMS, Corvallis, USA). Measurements were taken on the central section of a mature leaflet of the last youngest fully expanded leaf, between 07:00 and 19:00 h at flowering stage on two plants per replicate.

Estimation of crop water requirement

Collected meteorological data were calculated from weather station of the Central Laboratory of Agricultural Climate for Ismailia province located near the experimental field. Reference crop evapotranspiration (ET_0) was calculated on a daily basis using Penman-Monteith's empirical formula (Allen et al., 1998). The actual irrigation water was calculated following the crop evapotranspiration (ETc) method according to soil water balance equation:

$$ETc = ET_0 \times Kc$$

where ETc is the maximum daily evapotranspiration (mm); ET_0 is the reference evapotranspiration (mm); *K*c is the crop coefficient for different months based on crop growth stages, 0.45 initial; 0.75 developmental; 1.15 middle; 0.85 maturity for growth stages 30/40/40/25 days (Allen et al., 1998). Cumulative ETc was calculated to be 390 mm in FI treatment for a growing period of 135 days. The entire water requirements were supplied daily during the initial stage of growth to encourage plant establishment, but thereafter irrigation frequency was running at 3 days intervals to deliver the calculated amount of water for each treatment.

Measurements of crop parameters

Biomass accumulation throughout the entire growth period was determined by harvesting three representative plants per treatment replicate at 50, 80, 105 and 135 DAT intervals. Total nitrogen uptake of whole plant parts was determined at maximum biomass accumulation in shoot and fruit tissues. The different plant samples were separated and dried at 70 ºC in a forced air oven for subsequent dry weight determination. Tissue samples were ground to pass through a 0.5 mm screen and stored for dry weight analysis, with a thoroughly mixed 5 g portion of each sample stored. Tissue material was digested using H_2SO_4 in the presence of H_2O_2 and analyzed for total Kjeldahl N at the Analytical Research Lab (National Research Center, ARE) using the method described by Bremner and Mulvaney (1982). Seasonal N uptake was derived from the whole plant sample (shoots + fruits) data and as the product of the crop biomass (dry weight) and the N concentrations in plant materials from which the uptake per hectare was derived based on plant population. Harvesting of the tomatoes was made on last week of November until end of December. Total fruit yield was recorded during the harvest on at least 25 plants in a row in each treatment in all the replications and data were presented as ton per hectare. Water use efficiency was calculated from the total fruit yield (kg ha^{-1}) divided by seasonal crop water applied for each irrigation treatment during the growing season and expressed as kg $yield^{-1}$ mm^{-1}. Nitrogen use efficiency (NUE) was calculated using the following equation:

$$NUE = \left(\frac{Yt - Y0}{N}\right)$$

where Yt equals total yield under treatment, Y_0 equals total yield under control and N equals applied nitrogen. All equation variables are in units of kilogram per hectare. Postharvest N recovery was calculated using the following equation:

$$N\ recovery = \left(\frac{Nt - N0}{N}\right) \times 100$$

where Nt equals total crop N uptake (shoots + fruits) under treatment, N_0 equals total N uptake under unfertilized treatment and N equals applied nitrogen. The average crop N uptake from the unfertilized field plots (N_0) and total yield from the same plots (Y_0) were 12 kg N ha^{-1} and 0.815 t ha^{-1}, respectively for the whole growing season.

Statistical analysis

All data were subjected to the analysis of variance (ANOVA) appropriate to the experimental design to evaluate the effects of treatments on yield and yield components of tomato (total biomass, shoot dry weight and LAI). CoStat (Version 6.311, CoHort, USA, 1998-2005) was used to conduct the analysis of variance. Comparison of treatment means was carried out using the least significant difference (LSD) at significant level of P≤0.05.

Results

Soil moisture content

Analysis of soil moisture content was conducted directly at the position of drip lines during the period of maximum growth rate for SUR with FI and SDI with water saving treatment (PRD_{75}). Regardless of the amount of water applied, soil moisture content under SUR fluctuated in wide range (0.32 and 0.11 cm^3 cm^{-3}) for soil layer (0-20 cm) due to the effect of high temperatures (average T_{max} = 31.5 °C and T_{min} = 17.3 °C) for the period from 15th Sep to 30th of Oct (Fig. 2). For SDI treatment a relatively lower soil moisture fluctuation (0.27 and 0.15 cm^3 cm^{-3}) was observed at the corresponding soil depth as the movement of water by capillary forces was not enough to reach top soil. On the other hand, moisture content at soil layer (20-40 cm) recorded lower values (0.28 and 0.13 cm^3 cm^{-3}) with SUR than with SDI (0.30 and 0.17 cm^3 cm^3) indicating that most of the applied water was remained in the root zone although SDI received lower amount of irrigation water. Moreover, soil moisture content under SDI remains in higher levels during the growing season in relation to SUR because of intensive plant canopy shading for soil surface (two plant rows per one drip line) as was observed in the field.

Physiological responses

The evaluation of the plant physiological state showed remarkable differences between FI in SUR and the three water saving treatments following water restriction. After the beginning of the light period, stomatal conductance in plants grown under water saving treatments began to diverge with FI plants particularly when the temperature rises at midday. The highest LWP was observed under FI irrigation throughout the day, but the difference became most obviously in the afternoon (Fig. 3a). Mean values of LWP in control plants was significantly greater than in water saving treatments, however, the measured values in the PRD_{75} had experienced little bit lower LWP than in the other treatments at midday. Plants under RDI showed the lowest stomatal conductance suggesting that this method of irrigation imposes the greatest restriction on stomatal aperture (Fig. 3b). Further, the photosynthetic rate measured under PRD_{75} was nearly the same as the FI treatment; whereas, the RDI exhibited the lowest rate (Fig. 3c). Similarly, plant transpiration rate showed appreciable decrease following partial stomatal closure in water saving treatments, particularly in RDI plants, which recorded approximately 50% lower values than those of FI plants.

Yield and water use efficiency

Although PRD_{75} plants in SDI received 25% lower water compared to FI plants, shoot biomass and fruit yield were not significantly affected but almost the same yield was obtained (Tab. 2). When applying PRD_{50} under SDI, remarkable water savings was obtained while the yield reduced to only 20 and 18% during first and second season, respectively. Otherwise, tomato fruit yield depressed under RDI in SUR by 34 and 32% during first and second season, respectively mainly due to the decline in fruit weight and high fruit losses. This result indicated that the PRD technique had higher yield benefit along with substantial amount of water saving (50%) as compared to conventional RDI. Moreover, both PRD treatments facilitates 7-10 days early fruit harvest compared with FI plants which give an advantage for fresh market tomato over other treatments. Water saving treatments had higher percentage of fruit dry weight at which maximum value was obtained under both PRD treatments. Fruit harvest index (HI = fruit dry weight/total above ground dry weight at harvest) were higher under PRD_{75} compared to other treatments which related to greater fruit dry weight. However, harvest index tended to decrease with increasing water stress, so that RDI in SUR caused the lowest value. The highest dry biomass accumulation throughout the growth period was obtained under PRD_{75} in SDI although leaf area index (LAI) reduced the most under all water saving treatments compared to the corresponding value of FI in surface drip (Fig. 4a, b).

Water use efficiency was positively affected by both PRD treatments, suggesting that the crop yield was benefit from the water applied to the crop for the whole season (Tab. 2). As the amount of water applied was lower by 25% in PRD_{75}, the WUE increased by 30% over than FI treatment (from 177 to 230 kg ha^{-1} mm^{-1}). Moreover, when water amount was reduced by 50% in PRD_{50} the WUE increased by 65% (from 177 to 291 kg ha^{-1} mm^{-1}). Higher WUE in both PRD treatments might be owing to more water available to each plant due to retardation of water evaporation from surface soil area because of intensive plant cover (paired rows per one drip line).

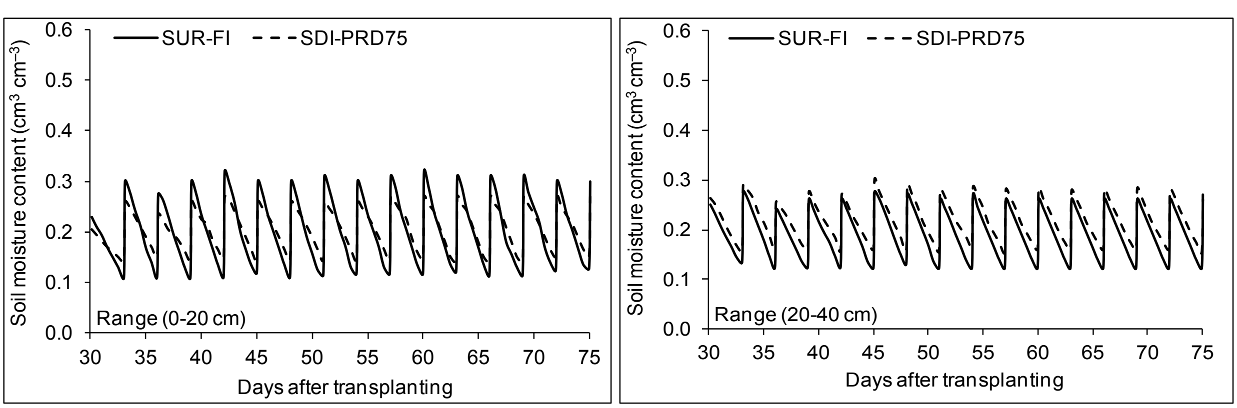

Fig. 2: Temporal changes of moisture content in two different soil layers during the developmental stage for SUR with FI and SDI with PRD_{75} (pooled data of the two years).
FI = full irrigation; PRD = partial root zone drying; SDI = subsurface drip irrigation; SUR = surface drip irrigation.

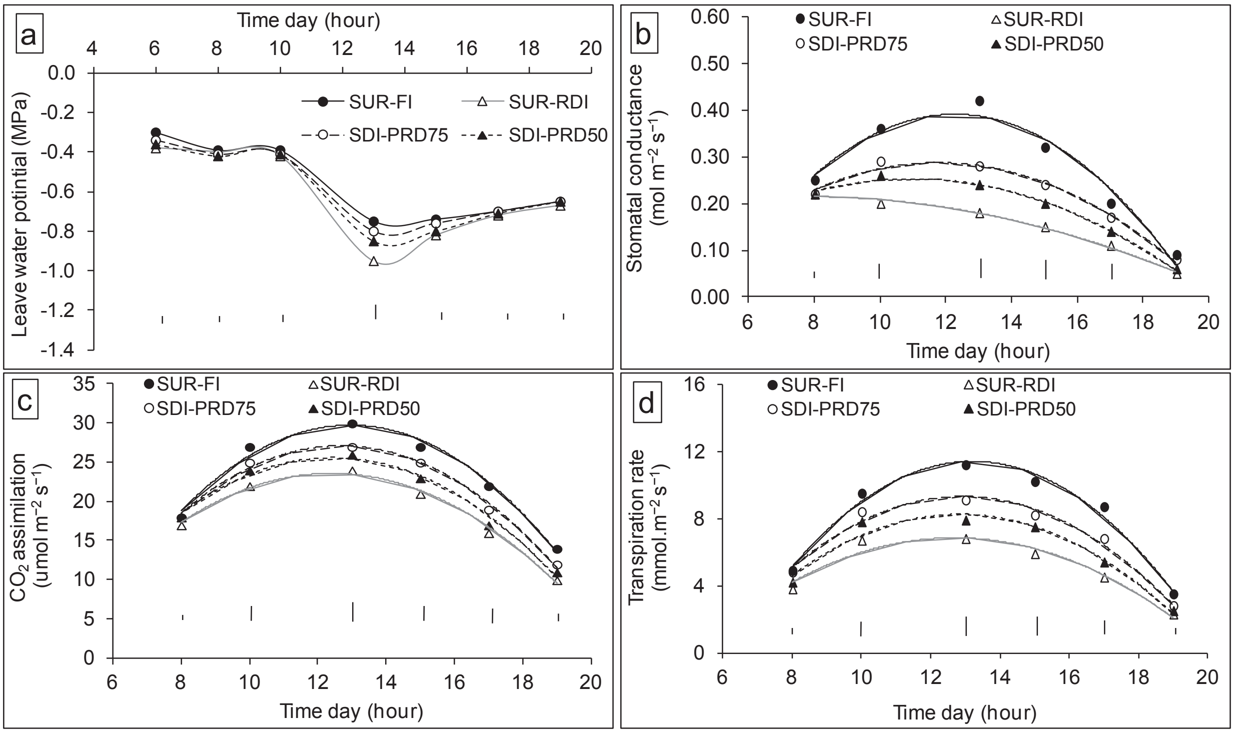

Fig. 3: Diurnal changes of leaf water potential (a), stomatal conductance (b), CO_2 assimilation rate (c) and transpiration rate (d) of tomato grown under different drip irrigation treatments at flowering stage. Data points are two years pooled data of three replications. Least significant differences (LSDs) at $P \leq 0.05$ are presented as vertical line bars.
FI = full irrigation; PRD = partial root zone drying; RDI = regulate deficit irrigation; SDI = subsurface drip irrigation; SUR = surface drip irrigation.

Tab. 2: Tomato fruit yield, shoot dry weight (DW), total dry weight, harvest index (HI) and water use efficiency (WUE) as affected by different drip irrigation treatments.

Treatments	Yield (t ha^{-1})			HI	Fruit DW	*I*	WUE
	Fruit	Shoot DW	Total dry weight		(%)	(mm)	(kg ha^{-1} mm^{-1})
Year 2015							
SUR-FI	65.32a	2.31a	5.65ab	0.59	5.12b	420	156c
RDI	43.29c	1.91b	4.48c	0.57	5.95a	210	206b
SDI-PRD_{75}	63.87a	2.19a	5.95a	0.63	5.90a	315	203b
PRD_{50}	52.14b	2.11ab	5.21b	0.60	5.95a	210	248a
Year 2016							
SUR-FI	68.87a	2.36a	5.89ab	0.60	5.12b	390	177c
RDI	46.74c	1.97c	4.70c	0.58	5.85a	195	240b
SDI-PRD_{75}	67.29a	2.27ab	6.25a	0.64	5.92a	293	230b
PRD_{50}	56.72b	2.08bc	5.44b	0.62	5.92a	195	291a

Values within the column followed by different letters are significantly different based on least significant difference (LSD) at $P \leq 0.05$.
FI = full irrigation; PRD = partial root zone drying; RDI = regulate deficit irrigation; SDI = subsurface drip irrigation; SUR = surface drip irrigation.

Nitrogen uptake, recovery and nitrogen use efficiency

Tomato fruits took up the largest portion of N compared to other plant parts, irrespective of drip irrigation treatment (Tab. 3). Although N translocation to the shoots was slightly higher with FI plants in SUR, the translocation was selectively towards fruits with PRD_{75} in SDI which accumulated 17 and 15% higher N in the fruits during 2015 and 2016, respectively. Total dry biomass (shoot + fruit) with PRD_{75} showed relatively higher total N uptake and recovery than with FI due to relative higher fruit dry weight and better utilization of N from the root zone.

On the other hand, the significantly lower yield with DI and PRD_{50} may be partially due to lower N uptake and recovery because of soil drying coincided with limited nutrient diffusion and mass flow to the root surface. The highest NUE was noted under the FI treatment whereas; it was the least under DI treatment although the same amount of N was applied. This result shows how deficit irrigation reduces capacity of the crop for uptake and efficient use of nitrogen particularly when N deficiency may cause drastic yield reductions.

Soil nitrogen content

The content of residual soil NH_4^+-N and NO_3^--N were determined for SUR with FI and SDI with PRD_{75} in the different soil layers at the last harvest of tomato (Fig. 5). There was a relatively higher level

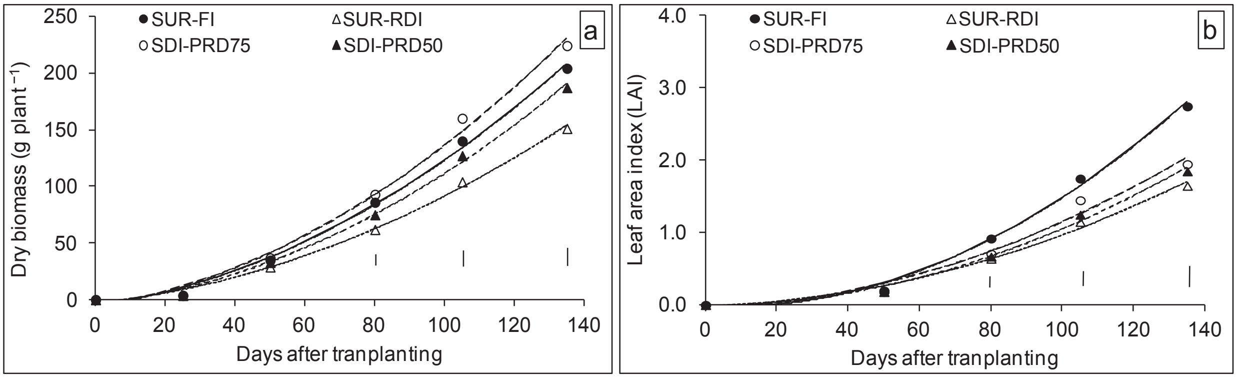

Fig. 4: Seasonal changes of dry biomass (a) and LAI (b) during the progress of growth season of tomato under different drip irrigation treatments. Data points are two years pooled data of three replications. Least significant difference (LSDs) at P ≤ 0.05 is presented as vertical line bars.
FI = full irrigation; PRD = partial root zone drying; RDI = regulate deficit irrigation; SDI = subsurface drip irrigation; SUR = surface drip irrigation.

Tab. 3: Nitrogen uptake, N recovery and N use efficiency (NUE) of tomato as affected by different drip irrigation treatments.

Treatments	Nitrogen uptake (kg ha^{-1})			N recovery	NUE
	Fruit	Shoot	Total	%	(kg yield kg^{-1} N)
2015					
SUR-FI	124b	73a	197b	58	202a
RDI	101c	47c	148d	42	133c
SDI-PRD$_{75}$	144a	71a	215a	63	197a
PRD$_{50}$	116b	54b	170c	50	160b
2016					
SUR-FI	130b	75a	205b	60	213a
RDI	105c	50c	155d	45	144c
SDI-PRD$_{75}$	149a	72a	221a	65	208a
PRD$_{50}$	126b	56b	182c	53	175b

Values within the column followed by different letters are significantly different based on least significant difference (LSD) at P ≤ 0.05.
FI = full irrigation; PRD = partial root zone drying; RDI = regulate deficit irrigation; SDI = subsurface drip irrigation; SUR = surface drip irrigation.

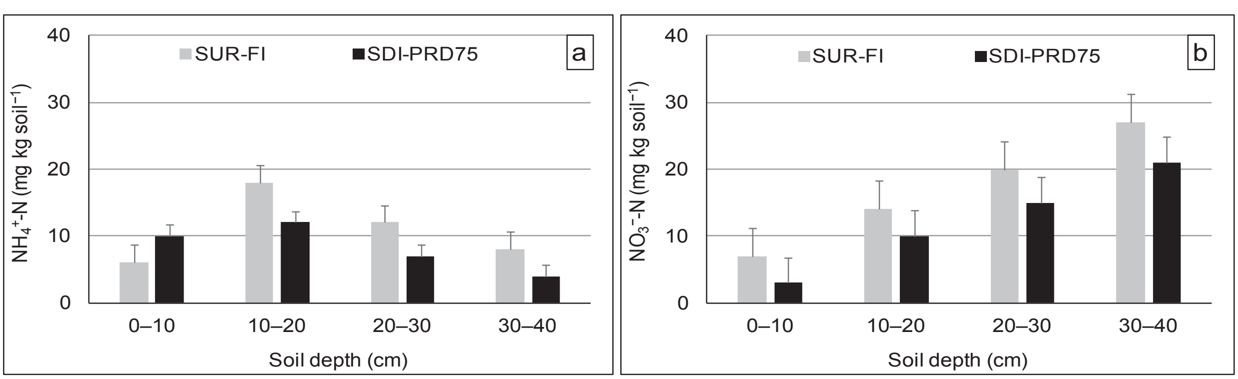

Fig. 5: Soil residual NH_4^+-N (a) and NO_3^--N (b) contents at different soil depths for SUR with FI and SDI with (PRD$_{75}$) at the last harvest of tomato in 2016. Error bars indicate standard error of the means (*n* = 3) ± S.E.
FI = full irrigation; PRD = partial root zone drying; SDI = subsurface drip irrigation; SUR = surface drip irrigation.

of NH_4^+-N content at the proximity of the water source in both drip irrigation systems because of adsorption on soil particles. Except for the surface soil layer (0-10 cm), residual NH_4^+-N content in PRD$_{75}$ was relatively lower compared to FI treatment. On the other hand, NO_3^--N content decreased from the topsoil to deeper soil layers for the both drip irrigation systems. The residual NO_3^--N content in the whole root zone was significantly 17% lower with PRD$_{75}$in SDI than with FI in SUR. The total residual N mineral content in the root zone was significantly 27% less in PRD$_{75}$ than FI in accordance with higher N uptake (221 kg ha$^{-1)}$ than any other treatments.

Discussion

Water scarcity has become a significant limitation in agricultural/horticultural production worldwide. Hence the need to accurately estimate the crop water needs, under different conditions in order to optimize irrigation and increase the water saving. Hence, customizing irrigation is a multi-faceted activity (GRUDA and TANNY, 2014).

Soil moisture status

Through the evaluation of both drip irrigation systems, the water delivered on top soil in SUR with FI exposed directly to evaporation components, which resulted in higher soil moisture fluctuation at surface soil layer (0-20 cm) compared to SDI treatment (Fig. 2). On the other hand, soil surface was usually dry in SDI treatment where the water was provided at a certain depth (15 cm from top soil) which ensures that a substantial fraction of applied water becomes available to the plant root system. However, SDI resulted in a relatively small increase in soil moisture content at soil surface where the upward capillary movement of water was not sufficient to reach top soil, which resulted in lower soil evaporation loss there by repressing the upward capillary movement of water (PATEL and RAJPAT, 2008; MESHKAT et al., 2000). Although PRD_{75} plants in SDI received lower water the buried drip line in SDI treatment produced relatively higher soil moisture content over time in the root zone (20-40 cm), where a reasonable amount of water below soil surface was maintained and helped in store and increase wetted soil volume more than SUR treatment (PATEL and RAJPAT, 2008). Similar indication of water distribution in the soil was noted by ZOTARELLI et al., (2009) who found that water applied through SDI remained at the root zone for utilization of plants and was not lost due to deep percolation. This finding holds, both in terms of amount of available water and distribution uniformity by placing the drip line sufficiently below the soil surface, which ensures that the applied water becomes available to the active part of crop root zone and cuts of evaporation losses due to restricted upward capillary flow (PATEL and RAJPAT, 2008). Therefore, SDI seems to be more suited to effectively address the limitation of low water storage capacity of sandy soils.

Leaf water potential and stomatal control

Fixed PRD technique, involves frequent irrigation of only one-half of the root zone in each irrigation event while the other half was always kept in a drying state. This made it possible that half root system absorb water easily, whereas the other half was subjected to partial water deficit. The roots in the dry side can sense soil drying and produce signals (mainly ABA) that move through the transpiration stream to the shoots. These signals can play a vital role in maintaining a highly water status in the shoots through the reduction of stomatal conductance and leaf expansion (HOLBROOK et al., 2002; BACON, 2003; LIU et al., 2006). As expected, the limited water supply under deficit irrigation, induced water competition among the growing plants, evaporative demand as fruits of tomato are highly water demanding (MINGO et al., 2003). However, less water availability in water saving treatments modified LWP of tomato with the minimal effect observed with both PRD plants (Fig. 3).

With inadequate water supply, or extreme heat and drought, the stomata close much earlier with negative consequences for gas exchanges and CO_2 assimilation. Because of the reduction in CO_2 assimilation in leaves, the metabolic processes are impacted resulting in many of the integrated physiological and biochemical processes that cause yield and quality reduced (GRUDA and TANNY, 2014; GRUDA and TANNY, 2015). Although it is difficult to determine whether stomatal closure limited photosynthetic rate, but this seems likely when the strong relationship of transpiration rate and yield is taken into account. This would explain the significant reduction in tomato yield under deficit irrigation (RDI) whereas loose-leaf turgidity adversely affects photosynthesis between the irrigations. Diurnal stomatal conductance was most significantly reduced under RDI suggesting that this method of irrigation cannot control stomatal aperture, which imposes the greatest water stress on plant growth. This would explain the reason behind the greatest yield reduction under deficit irrigation (RDI). However, coordinates of stomatal conductance under PRD_{75} fall closely to that of FI treatment whereas; photosynthetic rate almost follows the same rate or affected least between the irrigations. The outcome of this process is reasonably good yield with considerable water savings and higher WUE, which is of paramount importance in areas of limited water resources. Earlier studies indicated that at similar soil water deficit, PRD could intensify ABA signaling relative to the RDI treatment resulting in better control of plant water loss and avoiding water luxury causing further improvement of WUE (DODD, 2007; WANG et al., 2010).

Fruit production and water use efficiency

Coincide with changes in leaves physiology and growth, PRD_{75} did not significantly decrease yield of tomato, expressed as fresh fruit weight but 25% water saving was achieved during the completely growing season (Tab. 2). Similar results have been obtained in other studies with tomato (ZEGBE et al., 2003; KIRDA et al., 2004). Although PRD_{50} exert negative effect on vegetative growth, fruit yield reduced by only 18% corresponded with 50% lower of water applied as compared to FI, suggested that PRD technique induces a photosynthetic assimilates towards fruit growth to maintain yield production (TOPCU et al., 2007). This may explain the minimal effect on fruit yield in comparison with the pronounced yield reduction (32%) occurred on the plants grown under regulate deficit irrigation (RDI). Consistent with previous study by TOPCU et al. (2007), our results suggest that the PRD technique facilitates 7-10 days early harvest with high cash profit compared to FI plants. Fruit dry weight was greater in water saving treatments, particularly in both PRD treatments compared with FI. This represents a production of firmer fruits, a very important quality parameter for tomato in post-harvest process. According to GRUDA (2005) and GRUDA et al. (2018), product quality of vegetables is a complex issue and apart from visual characteristics and properties such as texture, the content of minerals and vitamins, flavor and other organoleptic characteristics should be considered. In our study, these characteristics were not investigated. According to BOGALE et al. (2016) PRD can enhance health-promoting qualities of tomato by increasing contents of vitamin C, lycopene, and -carotene in fruits as well as total phenolic content (TPC) and antioxidant activity. However, the impact on vitamin C, lycopene, external color and TPC appear to be cultivar dependent. Therefore, the authors emphasized that the choice of appropriate cultivars under different irrigation techniques is crucial for maintaining or modulating the quality and nutritional contents in tomato, while allowing for water savings.

Overall fruit harvest index declined significantly in response to water deficit in RDI but it was higher under both PRD treatments, which related to greater water use and fruit dry biomass. Tomato plants under PRD_{75} accumulated higher dry biomass than FI plants because of higher fruit dry matter translocation from shoots to reproductive organs (Fig. 4a). Leaf area index was remarkably lower in the all water saving treatments compared with FI (Fig. 4b). However, leaf expansion is highly sensitive to soil drying as observed on tomato (TOPCU et al., 2007) and other crops (KANG and ZHANG, 2004).

Water use efficiency was markedly improved when less amount of water was applied in PRD_{75} and this effect was more expressed in PRD_{50}, which relatively maintained tomato yield with lower amount of water but this effect was not apparent when the yield decreased markedly in RDI treatment. Accumulated evidence has shown that, PRD technique was found able to reduce irrigation water relative to FI and in turn WUE was appreciably increased (ZEGBE et al., 2004; CAMPOS et al., 2009).The observed higher WUE obtained at the PRD_{50} treatment was a result of a higher ratio of water reduction to yield reduction. Tomato is highly consumed of water in order to increase yields however; the important comparison with respect to WUE is the compromise between conventional FI and PRD technique. Thus, taking together WUE and yield, PRD_{50} seems to be the best water management option when plants utilized 50% less amount of water and resulted in substantial 65% increase in WUE in the drier environment.

Plant nitrogen indices

Growth conditions, N availability and water consumption by plants greatly affect the total N uptake in the plants (Tab. 3). Although PRD_{75} plants consumed less water (75% of FI) but also accumulated relative higher N amount and higher N recovery than FI plants. These results indicated that PRD treatment could improve translocation of N from shoot to fruits and increases dry biomass allocation, which in turn increases harvest index (Topcu et al., 2007). In addition, the higher uptake of soil nitrogen, under SDI coupled with PRD_{75}, should be attributed to delivering N fertilizer amount directly to plant root zone (Camp et al., 1997). These results therefore, confirm the earlier studies that the water deficit like in PRD technique could improve crop N nutrition and optimize N distribution in the canopy thereby recovering higher portion of N costs compared to FI or conventional RDI treatments (Stoll et al., 2000; Zegbe et al., 2003). Less N uptake in RDI and PRD_{50} might be caused by lower N uptake from the relatively dry soil zones where soil moisture content determines the soil N availability and its transport to the roots (Bahrun et al., 2002). However, soil nutrient availability is a function of soil chemistry and regulated by the dynamic changes of soil moisture. For the nutrient transport from the soil to the root surface, mass flow and diffusion are two different mechanisms. Kang and Zhang (2004) show further that soil drying reduced plant vegetative growth and also possibly reduced the total nutrient absorption as a consequence. This is because of reduced N absorption from the dry zones, which may result in N stress in this zone, and thus induce plant adaptation to the nutrient stress (Hu et al., 2009). The NUE under PRD_{75} was slightly lower compared to FI where such technique could maintain fruit yield of tomato. However, it has been shown that PRD can greatly induce the initiation and growth of secondary roots, which improve the ability of the plant to absorb both water (Liang et al., 1996) and nutrients from the soil matrix, which may increase the nutrient use efficiency (Han and Kang, 2002).

Status of soil nitrogen

For both drip irrigation systems, soil NH_4^+-N with (FI and PRD_{75}) remained higher at the proximity of the water source (Fig. 5a) due to adsorption on soil particles (Li et al., 2004; Hanson et al., 2006). The content of NH_4^+-N was relatively lower in PRD_{75} compared to FI although only in the top soil layer the reverse was true, which can be ascribed because of NH_4^+-N losses via nitrification and/or volatilization. However, there was no evidence on NH_4^+-N accumulation occurred in the soil profile at last harvest of tomato. By contrast, the residual soil NO_3^--N content decreased from the topsoil to deeper soil layers for both drip irrigation systems (Fig. 5b) as nitrate tended to accumulate at the periphery of the wetted soil volume (Li et al., 2004; Gardenas et al., 2005). However, in all soil layers the residual total N mineral content (NH_4^+-N + NO_3^--N) for the water saving treatment (PRD_{75}) tended to be lower than that of FI in the root zone of tomato. The lowered residual N in the soil under PRD_{75} treatment can be explained by enhancing N uptake, deeper roots and increasing root density. These effects of PRD technique have been reported by Poni et al. (1992) and Fort et al. (1997) who observed that root systems extend to deeper layers along with PRD induces the initiation and growth of the secondary roots which improves the ability of the plant to absorb water and nutrients from the active part of the root zone (Liang et al., 1996).

Conclusion

Design of drip irrigation system included SDI coupled with water saving treatment such as PRD represents unique practical benefits for tomato production and water saving. Partial root zone drying with moderate water saving (75% of ET crop) could enhance the balance of yield and WUE, which may provide a useful approach to apply this technique in arid regions. On the other hand, PRD with more water saving (50% of ET crop) can be realized by losses of only 18% fruit yield but with substantially water saving and a remarkable improvement in WUE. The sacrifice of some yield losses, but with a sustainably saving in irrigation water along with improving WUE could be acceptable under these conditions. Special attention should be paid to the importance of SDI with PRD technique for the reproductive of crops in areas where water shortage dominates or expensive in the view of water saving and yield maintenance.

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