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Effects of short duration partial rootzone drying (PRD) on soilless grown tomato crop

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Abstract

We have studied partial rootzone drying (PRD), on soilless grown greenhouse tomato. The tomato plants were grown hydroponically during 253 days of period from September to June in greenhouse in Mediterranean climate. Four treatments were used in the experiment: (1) Full-open irrigation and (2) full-close irrigation, where all roots under both treatments were wetted in every irrigation, (3) PRD open and (4) PRD close treatments where 30 to 50% reduced nutrient solution was applied compared to full irrigation treatments. Under the PRD treatments, the plant root system was separated to two parts and the root zone were interchanged every irrigation in subsequent irrigations during the day. In the open systems the excess irrigation or nutrient solution was discharged as drainage from the greenhouse. In the close systems drainage effluent from the base of the growth containers was collected, re-cycled and therefore re-used in the system. Irrigation frequency during the experiment was changed between 4 to 20 times, every hour or every 45 minutes from 6.00 am to 20.00 pm, per day depending on plant age and climatic conditions. There was no adverse effect of PRD on both plant growth and yield in soilless grown greenhouse tomato. The reason may be the frequent interval of the wetting and drying cycles of plant rootzone in soilless practice. The interval of changing the irrigated halves of the root zone may be as short as hours or even minutes. The soilless growing systems give better benefits to the plants to manipulate physiological responses in more proper conditions than in PRD soil application. The results additionally showed that the nutrient solution use efficiency was highest in “PRD-Close” due to saving of nutrient solution by the combined effects of deficit irrigation with PRD and re-cycling of nutrient solution. As conclusion the PRD applications in soilless grown greenhouse crops have good potential for saving water and nutrient solution as well as its environment friendly nature with minimized drainage discharge.

Key words: Hydroponics, *Lycopersicon esculentum* Mill., split root, partial rootzone drying (PRD), WUE, yield, greenhouse.

Introduction

Water has now become the most precious limiting resource in the world for irrigation which is essential for meeting food and fiber demand of ever increasing World’s population. Climate change scenarios predict increasing aridity in major areas of high agricultural production potential in coming decades owing to global warming. The situation is critically summarized in United Nation Millennium Declaration as “more crop per drop” [1]. Therefore, saving irrigation water and developing new techniques for increasing water-use efficiency are the major issues attracting increasing research efforts. Recently, partial rootzone drying (PRD) practice, developed based on split root studies, has been proposed as a new deficit irrigation technique to increase crop water use efficiency and thereby to save irrigation water [9, 10, 23-25, 37, 39, 40]. In the PRD practice, only one half of the roots are watered whilst leaving the other half dry during irrigation. The wetted and the dry half of the roots are alternated in the subsequent irrigations and thus significant savings of irrigation water can be achieved compared to fully irrigated plants [13, 28]. Plant water status is expected to equilibrate with the wettest part of the rhizosphere and maintaining therefore high leaf water potential similar to well-watered plants [19]. The partially dry half of the roots promotes abscisic acid (ABA) synthesis. The increased concentration of ABA in the xylem flow from root to leaves leads to partial stomatal closure to promote sparing use of water [7, 17]. Other mechanisms controlling stomatal aperture include hydraulic signals and pH changes of xylem sap [7, 38]. The half of the roots that are adequately irrigated and the other half remaining partially dry cause only small reduction of photosynthesis with, however, significant increase of water use efficiency [34].

Yield, fruit quality and crop physiological responses to PRD have been recently documented for grapevines [8, 10, 34], pot-grown tomato [6], processing tomato [39, 40], greenhouse soil grown table tomato [23], hot pepper [9], common bean [37], maize [25] and apple [36].

Soilless greenhouse cultivation is expending and preferred over soil grown greenhouse vegetables in recent years [16, 17, 27, 31]. Soil-borne pathogens are the main reasons for increasing preference of soilless systems. As hydroponics has proven to be an excellent alternative to soil sterilization, use of chemical soil sterilants is or will be soon forbidden due to the high toxicity [31]. However, to our knowledge only one earlier work [5] was carried out on assessing how the evolving new irrigation practice (PRD) would affect plant growth, nutrient uptake and fruit production in hydroponically grown plants in soilless greenhouses with the PRD's claimed benefits of water saving. Soilless cultivation is used in protected agriculture to improve control of the growing medium and to avoid any likely problems of watering and maintaining proper nutrient concentrations. Good control of plant growth and development in soilless cultivation of vegetables give proportionally higher yield and better quality crops compared to traditional greenhouse production in soil. The soilless cultivation technique is practiced with two ways: (1) using substrate medium and (2) hydroponic technique where plants are grown in continuously circulating nutrient solution. Two main systems are used with the substrate medium. The first is the "open" system with the surplus nutrient solution is discharged as waste. This is wasteful of water and nutrients and results in pollution of groundwater and soil. The second is the "closed" system with re-cycling and re-using of nutrient solution. Although the recycling of the nutrient solution brings about some difficulties in controlling of plant nutrition, it gives indispensable benefits in saving of both water and nutrients in addition to its environmental friendly characteristics [4]. The objective of this work was therefore to assess comparative benefits of open and closed systems under full and PRD practice of irrigation using soilless-greenhouse-grown tomato under Mediterranean climate.

Materials and Methods

Plant material and experimental conditions: The research was conducted over 253 days of growth period from 30 September 2004 to 7 June 2005 in a greenhouse at Cukurova University (36º 59' N, 35º 18' E, 20 m above sea level). The glass covered greenhouse oriented in north-south direction was 12m x 42 m in size. Plant material was tomato (*Lycopersicon esculentum* Mill., cv. F_1M19) and perlite was used as growing medium. During winter, for the period of November 15 till March 15, the greenhouse was heated to maintain a minimum temperature of 10ºC at nights. Seedlings were planted in density of 3.18 plants m^{-2} in perlite-filled containers made of white PVC in dimension of 78cm x 38cm x 22cm. Each container had 3 plants with 12 liters of perlite per plant.

Treatments: A randomized complete block experimental design with 4 replicates, 18 plants in each replicate, consisting of four irrigation treatments was used. Complete nutrient solution [4] was applied to meet water and nutrient requirements of the plants. The four irrigations treatments were: (1) Full-open (F-O), (2) Full-closed (F-C), (3) PRD-open and (4) PRD-closed systems. Under full irrigation treatments (F-O and F-C), all roots were wetted in every irrigation with the applied amount of nutrient solution using one line of drip irrigation. The treatments of PRD system received 30 to 50% reduced nutrient solution compared to full irrigation treatments (Table 1). In the open systems (F-O and PRD-O), the excess nutrient solution was discharged as drainage from the greenhouse. In the closed systems (F-C and PRD-C), drainage effluent from the base of the growth containers was collected and recycled in the system. The amount of nutrient solution applied in full treatments was determined based on daily measured drainage fraction from the base of the containers [32]. Range of drainage fraction was kept between 20% and 40% during the experimental period [32] (Table 1). Drainage ratio (i.e., discharged over applied water) and the irrigation frequencies were controlled and adjusted depending on plant age, and greenhouse climatic conditions (temperature and light). Total of 4 to 20 irrigations were made daily at every hour or every 45 minutes from 6:00 am to 20:00 pm. Irrigation frequency during early stage of experiment, until 30 days after transplantation, was daily 4 irrigations and gradually increased up to daily 20 irrigations at later stages (192 days after transplantation) of production. The irrigation frequency was the same in all treatments and it was timer controlled automatically.

The full-open (F-O) irrigation treatment which is commonly preferred in soilless greenhouses, was considered as the control among the tested treatments. Under the PRD treatments, both open (PRD-O) or closed (PRD-C), each half of the root system was separated using a hard polyethylene sheet to prevent leaching of the nutrient solution from one half to the other. Two drip irrigation lines with each line irrigating separately only one half of the root system were used. Only one half side of the root system was irrigated at a given irrigation event under the PRD treatments. The irrigated sides of the root zone were interchanged every irrigation in subsequent irrigations during the day.

The implementation of the PRD treatments was initiated fifty-six days after transplanting (DAT). During the following 117 days, the plants under the PRD treatments were grown under 50% deficit irrigation. The plant growth and fruit load increased with rising of spring-season temperature and of light intensity in the greenhouse. Therefore the levels of irrigation deficit implemented under the PRD treatments were reduced, respectively, to 42% and 31% of the full treatments for 21-day period starting 172 DAT and 59-day period starting 193 DAT of the experiment. Table 1 shows the amount of nutrient solution applied per plant, mean drainage rate, mean EC and pH values of nutrient solution during the progress of the experiment. The pH of nutrient solution was always maintained between 5.5 and 6.5 by applying nitric or phosphoric acids.

Nutrient solution: During the experiment the open-system plants were supplied with following nutrient solution [4] (in mg L^{-1}) : NO_3-N (135-200), NH_4-N (15-28), P (40-70), K (200-400), Ca (150-200), Mg (50-75), Fe (2.8-5.0), Mn (0.8-1.0), Cu (0.3-0.4), Zn (0.3-0.4), B (0.3-0.4) and Mo (0.05-0.1). The EC values of nutrient solution of the open systems were between 2.0-2.9 dSm^{-1} during the experiment. The EC values under PRD-C and F-C treatments varied within the range of 2.0-4.2 dSm^{-1} and 2.0-3.9 dSm^{-1}, respectively (Table 1).

Plant and root medium measurements: Some plant growth parameters such as plant height, leaf number and stem diameter between 3rd and 4th nodes were determined 31, 122 and 210 DAT (Table 2). At the end of the experiment, total shoot fresh weight including stem and leaves and plant leaf area were determined. Early yield and total yield and some fruit quality parameters were also investigated. Periodical plant leaf analysis for N, P, K, Ca, Mg, Fe, Mn, Zn, Cu and Na was conducted in order to compare nutritional status of the tomato plants grown under different treatments. The leaf samples were collected from the 9th or 10th leaves from the tops of the plants. Tomato leaves were dried at 65ºC for 48 hours. After drying, the samples were grounded to 20 mesh sieve size. Leaf powder was ashed at 550ºC for about 8 h and dissolved in 3.3 % HCl. The concentrations of K, Ca, Mg, Fe, Mn,

Table 1. Nutrient solution parameters for the treatments recorded during the different periods of the experiment.

	30 September - 24 November 2004 No deficit irrigation for 56 days				25 November - 24 December. 2004 50% PRD for 31 days				25 December 2004 -15 February 2005 50% PRD for 53 days				16 February - 20 March 2005 50% PRD for 33 days			
	Applied nutrient solution (mL plant day^{-1})	Mean drainage rate (%)	Mean EC (dSm^{-1})	Mean pH	Applied nutrient solution (mL plant day^{-1})	Mean drainage rate (%)	Mean EC (dSm^{-1})	Mean pH	Applied nutrient solution (mL plant day^{-1})	Mean drainage rate (%)	Mean EC (dSm^{-1})	Mean pH	Applied nutrient solution (mL plant day^{-1})	Mean drainage rate (%)	Mean EC (dSm^{-1})	Mean pH
PRD-O	570	20	2.0	5.7	402	20	2.6	5.8	452	28	2.9	6.2	774	30	2.8	6.3
PRD-C	570	20	2.0	5.7	402	20	3.2	5.9	452	28	3.7	6.0	774	30	4.2	6.2
F-O	570	20	2.0	5.7	804	20	2.8	5.8	903	35	2.9	6.2	1548	38	2.8	6.0
F-C	570	20	2.0	5.7	804	20	3.3	5.9	903	35	3.8	6.0	1548	38	3.9	6.3

	21 March - 9 April 2005 42% PRD for 21 days				10 April - 7 June 2005 31% PRD for 59 days				Total experimental period from September 30 to June 7 for 253 days			
	Applied nutrient solution (mL plant day^{-1})	Mean drainage rate (%)	Mean EC (dSm^{-1})	Mean pH	Applied nutrient solution (mL plant day^{-1})	Mean drainage rate (%)	Mean EC (dSm^{-1})	Mean pH	Applied total nutrient solution (L plant^{-1})	Mean drainage rate (%)	Mean EC (dSm^{-1})	Mean pH
PRD-O	1244	34	2.9	6.4	1824	39	2.6	6.3	228	29	2.7	6.4
PRD-C	1244	34	4.4	6.1	1824	39	4.1	6.2	228	29	3.7	6.2
F-O	2128	42	2.8	6.2	2628	43	2.6	6.3	356	33	2.8	6.3
F-C	2128	42	4.07	6.1	2628	43	3.4	6.2	356	33	3.5	6.2

PRD-O: Partial rootzone drying-open system, PRD-C: Partial rootzone drying-closed system, F-O: Full-open system, F-C: Full-closed system

Table 2. Effects of the treatments on the plant growth at the different growth stages.

Treatment	31 DAT (1 November)	122 DAT (1 February)	210 DAT (1 May)
	Plant height (cm)		
PRD-O	161.7	273.1 a	367.4 ab
PRD-C	161.5	271.2 a	370.1 a
F-O	155.7	262.6 a	363.6 ab
F-C	158.0	248.9 b	355.0 b
P	*0.0702*	*0.0005*	*0.0458*
LSD 0.05	*5.294*	*10.765*	*10.830*
	Leaf number (leaf plant^{-1})		
PRD-O	19.6	33.6	53.1
PRD-C	19.2	33.5	53.4
F-O	19.2	33.7	52.6
F-C	19.4	32.4	52.4
P	*0.6919*	*0.2872*	*0.6162*
LSD 0.05	*0.820*	*1.472*	*1.8345*
	Stem diameter between 3rd and 4th nodes (mm)		
PRD-O	6.9 ab	7.7 a	8.8
PRD-C	6.7 b	7.8 a	8.7
F-O	6.8 ab	7.4 b	8.4
F-C	7.0 a	7.4 b	8.6
P	*0.0652*	*0.0031*	*0.0840*
LSD 0.05	*0.260*	*0.356*	*0.346*

Data in each column followed by different letters show least significant difference at $P = 0.05$
PRD-O: Partial rootzone drying-open system, PRD-C: Partial rootzone drying-closed system, F-O: Full-open system, F-C: Full-closed system, DAT: Day After Transplanting

Zn, Cu, Na in leaves were assessed with atomic absorption spectrometry [2, 21]. Nitrogen and phosphorus concentrations were determined by Kjeldahl and Barton methods, respectively [22].

In order to determine ion accumulation in root medium, the water extracts of perlite-water mixture in ratio of 1:2 (v/v), were used [14]. The growth medium samples which were collected from the top to the bottom of the growth containers at the beginning and at the end of growing period. NO_3-N concentration was determined by the distillation of the water extracts with MgO and Devarda alloy, SO_4 and PO_4 concentrations were determined by the colorimetric methods [35]. The concentrations of K, Ca, Mg, Fe, Mn, Zn, Cu and Na were again determined by the atomic absorption spectrometry. The chloride (Cl) concentration was measured with $AgNO_3$ titration [20].

Data analysis: Treatment effects in the experiment were analyzed with analysis of variance (ANOVA) and treatments means were compared using L.S.D. ($P = 0.05$) procedure.

Results

Plant vegetative growth: Adverse effects of water stress on plant development were not evident under PRD practices which were irrigated with 30% to 50% less water compared to fully irrigated treatments (F-O and F-C). Although the plant-height measurements on 122 DAT and 210 DAT were showed some differences and the F-C plants were significantly ($P = 0.05$) shorter than those of the other 3 treatments (F-O, PRD-O, and PRD-C) (Table 2), however there were no significant differences among the treatments in respect to the number of leaves (Table 2). It was further noted that the plants, grown under open systems, had similar height as the PRD-C plants, irrespective of whether they were irrigated under full or PRD practice (Table 2). Although there were some differences in the stem diameter among the treatments on 31 and 122 DAT, at the end of the production period all treatments produced the same stem thickness.

Tomato plants under the treatments PRD-O, PRD-C and F-O had similar shoot fresh weight (leaves + stem) and leaf area (Fig. 1). However these parameters were higher, although not significantly (P= 0.05), than F-C plants (Fig.1). Total shoot fresh weight and leaf area were 16.5% and 16.0% lower with F-C plants, compared with plants under F-O.

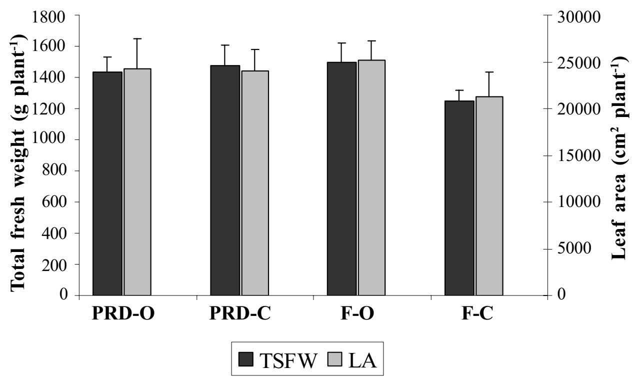

Figure 1. Total shoot fresh weight (TSFW), including leaf and stem excluding fruit, and leaf area (LA) per plant at the end of the experiment. Both data TSFW and LA are not significantly different at $P = 0.05$. PRD-O: Partial rootzone drying-open system, PRD-C: Partial rootzone drying-closed system, F-O: Full-open system, F-C: Full-closed system.

Early and total yield: Early tomato production was higher under PRD practices. The highest early yield (the period from January 3 to March 31) was obtained from the PRD-O treatment as 6.8 kg m^{-2} (Fig. 2). The PRD-C and F-O irrigations gave similar early yields (5.9 and 6.1 kg m^{-2}, respectively), and the lowest early tomato crop was from F-C plants as 5.5 kg m^{-2} (Fig. 2).

Effect of the treatments on total yield was significant (Fig. 2). The highest total yield (19 kg m^{-2}) was obtained from the plants under F-O system. Tomato yields under PRD-C and PRD-O treatments were 18.0 kg m^{-2} and 17.1 kg m^{-2}, respectively. The yield reductions in these treatments compared to F-O were 5.3% and 9.9%, respectively. The lowest yield was from the F-C treatment as 16.9 kg m^{-2} which was 11.3% lower compared with F-O.

Amount of nutrient solution applied: Although the plants under PRD treatment received 50% deficit irrigation from 25 November 2004 to 20 March 2005, for a period of 117 days, the deficit was first reduced to 42% and later to 31% owing to increased temperature, light intensity and fruit load in spring (Table 1). Therefore the overall irrigation deficit under PRD treatments was 36% compared to full irrigation (F-O, F-C) treatments. The plants in the full and PRD treatments received 356 L and 228 L nutrient solutions per plant, respectively during the whole experimental period (Fig. 3). The recycling of the nutrient solution contributed 129 and 65 L plant^{-1} for the closed systems, F-C and PRD-C treatments, with the fresh nutrient solution used was 227 and 163 L plant^{-1}, respectively (Fig. 3). The closed systems saved 29%

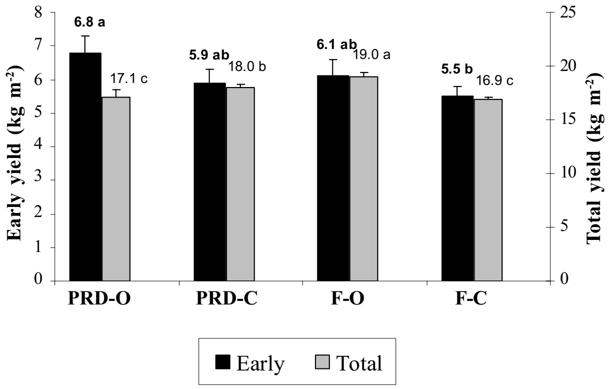

Figure 2. Early (from January 3 to March 31) and total (from January 3 to June 7) tomato yields (kg m^{-2}). Data shown with bars of the same shading and topped with different letters show least significant difference at $P = 0.05$. PRD-O: Partial rootzone drying-open system, PRD-C: Partial rootzone drying-closed system, F-O: Full-open system, F-C: Full-closed system.

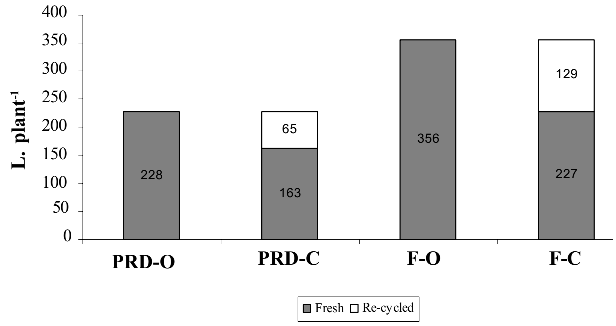

Figure 3. Total nutrient solution applied in the different treatments (L $plant^{-1}$). In closed systems amount of nutrient solution coming from re-cycling is written on the top of the bars. PRD-O: Partial rootzone drying-open system, PRD-C: Partial rootzone drying-closed system, F-O: Full-open system, F-C: Full-closed system.

and 36% nutrient solution under PRD and full treatments, respectively, compared to open systems. The combined use of deficit and recycling under PRD-C treatment saved 54% fresh nutrient solution compared to F-O treatment (Fig. 3).

Water use efficiency: Water use efficiency (WUE) was calculated as the amount of nutrient solution for producing 1 kg tomato. The re-cycling of nutrient solution is rather indispensable and worthy practice in soilless production systems for saving water and fertilizer with additional advantage of reduced drainage discharge to environment. Therefore in closed applications (F-C and PRD-C), only the amount of fresh nutrient solution used was considered and re-cycled solution was ignored in calculation of WUE. In this case the WUE was 42.4 , 28.8, 59.6 and 42.8 L kg^{-1} in PRD-O, PRD-C, F-O and F-C irrigation treatments, respectively. It should be noted that the WUE under closed systems was higher compared with the open systems. The PRD and full irrigations under closed systems showed 52% and 28% higher WUE compared with open system of full treatment (F-O), respectively.

Fruit properties: The fruit properties as mean fruit weight and total soluble solids in juice were different significantly ($P = 0.05$) among the tested treatments (Table 3). The heaviest fruits were from F-O irrigation. Both PRD treatments and F-C plants had similar fruit weights. The high soluble solids of fruit juice were noted under closed systems of both PRD and the full irrigation treatments (PRD-C and F-C) (Table 3).

Table 3. Effects of the treatments on some fruit quality properties.

Treatment	Fruit number per m^{-2}	Mean fruit weight (g)	Mean juice TSC (%)*
PRD-O	164	104.6 b	5.3 b
PRD-C	168	110.3 b	5.7 a
F-O	153	124.3 a	5.4 b
F-C	157	107.5 b	5.6 ab
P	*0.1415*	*0.0010*	*0.0163*
LSD 0.05	*1.449*	*7.538*	*0.258*

*: Total Soluble Content or Brix Data in each column followed by different letters show least significant difference at $P = 0.05$. PRD-O: Partial rootzone drying-open system, PRD-C: Partial rootzone drying-closed system, F-O: Full-open system, F-C: Full-closed system

Leaf nutrient content: The bi-monthly leaf analysis for N, P, K, Ca, Mg, Fe, Mn, Zn, Cu and Na showed that the tomato plants were adequately fed throughout the growth period (Table 4). Although the nutrients concentrations changed depending on the sampling time, the differences observed were not significant ($P = 0.05$) for a given sampling time. The ranges of nutrient concentrations recorded were within the order of "adequate level" except K which was lower than required ranges in March and May [3, 29].

Ion concentration in the growth medium: Ion concentrations in plant-rooting zone at the beginning and at the end of growing period are given in Table 5. Generally the ions increased toward the end of season in perlite (except Mg). At the end of the season, K and Ca concentrations were higher, although not significantly ($P = 0.05$), under full treatments (F-O and F-C) than with PRD practice. Under the closed-full treatments, the perlite had higher concentrations of K, Ca and Mg than with open-full treatments. The similar trend was observed as for the concentrations of H_2PO_4-P, NO_3 and NH_4 ions. Although undesired accumulation of Na, Cl and SO_4 may be expected particularly under the closed systems, such as the treatments of F-C and PRD-C, the SO_4 data of the PRD-C treatment did not confirm such expectation. Only Cl and Na accumulation were noted under the full treatments, and especially Cl content was higher compared with other treatments (Table 5).

Discussion

Some previous studies [8, 11, 15, 23, 33] have shown that plant growth would be reduced under PRD practices, although the growth reduction would not essentially be accompanied with significant yield reduction in soil grown plants. Contrary to these studies, the vegetative plant growth was not significantly reduced with PRD practice in soilless grown tomato (Table 2 and Fig. 1). Non significant reductions of leaf area were 4.0% and 4.8%, and total shoot fresh weight reductions were only 4.0% and 1.2%, in PRD-O and PRD-C treatments compared to F-O, respectively. In soybean plants reported that leaf area was not affected by withholding irrigation until leaf turgor had been significantly reduced [26]. Although we have not measured leaf turgor we did not anticipate any reduction of leaf turgor with the small

Table 4. Effects of the treatments on nutrient concentrations of tomato leaf (9-10 leaf from the top) during different periods of the growing.

	Novemb.	January	March	May	Novemb.	January	March	May
	N %				Fe mg kg^{-1} DW			
PRD-O	6.1	5.7	5.6	6.3	236	226	75	109
PRD-C	6.1	5.7	5.6	7.2	245	261	71	115
F-O	6.0	5.4	5.4	7.0	364	265	79	109
F-C	6.1	5.7	5.9	7.3	273	280	69	116
P	*0.6849*	*0.4586*	*0.4887*	*0.6256*	*0.2482*	*0.0926*	*0.2893*	*0.8350*
LDS0.05	*0.3434*	*0.3432*	*0.7029*	*1.9036*	*42.4167*	*42.6808*	*11.5470*	*21.8415*
	P %				Mn mg kg^{-1} DW			
PRD-O	0.61 a	0.73	0.56	0.71	247	277	226	268
PRD-C	0.54 ab	0.65	0.57	0.63	235	280	247	287
F-O	0.58 a	0.67	0.54	0.68	266	298	244	231
F-C	0.49 b	0.64	0.56	0.67	258	303	244	269
P	*0.0066*	*0.2410*	*0.4336*	*0.1721*	*0.2556*	*0.1474*	*0.7706*	*0.0912*
LDS0.05	*0.0601*	*0.1010*	*0.0458*	*0.0740*	*34.1390*	*27.7095*	*49.9171*	*43.8196*
	K %				Zn mg kg^{-1} DW			
PRD-O	3.5	3.3 a	2.6	2.3	50	50	52 ab	31
PRD-C	3.4	3.1 ab	2.5	2.3	48	47	41 c	28
F-O	3.4	3.1 ab	2.5	2.8	48	55	57 a	30
F-C	3.0	2.8 b	2.5	2.6	49	50	46 bc	30
P	*0.1775*	*0.0490*	*0.8538*	*0.5040*	*0.8944*	*0.2606*	*0.0065*	*0.2196*
LDS0.05	*0.5154*	*0.3286*	*0.2946*	*0.6342*	*7.0749*	*8.3543*	*7.6760*	*3.0659*
	Ca %				Cu mg kg^{-1} DW			
PRD-O	2.1	1.8 b	2.5	1.4	29	25	15	11
PRD-C	2.0	1.8 b	2.4	1.7	29	25	15	11
F-O	2.1	1.9 b	2.6	1.6	32	26	15	11
F-C	2.2	2.1 a	2.3	1.6	30	26	16	11
P	*0.2383*	*0.0038*	*0.1420*	*0.1518*	*0.3034*	*0.8893*	*0.9857*	*0.9957*
LDS0.05	*0.2168*	*0.1493*	*0.3055*	*0.2429*	*3.6941*	*3.9023*	*4.6502*	*3.2103*
	Mg %				Na %			
PRD-O	1.5	1.4	1.4	0.9 a	0.60	0.64	0.56	0.63
PRD-C	1.5	1.4	1.5	0.8 b	0.65	0.61	0.55	0.54
F-O	1.5	1.4	1.4	0.8 b	0.65	0.60	0.67	0.70
F-C	1.5	1.5	1.4	0.8 b	0.56	0.59	0.57	0.54
P	*0.8058*	*0.2472*	*0.5371*	*0.0059*	*0.2140*	*0.4873*	*0.5414*	*0.0809*
LDS0.05	*0.1959*	*0.1108*	*0.1734*	*0.0342*	*0.1060*	*0.0678*	*0.1975*	*0.1375*

Data in each column followed by different letters show least significant difference at P = 0.05. PRD-O: Partial rootzone drying-open system, PRD-C: Partial rootzone drying-closed system, F-O: Full-open system, F-C: Full-closed system DW: Dry weight

unsignificant reduction (4.0% and 4.8%) noted in leaf area with the PRD treatments. However, it is difficult to explain the decrease, although not significant, of 16% in leaf area and 16.5% in total shoot fresh weight of plants, under closed system of full irrigation (F-C). One reason might be toxic ion (e.g. Na, SO_4, Cl) accumulation and general increase of EC in continuously re-cycling nutrient solution. However, only accumulation of Cl ion was observed in the growing medium at the end of season (Table 5), in spite of maintaining EC of the substrate below 4.5 dS m^{-1} with washing if needed.

Although the PRD plants received up to 50% less nutrient solution (over all 36% throughout the season), there was no adverse effect evident on plant growth and fruit yield (Table 2 and Fig. 1). Although a reduction in supply of nutrients during switching from wet to dry cycle might have occurred, the nutrient solution available in the wet side of the root-zone was presumably sufficient for supplying nutrients to sustain plant growth as well as water. Some authors [9] indicated that plant water status would normally be determined through equilibration with the sufficiently moist part of the root-zone under PRD practice. We may expect therefore that the wetter part of the plant root-zone would similarly supply plant nutrients.

Results of this study showed that the PRD practice in soilless grown tomato was quite effective for saving water and nutrients. The reduction of total fruit yield noted under the PRD practice was not significant (P = 0.05). In processing tomato [40] the reduction of tomato yield under PRD practice depends largely on the frequency by which the irrigation was shifted to dry half of the roots. In our study, the irrigated side was alternated at rather short intervals, in minutes to hours, during the day. The short interval between the irrigations is the most important property of soilless growing technique. Therefore, marginal fruit yield

Table 5. Ion concentrations in root medium perlite at the beginning (November) and end (June) of the experimental period (mg L^{-1}).

	K		Ca		Mg	
	November	June	November	June	November	June
PRD-O	311	802	185 a	258	128	44
PRD-C	297	636	221 a	213	137	36
F-O	236	857	109 b	342	100	52
F-C	151	1001	166 ab	329	112	53
P	*0.1485*	*0.2106*	*0.0534*	*0.0966*	*0.1686*	*0.2032*
LSD 0.05	*154.226*	*355.443*	*77.080*	*115.384*	*36.594*	*18.754*
	H_2PO_4-P		NO_3		NH_4	
	November	June	November	June	November	June
PRD-O	20.2	106.2	1542	2053	297	523
PRD-C	18.8	76.2	1676	2195	329	560
F-O	23.4	105.7	1536	2300	343	413
F-C	16.5	106.7	1646	2248	308	568
P	*0.0990*	*0.6926*	*0.7791*	*0.7903*	*0.2126*	*0.3780*
LSD 0.05	*5.521*	*67.953*	*378.424*	*575.600*	*49.121*	*212.300*
	SO_4		Cl		Na	
	November	June	November	June	November	June
PRD-O	629	1113	111	284	217	179
PRD-C	484	1098	139	283	248	199
F-O	416	1172	76	376	166	300
F-C	485	1078	139	415	224	290
P	*0.6153*	*0.9820*	*0.0790*	*0.1888*	*0.1369*	*0.0774*
LSD 0.05	*361.853*	*551.354*	*53.5096*	*151.560*	*64.323*	*111.312*

Data in each column followed by different letters show least significant difference at $P = 0.05$. PRD-O: Partial rootzone drying-open system, PRD-C: Partial rootzone drying-closed system, F-O: Full-open system, F-C: Full-closed system

reduction of about 5 to 10% was not significant ($P = 0.05$) under the PRD practice where any adverse effect of plant water stress, if occurred, was eased off with continuous transpiration stream from the fully wetted side of the plant root zone. Although the yield reductions under PRD-O and PRD-C systems were 10% and 5%, respectively compared with that of conventional open full irrigation system, savings in nutrient solution were 36% and 54%, respectively. The higher proportion of nutrient solution saving under the PRD-C system came from combined benefits of deficit irrigation and re-cycling of nutrient solution. The re-cycling saved 36% nutrient solution, with however 11.3 % yield reduction, under F-C treatment compared to open system of full irrigation (F-O). Tomato WUE was the highest (54%) with PRD-C plants among all the tested treatments. In soil grown greenhouse tomato [23] , 17-22% yield reduction was reported with 50% deficit PRD irrigation for soil grown greenhouse tomato, although the PRD practice increased water use efficiency by 45-57%. In soil grown crops, in contrast to the soilless grown, only part of the root system is well watered, and the rest of the root zone remained partially dry, reaching soil water potentials of the order -0.5 to -0.7 MPa [23] for periods up to one to two weeks which should create harsh levels of water stress on plants. In PRD conditions since part of the root system well watered, there should be some defense against water stress and adequate supply of water to the fruits is maintained. The fruits in PRD plants, being major sink for photoassimilates, could compete with other plant parts and thus fruit yield reduction may be only marginal with significant increase of water use efficiency. It is also speculated that xylem derived signals of water stress would reach to fruits at somewhat later stage of development which is largely controlled by the phloem derived transport [6, 33]. Thus, the fruit development is influenced the least with water stress under PRD practice implemented to soil grown crops. The decreased stomatal conductance of vines under PRD had no major negative impact on carbon assimilation [8]. The benefits of PRD relative to full irrigation were result of restricted water consumption with however no adverse effect on CO_2 assimilation, leading therefore to improved water use efficiency [8]. Similar response was achieved in the present study and thus vegetative growth and yield of soilless grown tomato under PRD effect (up to 50% deficit irrigation) exhibited only marginal and non significant ($P = 0.05$) yield reductions.

Single fruit weight was significantly reduced under both PRD and full closed treatments, compared to full open system (Table 3). Fruit size can be reduced by water stress mainly as a result of a shorter fruit growth period [18]. Therefore, higher fruit load under the PRD treatments, although the differences were not significant ($P= 0.05$), might have led to the observed decrease in fruit weight. The reverse was also true: the smaller was the fruit size the higher was the fruit load. Interestingly the less fruit load and reduced fruit size observed under full closed system (Table 3) confirmed the view that the fruit size can be manipulated through controlling electrical conductivity of the nutrient solution (salt accumulation in re-cycling solution) in soilless production systems [18]. Although the plants under F-C treatment were not under water deficit, higher proportion of toxic ion accumulation (e.g. Na, Cl) in re-cycling nutrient solution caused smaller size of fruits.

Total soluble solid concentration increased under both PRD-C and F-C treatments. The high fruit sugar concentration likely developed through conversion of starch which must have increased through combined effects of deficit water application [30, 39] and higher EC of re-cycling nutrient solution [18] during the early stage of fruit development. The measured pH of the fruit juice was not significantly different in the tested treatments; however, PRD-C and F-C plants produced more acidic tomato fruits than those grown in the open systems (data is not showed). High EC of the feeding solution can result both increased sugar concentration and acidity of fruit [18].

Leaf analysis in short term (66 days) soilless grown eggplant with PRD (50% irrigation deficit) showed that macro and micro nutrients increased from 8% to 42% and 10% to 85%, respectively [5]. In soil grown-PRD applied processing tomato plants, leaf K and Mg contents were not affected by irrigation; however, Ca content was lower and caused the BER (blossom end root) incidence in the fruit [39]. In the present soilless tomato crop, such changes in leaf nutrient concentrations were not exhibited (Table 4). The leaf nutrient contents were nearly similar in all irrigation treatments, showing that the plants nutritionally were all fed adequately. As implemented here, the effect of PRD on half sides of plant root-zone was alternated, at rather short periods, by hourly or minutely basis (every hour or every 45 minutes from 6.00 am to 20.00 pm) during the day. Thus the frequency of irrigation in both halves of the root-zone was high enough, in contrast to soil application of PRD, not to cause any water or nutrient deficit. The soilless growing systems may give better benefits to the plants to manipulate physiological responses in more proper conditions than in PRD soil application.

Conclusions

Comparing to the soil grown tomato studies with PRD practice, there was no adverse effect on both plant growth and yield under the soilless application of PRD. The reason may be the frequent interval of the wetting and drying cycles of plant-root-zone halves in soilless practice. The interval of changing the irrigated halves of the root zone may be as short as hours or even minutes during the day. Therefore, the frequent interval prevents adverse effects of irrigation deficit on plant development than with soil grown crops**.** The results additionally showed that the nutrient solution use efficiency was highest in "PRD-Closed" due to saving of nutrient solution by the combined effects of deficit irrigation with PRD and re-cycling of nutrient solution in closed system. As conclusion the PRD applications in soilless grown greenhouse tomato have good potential for saving water and nutrients as well as its environmental friendly nature with minimized drainage discharge.

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