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Regulated deficit irrigation and partial root-zone drying irrigation impact bioactive compounds and antioxidant activity in two select tomato cultivars

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ABSTRACT

Since drought stress and low WUE both influence fruit quality, the corresponding relationship between water supply and synthesis of bioactive compounds requires investigation. In this study, the effect of regulated deficit irrigation (RDI) and partial root-zone drying irrigation (PRD) techniques on the lycopene, β-carotene, vitamin C, and total phenolic (TPC) contents in two tomato cultivars (*Matina* and *Cochoro*) were investigated. Antioxidant activity was evaluated using DPPH, FRAP and TEAC assays. Deficit irrigation treatments affected plant growth as well as yield, quality, and antioxidant contents of fruits. However, the effects on content of antioxidants were cultivar-dependent. Vitamin C and lycopene contents in *Matina* significantly increased, while values decreased in *Cochoro* under both PRD and RDI. TPC and β-carotene contents increased in both cultivars, but a greater increment of TPC (+88.1%fw) was recorded in *Cochoro*. Overall, vitamin C and TPC were found to be the main contributors to the total antioxidant activity in fruits. The study suggested that choice of appropriate cultivars subjected to deficit irrigation strategies can significantly influence the bioactive compounds, particularly vitamin C, lycopene, and TPC.

1. Introduction

Tomato constitutes an important role in the diet in many parts of the world since it serves as an important source of several health-promoting nutrients (Dorais et al., 2008). The nutritional and functional qualities of tomato are determined mainly by the accumulation of bioactive compounds and the resulting antioxidant activity. Carotenoids including lycopene and β-carotene as well as other substances such as vitamin C and certain phenols are the most important antioxidants in tomato (Helyes et al., 2012b; Leiva-Brondoa et al., 2012), which are believed to delay or inhibit the oxidation of lipids and other molecules scavenging the free radicals. Lycopene represents 80–90% of the total carotenoids in fully ripened tomato fruits (Krumbein et al., 2006) and is also an effective antioxidant exhibiting high quenching ability for singlet oxygen (Story et al., 2010). Considerable evidence from several epidemiological research suggested that lycopene has anti-carcinogenic and anti-atherogenic potential (Singh and Goyal, 2008; Biddle et al., 2013). Increasing consumer demand for nutritionally-rich foods justifies exploring suitable strategies that can augment the concentration of antioxidants in tomato fruits. For this reason, agronomic approaches offer a practical perspective for improving the nutritional and commercial quality of tomatoes.

Numerous investigations have demonstrated that many factors, including genetic, environmental conditions (light, temperature, nutrient and water supply), ripening stage and post-harvest storage conditions can influence the chemical composition and concentration of bioactive substances in tomato, which affect the antioxidant activity. It has also been reported that modifying agronomic practices can affect the concentrations of health-promoting compounds in vegetables and fruits (Martínez-Ballesta et al., 2008; Schreiner et al., 2013). Irrigation water and fertilization are the main cultivation practices that are thought to influence the biosynthesis of antioxidant compounds (Dumas et al., 2003; Fanasca et al., 2006). With a few exceptions (Krumbein et al., 2006), many investigations have revealed that the lycopene and other antioxidant contents in tomato fruits are enhanced when the plants were grown in saline soil or irrigated with saline water (Wu and Kubota, 2008; Cliff et al., 2012; Juárez-López et al., 2014).

Irrigation supply is important for consistent yield and crop quality, yet the agricultural sector faces increasing competition from household and industry demands which reduce the availability of fresh water. In addition, it is well argued that climate change will contribute to increasing water scarcity in the future. Consequently,

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water resources available for agriculture will need to be used more efficiently. In this regard, deficit irrigation (DI), based on the application of amounts of water lower than those actually required by the crop, is a prime tool to optimize water use efficiency (WUE). Two innovative water-saving DI techniques that are considered promising in terms of water saving potential are regulated deficit irrigation (RDI) and partial root zone drying (PRD) which mainly differ in supply strategy (Fereres and Soriano, 2007). Given the differences in soil-water dynamics, plant growth and crop productivity may be different under PRD and RDI (Spreer et al., 2007, 2009; Romero et al., 2015). For example, soil water dynamics are more 'static' under RDI than PRD, and on the other hand, PRD influences plant physiology (abscisic acid production), water relation and nutrient mineralization processes (Wang et al., 2012). Therefore, with the same water savings, PRD generally shows higher WUE than RDI. Much information is available on the potential benefits of DI strategies in maximizing WUE in crop production (Chai et al., 2016). However, results relating to the impacts of DI on the nutritional quality and antioxidant components (i.e. lycopene and β-carotene, vitamin C and phenols) in tomato are inconclusive. For example, Atkinson et al. (2011) found that levels of lycopene and β-carotene decreased in response to water stress. However, Jensen et al. (2010) found a 10% increase in antioxidant contents under PRD as compared to fully-irrigated fresh tomato plants. Theobald et al. (2007) also reported an increase of lycopene up to 27% in PRD-irrigated fruits. An enhancement of lycopene and β-carotene contents was also reported by Favati et al. (2009). Such increases in antioxidant activity under DI are a very desirable characteristic that enhance the health-promoting value of tomatoes while saving substantial amounts of water.

Previous studies also revealed that water stress during fruit development elevated the total phenolic (Barbagallo et al., 2013) and vitamin C contents (Dumas et al., 2003; Favati et al., 2009; Barbagallo et al., 2013) in tomato. The relationship between water availability and the contents of vitamin C, lycopene and other antioxidants in tomato, however, are complex and apparently cultivar-dependent (Dumas et al., 2003; Zushi and Matsuzoe, 1998). Therefore, further studies are needed in wider ranges of environmental, genetic, and management conditions to understand the interaction effects of these factors on antioxidant biosynthesis in tomato fruits. Thus, the objective of this study was to investigate the influences of PRD and RDI techniques on vegetative and reproductive growth, gas exchange and fruit yield as well as lycopene, β-carotene, vitamin C and total phenolic compounds and total antioxidant activity of fruits from two commercial tomato cultivars.

2. Materials and methods

2.1. Plant materials and growing conditions

The study was performed on two commercial tomato (*Solanum lycopersicum* L.) cultivars: *Matina*, an heirloom, early-indeterminate variety of German origin reported as drought-tolerant (Allerstorfer, 2014) and *Cochoro*, a determinate, Ethiopian cultivar that has been shown to perform well under DI. Seedlings were cultivated in trays until the development of 4–5 true leaves and then were transplanted into plastic pots. Single plants were established in a split-root setup constructed with two 18 cm × 18 cm pots bound together to divide the rooting system of each plant hydraulically in isolated compartments as shown in Fig. 1. Pots were filled with 5 kg of uniformly air-dried peat/sand mixture (1:1 by volume).

The study was conducted under greenhouse conditions from June to December 2014 at University of Hohenheim in Stuttgart, Germany. Plants were irrigated daily by watering both root compartments until the first plant truss developed. Thereafter, plants were subjected to different irrigation treatments. Plants were fertilized weekly by supplying 500 mL of nutrient solution prepared using professional NPK (8-8-6) fertilizer (WUXAL® Super with micronutrients) at a dilution of 1:1000. The final concentrations of nitrogen, phosphate, and potassium oxide in the nutrient solution were 0.0992, 0.0992 and 0.0744 g/L, respectively. For the PRD treatment, the nutrient solution was added to the corresponding root zone compartment that was receiving irrigation.

2.2. Water supply treatments

Plants were randomly arranged into three irrigation treatments assigned to complete randomized block design with four replications, commencing from the first truss development (30 days after transplanting) until the final harvest. Irrigation treatments included: full irrigation (FI) with 100% of water requirement applied to both sides of the root compartment, regulated deficit irrigation (RDI) with 50% of FI applied uniformly to both compartments, partial root-zone drying irrigation (PRD) with 50 % of FI applied to one root compartment. Irrigation was alternated between root zone compartments in 3–5 day intervals, dependent on when θ of the dry side had depleted to 6–10%. During the experimental period, soil water content (θ) of both compartments was recorded daily before and after irrigation using time domain reflectometry (TDR) (TRIME IMKO, Germany). The daily crop water requirement for the control treatment CWR_{FI} was estimated as shown in Eq. (1) according to a soil-water balance approach, where field capacity of the soil was set at 36.2% vol, θ_1 and θ_2 are the actual water content measured each compartment by TDR before irrigation and V is the volume of each soil compartment.

$$CWR_{FI} = V\left[(36.2 - \theta 1) + (36.2 - \theta 2)\right] \quad (1)$$

Daily crop water requirement for DIs ($CWR_{PRD,RDI}$) was calculated as

$$CWR_{PRD,\,RDI} = \frac{1}{2}CWR_{FI} \quad (2)$$

2.3. Measurements during plant growth

Stem height, leaf number, leaf area, truss number per plant as well as number of flowers were recorded throughout the experiment. Stem height was measured every two weeks after transplanting until the harvest. Leaf number and branches were counted and leaf length (*L*) and width (*W*) were monitored. Leaf area (LA) was determined as:

$$LA = kLW \quad (3)$$

where *k* is a constant value of 0.50 (Carmassi et al., 2007). Stomatal conductance was calculated as the mean of six measurements on the upper canopy of five fully expanded leaves per plant using a portable porometer (Decagon Device Model Sc-1) at ten day intervals 45–85 days after transplanting. Measurements were conducted from 12:00 to 14:00 and air temperature and relative humidity were recorded using a climate logger (Voltcraft model DL-120TH). During measurements, mean temperature was 24.5 ± 4.2 °C and mean RH was 34.6 ± 10.4%. Vapor pressure deficit (VPD) was determined as described by Allen et al. (1998).

2.4. Measurements of fruit yield and quality

Uniformly ripe healthy fruits were harvested from the middle plant region (third– fifth truss) 85 days after transplanting. Fruit yield including number of fruits, individual fruit mass, and total yield were determined. Water use efficiency (WUE) was calculated as the ratio between fruit yield (g) to total water use (L). Total