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Alternate partial root-zone drying irrigation improves fruit quality in tomatoes

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Abstract

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Alternate partial root-zone drying (PRD) irrigation and deficit irrigation (DI) are water-saving irrigation strategies. Here, comparative effects of PRD and DI on fruit quality of tomato (*Solanum lycopersicum* L.) were investigated. The results showed that the irrigation treatments had no effect on tomato yield but significantly affected several organic and mineral quality attributes of the fruits. Compared to DI, PRD significantly increased the fruit concentrations of Ca and Mg, and fruit juice concentrations of total soluble solid, glucose, fructose, citric and malic acid, P, K and Mg. It is concluded that PRD is better than DI in terms of improving fruit quality, and could be a promising management strategy for simultaneous increase of water use efficiency and fruit quality in tomatoes.

Keywords: water deficit; minerals; organic acids; sugars

Tomato (*Solanum lycopersicum* L.) is one of the most important fruit crops grown throughout the world. In terms of human health, tomato is a major component in daily diet and nutrition globally and constitutes an important source of minerals, vitamins and antioxidants (Atkinson et al. 2011).

Numerous management practices have been proposed to increase yields and improve quality attributes of tomatoes. Apart from fertilizer management, growers in recent years have attempted to develop water management strategies that maintain yields while imposing a moderate, controlled level of stress on the crops in order to improve fruit quality (Mitchell et al. 1991; Atkinson et al. 2011). Deficit irrigation techniques like conventional deficit irrigation (DI) and alternate partial root-zone drying (PRD) irrigation are among such practices which irrigate the crop with a volume of water less than the potential evapotranspiration, and the mild stress induced has a minimal effect on the yield (Dodd 2009). Accordingly, the moderate stress experienced by the plants under the DI and PRD treatments may bring about a positive effect on fruit quality (Wang, Frei 2011). Consistent with this, accumulated evidence demonstrated that, as compared with the full irrigation control, both DI and PRD could significantly increase dry matter content, firmness, and total soluble solids

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(TSS) concentration in tomato fruits (Davies et al. 2000; Zegbe et al. 2003, 2004, 2006). Such beneficial effects have mainly been ascribed to a reduced irrigation volume rather than the different irrigation techniques. Nevertheless, provided a same irrigation volume, it has often been observed that PRD causes significantly stronger root-to-shoot abscisic acid (ABA) signalling (Dodd et al. 2008), larger root systems (Mingo et al. 2004), better leaf resistance to drought stress (Xu et al. 2009), greater N and P use efficiency (Wang et al. 2010, 2012a), and higher water use efficiency (WUE) than does DI (Dodd 2009). However, whether these distinct responses induced by the PRD treatment could also cause an improvement of fruit quality remains largely elusive.

According to Mizrahi et al. (1988), TSS concentration is the most important quality criterion for tomato crops. Chemical analysis reveals that sugar and organic acids make major contribution to the TSS (Davies, Hobson 1981), and reducing sugars such as glucose and fructose represent 50% of the dry matter concentration of tomato fruit (Thakur et al. 1996). In ripe tomato fruits the organic acids are mostly malic and citric acids (Gould 1983). Studies have shown that the levels of sugars and acids and their ratio in tomato fruits affect not only the sweetness and sourness, but also the overall flavour (Jones, Scott 1984; Hobson, Bedford 1989). Often, an increase in these two organic components results in a corresponding increase in overall flavour intensity (Jones, Scott 1984). Besides organic constitutes, minerals are also important quality attributes in tomatoes (Dorais et al. 2001). Mineral elements commonly found in tomato fruit are K, Ca, Mg and P and may reach to 8% of the dry matter (Davies, Hobson 1981). Studies have revealed that the level and the ratio of these elements in fruit affect all aspects of fruit quality ranging from the firmness, the sugar and acid concentrations, to the overall flavour (Dorais et al. 2001). For example, K level is closely associated with the total acidity and the pH of the fruit juice; while Ca concentration affects the firmness and the shelf-life of the fruit, and Ca deficiency increases the incidence of blossom end rot.

It is well known that soil water dynamics have a profound effect on the bioavailability of mineral nutrients to the plants (Cramer et al. 2009). More dynamic changes in soil water content under PRD than under DI may cause distinct effects on the bioavailability of soil nutrients and their movement from the bulk soil to the root surface. Our own studies on tomato have demonstrated that PRD induced drying and wetting cycles in the soil can enhance soil N and P bioavailability (Wang et al. 2010, 2012a), and which may affect the root acquisition of other mineral elements thereby influencing the nutritional status of the plants (Wang et al. 2012b). This may, in turn, affect the mineral concentrations in the fruits. However, to date this possibility has not been intensively examined in tomatoes under PRD, and only a short communication paper is available showing that PRD has no significant effect on N, P, K, Ca, and Mg concentrations in tomato fruits in relation to commercial irrigation treatment (Nakajima et al. 2004).

In this study, tomato plants were grown in split-root pots and were subjected to PRD and DI treatments during flowering/early fruiting to fruit maturity stages. The main quality attributes of tomato fruit including firmness, TSS, sugar and organic acid as well as mineral concentrations in fruit dry mass and fruit juice were determined. The aim of the study was to investigate how do different water-saving irrigation regimes affect the quality of tomato fruits.

MATERIAL AND METHODS

Plant material and growth conditions. The experiment was conducted from January to April, 2012 in a climate controlled greenhouse at the experimental farm of the Faculty of Science, University of Copenhagen, Taastrup, Denmark. At the fifth leaf stage, tomato (*Solanum lycopersicum* L., var. Cedrico) seedlings were transplanted into 10 l pots (17 cm diameter and 50 cm depth). The pots were divided vertically into two equal-sized compartments with plastic sheets such that the water movement between the two compartments was prevented. The pots were filled with 14.0 kg of naturally dried soil with a bulk density of 1.36 g/cm^3. The soil was taken from a nutrient-depletion plot of a long-term soil fertilisation experiment located near the experimental farm. The texture of the soil was sandy loam, having a pH of 7.4, total C 12.7 g/kg, total N 1.4 g/kg, water soluble P 22 mg/kg, exchangeable Ca 3.0 mmol/kg, exchangeable K, Mg and Na < 1.0 mmol/kg. The soil was sieved through 5 mm mesh before filling the pots. The soil had a volumetric soil water content (% vol.) of 30.0% and 5.0% at pot water holding capacity and per-

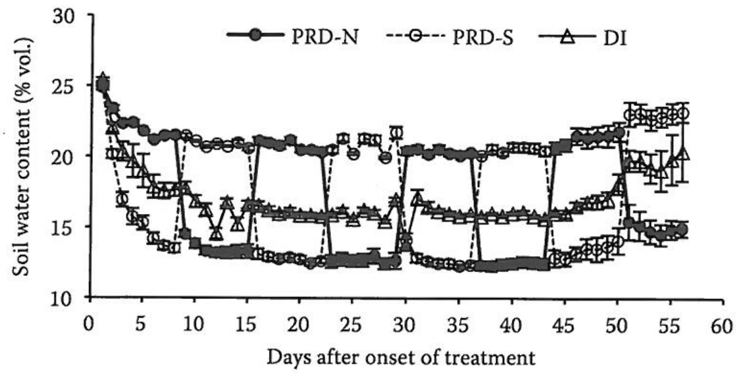

Fig. 1. Changes of volumetric soil water content in pots of tomato plants under partial root-zone drying (PRD) and conventional deficit irrigation (DI) treatments PRD-N and PRD-S – north and south sides of the PRD pots; error bars – standard error of the means (n = 4)

manent wilting point, respectively. For each pot, 3.0 g N, 0.87 g P, 4.0 g K and 1.68 g Mg were applied as $Mg(NO_3)_2 \cdot 6H_2O$, KH_2PO_4, KNO_3 and $MgSO_4 \cdot 7H_2O$ into the soil to meet the nutrient requirement for plant growth. The climatic conditions in the glasshouse were set at 20/17 ± 2°C day/night air temperature, 16 h photoperiod and a photosynthetic active radiation (PAR) of higher than 500 µmol/m^2·s supplied by sunlight plus metal-halide lamps (Philips Lighting N.V., Turnhout, Belgium). The lamps were switched off when the PAR provided by the sunlight was greater than 800 µmol/m^2·s.

Irrigation treatments. The tomato plants were well-watered in the first three weeks after transplanting. Thereafter, the plants were subjected to two irrigation treatments: (1) partial root-zone drying (PRD) irrigation, in which half of the root system was watered daily at 16:00 h to a water content of 28% while the other half was allowed to dry for seven days until the water content reached ca. 10%, then the irrigation was switched between the two soil compartments; (2) deficit irrigation (DI), in which the same amount of water used in PRD was evenly irrigated to the two soil compartments. The water used for manual irrigation was tap water with negligible concentrations of nutrients. The experiment was done in a randomized design with four replicates, i.e., four pots for each treatment (DI versus PRD). The irrigation treatments lasted for eight weeks during which each of compartments of the PRD pots had experienced four drying and rewetting cycles. The average soil water content in the pot was monitored by a time domain reflectometer (TDR, TRASE; Soil Moisture Equipment Corp., Santa Barbara, USA) with probes (35 m in length) installed in the middle of each soil compartment. The changes of soil water content in the pots are shown in Fig. 1.

Measurements of fresh fruit quality parameters. The tomato variety Cedrico is an indeterminate type. Therefore, after the fourth fruit trusses appearance the plants were pruned by removing the apex to stop the vegetative growth. The experiment was ended when more than half of the fruits from the four fruit trusses were ripen. All fruits were harvested and fresh fruit yields were recorded. From the four trusses, two fruits per plant at the firm red stage were chosen for quality measurements. Fruit firmness was measured with a FTX Fruit Tester (Wagner Instruments, Greenwich CT, USA), three readings were recorded for each fruit, and the mean value for each fruit was calculated. Thereafter, each fruit was divided into two halves. One half was cut into small pieces and homogenized thoroughly in a fruit blender. The homogenate was centrifuged at 4,000 × g for 5 min and the supernatant was filtered through a syringe filter (0.22 mm Acetate Cameo; Osmonics, Minnetonka, USA). Total soluble solids (TSS) concentration of the juice was then measured using a digital refractometer with automatic temperature compensation (RFM 90; Struers Ltd., Catcliffe Rotherham, UK) and was expressed in °Brix. Fruit juice concentrations of fructose, glucose, citric acid, malic acid, P, K, Ca, and Mg were analysed by ion chromatography (Metrohm AG, Herisau, Switzerland). The determination of fructose and glucose was done on a Metrosep Carb 1-150 column using 100 mM sodium hydroxide as eluent; while the measurement of citric and malic acids was done on a Hypersil Carbohydrate H^+ column using 0.5 mM sulfuric acid and 10% acetone as eluent. P concentration was determined on a Metrosep A Supp 4 analytical column (4 × 125 mm, 1.8 mM Na_2CO_3/1.7 mM $NaHCO_3$ eluent); and K, Ca, and Mg concentrations were determined on a Metrosep C4-100 analytical column (4 × 125 mm, 1.7 mM nitric acid/0.7 mM dipicolinic acid (DPA) eluent). The above measurements were done for 8 samples of each treatment.

Determination of mineral elements contents in dry fruit samples. The other half of the fruit was dried in an oven at 70°C until constant weight, and the dry fruit samples were ground into fine powder; and about 1 g powdered samples were ashed at 500°C in an electric muffle furnace (Controller B180; Nabertherm GmbH, Lilienthal/Bremen, Germany) for 8 hours. After cooling to room temperature, 5 ml of 3 M HCl was added into each crucible and the crucible was then placed onto a sand bath at 120°C and evaporated for 2–3 h to dryness. The crucible was removed from the sand bath and cooled to room temperature. To each crucible, 10 ml of 1 M HNO_3 was added to dissolve the ash. After complete stirring, the solution was transferred to a 50 ml volumetric flask. Thereafter, the crucible was washed several times with double deionized water, all of which was also transferred into the 50 ml volumetric flask. Then the samples were filtered into 50 ml tubes and kept in freezer at 4°C before analyses. The contents of K, Ca, and Mg in the leaf samples were determined by an Atomic Absorption Spectrometer (Perkin-Elmer 3300; Norwalk, USA), and the content of P was determined using a continuous flow analyser (Autoanalyzer 3; Bran+Luebbe GmbH, Norderstedt, Germany). The above measurements were performed for 8 samples of each treatment.

Statistical analyses. Independent t-test was applied to assess the differences between treatments at a significance level of 5%.

RESULTS AND DISCUSSION

The results showed that the fruit yields were similar between PRD and DI treatments (Table 1), implying that PRD did not outperform DI in term of improving fruit yield. This is somehow contrary to those observed in other studies (Dodd 2009). The reasons for this discrepancy, however, remain unknown. Nonetheless, here we do find that PRD significantly increased fruit firmness, TSS (Table 1), sugars, organic acids (Table 2), P, K, Mg concentrations in tomato juice (Table 3), and Ca and Mg concentrations in fruit dry matter (Table 3), implying that PRD treatment enhanced fruit quality as compared with the DI treatment. In good agreement with this, Xu et al. (2009) also noticed that, as compared with DI, PRD leads to greater sugar and organic acid concentrations in tomato fruits. It is well known that the total sugar and organic acid concentrations are the most important characteristics of tomato taste (Dorais et al. 2001). High sugar concentrations are required for the best taste (Kader 1986; Stevens 1986). Thus, the greater concentrations of glucose and fructose in the fruit juice under the PRD treatment entails an improvement of fruit taste. Here we also found that the concentrations of organic acids including citric and malic acid were significantly increased under PRD as compared with DI. This increase of organic acid, however, did not necessarily imply a lower quality of the fruits. Earlier research by Stevens et al. (1977) have indicated that in tomatoes with low total sugar concentration, citric acid reduces sweet-

Table 1. Effect of alternate partial root-zone drying (PRD) irrigation and deficit irrigation (DI) on fruit yield, fruit firmness and fruit total soluble solids (TSS) concentration in tomato

Factor	Yield (kg/plant)	Firmness (kg/cm^2)	TSS (°Brix)
PRD	1.21 ± 0.01	7.04 ± 0.24	6.26 ± 0.24
DI	1.22 ± 0.03	5.86 ± 0.21	5.27 ± 0.10
P-value	0.879	0.007	0.048

Table 2. Effect of alternate partial root-zone drying (PRD) irrigation and deficit irrigation (DI) on concentrations of glucose, fructose, citric and malic acids in fruit juice of tomato

Factor	Glucose (g/l)	Fructose (g/l)	Citric acid (g/l)	Malic acid (g/l)
PRD	16.2 ± 0.61	28.1 ± 0.49	5.97 ± 0.77	0.91 ± 0.09
DI	12.9 ± 0.44	22.6 ± 0.70	3.42 ± 0.32	0.63 ± 0.03
P-value	0.024	0.009	0.040	0.045

Table 3. Effect of alternate partial root-zone drying (PRD) irrigation and deficit irrigation (DI) on concentrations of P, K, Ca, and Mg in fruit juice (mg/l) and dry matter of tomato (mg/g)

Factor	P	K	Ca	Mg
Tomato fruit juice				
PRD	516 ± 18.2	1.51 ± 0.18	10.4 ± 0.59	45.4 ± 0.49
DI	433 ± 18.2	1.28 ± 0.24	9.69 ± 0.95	35.6 ± 1.10
P-value	0.038	0.007	0.611	0.003
Tomato dry matter				
PRD	1.82 ± 0.10	27.1 ± 0.18	1.23 ± 0.09	1.62 ± 0.07
DI	1.85 ± 0.12	29.7 ± 1.30	1.05 ± 0.09	1.49 ± 0.10
P-value	0.660	0.237	0.031	0.049

ness; whilst in fruits with high sugar concentration citric acid actually has a positive effect on sweetness (Petró-Turza 1986–87). Thus, a higher sugar concentration together with a higher organic acid concentration under the PRD irrigation may bring about an improvement of general taste of the tomato fruits.

Despite the fact that PRD significantly increased the sugar and organic acid concentrations in tomato juice, the biochemical and physiological mechanisms underlying those effects remain unknown. The slightly smaller fruits of PRD plants may account some of the changes in the fruit quality attributes (data not shown), since small fruits often associate with higher TSS concentration in tomatoes (Mitchell et al. 1991). For increasing the sugar concentration in tomato fruits, it is postulated that at least two possibilities may be involved. First, PRD might have increased starch accumulation in the fruits during their earlier stages of development, and consequently a higher conversion of starch into hexose during fruit ripening (Ruan, Patrick 1995; Zegbe et al. 2007). Second, the activities of carbohydrate-metabolizing enzymes could have been enhanced by the PRD treatment. Among those enzymes, invertase plays a crucial role in regulating hexose concentration in tomato fruits (Ho 1996), and its activity can be modulated by ABA (Ruan et al. 2010). Compared to DI, PRD treatment was shown to induce greater ABA concentration in the xylem of tomatoes (Wang et al. 2010; Sun et al. 2013). The hormone may be accumulated to a high level in the fruits, stimulating invertase activity and resulting in higher hexose concentration in the fruits (Ruan et al. 2010).

In addition to sugar and organic acid, the amount and relative composition of minerals mainly K, Ca, Mg and P in the fruit also have a direct influence on the quality of tomatoes (Dorais et al. 2001). In the present study, P, K and Mg concentrations in the fruit juice was significantly higher for PRD than for DI plants (Table 3). Also, in the fruit dry matter, Ca and Mg concentrations were significantly greater in PRD than in DI (Table 3), consistent with findings by Xu et al. (2009) in tomatoes. Increases of mineral elements concentrations in fruit juice under the PRD irrigation indicates the plant uptake of these minerals might have been enhanced by the irrigation treatment (Wang et al. 2012b). Nonetheless, we are not able to exclude the possibility that the partitioning of the minerals in the plants toward the fruit could have also been promoted by the PRD, and which is likely due to an enhanced xylem connection to the fruits (Davies et al. 2000).

CONCLUSION

In conclusion, our results clearly showed that when irrigating plants with the same amount of water, PRD resulted in better quality of fruits than did DI as exemplified by greater fruit firmness, concentrations of TSS, sugar, organic acid, and some minerals in the fruits. Therefore, under conditions where irrigation water resources are limited, PRD could be a feasible strategy for simultaneous improvements of water use efficiency and fruit quality in tomatoes.

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